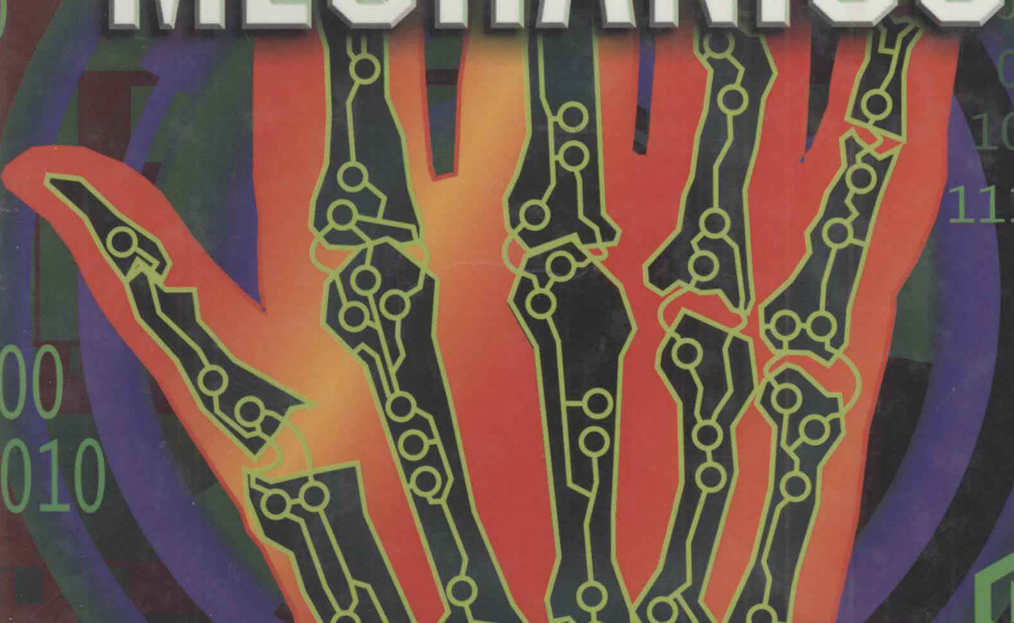
APPLIED BIOMEDICAL ENGINEERING MECHANICS



Dhanjoo N. Ghista

CRC Press
Taylor & Francis Group

APPLIED BIOMEDICAL ENGINEERING MECHANICS

Dhanjoo N. Ghista

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

No claim to original U.S. Government works
Printed in the United States of America on acid-free paper
10 9 8 7 6 5 4 3 2 1

International Standard Book Number-13: 978-0-8247-5831-8 (Hardcover)

Library of Congress Cataloging-in-Publication Data

Ghista, Dhanjoo N.
Applied biomedical engineering mechanics / Dhanjoo N. Ghista.
p. ; cm.
Includes bibliographical references and index.
ISBN 978-0-8247-5831-8 (alk. paper)
1. Biomechanics. 2. Human mechanics. I. Title.
[DNLM: 1. Biomechanics. 2. Cardiovascular Physiology. 3. Diagnostic Techniques and Procedures. 4. Movement--physiology. 5. Musculoskeletal Physiology. 6. Sports--physiology. WE 103 G422a 2008]

QP303.G54 2008
612.7'6--dc22 2008003601

Visit the Taylor & Francis Web site at
http://www.taylorandfrancis.com

and the CRC Press Web site at
http://www.crcpress.com

APPLIED BIOMEDICAL ENGINEERING MECHANICS

In Loving Memory of

My Dearest

Father and Mother,

Grandparents and Great-Aunt,

Maternal and Paternal Uncles and Aunts

Preface

There has been a long-standing need for a comprehensive book on biomedical engineering that covers the analyses and applications of biomedical and physiological systems as well as human fitness and sports. In addressing this need, this book can serve as a definitive textbook as well as a major reference source.

