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A Review for the Interaction of Fluid and Structure in Porous Tissues

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***Abstract* – The purpose of this review is to motivate the quantitative study of biological porous tissues where fluids and structures are interacting; this will brings two fields into focus Poroelasticity (PE) and Fluid-Solid Interaction (FSI). Both fields were initiated few decades ago and have been growing but received little attention in funding and research. PE focuses on deformation of porous medium that is saturated with fluid and it lies in the intersection of elasticity, solid mechanics, fluid mechanics, and continuum mechanics while FSI lies in the intersection of fluid mechanics, solid mechanics and dynamics. What has been impossible few decades ago is possible to do today with latest development in computational techniques and technology. This development have resulted in emerging of new research fields [1] – [6]. The new frontier will compel researchers to grasp fundamentals with depth in physics, biology, mathematics and engineering. The significance of the work is the potential to lead to development of new smart materials based on biological concepts. Honey comb beams and structures were developed from nature and they are widely used today in many applications including aerospace. More studies on poroelastic behavior of biological tissues can lead to a break through in materials science. Also, further research in PE and FSI will push the limits of knowledge in mechanics and quantitative analysis of biological tissues and determination of their mechanical properties. Furthermore, the research will improve our knowledge about current challenges such as osteoporosis, arthritis, failure of artificial heart valve, medical implants, and artificial limbs.**

***Keywords* – Porous Tissues, Porous Medium, Articular Cartilage, and Biological Porous.**

I. Background

In the last few decades the development of technology and science has allowed the growth of new fields in engineering that are considered multidisciplinary within the same discipline and also among different disciplines. In fact coupled systems involving two or more disciplines are often encountered in engineering practice today. Problems involve both fluid and solid media are often referred to as fluid-structure or fluid-solid interaction (FSI), while PE deals with porous objects saturated with fluid. In this review we will focus on Poroelasticity applications.

The theory of Poroelasticity was developed by Biot [7] to deal with the time-dependent response of the fluid-saturated porous media derived from the coupling of the mechanical deformations and the deformations of pore fluid. Poroelasticity lies in the intersection of elasticity, solid mechanics, fluid mechanics, and continuum mechanics, while its applications spans among different disciplines in biomechanics and geo-mechanics. The theory was established in [7] where the isotropic case was considered, and in [8] the theory was generalized to anisotropic materials. General solutions to the elastic equations were established in [9].

Applications of the theory of poroelasticity to biological tissues is a growing area of multidisciplinary research for biology, mathematics, mechanical engineering, biomedical engineering, chemical engineering, materials engineering, and medicine.

General FSI problems will involve computations of blood flows interacting with the heart and heart valve, design of prosthetic cardiac valves, swimming motion of marine worms, wave propagation in cochlea and biofilm processes, …etc, [4]. In FSI problems the focus is mostly on the interface of the fluid and the solid which can be modeled as springs as in the immersed boundary method [4].

II. Introduction

The study of the mechanical loading of the skeletal system and its effects on biological tissues is a major element of the field of biomechanics. The usefulness of mathematical and mechanical modeling in elucidating biological phenomena has become evident in the 20th century, as advances were made in physiology as well as mechanics. A variety of orthopedic biomechanical problems arise from the normal and pathological behavior of the skeletal system. The concept of bone adaptation in response to mechanical environment was described by Wolff in 1892 and is known as Wolff's law which states that bone in a healthy person or animal will adapt to the loads under which it is placed. If loading on a particular bone increases, the bone will remodel itself over time to become stronger to resist that sort of loading. The fluid movement from the perivascular regions to the bone cells in the bone matrix and vice versa needs to be investigated. The perivascular regions in bone are the domains exterior to the blood vessels but interior to the blood vessel tunnels in bone tissue (Haversian or osteonal and Volkmann canals). An understanding of this fluid movement is key to understand bone health and its mechanosensory system. There is a connection between fluid movement and mechanosensation in bone. In bone, there is a fluid movement-activated strain magnification system that amplifies the stiff bone tissue strain levels to those a cell can sense. This occurs when the interstitial fluid passes over the bone cell's dendritic surface in the approximate 400 nm diameter canaliculi; the dendritic structures, or cytoplasmic processes, are about 200 nm in diameter. Understanding bone mechanotransduction is fundamental

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to the understanding of how to treat osteoporosis, how to cope with microgravity and how to design prostheses that are implanted in bone tissue.

