Chapter

Introductory Chapter: Biomechanics

Hadi Mohammadi

1. Introduction

Biomechanics or biomechanical engineering is the application of mechanical engineering and its concepts and principles in biological systems, living tissues/organs, and medical devices. Mechanical properties of tissues can be characterized as anisotropy, hyperelasticity, viscoelasticity, viscoplasticity, preconditioning performance, and the existence of residual stresses [1]. Most experiments on the mechanical characterization of tissues are based on the laboratory work. Often, samples are removed from cadavers or animals and are cut in order to be tested which are either fresh or after storage. Testing machines are often based on electromechanical or hydraulic systems which are often performed in living animals or patients. Mathematical interpretation of data is often considered an important part of tissue mechanics such as 3D modeling of stress-strain behavior. Modeling may be either phenomenological, which is to some extent seeking to define behavior using model systems that do not reference structure, or plainly based on information of tissue construction. Phenomenological models are often based on linear or quasi-linear viscoelastic theory. Constitutive equations, mostly those based on improvement of strain energy density functions, are often as a means to explaining tissue behavior under random loading.

Tissue mechanics or tissue biomechanics is the field of endeavor that seeks to understand and describe the correlations between structure, composition, and mechanical functionality in a variety of tissues such as connective tissues, cardiovascular tissue, epithelial tissues, etc., in the human body [2]. Much of the research work has been done in the connective tissues of the body, such as the bone, tendons, cartilage, arteries, and skin, where mechanical demands are greatest; however, all tissues have mechanical features of interest. An interesting area of research could be made around the (1) use of structural anatomy as a means to understanding natural design, (2) mechanical engineering analysis of structures based on continuum mechanics, and (3) materials science study of detailed links between structure and function. As all natural tissues are composite materials, understanding their mechanical function requires study of the mechanical properties and architectural arrangement of the individual structural components, particularly strong, stiff collagen fibers; the physiological rubber elastin; hydroxyapatite mineral; and proteoglycan sol/gels. The mechanical features of tissues include marked anisotropy, nonlinear stress-strain relations, viscoelasticity, preconditioning behavior, and the presence of residual stresses. Most studies of the mechanical behavior of tissues have been carried out in the laboratory, with samples removed from cadavers or animals, cut or machined to shape, and tested either fresh or after storage. Commercial testing machines based on electromechanical or hydraulic systems are widely used, as are custom-built apparatus. Testing is also carried out in living animals or patients. In either case, determination of sample geometry or deformations is difficult. Mathematical description of data is an important part of tissue mechanics, as is modeling of 3D stress-strain behavior. Soft tissues require the use of large deformation (finite) elasticity equations. Modeling may either be phenomenological (seeking to describe behavior using model systems that do not reference structure) or may be explicitly based on knowledge of tissue architecture. Phenomenological models have often been based on linear or quasi-linear viscoelastic theory derived from previous work on polymer materials. Constitutive equations, particularly those based on the development of strain energy density functions, have been widely used as a means to describing tissue behavior under arbitrary loading. In a complementary development, finite element analysis has found wide use for analysis of complex structures. I believe tissue mechanics is a tool both for (1) the study of natural structures in health and disease and (2) technological application, which, in recent years, has included the design of surgical replacements and surgical technique and evaluation and design of tissue engineered replacements and analysis/prevention of injuries. Native and functioning tissues display an exciting and dynamic response to mechanical loading. In fact, living tissues are capable of adapting to the micromechanical environment surrounding them which may be characterized by changes in their composition and structure due to their external conditions. Following this concept, tissue differentiation and profanation are good examples in which they are highly dependent and significantly affected by on their micromechanical environment. A quantifiable understanding of these concepts, by the means of experimentation and/or computational modeling, is of fundamental significance for many applications in the area of biomechanics or biomechanical engineering such as tissue and cell damage due to continued loading (e.g., decubitus), the usage of suitable biomaterials in the design of prostheses (e.g., intervertebral disc or in small size blood vessel, i.e., coronary arteries), and heart valve tissue engineering [1].