The book's contents include the following:

1. An introductory chapter that develops the foundation of how physiological systems and their assessment can be described by means of governing differential equations, whose parameters can be combined into nondimensional physiological diagnostic indices
2. A section on cardiological engineering mechanics, including three chapters dealing with cardiac mechanics, left-ventricular contractility indices, and vascular mechanics
3. A section on pulmonary engineering mechanics, including three chapters on lung ventilation and disease diagnosis, lung gas-transfer mechanics and determination of O_2 and CO_2 diffusion coefficients, and lung-ventilatory indices for extubation of chronic obstructive lung disease patients from mechanical ventilatory support
4. A section on glucose–insulin regulation (in diabetes) engineering mechanics, which has three chapters covering glucose–insulin regulatory analysis, responses of glucose and insulin to glucose tolerance tests, and indices for differential diagnosis of diabetic patients and those at risk from becoming diabetic
5. A section on orthopedic engineering mechanics, involving three chapters dealing with the analyses and design of internal bone fracture-fixation plates as well as the design analyses of human spinal vertebral body and intervertebral disc as optimally designed human body structures
6. A section on fitness and sports engineering mechanics, on (i) heart-rate variation during and after exercising on treadmill, optimal walking, and jogging modes requiring minimal work expenditure, and analyses of hip joints to determine their stiffness and damping coefficients, and (ii) analyses of sports events

(namely soccer, baseball, basketball, and gymnastics) delineating the analytical basis for intricacies of their techniques and performance (such as the basis of curving soccer kicks, baseball throws and batting technique, and high-performance of Yurchenko layout vault)

In addressing this comprehensive range of topics, the book covers a wide spectrum of engineering mechanics disciplines of solid and fluid mechanics, dynamics and vibrations, gas diffusion and transfer, and control systems. The book can therefore be ideally employed as a textbook for a biomedical engineering course at the senior undergraduate level or at the graduate level.

In the first section on cardiological engineering mechanics, Chapter 2 describes left ventricular (LV) mechanics. This chapter deals with (1) determination of the pressure drop across a stenotic valve, (2) determination of the constitutive properties of mitral and aortic valves from their static and dynamic analyses, (3) determination of the intra-LV blood flow velocity and pressure distributions (in normal and myocardial infarcted cases) before and after nitroglycerin administration as a means of deciding if coronary bypass surgery would benefit patients with myocardial infarcts, and (4) LV passive and active elastances, as measures of LV pressure dynamics response to LV volume changes and of LV contractility.

Chapter 3 deals with left ventricular contractility indices. Here, we first determine the wall stress (σ) in an ellipsoidal model of the LV, normalize it (to σ^*) with respect to LV pressure, and employ this noninvasive computational index $(d\sigma^*/dt)_{max}$ as a contractility index. It is found that this index has a good correlation with the traditional LV contractility index $(dp/dt)_{max}$, which requires determination of LV pressure by cardiac catheterization. It is also found that more ellipsoidally shaped LVs have higher values of this contractility index $(d\sigma^*/dt)_{max}$. The second part of this chapter deals with the formulation of the sarcomere model of a myocardial-wall fiber, and the expression of its contractile element characteristics (of force vs. shortening velocity) in terms of the monitorable data (of LV pressure, volume, wall thickness, and myocardial volume). Again, this index bears a good correlation with $(dp/dt)_{max}$.

Chapter 4 is on vascular biomechanics. It deals with (1) noninvasive determination of aortic pressure (as well as aortic stiffness and peripheral resistance) in terms of LV volume (ejected into the aorta) versus time data, and auscultatory diastolic and systolic pressures; (2) determination of aortic constitutive property (of E vs. σ) from measurement of pulse wave velocity, aortic dimensions, and auscultatory diastolic pressure; (3) arterial bed peripheral resistance (as the ratio of mean arterial pressure and flow rate) and arterial impedance (as the ratio of arterial pulse pressure and flow rate); (4) the phenomenon of wave reflection at aortic (arterial) bifurcations; and (5) the composition and amplitude variation of the composite wave in aorta, with an interesting postulation that in an ideal situation the heart is located at the site of minimum value of the composite wave pressure amplitude so that it has minimal after-load.

