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Biomechanics: A Current Perspective

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Biological structures and tissues are very complex systems, whose behaviour is of particular relevance in assessing their healthy or pathological state, in applying diagnostic criteria, in designing prostheses and devices and, more generally, in interpreting their functions. Medical and biological sciences offer the basic knowledge of biological matter at different scale levels from molecules to organism. This knowledge is largely based on observations, experimentations, statistical analyses and usually there is a lack of a physical and mathematical approach. Biomechanics is one of the emerging disciplines which contributes to the understanding and interpreting of the mechanical behaviour of biological matter.

It is very common to suppose that biomechanics is the application of mechanics to biology, thus implying that biological matter is only that part of the physical world where biological phenomena occur. This approach seems to be dated, and biomechanics is being more and more frequently regarded as a different way to make progress in biology. One of the most widely acknowledged books on biomechanics was written by Y.C. Fung in 1981 with the subtitle ”Mechanical properties of living tissues”. What is characteristic and enlightening in this concise definition of biomechanics is the word *living*, which refers to the exclusive feature of the biological matter. *Living* means *able to react, grow, modify, reproduce and die*. As an example of a typical biomechanical problem one can refer to bone remodelling. Bone is a living tissue composed of cells, which provide the living behaviour, and extracellular matrix and ground substance, which provide the mechanical properties. Bone sustains the loads due to external forces and muscle contractions; bone also accumulates and releases calcium, which is one of the prominent bioelements as its concentration into the extracellular fluids must be kept constant to provide proper muscle contraction and nervous signal transmission. From a strictly mechanical viewpoint, the loads applied to the bone cause stress and deformation patterns depending on bone shape and mechanical properties. This is basically the same for a piece of metal, which mainly differs from a piece of bone, in purely mechanical terms, in that it is representable as an isotropic, homogeneous and linear elastic continuum, while bone is an anisotropic and viscoelastic composite. But from the biomechanical point of view, what is crucial is the quantitative determination of the bone evolution as a consequence of the stress and deformation local pattern. Biology gives a qualitative description of this behaviour which consists in the deposition or resorption of ground substance in order to adapt to functional requirements. This is the so called bone remodelling. Similar phenomena of functional adaptation are displayed by different types of living tissues, and biomechanicists in the third millennium are presented with the challenge of writing the laws which predict the reaction of the living matter under load.

Biomechanics has different fields of application and different methods of investigation. It is very difficult, and probably futile and improper, to give a complete list of topics in biomechanics. The following is only a selections of subjects which serves to emphasize the vastness of this field. Cellular biomechanics, tissue biomechanics and system biomechanics are all macrosubjects, which refer to the biological way of organizing biological matter according to a hierarchical scheme. Among these topics, tissue biomechanics includes different approaches and methods, as tissues display very different features depending on their role in a specific application. Generally four main types of tissue are considered from a mechanical point of view: hard tissue including bones and teeth; collagen rich soft tissues including tendons, ligaments, vascular walls and skin; contractile tissue such as muscles; fluid tissue, mainly blood. While bone shows very small deformations under normal loads, soft tissues are able to undergo large viscoelastic deformations in nor-

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mal function. Bone behaviour depends on the hydroxyapatite content as this is a rigid mineral of calcium phosphate produced by bone cells; soft tissue behaviour relies on the relative amounts of collagen and elastin (both are structural proteins) in the tissues and on their three-dimensional arrangement.

Muscle is a very interesting tissue in that it is able to react very rapidly to signals in such a way as to shorten or produce forces, if external constraints oppose its contraction. This is a very peculiar feature of muscle tissue that has no similarity to any other material.

Blood is also very special from the mechanical point of view, because it is a particle suspension in a fluid thus showing no Newtonian viscous properties. When studying blood motion in the cardiovascular system, its actual viscosity plays a more and more remarkable role, as the vessel lumen decreases from arteries into capillaries.