As of the future research directions, developing computational multiscale models to study the micromechanical loadings on discrete cells in an engineered tissue such as cartilage tissue or heart valve leaflet tissue is of particular importance. This is because these models will help understand the process by which normal living cells detect and realize mechanical loadings such as shear forces or tensile strains and convert them into a multiple of chemical events in tissues at multiscale levels that trigger and affect the cellular function in health and disease [3, 4]. Living cells vigorously detect, realize, and process micromechanical signals surrounding them, and all their motility, differentiation, and growth are significantly affected by them. It is of particular importance to understand the micromechanical language between the extracellular matrix (ECM) and cells embedded in it and the fundamental mechanisms of this mechanical communication simply because an abnormality in the mechanical properties of the ECM may lead to numerous diseases, such as fibrosis and cancer. Furthermore, ECM mechanics plays a major role when stem cell differentiation is programmed for organ-on-chip applications. Mechanotransduction is a developing multidisciplinary area that embraces cell and developmental biology, biomaterials, biochemistry, biomedical engineering, and medical biophysics [5, 6].
The following topics are a few applications of biomechanics in order to further understand the mechanobiology associated with tissues in health and disease.

2. Spine biomechanics

To understand the motion of the spine and how it supports movement, we must first understand each component and the overall structure of the spine. The spine serves as a structural column providing the human body physical durability and protection. There are 32–34 total bones in the spine, divided into 5 regions: 7 vertebrae in the cervical region, 12 in the thoracic region, 5 in the lumbar region, 5 in the sacral region, and 3–5 in the coccygeal region. In between these spinal bones, there are 23 discs. The bones and discs, in combination with muscles and ligaments, allow the lumbar, thoracic, and cervical spine, different degrees of mobility. This is measured through rotational, side to side, and front to back bending. As mobile humans, it is important to realize the impact of certain activities on the spine, in order to avoid injuries and spinal conditions. Looking at the spine as a purely mechanical system, solutions can be identified using engineering principles. By making use of medical professionals' expertise in surgical procedures and the human body and engineers expertise in mechanical systems and hardware, spinal disorders can be treated. The motion of the spine is very complex, and in order to fully understand the biomechanics of this system, the components, motion, force transmission, conditions, and treatment of the spine must be examined. Understanding the motion of the spine and how it supports movement eases the understanding of each component and the overall structure of the spine. The spine serves as a structural column providing the human body physical durability and protection. The bones and discs, in combination with muscles and ligaments, allow the lumbar, thoracic, and cervical spine to move with different degrees of mobility. This is measured through rotational and lateral bending and flexion/extension. As discussed the motion of the spine is complex. By fully understanding the biomechanics of the spine as a mechanical system, the components, motion, force transmission, and conditions of the spine can be harnessed to develop new technologies in vibration reduction, sports performance, and new methods and practices for spinal surgery.

3. Articular cartilage biomechanics

Cartilage is an essential component of the human body. It plays multiple roles throughout the body, and without it our bodies would not have the ability to respond to the demanding nature of our everyday lives. Cartilage is the basis of skeletal growth; it transmits and cushions demanding loads throughout brittle bone structures. Also, it gives elasticity and shape to surrounding tissues, all this while being an avascular tissue. The complexity of cartilage's biomechanical behavior makes cartilage a demanding field of research within the biomedical engineering industry. There is ample information in the literature on the three different types of cartilage: hyaline, fibro, and elastic cartilage. Studies of the composition of articular cartilage concluded that the ECM is made up of collagen, proteoglycans, chondrocytes, and water. Collagen is the main structure in the extracellular space, while proteoglycans are heavily glycosylated proteins with a core protein with one or more covalently attached sugar chains. Chondrocytes are the single existing cell within the articular cartilage and are highly specialized and metabolically active while water is the most abundant component contributing to approximately 80% of the wet weight. Further research into the structure of articular cartilage (AC) found four distinct zones, including superficial, middle, deep, and calcified; all of which have distinct differences in composition. Within these four zones, three regions are present referenced as the territorial, pericellular, and interterritorial region. Initiating signal transduction throughout the loaded cartilage between chondrocytes and the ECM is controlled by the territorial region, which also surrounds the pericellular region. Bundles of large collagen fibers that are randomly oriented and have varying proteoglycans define the interterritorial region. Articular cartilage was found to be biphasic and anisotropic giving it distinctly different tensile and compressive properties. The viscoelastic nature of AC is also governed by its liquid and solid ECM phases leading to creep and stress relaxation behavior. Boundary layer lubrication transitioning to fluid film lubrication yields the very low coefficient of friction required to prevent cartilage deterioration between joints. Mechanical materials available today do not present the combination of elasticity and strength articular cartilage possesses making medical replacements less than ideal.

Finally, medical conditions and treatments were covered including osteoarthritis, microfracture, osteotomy, arthroplasty, stem cell therapy, and hydrogels. Current treatments do provide some alleviation of pain and discomfort; however, high costs and unwanted growth of fibro instead of hyaline cartilage leave room for further improvement in this area of the biomedical industry.