Piekarski and Munro, [10], postulated a chemical mechanism based on the notion that load-induced fluid flow in bone enhances the rate of nutrient supply and waste removal to and from osteocytes, thereby providing a more favorable environment for production of additional bone mass. The observation of strong electric potential gradients in the vicinity of Haversian canals of cortical bone undergoing different types of loading added support for electrical mechanisms [11]. Subsequently, investigators proposed that the nature of these electrical fields could be explained and attributed to fluid flow in the pores of the hydroxyapatite matrix [12], or flow in the larger canaliculi [13]. Alternatively, it has been proposed that shearing stresses from the oscillating flow of viscous bone fluids exert stimulatory stresses on the osteocytes or their processes [14]. Still further works have been aimed at determining whether or not the fluid pressure in bone during physiological dynamic loadings can possibly serve as the stimulus to which osteocytes respond.

III. Hierarchical Structure and Porosity of Cortical Bone

Bone in human and other mammal bodies is generally classified into two types 1: Cortical bone, also known as compact bone and 2) Trabecular bone, also known as cancellous or spongy bone. These two types are classified as on the basis of porosity and the unit microstructure. Cortical bone is much denser with a porosity ranging between 5% and 10%. Cortical bone is found primary in the shaft of long bones and forms the outer shell around cancellous bone at the end of joints and the vertebrae. The porosity of Trabecular bone ranging between 50% - 90%.

The pore sizes in cortical bone are approximately three discrete sizes; the largest pore size (approximately 50 μm diameter) is associated with the vascular porosity (PV), the second largest pore size (approximately 0.3 μm diameter) with the canaliculi in the lacunar-canalicular porosity (PLC) and the smallest pore size (approximately 10 nm diameter) is in collagen-apatite porosity (PCA) [15].

Existing theories of the poroelasticity of materials with multiple connected porosities of different characteristic pore sizes and different permeabilities do not appear to cover the case of nested porosities. Porosity is considered to be homogeneous in traditional treatments of poroelasticity. There are severe mathematical difficulties associated with the solution of problems involving inhomogeneous porosity. The developmental objective for multiple pore size porosities models is to simplify the problem of modeling materials with inhomogeneous porosity. The special type of nested porous structures is described as the Russian doll where a porous structure is nested within a bigger porous structure and both porous structures are exchanging fluid. The animal vascular tree is an example of a pore structure as two connected nested systems.

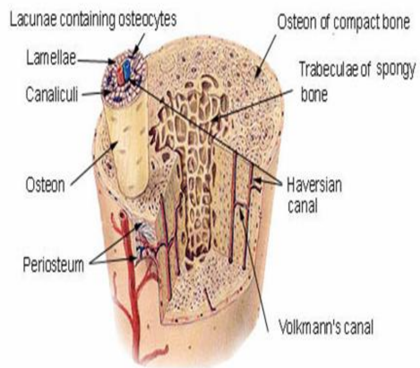


Fig.1. The PV and PLC models for fluid flow. The Medullary canal can be idealized to run in the center of the bone.

IV. Materials Models

As mentioned earlier generally porosity is considered to be homogenous in the general treatment of poroelasticity. In [16] an isotropic and incompressible model of articular cartilage in unconfined compression did not achieve a good curve fit. However, it has been shown that a transverse isotropy model will achieve better curve fit [17]. Compressibility has been restricted to the fluid only, but recent studies freed the constitutive equations from the constituent incompressibility constraints and used a transverse isotropy model [1], [18]. For the analysis of soft tissues the assumption that the fluid and solid constituents of the poroelastic medium are both incompressible is reasonable. However in the case of hard tissues the constituent incompressibility assumption is not appropriate because the effective bulk modulus of the poroelastic solid constituent is almost an order of magnitude stiffer than that of the poroelastic fluid constituent, thus the solid constituent shields the fluid constituent from stress [1], [18].