The second section of the book is on pulmonary engineering mechanics. In this section, Chapter 5 deals with lung ventilation modeling (with application to lung disease determination) based on the differential equation of lung volume (V) response to lung driving pressure (P_N) (in an intubated patient), in terms of lung compliance (C) and resistance to airflow (R). These parameters, R and C, are then combined into nondimensional ventilatory performance indices. The lung volume response expression can also be fitted to the lung volume data in terms of R and C as well as the product of pressure and compliance terms. The corresponding ventilatory performance index would not require intubation of the patient. A two-lobe lung model is also developed, and its total lung volume expression is determined. By fitting this expression to the monitored lung volume data, we can evaluate R, C, and ventilatory indices of left and right lung separately.

Chapter 6 deals with lung gas-transfer performance analysis. We first deal with inspired and expired air composition analysis, based on mass balances. We then derive the expressions for O_2 and CO_2 diffusion coefficients in terms of O_2 consumption rate and CO_2 production rate (from the inspired–expired air composition analysis), alveolar air O_2 and CO_2 partial pressures, and O_2 and CO_2 concentrations in the venous blood.

Chapter 7 deals with evaluation of the lung status of mechanically ventilated intubated patients, and the index for deciding that they are ready to be weaned off the mechanical ventilator. This index is expressed in terms of lung capacitance (C) and flowrate resistance (R), as well as monitored tidal volume (TV), breathing frequency (RF), and peak inspiratory pressure (P_k). The values of R and C are obtained by again modeling the lung ventilatory volume response to its driving pressure, and evaluating them in terms of the monitored values of lung volume (specifically, tidal volume) as well as inspiratory peak pressure and pause pressure (when the lung volume is maximum).

In the third section on glucose–insulin regulation (in diabetes) engineering mechanics, Chapter 8 first deals with the basics of blood glucose–insulin regulatory mechanics. This entails second-order differential equations modeling and solutions of glucose and insulin blood-concentration responses to glucose injection for three different types of glucose inputs: glucose input as a step function, glucose input as an impulse function, and glucose input as a rectangular pulse. The solutions of the governing equations of glucose and insulin blood concentrations to these three inputs are expressed in terms of the intrinsic parameters (α, β, γ, and δ) that relate the time rates of change of blood glucose and insulin concentrations to blood glucose and insulin concentrations as well as glucose input function, in the form of two first-order differential equations. These two first-order differential equations are combined into second-order differential equations of glucose and insulin responses to glucose inputs. These second-order differential equations have parameters of attenuation (or damping) constant (A) and system natural frequency (ω_n), which are in turn expressed in terms of the intrinsic parameters (α, β, γ, and δ). The relations between these parameters A and ω_n (and hence between α, β, γ, and δ), in turn, enable us to designate the system response as underdamped (for normal subjects), overdamped (for diabetic subjects), and critically damped (for subjects at risk of becoming diabetic).

Chapter 9 entails analytical simulation of the oral glucose tolerance test involving the governing equation of blood glucose concentration (y) response to glucose ingestion. This governing equation is a second-order damped-oscillatory differential equation in glucose concentration (y) response to an impulse glucose-input function. This model equation parameters are the system's damping constant (A), natural frequency (ω_n), and damped frequency (ω_d). The equation is solved for (1) underdamped response pertaining to the data of "glucose concentration versus time" for a normal subject and (2) overdamped response to simulate the "glucose concentration versus time" data of a diabetic subject. The equation solutions are fitted to the data, and the model parameters are determined analytically.

The values of the model parameters are distinctly different for normal and diabetic subjects. The purpose of this analytical simulation of the glucose-tolerance test (by means of the solutions of the governing differential equation) is to provide an analytical method to characterize the glucose concentration (y) versus time data in terms of the values of the model parameters. This is deemed to more reliably represent the entire data (of y vs. t), instead of merely employing discrete values (y) of the data to differentially diagnose diabetic subjects and borderline diabetic subjects (whose data is represented by a critically damped solution of the governing equation) from normal subjects.