4. Biomechanics of atherosclerosis

Currently, atherosclerosis is the leading cause of deaths in the developed world. Due to the nature of this disease and how prevalent it is in our modern society, it is important for all to understand how this disease manifests and is detected, as well as how it can be prevented. Atherosclerosis is a silent killer and contributes to many deaths throughout the world every year. It develops over a long period of time due to a buildup of LDL on the arterial wall before the body contains it with a mesh of collagen and elastin fibers called a fibrous cap. Based on the volume that the soft plaque occupies and the thickness of the fibrous cap itself, a person can live for years without that plaque being a danger to their health. The issue arises when the necrotic core takes up 40% or more of the volume of the plaque or if the fibrous cap is less than 65 μm thick. If either of these criteria are met, the plaque is at risk of rupturing and creating a thrombus that will kill the victim. Even without rupturing, the stiffening of the arterial wall leads to physical changes in the body's function. These changes include increased shear stress in the blood vessels, changes in systolic and diastolic blood pressures, and increased pressure fluctuations in the arteries. Thankfully in our modern age, atherosclerotic plaques can be detected and treated through a variety of methods. Each method has its advantages and disadvantages. Certain procedures excel at identifying atherosclerosis in certain arteries but struggle in other arteries. For these reasons, multiple procedures can be used together to allow a better picture of the health of a patient's arteries. It is becoming more common to use noninvasive procedures as they become more advanced. In many cases, they are just as effective as invasive procedures at detecting atherosclerosis. As atherosclerosis becomes more common, research on the disease is expanding. Every year, doctors are becoming more equipped to handle atherosclerosis.

5. Knee joint biomechanics

During everyday activities like walking and climbing up stairs, the knee experiences 2.7–4.9 times the body weight. It is a wonder how the knee can withstand so much weight over such a long period of time. Millions of years of evolution and adaptation can be found in the knee as it seems to be built for exactly what humans need it to do. The knee is meant to bear load and help the body move at the same time, and it does just that. The meniscus not only reduces the friction between our femur and tibia but also reduces the stress felt on the tibia. Humans often stand for longer periods of time, and the knee has a mechanism to reduce the amount of force needed to stay standing upright. More recently in the field of biomedical engineering, procedures are being developed to fix the issues caused by trauma or simply by degradation.

6. Muscle biomechanics

Muscle is a complex tissue that is involved in many processes and systems essential to human life. They are used for balance, stability, movement, organ function, lifting objects, and many other things. This tissue needs to be analyzed from the smallest unit all the way up to the macroscale of its involvement in complex functions. Furthermore, certain engineering applications and considerations needs to be covered. Through analysis of fundamental structures and functions, the role of the muscle in the body needs to be explored, and its relevance to human life needs to be discussed. Muscle is a contractile tissue within the body responsible for internal and external locomotion and posture. There are different types of muscle tissue, composed of different types of fibers. Contractions are stimulated by the nervous system and have a specific need for energy depending on their environment. In addition, adaptations to the structure and function will arise when exposed to stimuli such as exercise. Muscle is a complex, versatile tissue which provides humans with the ability to execute a variety of tasks. Both muscles as a complex functional group and single muscle fibers as an individual functional unit have been discussed. The interactions of muscle tissue with the rest of the body perform many different functions that need to be carried out simply and effectively. From the contraction of single muscle fibers all the way to the entire muscle groups working together to complete a movement, the structure and fundamental properties of muscles work cooperatively to fulfill different functions and needs of the body.

7. Vascular grafts

Proper circulation of blood throughout the body is extremely crucial to a long and healthy life. Any infliction that inhibits the normal flow of blood through the vast network of blood vessels poses an extreme risk to patients and can cause numerous potentially fatal conditions depending on their location. Vascular grafts are a surgical method utilized to redirect blood flow from one area to another whether to bypass a clogged or narrowed blood vessel or provide an easy access point for other procedures such as blood dialysis. It is an unfortunate truth that, in their current state, synthetic grafts are not a long-term solution to vascular stenosis and provide only small extensions on expected life spans. With the current state of undesirable compliance mismatch that exists between them and the vessels that they are grafted too, it is clear that there is a lot of room for improvement. Future research on the use of multicomponent synthetic grafts in which multiple materials are used together to better mimic the elastin and collagen mechanical properties of natural arteries and veins has a potential for improving the compliance of synthetic grafts, which ultimately leads to improved patency over time. As for tissue engineering, it is being constantly improved upon every single day. The future of biomedical engineering lays in the replication of human tissues through tissue engineering. The only way to correctly mimic the compliance of a human blood vessel is to use a form of tissue engineering. Many improvements have been made already, with some very promising results as seen in the hybrid scaffold methods as well as the decellularized matrices. It is important to note that the highest potential lies in the assembly processes. These are the processes that will allow for any mechanical property and shape to be designed exactly. The only limiting factor being the excessive amount of time required in order to manufacture these grafts. Finally the research toward sutures and the anastomotic site is also a very key area. With the hypercompliant zone being so detrimental, it is very important to consider alternate forms of sutures to combat the high compliance mismatch of those areas.

