***Open Access Maced J Med Sci* electronic publication ahead of print, published on April 08, 2018 as https://doi.org/10.3889/oamjms.2018.149**

ID Design Press, Skopje, Republic of Macedonia
Open Access Macedonian Journal of Medical Sciences.
https://doi.org/10.3889/oamjms.2018.149
eISSN: 1857-9655
Review Article

Advanced Computational Methods in Bio-Mechanics

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Citation: Al Qahtani WMS, El-Anwar MI. Advanced Computational Methods in Bio-Mechanics. Open Access Maced J Med Sci. https://doi.org/10.3889/oamjms.2018.149

Keywords: Biomechanics; Finite Difference Method; Finite Element Method; Finite Volume Method; Applications; Computational Techniques; Computational Methods

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Received: 30-Dec-2017; **Revised:** 22-Feb-2018; **Accepted:** 01-Mar-2018; **Online first:** 08-Apr-2018

Funding: This research did not receive any financial support

Competing Interests: The authors have declared that no competing interests exist

Abstract

A novel partnership between surgeons and machines, made possible by advances in computing and engineering technology, could overcome many of the limitations of traditional surgery. By extending surgeons’ ability to plan and carry out surgical interventions more accurately and with fewer traumas, computer-integrated surgery (CIS) systems could help to improve clinical outcomes and the efficiency of healthcare delivery. CIS systems could have a similar impact on surgery to that long since realised in computer-integrated manufacturing. Mathematical modelling and computer simulation have proved tremendously successful in engineering.

Computational mechanics has enabled technological developments in virtually every area of our lives. One of the greatest challenges for mechanists is to extend the success of computational mechanics to fields outside traditional engineering, in particular to biology, the biomedical sciences, and medicine. Biomechanics has significant potential for applications in orthopaedic industry, and the performance arts since skills needed for these activities are visibly related to the human musculoskeletal and nervous systems.

Although biomechanics is widely used nowadays in the orthopaedic industry to design orthopaedic implants for human joints, dental parts, external fixations and other medical purposes, numerous researches funded by billions of dollars are still running to build a new future for sports and human healthcare in what is called biomechanics era.

Introduction

The term biomechanics had been developed during the early 1970s. Biomechanics has been defined as the study of the movement of living things using the science of mechanics [1], while Biomedical Engineering is the engineering branch that is concerned with solving problems in biology and medicine. Biomedical engineers use principles, methods, and approaches drawn from the more traditional branches of electrical, mechanical, chemical, materials, and computer engineering to solve this wide range of problems. On the other hand, numerical methods are mathematical techniques for performing accurate, efficient and stable computations, using a computer, to solve mathematical models of biomedical systems.

Governing equations, material properties, mechanisms, etc., may lead to nonlinearities. Simulating, and analysing such complicated and challenging problems may be impossible to be done analytically. Where, the analysis is done in an iterative process of hypothesis and verification, including several steps of modelling, computer simulation and experimental measurements.

Branches and Applications of Biomechanics

As illustrated in Figure 1, human beings, Biomechanics can be divided into three major branches of applications; Sports Biomechanics (kinematics), Orthopedic Biomechanics (kinetics) and Anthropometry.

Biomechanics is widely used in orthopaedic industry to design orthopaedic implants for human joints, dental parts, external fixations and other medical purposes. Biotribology is a very important part of the study of performance and function of biomaterials used for orthopaedic implants. It plays a vital role to improve the design and produce successful biomaterials for medical and clinical purposes.

Biomechanics is also applied to studying human musculoskeletal systems. Such research fields utilise force platforms to study human ground reaction forces and infrared videography to capture the trajectories of markers attached to the human body to study human 3D motion [2]. Research also applies electromyography systems to study the muscle activation. By this, it is feasible to investigate the muscle responses to the external forces as well as perturbations.

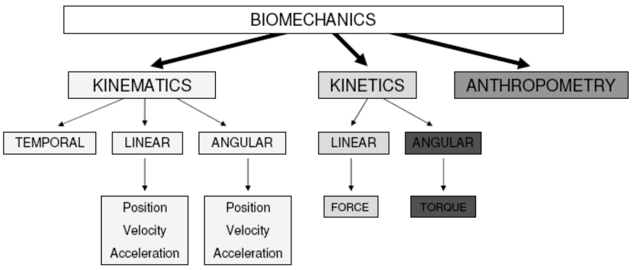

Figure 1: Major branches of mechanics used in most biomechanics studies [2]

Body displacements often lead to strains within the body. Strains are deformations that result in changes of shape within the body. These strains, in turn, lead to stress, the interior forces due to the stretching or compression of atomic bonds. These forces result in the acceleration of the material, affecting the motion and hence the evolution of the strains.

The equations of elasticity consist of Newton's law relating force to acceleration together with stress-strain relations (depends on the material) describing the force that results from a given strain. For sufficiently small strains the stress may be assumed to vary linearly with strain, resulting in the equations of linear elasticity. On the other hand, Rigid-body motions (translations and rotations) in which the body is simply moved as a rigid entity do not lead to any internal strain or stress.

