

PART I

ANATOMY, BIOMECHANICS, AND ALLOARTHROPLASTY OF HUMAN JOINTS

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CHAPTER 1

BIOMECHANICS OF THE HUMAN SKELETON AND THE PROBLEM OF ALLOARTHROPLASTY

1.1 INTRODUCTION TO HISTORY OF BIOMECHANICS AND ALLOARTHROPLASTY

Scientific branches were historically divided into five separate branches—physics, mechanics, chemistry, geology, and biology. Until the first half of the nineteenth century these branches were mutually isolated and independent. From the second half of the nineteenth century, and mainly during the twentieth century, these scientific branches started to cooperate. As a result new scientific branches, such as biophysics, biomechanics, biochemistry, and geophysics, have developed.

Modern physics creates theoretical background for our understanding of nature and its regularities. The principles and laws were found in physics, namely in classical mechanics, relativity, and quantum physics. Quantum mechanics facilitates an understanding of the structure of matter and the chemical coupling as well as further properties of mass. Statistical mechanics facilitates analyzing separate chemical reactions, therefore, facilitating the study of the fundamental basis of chemical reaction theory. Knowledge of the physical principles and regularities of the physics of nonliving mass was then applied to the physics of living mass, which creates a new branch—biomechanics. Understanding a living organism, its functions, its reproduction, as well as its further evolution on the higher qualitative level, yet realizing its dependence on previous evolutionary states, represents the assignment of biology. Biology as a scientific branch is divided into such fields as biophysics, biomechanics, and biochemistry.

Mechanics is the part of physics that is concerned with motion and deformation of bodies, which are or are not in mutual contact and which are loaded by external

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and internal forces. Mechanics is a very old branch of physics, dating back to the time of Aristotle (384–322 BC) and Archimedes (287–212 BC) and later to the time of Galileo Galilei (1564–1642) and Isaac Newton (1642–1727). The word “mechanics” was first used by Galileo in his book *Discorsi e dimostrazioni matematiche intorno a due nuove scienze, attenenti alla mecanica & i movimenti locali* (1638), where he describes force, motion, and strength of materials. Galileo made the first fundamental analyses in dynamics and mechanical experiments, while Newton formulated the laws of motion and gravity. As the study of mechanics evolved, it was shown that with greater experimental experience in the field of elastic mass properties our conceptions changed, but the fundamental idea that mass is continuously spread and that this mass spreading is due to the force actions, including thermal loading, was changed. Then we spoke of the continuum and about a branch called continuum mechanics.

Classical continuum mechanics of nonliving nature studies mass properties by considering the thermodynamics of closed systems. This idea was based on the fact that these systems do not need any further energy or any change of the mass with their neighborhood. Therefore, a change of entropy with the neighborhood is always positive in the closed system. Owing to dissipative processes the degree of the system organization decreases continuously.

Systems having properties of regularization, reproduction, and possibility of conservation of information represent open systems, for example, systems having an ability to change mass as well as energy with the surroundings. Such systems have dynamic equilibrium and their invariability is ensured by means of a mass exchange. Such systems describe the biological systems. The living systems receive mass by means of meals. The most important assignment of the control system is the conservation of its energetic foundation with the aim to conserve a certain level and stability of the function of the biosystem, also under the changed conditions of an outer medium. It is evident that the law of conservation of the living mass is a part of other conservation laws, known from classical and relativistic mechanics. The processes of acquisition, cumulation, transfer, and employment of energy in biosystems ensure both the growth of a living mass and conservation of the structure and realization of the function of the biological system, which is realized in the cooperation with receiving, processing, protection, and employment of the information.