Chapter 10 constitutes solutions of the governing differential equations of glucose concentration (y) and insulin concentration (x) to impulse glucose input function (to simulate glucose tolerance test data). These solutions' expressions (representing underdamped, overdamped, and critically damped responses) of the system differential equations model are fitted to the "y versus t" and "x versus t" data. Depending on the value of the regression correlation coefficient, a particular response function (i.e., underdamped or overdamped or critically damped function) is selected to best fit the data. It is found that the data of some subjects, who were clinically classified as normal or diabetic, are better fitted by means of a critically damped solution; this then placed these subjects in the category of being borderline diabetic or at risk of becoming diabetic. Next, the model parameters are combined together in the form of indices characterizing glucose and insulin concentration data. These two indices are further combined into one index, which is evaluated for all the patients studied. It is found the values of this index fall in distinct ranges for normal subjects, diabetic subjects, and borderline diabetic subjects. Hence, it can be concluded that this index value can be reliably employed for the differential diagnosis of diabetes.

We now move to Section IV on orthopedic engineering mechanics. Therein, Chapter 11 deals with osteosynthesis of fixation of fractured bone by means of a bone plate and screws, when the bone–plate assembly is subjected to axial loading and bending loading. Both analytical and finite-element solutions are carried out. The issue that is explored at length is to design the placement of the screws (with respect to the fractured site) and the stiffness grading of the plate, such that at the fracture site the bone callus is not subjected to tensile stresses and that away from the fracture site the bone has minimal stress shielding. A novelty explained in this chapter is our deploying a helical plate for fixing bones with helical cracks. A detailed finite-element stress analysis is carried out to demonstrate how a helical plate (and its screws) can be employed to provide maximal stiffness to the fractured bone–plate assembly. The advantage of the helical plate is that the screws fixing the plate to the bone are in different planes, and thereby provide optimal stiffness to the fractured bone–plate assembly under varied loading conditions.

Chapter 12 is on the analysis of the spinal vertebral body (VB), modeled as a hyperboloid cortical-bone shell, subjected to axial, bending, and torsional loadings. It is shown that under all of these loading states, the forces are transmitted across the VB (from the top to the bottom of the VB) as axial forces through the generators of the hyperboloid shell. In other words, the vertebral body is shown to be so intrinsically shaped and designed such that it has only axial forces transmitted through it. This makes it bear heavy loads with minimal weight (represented by a thin cortical shell thickness). We can employ this intrinsically optimal VB design concept to propose the design of an anterior fixator made up of two rings (fixed to the upper and lower end-plates) and connected by straight generators to form a hyperboloid shaped structure (resembling a cane stool), into which the fractured vertebral body fragments can also be deposited to eventually form a solid fixator.

We next go on to analyze the intrinsic design of an intervertebral disc. The disc is modeled as a thick-walled isotropic cylinder, filled with nucleus-pulposus (NP) fluid material. When this disc model is axially loaded, the NP fluid is also pressurized, in addition to the disc wall being stressed by the axial loading. The pressurized NP then exerts radial pressure on the cylindrical disc wall, and subjects it to further radial and circumferential stresses. Now the disc wall material has a stress-dependent elastic modulus (typical of anatomical structures). Hence when the disc wall is further stressed by the radial pressure exerted on it by the NP fluid, its elastic modulus value is enhanced, and the resulting radial displacements do not increase in the same proportion as the increasing axial load. In other words, the disc is able to contain the radial displacements under increasing axial loading, without bulging radially. This is the feature of its optimal intrinsic design. Now, when a disc has radial cracks (due to being excessively loaded), the NP fluid seeps out of the cracks onto the surrounding nerve roots, and causes back pain. The orthopedic solution for such a herniated disc is to denucleate the herniated disc. However, based on our analysis, if the NP fluid is removed, then the disc wall is no longer radially stressed and its modulus is not correspondingly increased. In fact, we have shown that a denucleated disc undergoes greater deformation compared to a normal disc for the same level of loading. Hence, a better solution would be to place a jell sac in place of the NP fluid, which can simulate the role of the NP fluid.