All these specialized features should be properly represented when studying the mechanical behaviour of a biological structure. A large number of research studies in biomechanics are devoted to setting up experimental tests to understand the mechanical properties of tissues.

The experimental approach to the analysis of biological structures is fundamental, since the complexity of these systems, as well as the lack of knowledge about their structure and behaviour, often make analytical and numerical analyses unreliable.

Even though the experimental studies are necessary, they present various limitations. It is often expensive and time consuming to collect quantitative data from the experimental tests, particularly where the quantities to be measured are vector or tensor fields. Also for this reason computational techniques are being used more and more, with enormous advantages, by researchers in all fields of biomechanics.

In the last two decades, great efforts have been directed toward numerical simulations in biomechanics resulting in not only describing the mechanical behaviour of tissue, but also of complex structures and organs.

The difficulties encountered in applying the various computational techniques for the simulation of biomechanical processes can be summarized as follows.

It is difficult and costly, in terms of time, to create numerical models having the complexity required by real biomechanical models. It is almost always necessary to produce a mesh of a geometric model, and this operation is very often difficult even with the most recent and sophisticated automatic mesh generation software. Owing to the complexity of the models it is often difficult to impose the boundary conditions in a realistic way. The computational cost is often very high, because of the enormous number of spatial degrees of freedom involved, and the high number of time steps necessary to simulate biomechanical problems, which are almost always time dependent. Finally, the enormous amount of data collected from the processing must be manipulated in order to collect significant and useful information in a real time.

The most common and important numerical method to simulate biomechanical problems is surely the Finite Element Method. It is the most popular technique, being a reliable tool to analyse physical phenomena in many fields such as structural mechanics, solids and fluids mechanics, as well as being a useful tool to simulate various engineering processes.

J. Mackerle assembled a bibliography composed of 2188 citations regarding biomechanics using the Finite Element Method which had been published in the ten year period from 1987 to 1997 [Mackerle (1998)].

The bibliography, containing references of works published in journals, conference proceedings and thesis/dissertations regarding biomechanics, shows the vast use of this method that has the advantage of not only being very effective but also of being based on a solid mathematical structure and having numerous commercial codes.

One of the biggest drawbacks in using the Finite Element Method regards the creation of a three-dimensional mesh that, as already mentioned, in many problems of biomechanics results in being problematic and expensive. This drawback can be overcome by the new and promising meshless methods [Atluri & Shen (2002 a, b)]. These methods, developed to avoid the creation of a mesh for three-dimensional problems involving domain changes, as in the case of large deformations or crack propagation, lend themselves well to the solution of complex biomechanical problems.

The most recent method of Finite Volumes [Atluri & Shen (2002 a)], having good conservation properties, has been widely used in biomechanics for all problems regarding the fluid dynamics (for example vascular hemodynamics). Furthermore, with this method, it is possible to discretize complex domains in a more simplified way than with the Finite Element Method.

Other methods have been used recently in the biomechanical field including Spectral Methods, the Boundary Element Method and the Cell Method. The Spectral Methods are not used extensively, their field of application essentially concerning vascular fluid dynamics. Also the Boundary Element Method is not yet being widely used in biomechanics. However, the greatest advantage of this method is the need to model and to discretize only the surface of the continuum to be studied without having to discretize the volume. The most frequent fields of application regard the three-dimensional analysis of bones and implants, bone remodeling and skeletal mechanics. There have been very few applications using the Symmetric Galerkin Boundary Element Method, also because of the lack of commercial codes.

In recent years, new numerical methods have made progress in resolving problems in physics and engineering and have inverted the classical treatment that usually begins with the differential formulation of the problem to find a discrete formulation through one of the many methods of discretization. E. Tonti (2001) has shown that, thanks to a series of reflections and observations on very intuitive concepts, it is possible to make a discrete formulation of a physical problem from the beginning, without going through the differential treatment of the problem itself, by using basic notions of algebraic topology. The method thus obtained, called the Cell Method, permits a direct discrete formulation, starting from the experimental data, and highlights precious information that is lost in the limit process.

