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Identification of stiffness variations in supporting substances of a human canine tooth with a bracket-beam-piezoelectric sensor and its electromechanical impedance

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ABSTRACT

In this paper, an experimental method is described to identify the stiffness variations produced by drillings done in different supporting substances of a human canine tooth. To measure the supporting substances parameters through of a canine, a sensor-actuator system was developed. The sensor-actuator device was composed of a stainless steel bracket bonded to a steel wire attached to two piezoelectric transducers, with a concentrated mass attached to the end of the wire. To excite the device, high frequency voltage (between 5 and 10 KHz) was applied through the piezo-transducers, which affects the tooth by means of the vibration of the wire. High frequency mechanical vibrations allowed the appraisal of the mechanical response from the supporting substances. Mechanical responses associated with the stiffness of the support were quantified with the electrical impedance of the piezo-transducers. The device was coupled to the crown of a canine tooth simulating a condition of fixing as in the bone, the tooth was fastened by the root portion inside the supporting substance. Four supporting substances were characterized for the tests. After establishing base values of the stiffness of each supporting substance, the stiffness variations were assessed in two stages (two drillings); these were made perpendicularly to the longitudinal axis of the tooth, Results show that it is possible to assess stiffness variations with the proposed methodology as well as to quantify the stiffness differences, by means of variation indexes.
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1. Introduction

Orthodontic treatments have helped to correct discrepancies in dento-maxillary with the aim to modify the teeth positions and maxilla-facial growth, by means of mechano-biological intervention of related structures. In orthodontic treatment, teeth are moved to a favorable position, a procedure that can be done in months or years, depending on final location. Orthodontic tooth movement (OTM) is due to biological events that take place in the alveolar bone when mechanical forces are applied to the teeth. The alteration of structural environment in the bone structure produces changes on it during the treatment [16,31]. Alveolar bone fraction and tissue mineral density can vary by age, during OTM and metabolic processes among others [6,9,37,40]. The fact that bone tissue is an ever-adapting structure, responding to a wide range of external and internal stimuli, contributes to the complexity involved in studying its behavior. Researchers face a daunting task when seeking better understanding of how different factors affect its metabolism, especially because continuous modeling, remodeling and adaptation processes of bone structures inherently imposes the need for repeated
intra-subject assessment of bone mineral density (BMD). To study the effects of age [13,25], sex [5,39], diet [11,28,29], physical loading [7,20], systemic health [2,12,22], environmental factors [3,15,18], on BMD, reliable measurements must be performed on live human subjects. Techniques for BMD assessment include Radiogrammetry (RG), Compton Scattering Technique;
Radiographic Photodensitometry (RP); Dual-energy Photon Absorptiometry (DPA) among others [8]. In general, the majority of

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current techniques are considered invasive, since quantification of bone density involves the use of ionizing radiation (X rays), validating the need for development of a more conservative method to evaluate variations in BMD that permit repeated intra-subject valuation.

Electromechanical phenomenon provided by piezoelectric transducers (PT) have evidenced a great potential in different engineering applications. In the structural field, PT helps to evaluate, identify, classify and estimate different structural conditions as it has been proven in different engineering fields as for example; Non-Destructive Evaluation (NDE), Structural Health Monitoring (SHM) and Control among others [23,32,34,38,42]. In these fields, different methodologies and techniques have been developed to integrate and to use PT in the structures due to the electromechanical coupling that these present naturally. Specially, we can mention a technique that has gained widespread attention in last two decades as a result of its high local sensitivity, easy implementation and the nonparametric analysis that are constructed with noncomplex theories; this is defined as the electromechanical impedance technique (EMI). EMI technique is applied in structural identification and monitoring conditions in real-time which has demonstrated a great capacity and sensitivity of capturing structural variations with high frequency vibrations [14,21,41]. Actually, different applications are being explored in the bio-medical field, such as the use of biomedical sensors for monitoring condition of bones, through experimental studies on human and rabbit bones as it was experimented in the study of [4]; where the changes in the EMI signatures correlated fairly well variations in the condition of the bones. Additionally [26,27], proposed a technique for monitoring dental implant stability applying the EMI technique. The method involved bonding a piezoelectric transducer to the implant in which the electrical admittance was measured to evaluate its stability, which in turn was correlated with the mechanical parameters of the bone. This shows that exists an opportunity to apply the EMI technique in the monitoring of different biological structures.