Biomedical engineers start with a continuous mathematical model to explain an observed phenomenon in a biological system. Simulating and modelling such system is too difficult or impossible to be solved analytically. Therefore, a numerical analysis that used mathematical theories leads to algorithms for solving mathematical models approximately on computers. Continuous functions are approximated by finite arrays of values, and algorithms approximately solve the mathematical problem efficiently, accurately, and reliably.

For example, the application of imaging methods to assess solid and fluid biomechanical events is becoming increasingly powerful and important. Imaging methods have classically been used for assessing the relative motion of objects, such as blood cells in the microcirculation, or markers on tissues [3]. With the advent of CT, MRI and other molecular tagging methods, both solid and solute mechanics can be assessed. Case studies include simulation of tumour compression, experimental compression and ultrasound imaging, in vitro high - resolution breast tumour imaging and cardiac imaging are representing typical cases nowadays [3].

Biomedical engineers use/develop computer programs, which control precision and accuracy of the measurements and computations as an integral part of solutions to real-world bioengineering problems. There are tons of biomedical problems require the solution of nonlinear equations. Most nonlinear equations cannot be explicitly solved using analytical methods, however. Unlike linear equations, whose roots can be found using analytical methods, solvers need to be formulated to determine the roots of nonlinear equations.

Systems that have one independent variable can be modelled by ordinary differential equations, whereas systems with two or more independent variables require partial differential equations. The great majority of differential equations, especially the nonlinear ones and those that involve large sets of simultaneous differential equations, do not have analytical solutions but require the application of numerical techniques for their solution. Several numerical methods for differentiation, integration, and the solution of ordinary and partial differential equations are based on the concept of finite differences.

The calculus of finite differences enables to take a differential equation and integrate it numerically by calculating the values of the function at a discrete (finite) number of points. Another very useful application of the calculus of finite differences is in the derivation of interpolation/extrapolation formulas, the interpolating polynomials, which can be used to represent experimental data when the actual functionality of this data is not known [3]. Three basic formulations can be used in the representation of the PDE terms; Backward, Forward, and Central Finite Differences. On the other hand, a huge number of different schemes can be found in the literature for scanning time, or spatial domain(s).

Finite difference method changes the set of governing PDE into another set of algebraic equations, once this set is formulated in matrices form can be solved. Direct or iterative root finding, and/or matrix inverse can give solution(s) for the algebraic equations. On the other hand, drawbacks of using finite difference method appear in irregular domain boundaries, selecting spatial and time steps, and its effect on solution stability. Poor selection of these steps may alter the solution convergence rate and may lead to diverged or no solution.

The Finite element method (FEM) is a powerful computational technique for approximate solutions to a variety of engineering problems having complex domains subjected to general boundary conditions. Analyses by finite element become an essential step in the design or modelling of a physical phenomenon in various engineering disciplines. A physical phenomenon usually occurs in a continuum of matter (solid, liquid, or gas) involving several field variables. The field variables vary from point to point, thus possessing an infinite number of solutions in the domain.

FEM relies on the decomposition of the domain into a finite number of sub-domains (elements) for which the approximate systematic solution is constructed by applying the variational or weighted residual methods. FEM reduces the problem to a finite number of unknowns by dividing the domain into elements and by expressing the unknown field variable regarding the assumed approximating functions within each element. These functions (also called interpolation functions) are defined regarding the values of the field variables at specific points, referred to as nodes (connect adjacent elements). The ability to discretise the irregular domains with finite elements makes the method a valuable and practical analysis tool for the solution of the boundary, initial, and eigenvalue problems arising in various engineering disciplines [3].

Finite volume methods are closely related to finite difference methods. That finite volume method can often be interpreted directly as a finite difference approximation to the differential equation. However, finite volume methods are derived on the basis of the integral form of the conservation law, a starting point that turns out to have many advantages. Classical finite difference methods, in which derivatives are approximated by finite differences, can be expected to break down near discontinuities in the solution where the differential equation does not hold. Finite volume methods are based on the integral form instead of the differential equation. In one space dimension, a finite volume method is based on subdividing the spatial domain into intervals (the “finite volumes,” also called grid cells) and keeping track of an approximation to the function integral over each of these volumes. In each time step these values using approximations to the flux through the endpoints of the intervals to be updated. Rather than point-wise approximations at grid points, that break the domain into grid cells and approximate the total function integral over each grid cell, or the cell average of the function, which is this integral divided by the volume of the cell [4].

Instrumentation such as the blood pressure (BP) monitor, computed tomography (CT) or magnetic resonance imaging (MRI), and the microscope; have a common structure. In all cases, the computer controls the electronic interface (the user interface and data collection), which is connected to the subsystems that sense the tissue properties and control the sensor. The computers embedded in the instruments have helped to standardise the operation. Thus non-trained users can operate the BP monitor and other medical devices while being in better control of their healthcare. Computerized systems of sensor and controllers are undergoing continuous development for several goals like increasing accuracy, reducing the cost of testing and inspection, etc. [5].