We know of only one work that has been published where the Cell Method was used for the solution of a biomechanical problem. However, we are convinced that the finite formulation, such as the Cell Method, of complex physical problems, as are found in bioengineering, will undergo significant development in the future.

The spread of articles included in this special issue provide a representative scope of the type of research currently being pursued in the biomechanics field. The papers report mainly works on bone/skeletal mechanics, joint mechanics, artificial ligaments, dental and implant mechanics, biological flow, biological growth and remodelling, and bioheat transfer.

Liu and Ferrari apply a microstructure-accounting mechanical field approach to the problem of reflection from a granular thin layer embedded between two solid substrates to study the direct relationship of the microstructural parameters and the overall reflection coefficients of the thin layer. Vena and Contro present an anisotropic damage model able to describe the mechanical behaviour of composite artificial ligaments, with specific reference to the tensile load carrying capacity. Corradi and Genna compare critically several Finite Element models, with reference to the analysis of the stress and strain states around a tooth or a fixed dental implant. Genna, Paganelli, Salgarello and Sapelli study the mechanical behaviour of a prototype osseointegrated dental implant containing a thin, non-linear, internal layer, designed in such a way as to simulate the existence of the periodontal ligament. Alexander, Bregler and Andriacchi describe a new approach to human motion capture for biomechanical analysis, providing a complete solution to the dynamic skeletal modeling problem. Fischer, Bastidas, Pfaeffle and Towers estimate the relative loads in the radius and ulna for a range of proximal-distal levels in the forearm, accounting for all in vivo mechanical stimuli. The adopted computational technique is based on bone remodeling theory and computed tomography data of the bones. Skovoroda and Goldstein discuss the recovery of the distribution of the elastic moduli of a stratified layer, based on measures of the surface displacements under localized surface loads. The problem and its solution are related to the monitoring of elastic properties of living tissues. Rao, Humphrey and Rajagopal examine a newly proposed constrained mixture model for growth and remodeling process. They present illustrative computations in a representative, transversely-isotropic soft tissue subjected to homogeneous deformations under uniaxial loading. Auricchio, Petrini, Pietrabissa and Sacco present a beam finite-element with a one-dimensional constitutive law, able to describe the "shape memory alloys" superelasticity and shape memory effect, with orthodontics applications. Thiriet, Naili and Ribreau study the laminar steady flow of incompressible Newtonian fluid in rigid pipes with cross configuration of a collapsed tube to determine both the entry length and the wall shear stress. The goal is to design flow chambers in order to explore the mechanotransduction function of the endothelial cells. Ho Ba Tho, in order to model bone and joints with appropriate geometric and mechanical properties, apply a methodology based on a semi-automatic generation of a three dimensional geometric model of bone and joints anatomy derived from medical Computed Tomography or Magnetic Resonance Imaging data. Mochnacki and Majchrzak present the analysis of transient temperature field of biological tissue subjected to an external heat source. The first and second order sensitivity of the so-called Henriques integrals with respect to the thermophysical parameters are analyzed. Majchrzak and Mochnacki discuss the biological tissue freezing process using one domain approach. In order to estimate the influence of cryoprobe tip temperature on the course of freezing, the direct approach of sensitivity analysis is applied.

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Finally, it is our hope that the publication of this special issue will stimulate further progress in the biomechanics arena.

References

Y.C. Fung (1981): Biomechanics, *Mechanical Properties of Living Tissues*, Springer-Verlag.

J. Mackerle (1998): A Finite Element Bibliography for Biomechanics (1987-1997), *Appl. Mech. Rev*., Vol. 51, pp. 587-634.

S.N. Atluri & S. Shen (2002a): *The Meshless Local Petrov-Galerkin (MLPG) Method*, Tech Science Press, CA. 440 Pags.

