APPLIED PHYSIOLOGICAL MECHANICS

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harwood academic publishers
chur london new york

Published under license by:

harwood academic publishers gmbh
Postrasse 22
7000 Chur, Schweiz

Editorial Office for the United Kingdom:
Chansitor House
37/38, Chancery Lane
London WC2A 1EL

Editorial Office for the United States of America:
Post Office Box 786
Cooper Station
New York, New York 10003

Library of Congress Cataloging in Publication Data

Main entry under title:

Applied physiological mechanics.

(Biomedical engineering and computational series; v. 1 ISSN 0194-2778)
Includes bibliographies and index.
1. Biomedical engineering. 2. Human mechanics. 3. Human physiology. I. Ghista, Dhanjoo N. II. Series [DNLM: 1. Biomechanics. W1 BI854IH v. 1 / WE103.3 A652]
R856.A67 612'.0142 79-5384
ISBN 3-7186-0013-7

APPLIED PHYSIOLOGICAL MECHANICS

BIOMEDICAL ENGINEERING AND COMPUTATION SERIES

Volume 1

Applied Physiological Mechanics
edited by Dhanjoo N. Ghista

Volume 2

The Organs of Equilibrium and Orientation as a Control System
by Máximo Valentinuzzi

[redacted]

Editor's Introduction to the Series

Biomedical Engineering is in the throes of developing a well defined identity in the educational as well as professional set-ups. Since the educational framework is dependent on the professional set-up and need, let us probe into the etiology of this current status of Biomedical Engineering.

At this stage, Biomedical Engineers are primarily involved in deciphering physiological phenomena as well as in developing monitoring devices (for quantitating physiological processes) and prosthetic-rehabilitative aids. Such an activity finds its way to the clinician, in the form of gadgetry (via the industry), who ends up using the products but not necessarily closely working with biomedical engineers (except at a few medical centers). In fact the lack of such direct involvement of biomedical engineers, in day-to-day medical and surgical practice, is what has not given biomedical engineering the distinctive professional slot that it merits.

This syndrome may be due to the nature of educational backgrounds of biomedical engineers, as fashioned in turn by the structure of biomedical engineering educational and training programs. While the emphasis in these programs is primarily technological, the lack of an equally rigorous involvement with medical sciences precludes the trainees from having the capability to offer biomedical engineering solutions for medical disorders and surgical approaches. The trained biomedical engineer is on the other hand more comfortable in developing devices to, say, monitor some physiological activity or to assist body organ function, at the suggestion and as defined by the medical colleague.

This lacunae on the part of trained biomedical engineers involves them only indirectly and peripherally with day-to-day clinical activity. Not only does that fail to create a set-up in which biomedical engineers constitute integral components of the health care profession, but it also fails to create an awareness of the potential of biomedical engineering.

Thus with an ill-defined professional slot, the educational component of the discipline finds itself (at most universities) without a distinct home. Most programs are located in the colleges of engineering, in which case (for want of a well-identified professional need) they do not invariably enjoy departmental status, and moreover also suffer from the above described shortcoming of failing to inculcate a medical based outlook. The rare programs that are fortunate to be located in the medical school should on the other hand justify their existence and departmental status, by arranging to have their courses accepted as components of either undergraduate or postgraduate medical instruction and training. A distinct attempt must be made by them to elicit recognition of biomedical engineering as the foundational base of medical and surgical procedures, devices and techniques.

Biomedical engineering books likewise reflect the above delineated approaches of biomedical engineering educators and researchers. Clearly, a definite thrust is needed to help biomedical programs enable their trainees to work shoulder to shoulder with their medical and surgical colleagues, in being able to interpret and develop solutions for a diagnosis and therapy, the guts of medical practice. While such a purposeful orientation of the series cannot be achieved right away, this at least is our long term intent.