Element elastic modulus values from the CT images were determined via two main steps. First, averaging element brightness values (B), based on the CT image pixels brightness data were calculated. The relationship between image brightness of normal and osteoporotic bone and density was used to estimate the density of each element.

The finite element model [6] was used to examine the mechanical response of normal and osteoporotic L5 human vertebral body under compressive stress. Results showed that during the elastic range of the vertebral bone there is a linear relationship between applied load and displacement, but with a different slope for normal and osteoporotic vertebral body. Further increase in the applied load increases the displacement especially for the osteoporotic vertebral body reaching 50% increase in the deformation more than the normal one. The proposed model can expect the maximum fracture risk in the L5 as well as detecting the beginning of osteoporosis.

A similar complex biomechanical analysis of the human lumbar spine was performed [7], aimed to improve the efficiency of conservative traction therapies and to prevent osteoporosis. The former concerns tension, the latter compression of the lumbar spine. As for tension, time-related in vivo elongations were measured during the regular traction hydrotherapy of patients. Based on the experimental results, parameter-dependent viscoelastic numerical tensile models of the lumbar functional spinal units were created for numerical simulation and parameter identification.

A research team from Katholieke Universiteit, Leuven, Belgium, studied the biomaterial surface characteristics modulate the outcome of bone regeneration around oral implants. Experimental investigations have demonstrated the importance of platelets and their activation for bone regeneration around implants. A higher amount of bone-to-implant contact has been observed on “micro rough” sandblasted/acid-etched versus “smooth” turned implant surfaces.

The team performed numerical demonstration [8] for the key role of activated platelets which is controlled by implant surface characteristics.

Dental implantology problems were numerically studied [9] [10] [11] from different perspectives. Results of these studies showed that implant stability depends on implant design parameters [12]. For example, increasing implant diameter and length generates better stress distributions on spongy and cortical bones. Approximate implant design equations and curves were obtained [9]. Bone stresses increase as bone level decreases with varying values depending on implant parameters.

Increasing value of the ratio between dental implant side area and its cross-sectional area reduces stresses transferred to cortical and spongy bones. Therefore, using implants with a higher ratio of side area to cross-section area, especially with the weak jaw bone, is recommended [11].

Recent numerical studies of rotary and reciprocating instruments proved that modelling of the instrument with equivalent circular cross-sectional area did not affect results quality, while the cross-sectional shape and its cutting angles could affect instrument cutting efficiency [13] [14]. The reciprocating system has great advantages over other root therapy instruments.

There are many examples of how applying biomechanics in changing equipment designs had improved sports performance. When improved javelin designs in the early 1980s resulted in longer throws that endangered other athletes and spectators, redesigns in the weight distribution of the “new rules” javelin again shortened throws to safer distances [15].

Aiming to break world records, many biomechanics studies aimed to improve performance in exercise and conditioning programs. Biomechanical studies of exercise movements and training devices serve to determine the most effective training to improve performance. Strength and conditioning professionals can better apply the principle of specificity when biomechanical research is used in the development of exercise programs. Computer-controlled exercise and testing machines are another examples of how biomechanics contributes to strength and conditioning [2].

Movement safety, or injury prevention/treatment, is another primary area where biomechanics can be applied. Those biomechanical studies of auto accidents had resulted in measures of the severity of head injuries, which has been applied in biomechanical testing, and in the design of many kinds of helmets to prevent head injury. Sports medicine professionals have traditionally studied injury data to try to determine the potential causes of disease or injury (epidemiology). Engineers and occupational therapists use biomechanics to design work tasks and assistive equipment to prevent overuse injuries related to specific jobs. Combining biomechanics with other sports sciences has aided in the design of shoes for specific sports [16], especially running shoes [17].

In conclusion, biomechanics is used in a diverse range of disciplines including biology, ergonomics, engineering, physiology, medicine, dentistry, and mechanical physics. It may be the major area of concern in some instances (e.g. artificial joints, prosthetics and orthoses, mechanisms of physical injury) or it may be a vital adjunct to another area (e.g. design of an implantable pacemaker or specialist surgical tools).

Many professionals, engineers, designers, physical therapists, oral and orthopaedic surgeons, cardiologists, and aerospace engineers use practical applications of biomechanics. That biomechanics helps the physical therapist prescribe rehabilitative exercises, assistive devices, or orthotics.

Biomechanical research is a powerful ally in the sports medicine quest to prevent and treat the injury. Biomechanical studies help prevent injuries by providing information on the mechanical properties of tissues, mechanical loadings during movement, and preventative or rehabilitative therapies.

Numerical solution of physical phenomena's governing equations using finite techniques is a vital step in many case studies. That it helped in better understanding of the effect of many oral/dental devices and materials.

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