Biomechanics is a scientific branch that combines the field of applied (e.g., engineering) mechanics with the fields of biology and physiology and it is concerned with a human body. In biomechanics, the principles of mechanics are applied to the conception, design, development, and analysis of the equipment and systems in biology and medicine. One of the main goals of biomechanics is to study responses of living tissues on an external energetic function from the physiological point of view, where we assume that the living tissue is a composite material with controlled properties. A biological material is a strongly organized material with the ability of self-evolution, reproduction, and a possibility of conforming to the surroundings. The modern development of biomechanics started in the fifteenth century, based on the studies of Leonardo da Vinci (1452–1519), though the concepts of biomechanics were probably given in Greek (Aristotle 384–322 BC) and Chinese writings. Later the contributors to biomechanics were Galileo Galilei (1564–1642), René Descartes

(1596–1650), Giovanni Alfonso Borelli (1608–1679), Robert Boyle (1627–1691), Robert Hooke (1635–1703), Isaac Newton (1642–1727), Leonard Euler (1707–1783), Thomas Young (1773–1829), Jean Poiseuille (1797–1869), Hermann von Helmholtz (1821–1894), and the others. The development of the biomechanics as a separate branch has improved our understanding of the mechanics of human joints. In the last several decades this understanding has grown to include the total replacements of joints as well as implants, the mechanics of a blood flow, the mechanics of an airflow in the lungs, the mechanics of soft tissues, and the mechanics of the growth and a form of joints. Moreover, biomechanics has contributed to the development of medical diagnostic and treatment procedures as well as to the development of designing and manufacturing medical instruments and devices for the handicapped. It has also contributed to the development of sport and forensic medicine.

Materials of nonliving nature, because of their low organization, are only slightly accepted or not accepted by highly organized living systems because they cannot be quickly regenerated and renovated. Another disadvantage is the insufficient adaptability of contacts between living and nonliving systems. This contributes to the problems that artificial replacements for biological organs and their parts experience. One of the main aims of biomechanics is the detailed research of composite materials suitable for the development of artificial replacements for human organs and joints. To apply materials of nonliving nature for the development of artificial replacements for human organs the following fundamental criteria and properties must be satisfied:

1. Unconditional adaptability to the surrounding materials of the living systems
2. Sufficient range of elastic deformations with reasonable nonlinearity and with useful elastic modules
3. Useful orientation of deformable properties with regard to the type and direction of force actions
4. Useful nonreturned deformations rendering an adaptation possible without great time and space changes of properties and evoked damages, but rendering a stress relaxation and precluding microdamage origins possible
5. Limitation of a total deformation during the growth of stresses with reinsurance of an elastic behavior with high local solidity and with a minimal requirement of a further delivery of energy
6. High biocorrosion resistance
7. High solidity against cyclical loading with high initial damping
8. High quality of the surface design, ensuring biocompatibility and a decrease in the possibility of biocorrosion
9. Having an ability of certain regeneration in connection with a neighboring living mass–tissue, as a higher form of biocompatibility

At present a most vigorous development of biomechanics is associated with orthopedics because the most frequent use of surgical intervention is with patients with

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musculoskeletal problems. In orthopedics, results of biomechanics have become everyday clinical tools. Therefore, the most urgent problems in biomechanics are problems connected with static and dynamic loading of human joint systems and their artificial joint replacements. Then fundamental research has included not only surgery, prostheses, implantable materials, and artificial limbs but also cellular and molecular aspects of healing in relation to stress and strain and, moreover, tissue engineering of a cartilage, tendon, muscle, and bone. Thus, rheology of biological tissues, transfer of a synovial fluid between both parts of joint systems, mass transfer through membranes, microcirculation, and interfacial phenomena must be investigated. We see that biomechanics represents a strongly interdisciplinary branch.