In the future it can be said that a form of biocompatible glue or laser or even a combination of both may be the best choice of suture. In order for this to happen a lot of work needs to be done in those areas in order to formulate techniques in which the negatives previously mentioned are mitigated.

8. Transcatheter heart valves

Severe aortic stenosis is the calcification of the aortic heart valve that affects 3% of the world's population over the age of 75. This disease may have a variety of causes, such as age, gender, hyperlipidemia, rheumatic fever, hypertension, heart infection, abnormal stresses, and congenital abnormalities. Due to the extremely invasive nature of open-heart surgery, the mortality rate for older patients is very high, and until 1992 these patients would have had to take the risk of open-heart surgery or have no treatment and left to endure cardiac failure. Henning Rud Andersen invented an alternative surgery to replace the native aortic valve, known as a transcatheter aortic valve replacement (TAVR), also known as a percutaneous aortic valve replacement (PAVR). This surgery is done by using various catheters and medical imaging machines to allow for a replacement valve to be directed up an artery to the diseased native aortic valve. The catheter is most commonly inserted into the iliac artery or femoral artery, but there are other methods surgeons use based on their patient. A sheath is placed in an incision located near the groin to aid in inserting various surgical tools and the replacement valve into the artery. A flexible guide wire is transported to the valve to guide the surgical tools and new valve to the native valve. The native valve is then crushed using a procedure called aortic balloon valvuloplasty. Doctors will often use a method called fast pacing during an aortic balloon valvuloplasty to reduce the pulsatile aortic flow by increasing the heart rate to approximately 200 beats/min or greater. After crushing the native valve, a new bioprosthetic aortic valve is set in place using either a balloon expandable PAV or a self-expanding PAV. Doctors use various medical imaging techniques such as fluoroscopy, aortography, and echocardiography in the procedure to monitor flow characteristics and valve deployment location. This procedure is far less invasive than open-heart surgery and gives a safe alternative for older patients or patients characterized with a high mortality rate to receive a new aortic valve. The percutaneous valve is still a growing technology and is still in its optimizing stage. Issues with the valve include thrombosis (blood clotting), valve migration (due to the valve not being sutured in), stent malposition (due to physician error or valve migration), coronary obstruction, and issues with the catheter-based delivery and valve durability. Research into correcting these issues is essential for further optimizing the current models of the percutaneous heart valve and for minimizing negative inoperative and postoperative implications.

Author details

Hadi Mohammadi
Heart Valve Performance Laboratory, School of Engineering, University of British Columbia, Kelowna, BC, Canada

*Address all correspondence to: hadi.mohammadi@ubc.ca

References

[1] Mohammadi H, Mequanint K, Herzog W. Computational aspects of mechanical modeling of articular cartilage. IMechE, Part H: Journal of Engineering in Medicine. 2013;**227**(4):402-420

[2] Mohammadi H, Mequanint K, Herzog W. Multiscale modeling of O_2 transport in articular cartilage. Biophysical Journal. 2012;**102**(3):592a

[3] Raustin R, Mohammadi H. Towards multiscale modeling of wave propagation in arteries. Journal of Mechanics in Medicine and Biology. 2015;**16**(2):1650027 (1-10)

[4] Mohammadi H, Mequanint K. Prosthetic aortic heart valves: Modeling and design. Medical Engineering & Physics. 2011;**33**(2):131-147

[5] Mohammadi H, Fradet G. Prosthetic aortic heart valves: Review article. Cardiovascular System. 2017;**2**(1). 55p

[6] Haley JP, Mohammadi H, Boughner DR. The effects of hammer pressure on cellular response in a porcine heart valve tissue. Cardiovascular Engineering. 2010;**10**(3):157-162