Dhanjoo N. Ghista

PREFACE

Physiological processes are intricately elegant. However, in order to understand and appreciate their intricacies, we need to invoke the appropriate rigor of mechanics disciplines to represent them. Although, Biomechanics has made significant advances in the past two decades, yet one only has to think of the mechanisms of cardiac excitation and contraction and bone growth to realize that we do not currently have unified mechanics formulations for these phenomena. This is because hitherto physiological mechanics has primarily entailed the study of physiological processes by employment of the state-of-the art mechanics rigor, rather than the delineation and study of complex mechanics phenomena governing a physiological process. This former mode of physiological mechanics research has been conducive to the present-day emphasis on the development of monitoring-diagnostic and organ assist type of devices, rather than of therapeutic approaches (which would result from the latter mode of research).

In the context of this setting, the title of this book, namely Applied Physiological Mechanics, implies a quantitative study of particular physiological processes by adroit formulations of mechanics so as to provide the basis of formulations of in vivo organ function evaluation and treatment. Within the framework of this book theme, our aim is to elucidate some select physiological phenomena and mechanisms, by invoking appropriate rigor in the pertinent disciplines of Applied mechanics (such as elasticity, Fluid mechanics, Vibration theory). It is impossible to do justice to the entire domain of physiological mechanics; only a handbook can provide such a comprehensive treatment. Hence, particular topics are selected by virtue of their need for comprehensive analysis and treatment.

Each chapter is a fairly comprehensive presentation of the physiological topic, and demonstrates the gainful employment of mechanics in fulfilling our above mentioned aim by providing the foundations of monitoring-diagnostic applications of the physiological processes. No doubt a reasonably advanced (senior undergraduate to first year graduate type) level of mechanics background is expected of the reader of the book. When the book is employed as a text book in a "Physiological Mechanics" or "Quantitative Physiology" course, the instructor would (in some cases) need to provide a brief coverage of the mechanics foundations of the concerned analysis employed in that chapter.

The book consists of five physiologically based divisions. The first section is on Bioenergetics and Biomaterials.

Herein, evolution is described as an energy related process of increasing cellular orderliness, involving a combination of subsystems of lesser entropy and greater information. The living organism is simulated as a thermodynamic system, which employs its energy intake to do muscular work, for cellular growth and reproduction. The energy intake also maintains the integrity of the cells of anatomical tissues, whose strain energy density functions govern their deformation response to loadings regimes; the associated mechanical properties for both soft and hard tissues are provided. The waste energy is expelled as heat; the modeling of heat transfer (by conduction through the tissues and convection through the blood vessels) is shown to govern the distribution of body temperature (from the core to the skin), based on the nature of skin-environment heat exchange conditions.

The subject matter of the second section on Skeletal Mechanics, although currently more fundamental in nature, has powerful potential therapeutic applications. In the area of bone remodeling, the plausible mechanisms as well as the associated experimental studies and theoretical formulations are presented for linking bone loading, stress distribution (accounting for the bone geometry), strain distribution in the bone, piezoelectric polarization and potential, and the material time derivative (characterizing bone remodelings); computational developments, of the presented models governing the concerned phenomena, would help in accounting for the irregular skeletal geometry to develop quasi precise applications in controlling remodeling, fracture healing and prevention of disuse osteoporosis. The other topic in this section deals with the mechanism of low frictional coefficient lubrication in articular joints and its relation to the joint load carrying capacity, which information is useful for the understanding of elevated frictional coefficient and in general of the mechanical factors in osteoarthritis (for the development and interpretation of evaluation measures for pathological joints). It is interesting to know that Bichromatic microscopy and Scanning electron microscopy of Ferrograms of synovial fluid aspirates of degenerative arthritic joints have revealed presence of cartilagenous, osseous, meniscal and synovial parts.

The third section is on Cardio-Pulmonary Mechanics. The chapter on Mitral valve deals with the stress-deformation and vibration analysis of the mitral valve leaflet, resulting in the development of nomograms enabling the computation of the associated values of the leaflet stress and elastic modulus corresponding to a set of monitorable values of the leaflet size parameter, deformation and pertinent frequency of the heart sound vibrational spectrum; the set of values of the leaflet stress and modulus enables characterization of the normal and diseased states of the mitral valve leaflet. Vascular elasticity, the subject of the following chapter, is of homeostatic importance in health and disease. The chapter provides empirical as well as rigorous mechanics formulations (with their detailed derivations) for determining the (linear and nonlinear) elasticity parameters, of relevance in characterizing arterial disease.