S.N. Atluri & S. Shen (2002b): The Meshless Local Petrov-Galerkin (MLPG) Method: A Simple Less-Costly Alternative to the Finite Element and Boundary Element Methods, *CMES: Computer Medeling in Engineering & Sciences*, Vol. 3, No 1, pp. 11-52.

E. Tonti (2001): A Direct Discrete Formulation of Field Laws: The Cell Method, *CMES: Computer Modeling in Engineering & Sciences*, Vol. 2, No 2, pp. 237-258.

J. Liu and M. Ferrari (2003): A Discrete Model for the High Frequency Elastic Wave Examination on Biological Tissue, *CMES: Computer Modeling in Engineering & Sciences*, Vol. 4, No. 3&4, pp. 421-430.

P. Vena, R. Contro (2003): An Anisotropic Damage Model for Evaluation of Load Carrying Capacity of Composite Artificial Ligaments, *CMES: Computer Modeling in Engineering & Sciences*, Vol. 4, No. 3&4, pp. 497-506.

L. Corradi, F. Genna (2003): Finite Element Analysis of the Jaw-Teeth/Dental Implant System: A Note about Geometrical and Material Modeling, *CMES: Computer Modeling in Engineering & Sciences*, Vol. 4, No. 3&4, pp. 381-396.

F. Genna, C. Paganelli, S. Salgarello, P. Sapelli (2003): 3-D Numerical Analysis of the Stress State Caused by Short-term Loading of a Fixed Dental Implant Containing a "PDL-like" Nonlinear Elastic Internal Layer, *CMES: Computer Modeling in Engineering & Sciences*, Vol. 4, No. 3&4, pp. 405-420.

E.J. Alexander, C. Bregler, T.P. Andriacchi (2003): Non-rigid Modeling of Body Segments for Improved Skeletal Motion Estimation, *CMES: Computer Modeling in Engineering & Sciences*, Vol. 4, No. 3&4, pp. 351-364.

K.J. Fischer, J.A. Bastidas, H.J. Pfaeffle and J.D. Towers (2003): A Method for Estimating Relative Bone Loads from CT Data with Application to the Radius and the Ulna, *CMES: Computer Modeling in Engineering & Sciences*, Vol. 4, No. 3&4, pp. 397-403.

A.R. Skovoroda, R.V. Goldstein (2003): The Reconstruction of the Elastic Properties of an Inhomogeneous Layer Under the Local Surface Loading. Biomedical Applications, *CMES: Computer Modeling in Engineering & Sciences*, Vol. 4, No. 3&4, pp. 457-472.

I.J .Rao, J.D. Humphrey, K.R. Rajagopal (2003): Biological Growth and Remodeling: A Uniaxial Example with Possible Application to Tendons and Ligaments, *CMES: Computer Modeling in Engineering & Sciences*, Vol. 4, No. 3&4, pp. 439-455.

F. Auricchio, L. Petrini, R. Pietrabissa and E. Sacco (2003): Numerical Modeling of Shape-Memory Alloys in Orthodontics, *CMES: Computer Modeling in Engineering & Sciences*, Vol. 4, No. 3&4, pp. 365-380.

M. Thiriet, S. Naili and C. Ribreau (2003): Entry Length and Wall Shear Stress in Uniformly Collapsed-pipe Veins, *CMES: Computer Modeling in Engineering & Sciences*, Vol. 4, No. 3&4, pp. 473-488.

M.C. Ho Ba Tho (2003): Bone and Joints Modeling with Individualized Geometrical and Mechanical Properties Derived from Medical Image, *CMES: Computer Modeling in Engineering & Sciences*, Vol. 4, No. 3&4, pp. 489-496.

B. Mochnacki and E. Majchrzak (2003): Sensitivity of the Skin Tissue on the Activity of External Heat Sources, *CMES: Computer Modeling in Engineering & Sciences*, Vol. 4, No. 3&4, pp. 431-438.