The first replacement of a human joint was made by Carnochan in 1840 in New York. The first replaced human joint was the temporomandibular joint. This attempt was unsuccessful because the implanted material was a wood. The first successful attempts of the hip prosthesis were made at the turn of the twentieth century. A successful replacement was made by Jones. His attempt was based on a gold plate used as an insert into the hip joint. This replacement functioned for 21 years, that is, until the patient's death. In the twentieth century Smith-Petersen accomplished marked successes by putting a cap on the femur head. Next attempts are connected with Delbet, Hey-Growes, and Judet. Delbet and Hey-Groves were the first to implant an artificial replacement of the whole head of the femur (in the twentieth century). Later, Judet used a type of replacement that was further developed by Thompson, Zanoli, Townley, Movin, Güntz, Merle d'Aubigue, Lange, Neff Marine-Zuco, and Gosett. Moore implanted a new type of a whole-metal femoral component—an artificial head of the femur with the stem fixed in the medullar cavity. This type was modified by Thompson, Eichler, Lipmann, McKee, Reiley, and others. In 1951 Haboush introduced a bone cement for fixation of the stem into the marrow channel. This technique was also applied by McKee and Charnley. In 1950 Urist and in 1960 McBride implanted in addition to the stem also the acetabular cup. In this way they were able to do a total hip joint replacements. From this time on we speak about total hip replacements. The modern arthroplasty of the hip joint and then of the knee and other joint replacements started with the Charnley shape of the hip joint replacement and mainly with his “low-friction arthroplasty” (Charnley, 1979). After a transient failure in which Teflon was used like a material for an artificial acetabulum, Charnley established the ultra-high molecular polyethylene—UHMWPE—into the construction. His replacement was solved as a metal femoral component with the metal head, whose stem was fixed by a bone cement. The artificial acetabular cup made of UHMWPE was also fixed with bone cement, and a mutual motion between the head of the femur and the cup of the acetabulum was realized by pairing metal–polyethylene. This “low-friction arthroplasty” was a model for many other authors and it has been used in most up to the present time. A change in the shape of the femoral stem, made by Müller in the late 1960s, was important and it enabled a component implantation without the necessity to apply a large femur trochanter. Because of this all new types of artificial joints were introduced. Ceramics were the preferred material for the production of the femur head (pairing ceramics–polyethylene), although some replacements were made without contact with polyethylene (pairing metal–metal or ceramics–ceramics).

The problem of fixation of individual components in a bone without using bone cement was solved by developing cementless types of joints.

Subsequently primal and revised types of implants were developed. Both types of implants were available as cemented or cementless. At present, replacements for temporomandibular joints have been developed and are available for use.

1.2 BIOMECHANICS OF HUMAN JOINTS AND TISSUES

Biomechanics as a modern science combines the developments in engineering mechanics with developments in biology and physiology. Biomechanics is concerned with the human body; thus it is a natural science concerned with living systems mechanics. It is the study of mechanical movements, their function in the whole biosystem as well as its individual parts. Modeling biosystems and the simulation of their functions developed into a significant understanding of the construction and function of living mass (Valenta, 1985, 1993). In biomechanics, the principles of classical mechanics are applied to the conception, design, development, and an analysis of equipment and systems in medicine.

Modeling of biosystems can be divided into two categories of models. The first one introduces mathematical models that model structures, functions, and quantities of investigated biosystems. Into this group we can add mathematical-mechanical models, which model specific biomechanical systems and simulate their functions. Models of physical-mechanical properties, thermodynamic models, structural models, and function models also belong here. Theoretical biomechanics is concerned with these problems. Real experimental models, modeling of specified biomechanical actions, or biomechanical objects belong in the second category. These models' task is to verify theoretical possibilities concerning their structure and function or why a biomechanical object such as a unit or its parts can verify the rightness, exactness, and accuracy of a solution of abstract mathematical models, to investigate biomechanical problems such as stress states, deformation ability, and the like. Experimental biomechanics is concerned with this topic. For that reason when artificial joint replacements have to be reliable and function long term, their construction must follow the principles of biomechanics and biomechanical relationships in an appropriate joint sector of the movement system. The study of the forces that have an effect on the joint system, natural or artificial, concerns fields such as biostatics, biodynamics, biokinematics, biokinetics, and tribology. In biomechanics we are concerned with the study of external and internal forces, which are summarized and transferred by joints. As a consequence of external and internal forces, we study the distributions of deformation and stresses in the movement apparatus, their character and relationship in the course of movement through time.

Arrangements and shapes of human joints establish their kinematic and dynamic characteristics. A kinematic characteristic is given by a joint geometry, by a shape of contact areas, and by their cartilaginous surface. Ligaments satisfy a function of mechanical stops or leading and stabilizing elements. From analyses of movements of other living creatures it is evident that their movement organs are constructed on

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the principle of the lever system with an alternating movement. Shapes and forms of individual structural elements of joint connection are so various that it is not possible to construct a universal artificial replacement for whatever human joint to fully comprehend its real functional properties in a human organism. It is the main goal of orthopedic specialists and design engineers to approach this ideal state. In that case mathematical modeling and mathematical simulation of the function of a joint and of its optimal replacements can be also helpful.