Compared to cardiovascular mechanics, pulmonary mechanics is in a relatively developing stage. This is why three chapters are assigned to fairly comprehensively treat this field. These chapters together provide the lung macro-micro structural mechanics and the pulmonary airway mechanics based foundations of the regional distributions and interactions of the lung structures pressure-deformation, the gas exchange and blood gas concentrations characteristics in health and disease, for (i) characterizing and distinguishing alveolar and bronchial inflammation, constriction and congestion (with and without capillary pressure elevation), due to, say, emphysema, bronchitis, pneumonia, edema, as well as for (ii) quantitative guidelines for administration of anesthesia and positive pressure mechanical ventilation.

The fourth section is Uterine and Urological Mechanics. The passive and contractile properties of the uterus and its mechanics during labor are presented; it is shown that the biomechanics of the uterus during labor is concerned with (i) the influence of geometrical changes of the uterus in labor to amplify the contractile tension of the fundus of the uterus, (ii) the influence of uterine contraction of cervical dilatation, (iii) the mechanics of dilatation of the cervix in response to the fetal head-to-cervix pressure, and (iv) the response of the cervix to repeated contractile stretches. The next two chapters deal with the mechanics of the kidney and the upper urinary tract. The mechanics of renal functions at the nephron, glomerular and tubular levels are presented along with the associated clinical evaluations of renal perfusion, glomerular filtration rate and renal tubular function. Following that, a simulation model of the urometrogram is developed to link the urine flux to the parameters of the urometrogram derived pressure-time variations, and explain the function of the uretero-vesicle junction, the mechanism of upstream migration of bacteria, and the consequences of disorders of the ureteral peristallic activity.

The final section, on the Mechanics of Ocular and Vestibular organs, deals with the regulation and measurement of the intraocular pressure, modeling of the equilibrium-orientation providing function of the vestibulo-ocular reflex, and clinical vestibular analysis. Rigorous mechanics analyses are presented for (i) the applied force versus deformation (or associated induced eyeglobe volume change) characteristics, in terms of the intraocular pressure, geometrical and mechanical properties of the corneal-scleral shell, and (ii) the induced eyeglobe volume-time variations, in terms of the ocular pressure-time variations, aqueous humour inflow-outflow rate, blood vessel volume, ocular and blood vessel rigidities. These analyses are employed for (i) the design and calibration of Indentation, Applanation and Suction-cup type tonomerors, and Ophthalmodynamometer, and (ii) the detection of carotid occlusions. The final chapter is on the Vestibulo-ocular reflex (VOR), in which case the oculomotor system interacts with the vestibular system to arrange for compensation of the head movement by the eye movement in order to maintain the image of the world stable on the retina. A comprehensive mathematical model of the VOR is derived, to simulate rotatory test data, for interpretation of vestibular disorders; a microcomputer based system is developed for automated analysis of rotatory vestibular tests.

The analyses of the various physiological phenomena and mechanisms in the book chapters have entailed graduate level treatments of Applied Mechanics disciplines, namely Elasticity, Plates and Shells, Vibration, Fluid Mechanics, and Control system. The course developed from this book would hence assume acquaintance with these subjects. However, aside from its use as a course text, the book can provide the starting blocks of several avenues of research, as suggested above.

ACKNOWLEDGMENT

To all my dear departed ones:

To my grandparents, who developed the environment of my upbringing,

To my aunts and uncles, who showered me with affection,

To my father, whose departure has left a permanent vacuum,

I pay homage!

And I thank Him Lord Anandamurti,
for nurturing me in such a loving abode.

Dhanjoo Noshir Ghista

Houghton, April 1979

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