V. Recent Developments in Imaging and Testing Technologies

With the current fast trends in technology from macro to micro to nano, what have been impossible a few decades ago is possible to do today. For example in our lab we were able to extract a single osteon (less than 300 micrometers in diameter, Fig.1, and test it to determine its permeability, which ranges in general according to many researchers between 10^{-18} – 10^{-24} m^2, using a testing system that is locally designed in our lab, [3], as shown in Fig. 2. The commercial products are begining to move faster, for example *Micro*-EP (Admit Corp.) is a miniature testing machine that can fit the *palm of a hand* and can perform testing inside a liquid bath and is compatible with video microscope.

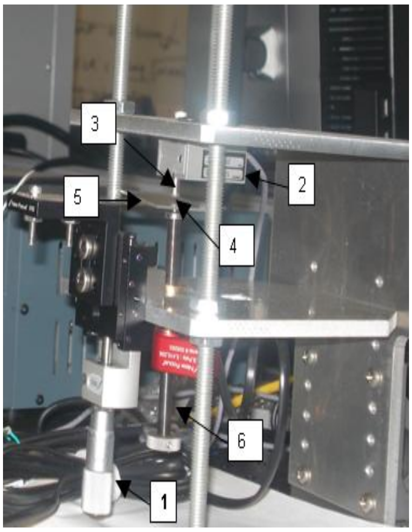


Fig.2. Photograph of material testing stage to load osteons (250 µm in diameter) that is designed and fabricated in our lab. It consists of: (1) micrometer, (2) load cell (10 grams, 0.05% FOM), (3) steel platens, (4) osteon sample, (5) sample stage, (6) picomotor linear actuator (30 nm displacement/step) [3].

The development of micro- and nano-computed tomography (µCT, and nano CT), transmission X-ray microscopy CT (TXM CT), and synchrotron radiation micro-computed tomography (SR-µCT) have opened a myriad of possibilities to investigate bone micro architecture. In contrast to photons, X-rays can penetrate dense materials such as bone, and most of these approaches produce true 3D representations of the vascular and lacunar porosities. Laboratory desktop µCT and nanoCT systems can achieve micron and submicron resolution images, respectively. SR-µCT can achieve resolutions up to 50nm, with better contrast than laboratory-based µ-CT and nano-CT. These technologies can produce representations of a 3D volume composed of approximately 1000 × 1000 × 1000 pixels, Cardoso et al. (2013). Electron microscopy has higher imaging resolution capabilities than imaging approaches based on photons or X-ray light. Scanning and transmission electron microscopy (SEM, TEM) can produce images with about 1-nm resolution. Three dimensional renderings of osteocytes and their cell processes have been reported using ultra high voltage electron microscopy (UHVEM) at 22.8-nm resolution, [19], and 1.2-nm resolution [20]. The recent developments of atomic force microscopy (AFM) and serial focused ion beam/scanning electron microscopy (FIB/SEM) seem to be well positioned to image both lacunae and canaliculi, diameters are 10 – 20 and 0.3 – 0.5 µm respectively. In addition, bone mineral density, micro architecture, and tissue composition have started gaining researchers interest due to their role in bone properties. Thus, ultra sound propagation is becoming focus of interest because it is sensitive to bone mass density, tissue composition and bone micro-architecture as well as being non-invasive and inexpensive [22]

VI. Discussion

The reviewed research work will help bringing the attention and focus of researchers to applications of coupled systems of structures and fluid in quantitative biomechanics *and shift the research focus from the theoretical aspects to the application aspects*. Historically since 1941 the literature in the subject was scattered and in the last two decades the subject started attracting more attention. This attention was fostered by the rapid development in technology. The area could be of interest to many research fields and industries including but not limited to: the aerospace, materials, and medical industries. The subjects can be interesting for biologists, chemists, material scientists, and engineers from different disciplines.