We now come to the final section on fitness and sports engineering mechanics. Here, Chapter 14 describes the biomechanics of a fitness index, optimal jogging modes, and assessment of the hip joint pathology. The first part of the chapter deals with the formulation of a cardiac fitness index composed of the parameters of a first-order differential equation modeling of heart-rate response during and after treadmill exercising. This index is shown to clearly differentiate fit subjects from unfit subjects. We next analyze human jogging by stipulating that for an optimal jogging mode, a subject would involve minimal muscle actuation if he or she were to have the stride frequency of the free-swinging leg simulated as a double-compound pendulum. The stride frequencies are derived in terms of the limb segment's masses, lengths, and locations of the center of mass of upper and lower limb segments, and the mass moment of inertia at the centers of masses of the upper and lower limbs. The lower of the two computed stride frequencies is employed to stipulate the optimal jogging leg frequency. This optimal jogging mode is especially recommended for subjects undergoing cardiac rehabilitation. Next, we want to ensure that jogging is not causing hip problems. For this purpose, we model the swinging leg by means of a second-order differential equation of free damped oscillatory motion of the swing angle (θ) of the simple compound leg-pendulum model, in terms of a viscous damping constant (b), and a joint-stiffness parameter (k). The solution of the governing differential equation is obtained (for the case of small damping) as a "θ versus t" damped-oscillatory response. From the measured amplitudes of the extreme values of θ, we then evaluate the parameters b and k, to characterize the joint pathology.

Chapter 15 analyzes how spin can impart lateral acceleration and force (due to the magnus force effect) to a soccer ball (while kicking it), and make the ball swerve. The resulting planes of the ball trajectory (normal to the ground) are computed to simulate some real data derived from videos of world-cup soccer matches. It can be seen how (1) a right footer taking a corner kick from the left corner can make the ball swerve toward the goal (to deceptively beat the goal keeper) by imparting an anticlockwise spin to the ball and (2) how a left footer, taking a corner kick from the left corner, can make the ball swerve away from the goal (to facilitate heading into the goal) by imparting a natural clockwise spin to the ball.

Chapter 16 describes the mechanics of pitching a baseball, of ball–bat interactions, of batting, and of an optimal bat, replete with theory and applications in the form of simulations. The first part of the chapter demonstrates (1) how a pitcher imparts spin-induced lateral deflection to the baseball to pitch a curve ball and (2) how spin-induced drop and lift can be imparted to the baseball. In the second part of the chapter, on bat–ball collisions, the primary emphasis is on where the ball should strike the bat, such that maximum energy is transferred by the bat to the ball or maximum ball speed is imparted to the ball. This "sweet spot of the bat" can be defined as the center of percussion, or the node of the fundamental bat-bending vibrational mode. The third part of the chapter, on the mechanics of the bat, deals with the ideal bat weight for a batter. Now based on the conservation of momentum equation for bat–ball collision, a player can transfer maximum momentum to the ball either (1) by using a lighter bat and swinging his or her arm more vigorously or (2) by using a heavier bat and leaning his or her body more into the ball when striking it.

The final Chapter 17 is on the dynamic analysis of gymnastics' Yurchenko layout vaulting. The Yurchenko layout vault, pioneered by Natalia Yurchenko in the 1982 World Cup Gymnastics competition, comprises a forward running approach, followed by a cartwheel half-turn to orient the body such that the back faces the vaulting horse at the point of takeoff from the springboard. The gymnast then takes off from the springboard using a back-flip action to impact the horse, and finally completes a one-and-half somersault rotation with the body fully extended (or laid out) before landing. The chapter discusses the optimal technique for this Yurhcenko layout vault (for a given gymnast), defined by a decrease in horse impact time, and the position and alignment of the body segments at the end of the postflight. For this purpose, a five-segment rigid-linked model is developed, which consists of the hand, whole arm, upper and lower trunk, and the whole leg. In this model, each segment has a center of mass (CM), the segments are linked by hinges, gravitational forces are exerted at the segment's CMs, the ground reaction forces on the segments are considered to act at the centers of pressure, and the effect of the segment's muscles is to produce moments at the joints. The governing equations of motion are formulated for the segments. For input anthropometric, kinematics, and ground reaction-force data, we can obtain solutions for the muscle moments at the joints and for the joint reaction forces. The optimization procedure determines the set of joint torques and kinematics required to produce this optimal technique (as indicated above), in terms of vault duration and loading angle.

