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Analysis of Bone Remodeling Under Piezoelectricity Effects Using Boundary Elements

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Abstract

Piezoelectric materials exhibit a response to mechanical-electrical coupling, which represents an important contribution to the electrical-mechanical interaction in bone remodeling process. Therefore, the study of the piezoelectric effect on bone remodeling has high interest in applied biomechanics. The effects of mechano-regulation and electrical stimulation on bone healing are explained. The Boundary Element Method (BEM) is used to simulate piezoelectric effects on bones when shearing forces are applied to collagen fibers to make them slip past each other. The piezoelectric fundamental solutions are obtained by using the Radon transform. The Dual Reciprocity Method (DRM) is used to simulate the particular solutions in time-dependent problems. BEM analysis showed the strong influence of electrical stimulation on bone remodeling. The examples discussed in this work showed that, as expected, the electrically loaded bone surfaces improved the bone deposition. BEM results confirmed previous findings obtained by using the Finite Element Method (FEM). This work opens very promising doors in biomechanics research, showing that mechanical loads can be replaced, in part, by electrical charges that stimulate strengthening bone density. The obtained results herein are in good agreement with those found in literature from experimental testing and/or other simulation approaches.

Keywords: bone remodeling, numerical methods, piezoelectricity, boundary element, anisotropy

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1 Introduction

The way living beings walk generates complex level of stresses, deformations and internal loads. These flows of stresses and deformations are transmitted and distributed along the body and must be studied carefully. They are responsible, in part, of the mechanical stimulus on bone tissue and therefore, of the bone remodeling and growth. In this sense, the relationship between the regulation process of bone tissue and the mechanical external loads is well known. However, it is unclear how the cells control the formation and bone resorption based on the mechanical condition. The piezoelectricity properties exhibited by some biological tissues are of great importance to explain how bone cells act on the mechano-regulation process and how the external electrical stimulation on bone tissue may contribute to the process of healing and repair.

The remodeling process is carried out by an ARF process: activation (A), followed by reabsorption (R) and then formation (F), where reabsorption by a basic cell group is activated in order to replace old bone with new bone in discrete packets. Biological tissues are complex structures which are subject to different external stimuli, such as mechanical forces, electrical signals, temperature variations and others; determining the tissue structure and allowing them to adapt themselves or change their shape. Since the discovery of the piezoelectric property on bones and collagen fibers[1,2] it has been an increase in the interest in understanding the mechanism of osteogenic control works of electrical stimulation in the remodeling process and emphasis on the need to study mechanical and piezoelectric models.

A unified theory that explains how the electrical

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signals and mechanical loads are involved in the adaptation of the bone is piezoelectricity. This mechanism makes mechanical stresses result in electric polarization (indirect effect) and the application of an electric field causes deformation (convert effect, see Ref. [3]). Healing and bone growth are controlled by the deposition rate of hydroxyapatite which is attributed to the work of osteoblasts, which are attracted by the electrical difference produced by piezoelectricity or bone formation (especially the collagen).

Furthermore, a number of theories about how the bones adapt to functional applications have proposed models that help predict bone behavior. These theories are mostly focused on mechanical stimuli influence on cell proliferation and how the bone adapts to the functional mechanical stresses of daily activity. The adaptation of the bones to load function has been investigated for several decades. Some mathematical laws can describe this behavior and have been proposed (see Ref. [4]). These proposals are addressed to adaptive models of bone density based on deformations[5], stresses[6,7], strain energy[8–11], mechanical damage[4,12,13], contact mechanics[14], cell proliferation[15,16] or a combination of all of them, which represent different aspects of the adaptive process. Although there are important aspects in bone dynamics, they are only limited to the study of a specific stimulus.

As mentioned before, some authors[1,2] have observed the piezoelectric effect on the bones in three different experiments, by measuring the direct effect of both the static direct and indirect dynamic effects. The piezoelectric effect appears only when the mechanical forces are applied to the collagen fibers where the collagen molecules are highly oriented and crystallized, the formation of callus in areas not traumatized by the compression can be observed. If an external voltage is applied to the bone it causes a mechanical deformation. Bone walls are composed of numerous fine fibrous sheets about the axis of the bone in which collagen molecules are unidirectionally oriented in a system with crystals of hexagonal symmetry[17]. Bone structure changes in response to genetic control, hormonal and mechanical environment information. The relationship between polarization and stresses whose effect is truly piezoelectric, resulting from sliding of the collagen fibers each other[1]. The potential and electric current (see Ref. [18]) are responsible for the transduction of mechanical stress into a cellular response. Also, they are involved in the structure and composition of bone and cartilage[19].

Several authors have described the piezoelectric effects on bone tissue. Gjelsvik[20] presented a physical description of the remodeling of bone tissue in terms of a simple form of piezoelectric linear theory. A piezoelectric model for the analysis of a cantilevered beam subjected to a vertical load has also been presented[21]. McDonald and Houston[22] added the identification of sites of maximum stress in tension and compression. They were measuring the difference of potential on the bone surface *in vivo* nearby periosteum artificial loads. Likewise, the external voltage generated by the result of motor nerve and consequently depolarization and muscle contraction. Some descriptive theories of electromechanical remodeled are also available[23] while Ramtani[3] added the influence of damage on the model and maintaining bone matrix. Other works[24,25] show the influence of the electromagnetic field on the process of remodeling and healing under the effect of mechanical and electrical loads. Also some models[26–28] have included the effect of mechanical, electrical and thermal external loads on the process of remodeling, among others. However, how these factors can affect the remodeling process is still an open research question. For instance, this understanding is a key factor to improve implants designs[29].

This work is mainly focused on the development of an electromechanical model using boundary integral methods (instead of domain methods) and a density function to ensure that the electric field is increased[11]. Also, for an elastic-piezoelectric body the strain tensor and the polarization vector are assumed to be a function of both stress and electric fields. The form of these functions and the number of material constants are related to the degree of non-linearity of the relationship and the type of anisotropy in the material. Thus, the evaluation of the stresses is done in an easier way, by using boundary methods that simplify the mesh generation and eventually the remeshing in adaptative processes.

2 Materials and methods

2.1 Bone tissue: a brief summary

Bone tissue is classified according to the observed level. There are two types of bone at the macroscopic level, cortical (compact) and spongy (trabecular) bone. Both tissues have the same structure and composition