The effect of microgravity on astronauts is one of the concerns of aerospace industry. The most common disease affecting bones, osteoporosis - literally meaning porous bones - results in the loss of bone mass, rendering bones brittle and more susceptible to fractures. Exposure to the microgravity environment of space causes astronauts to lose calcium from bones. This loss occurs because the absence of earth's gravity disrupts the process of bone maintenance in its major function of supporting body weight. Exposure to the microgravity environment of space causes men and women of all ages to lose up to 1% of their bone mass per month. The puzzle is what signals permit bone tissue to adapt to a weightless or an earth environment and whether weightless conditions affect osteoblast and osteoclast function. Osteoclasts and osteoblasts are bone cells that are responsible of bone tissues removal and formation respectively in the process of bone remodeling. In a weightless environment there is less bone fluid movement due to less physical activity and many think that the bone fluid movement is sensed by the bone tissue in the mechanotransduction process.

Honeycomb composites which adopt the geometrical hexagonal shape of a honeycomb are a good example of materials that inspired by nature. In fact, the idea of these honey comb structures was historically inspired from the structure of cortical bones. These materials have high strength-to-weight ratio and they are used widely in aerospace.

Table 1. Imaging technologies used to characterize the vascular and lacunar-canalicular porositie. [22].

Technology	Resolution	2D / 3D	Comment
VM	~20 µm	2D	Lowest resolution, largest volume of interest
MRG	~5 µm	2D	Low resolution, sensitive to tissue mineral density
µCT	~1 µm	3D	Incoherent X-ray light, relatively large field of view
nano CT	~ 500 nm	3D	Incoherent X-ray light, small field of view
LM	~300 nm	2D / 3D	Destructive and time consuming processing

CLSM	~200 nm	2D / 3D	Functional imaging using fluorescent labeling.
SR-µCT	~ 50 nm	3D	Coherent X-ray light, phase contrast, small field of view
TXM CT	~ 50 nm	3D	Limited VOI, high X-ray radiation dose
TEM CT	~ 50 nm	3D	Limited penetration depth, high X-ray radiation dose
AFM	~ 50 nm	2D	Destructive and time consuming processing, small field of view
FIB/SEM	~ 10 nm	3D	Destructive and time consuming processing, small field of view
SEM	~ 2 nm	2D	Ultra thin sectioning. Limited field of view
TEM	~ 1 nm	2D	Ultra thin sectioning. Limited field of view
UHVEM	~ 1 nm	2D / 3D	Ultra thin sectioning. Limited field of view

Abbreviations: Video microscopy (VM), micro-radiography (MRG), light microscopy (LM), confocal laser scanning microscopy (CLSM), micro computed tomography (µCT), synchrotron radiation-based micro-CT (SR-µCT), transmission X-ray microscopy CT (TXM CT), transmission electron microscopy CT (TEM CT), serial focused ion beam/scanning electron microscopy (FIB/SEM), atomic force microscopy (AFM), ultra high voltage electron microscopy (UHVEM). Two dimensional (2D), three dimensional (3D).

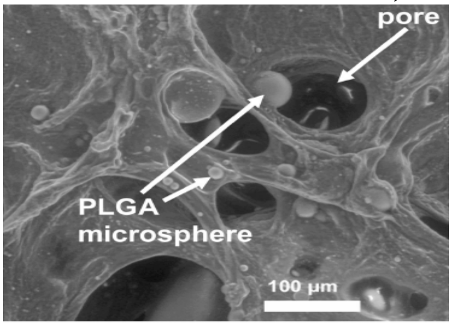
The hexagonal packed osteons in cortical bone and the nested porosity model can lead to new concepts in load bearing and absorption which might be useful in artificial limbs and biomechatronics. Contributions of fluid flow and fluid flow direction in the microscopic level to the mechanical properties in the macroscopic level may lead to new horizons in research. The advances in imaging and testing can provide more details about biological tissues and materials characterization and structure and lead to better understanding and insight into bone poroelasticity. The most of important aspect will be the influence of the mechanical properties in the nano and micro scales on the properties in the macro scales.