This paper presents an experimental technique that permits to identify the stiffness variations produced by drillings in supporting substances chosen for a human canine tooth. The supporting substances simulate the bone structure in the experiments. A bracket-Beam-Piezoelectric sensor system is developed to measure stiffness parameters of the supporting substances through of a human canine tooth. The main motivation of this study is to search lesser invasive, cost and time effective technologies to identify bone mineral density (BMD) variations as a future application.

2. Materials and methods

2.1. Electromechanical impedance principles in piezo-transducers

Electrical impedance $Z_p(\omega)$ describes a measure of resistance to the current i (alternant current/AC) when a harmonic voltage V is applied on the electrical circuit. The electrical impedance depends on the elements that compose a circuit and therefore we can have electrical resistances (R), inductances (L) and capacitances inside it. The combination of these elements define the behavior of a circuit in the time or in the frequency domain. An illustration of a series circuit is depicted in Fig. 1a, in which an alternant voltage is applied on it. In the frequency spectrum, the electrical constants (R, L and C) act as vector quantities in a complex system, therefore it is possible to establish an impedance triangle, as illustrated in Fig. 1b; such that ϕ is the phase and $Z_p(\omega)$ is the magnitude of the electrical impedance. Depending on the nature of the circuit (frequency domain), capacitance and inductance take the name of capacitive and inductive reactance, which represent the imaginary part and the resistance the real part. By definition, we can briefly mention that the electrical impedance is a parameter that it does not depend on the voltage input neither the current output or vice versa. Additional information about the electrical impedance principles can be reviewed in study done by Ref. [19].

It is well known that electrical properties of the piezoelectric transducers (PT) are coupled to the mechanical properties due to the electromechanical phenomenon. For example, when a piezo-transducer is deformed; electrical charges are produced through the poling direction or when an electrical field is applied on it changes its shape [33]. According to [30]. PT can be analyzed as an open electrical circuit or short circuit, respectively. If a piezo-transducer is connected to an electrical circuit, this is considered as a resistive-capacitive element [17]. It means that there is no inductance in a piezo-transducer. Then, the properties of electrical circuits satisfy to the PT. Therefore, the electrical impedance $Z_P^E(\omega)$ is composed by a real part (resistance R) and an imaginary part (reactance X) and it may be described as

$$Z_P^E(\omega) = \frac{V}{i} = R + Xj, \tag{1}$$

where ω is the frequency, X is the reactance which can be inductive and capacitive; being V and i the input voltage and output current. In practical terms, the constants inside X can be determined using a parameter identification from the electrical impedance.

Fig. 2a shows a simple model that couples a mechanical system

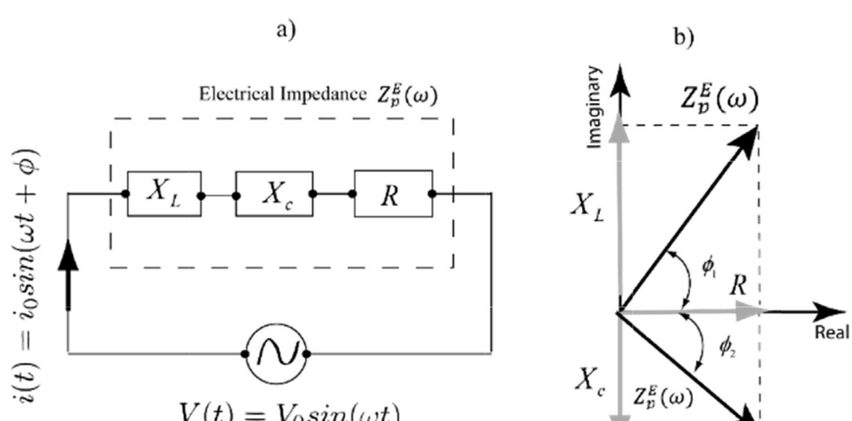

Fig. 1. a) Series combination of LCR circuit (resistance R, inductance L and capacitance C). b) Impedance triangle for RLC circuit [34].

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