As can be noted, the book covers the detailed analyses of (1) cardiological, pulmonary, glucose–insulin regulation systems, to address their medical applications in terms of disease assessment, (2) the most effective orthopedic osteosynthesis designs as well as of spinal vertebral body and intervertebral disc that make them intrinsically optimally designed structures, and (3) of sports events and simulations, to provide insights into the techniques required for high performance of these sports events. The book is tailored to serve as a textbook for a one- or two-semester biomedical engineering mechanics course. However, it can also be effectively employed by clinicians for assessment of physiological systems, by anatomists to obtain insights into optimal anatomical designs in nature, and by sportsmen and sports coaches to optimize performances.

Dhanjoo N. Ghista
Singapore
Email: d.ghista@gmail.com

Acknowledgments

I am very grateful to my colleague Assistant Professor Dr. Sridhar Idapalapati for his immense help in making the book manuscript ready for production. I am also thankful to Satttu Sreenu Babu for his help in wordprocessing the chapters and in formatting them for production.

Author

Professor Dhanjoo Ghista is a pioneer and a world authority in biomedical engineering. He has developed biomedical engineering programs and departments at universities in the United States, Canada, India, United Arab Emirates, and Singapore. He has published several books on many aspects of biomedical engineering, including physiological mechanics, human body mechanics and dynamics, cardiac mechanics, cardiovascular engineering and physics, orthopedic mechanics, osteoarthro mechanics, spinal injury medical engineering, biomechanics of medical devices, cardiac perfusion and pumping engineering, and biomedical and life physics. His academic involvements span engineering, medical, and even social sciences (wherein he has authored a definitive book on socio-economic democracy and the world government, to provide the basis of sustainable communities and sustainable peace).

In an academic career spanning over 40 years, he has taught many courses, including physiological engineering, clinical engineering, biomechanics, and cardiovascular engineering. He has published over 400 papers in peer-reviewed journals and conference proceedings. He has guided several PhD students and postdoctoral fellows, many of whom have gone on to hold responsible positions in universities and research institutes. He has been editor of *Automedica* and *Renaissance Universal*, and has served on the editorial boards of *Mechanics in Medicine and Biology* and *Biomedical Engineering Online*. He has been reviewer of grant proposals for several national agencies, including the International Spinal Trust, Medical Research Council (Canada), Ontario Research Foundation, and Agency for Science and Technology (Singapore).

Author

Dhanjoo N. Ghista (Formerly) School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore. E-mail:d.ghista@gmail.com

Contributors

A. Terry Bahill Department of Systems and Industrial Engineering, University of Arizona, Tucson, Arizona, U.S.A.

David G. Baldwin (Formerly) Major League Baseball, Yachats, Oregon, U.S.A.

Sridhar Idapalapati School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore

Leslie Jennings Department of Mathematics and Statistics, University of Western Australia, Perth, Australia

Michael Koh School of Sports, Health and Leisure, Republic Polytechnic, Singapore

Ramakrishna Kotlanka (Formerly) School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore

Geok Hian Lim School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore

Xiang Liu (Formerly) School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore

Kah Meng Loh (Formerly) Division of Engineering, Science & Technology, University of New South Wales Asia, Singapore

Jor Huat Ong School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore

Rohit Pasam Department of Bioengineering, University of Illinois at Chicago, Chicago, Illinois, U.S.A.

Meena Sankaranarayanan Signal Processing Department, Institute for Infocom Research, Singapore

Dittakavi Sarma Department of Biomedical Engineering, Osmania University, Hyderabad, India

Liang Zhong Department of Cardiology, National Heart Center, Singapore