Fig.3. Articular cartilage in a knee (source: www.revivalhospital.com)

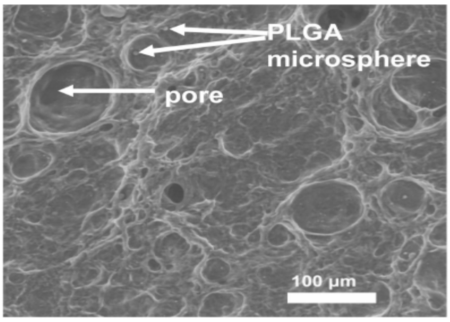
Cartilage repair for patients with osteoarthritis is a good example where materials science, biomedical engineering, mechanical engineering, biology, chemistry and medicine intersect. According to the American Orthopedic Society for Sports Medicine, More than 4 million patients undergo non-arthroplasty treatment for articular cartilage worldwide each year, of which 800,000 are in the US, which cost $400 million and according to public information, between 250,000 and 300,000 total knee implants are performed each year in the United States alone.. According to public information, between 250,000 and 300,000 total knee implants are performed each year in the United States alone. Degradation of the cartilage is a main cause of osteoarthritis which affects 27 million people in the US and 8 million people in the UK.

Articular cartilage, Fig.3, repairs are done through different procedures. According to a new research by Dr. Robert Litchfield, September 2008, of the University of Western Ontario concluded that routinely practiced knee surgery is ineffective at reducing joint pain or improving joint function in people with osteoarthritis. The challenge of designing a construct for the repair of focal cartilage defects such that it mimics the mechanical properties of and can integrate with native cartilage has not been met [21]. An interesting approach, [21], suggested designing a porous construct consisting of non-degradable polyvinyl alcohol (PVA) with ***varying*** degradable polylactic glycolic acid (PLGA) to control the porosity of the construct (10% – 75%), see Fig. 4.

Osteoporosis is a disease of bones that leads to an increased risk of fracture. In osteoporosis, the BMD is reduced, bone micro-architecture deteriorates, and the



75% PLGA



10% PLGA

Fig.4. Construct of PVA and PLGA to be transplanted to the cartilage. The figure shows different porosities controlled by the degradable PLGA. [21]

amount and variety of proteins in bone are altered. According to the National Osteoporosis Foundation about 10 million Americans have osteoporosis. About 34 million are at risk for the disease. Estimates suggest that about half of all women older than 50, and up to one in four men, will break a bone because of osteoporosis. More than 2 million osteoporosis-related fractures happened in 2005 that cost approximately $19 billion. These costs are predicted to increase to approximately $25.3 billion by 2025. Bisphosphonates are anti-resorptive medicines, which means they slow or stop the natural process that dissolves bone tissue, resulting in maintained or increased bone density and strength. The study of Permeability can impact pathology and determine whether long term bisphosphonate treatment in osteoporotic patients alter the permeability and porosity of bone tissues, thus *impacting the mechanics and nutrition of bone*. On the other hand, porosity has visited the court room as well. Law suits have been filed and won against I-Flow and Breg Inc. for over delivery of pain relief medication through their pain pumps. The defects caused severe cartilage loss (chondrolysis) which required the patients to undergo shoulder arthroplasty.

The research can highlight new types of problems that involves contact between two porous materials or contact between porous and solid materials. A good example will be total knee replacements (TKR), hip replacements, and long bone fracture implants. According to an article in the New York Times, the United States Food and Drug Administration is planning to launch new metal hip implant regulations. Due to a large number of metal-on-metal hip implant recalls in the past few years, the FDA will place the devices in a higher-risk category that will require a more rigorous FDA review prior to approval. Under the proposed guidelines, the agency will require all metal-on-metal hip implant manufacturers to prove that the devices are effective and safe prior to market entry. This ruling applies to devices under development and devices currently on the market. Under current guidelines, manufacturers don't have to conduct clinical studies if their devices are similar to other products on the market. The new initiative by the FDA is designed to close a loophole in 30-year-old federal law under which healthcare devices are regulated. Many traditional hip replacements are made from a combination of plastic and metal; these devices usually last for at least 15 years. However, all-metal hips, devices that have received little clinical testing, are failing at a very high rate within a few years of implantation. Patients with these faulty metal hip implants must undergo expensive and painful operations for replacement. In addition, the shearing force between all-metal components has lead to the dispersion of microscopic metal fragments through a patient's body. This has caused extensive damage to joints and tissue.

VII. Conclusion

- This area of study requires collaboration from different disciplines
- Applications in this area have direct impact on society and economy.
- The advances in imaging and testing can provide more details about biological tissues and materials characterization and structure and lead to better understanding and insight into bone or tissues poroelasticity.

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