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Modeling the electromechanical impedance technique for the assessment of dental implant stability

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ABSTRACT

We simulated the electromechanical impedance (EMI) technique to assess the stability of dental implants. The technique consists of bonding a piezoelectric transducer to the element to be monitored. When subjected to an electric field, the transducer induces structural excitations which, in turn, affect the transducer's electrical admittance. As the structural vibrations depend on the mechanical impedance of the element, the measurement of the transducer's admittance can be exploited to assess the element's health. In the study presented in this paper, we created a 3D finite element model to mimic a transducer bonded to the abutment of a dental implant placed in a host bone site. We simulated the healing that occurs after surgery by changing Young's modulus of the bone–implant interface. The results show that as Young's modulus of the interface increases, i.e. as the mechanical interlock of the implant within the bone is achieved, the electromechanical characteristic of the transducer changes. The model and the findings of this numerical study may be used in the future to predict and interpret experimental data, and to develop a robust and cost-effective method for the assessment of primary and secondary dental implant stability.

1. Introduction

Dental implants replace functionally and esthetically the natural teeth. The conventional surgical protocol has two stages (Adell et al., 1981; Brånemark et al., 1969). In the first stage, the implant is placed in the jawbone under the soft tissue and the surgical site is sutured. Stage two is generally performed three to six months later: the soft tissue is opened, an abutment is connected to the implant and a crown is placed on the abutment. When the structural and functional contact between the living bone and the implant is achieved, it is said that fully osseointegration is attained (Bränemark, 1985). Recent advancements have shown that a single stage is possible (Kawai and Taylor, 2007).

Typically, surgeons use empirical methods based on palpation to assess the peri-implant wound healing and determine when to load the implant with the prosthesis (Sullivan et al., 1996). Alternatively, imaging and biomechanical techniques are used. Imaging methods use radiography (Batenburg et al., 1998; Blanes et al., 2007), computer tomography, magnetic resonance, and X-ray micro-computed tomography (Wang et al., 2010a; Zhao et al., 2009). These techniques are limited to measure the bone–implant interface because of diffraction effects; moreover they are not as portable and economical as the commercial biomedical devices Periotest and the Osstell. The Periotest®, introduced by Schulte et al. (1983), consists of a small tapper impacting the implant. The deceleration of the tapper is measured, converted into a Periotest value (PVT), and related to the implant stability (Crum et al., 2014; Geckili et al., 2014). The Osstell system, introduced by Meredith (1997), is based on the resonance frequency analysis (RFA). An L-shaped transducer is screwed onto the implant or its abutment and it is excited by a sine wave varying in frequency from 5 to 15 kHz (Pattijn et al., 2006). The indicator of stability is provided by the first resonance frequency of the implant converted into the implant stability quotient (ISQ).

As the quest for a perfect biomechanical method is not limited to the improvements of the two commercial systems, some authors have proposed alternative approaches based on quantitative ultrasounds (De Almeida et al., 2007; Mathieu et al., 2011a, 2011b; Vayron et al., 2015) or the electromechanical impedance (EMI) (Boemio et al., 2011; La Malfa Ribolla et al., 2015; Tabrizi et al., 2012). The latter technique consists of bonding one wafer-type lead zirconate titanate transducer (PZT) to the implant or the abutment to be monitored and of measuring the electrical characteristics of the transducer which are related to the mechanical characteristic of the host structure. When subjected to an electric field, the transducer induces low to high frequency structural excitations which, in turn, affect the

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transducer's electrical admittance. As the structural vibrations depend on the mechanical impedance of the host structure, the measurement of the PZT's admittance can infer the health of the surgical site. The EMI technique is popular for the health monitoring of engineering infrastructures (Annamdas and Soh, 2010; Park et al., 2003; Soh et al., 2012); however its application in bioengineering is limited (Bender et al., 2006; Bhalla and Bajaj, 2008; Giurgiutiu et al., 2004).

In the study presented in this paper, we complemented the experiments we conducted recently (Boemio et al., 2011; La Malfa Ribolla et al., 2015; Tabrizi et al., 2012), with a numerical analysis of the biomechanical osseointegration process monitored with the EMI technique. The electromechanical coupling between a PZT patch and a host generic structure was first validated by comparing our finite element (FE) model with analytical or literature-known solutions. In all cases a coupled field analysis (CFA) was performed using the commercial software ANSYS APDL 13.0 (ANSYS, 2009a).

2. Background

The FE analysis of the implant–bone interaction can be static or dynamic. In elastic–static analysis the bone is considered a homogeneous material, the implant is considered fully osseointegrated, and the analysis finds the design that minimizes the implants stress (Baggi et al., 2008; Chun et al., 2002; Saab et al., 2007).

A dynamic analysis investigates the factors that affect the vibration characteristics of an implant (Deng et al., 2007; Pattijn et al., 2006; Li et al., 2011, Pérez et al., 2008). These characteristics constitute the basis of the Osstell measurements. For example, Natali et al. (2006) simulated the resonant frequency of an implant by considering the presence of a peri-implant interfacial tissue whose mechanical properties changes during the integration process. Wang et al. (2010b) ran a modal analysis of an implant–interface–bone system where a 1.3 mm thick interface tissue was considered much softer than the surrounding bone.

The mechanical impedance Z_s of a point on a structure is the ratio of the force applied on the point to the resulting velocity at that point. A PZT embedded to the structure of interest can be used to assess indirectly the impedance of the structure by measuring the electrical admittance $\bar{Y}$ of the patch. The admittance consists of the real term known as conductance (G) and the imaginary term known as susceptance (B). Analytically

$$\bar{Y} = G + jB \ (j = \sqrt{-1}) \tag{1}$$

A plot of G and B as a function of the actuation frequency present peaks associated with the modes of vibrations of the PZT-host element and they represent a unique health signature of the structure within the sensing region of the patch.

The coupling effect of the PZT's electromechanical impedance can be investigated using the idealized 1-D system shown in Fig. 1. The impedance of the host structure is characterized by the mass m, the stiffness k, the damping c, and the boundary conditions. The relationship between the electrical admittance of the PZT and the mechanical impedance Z_S of the host structure can be expressed as

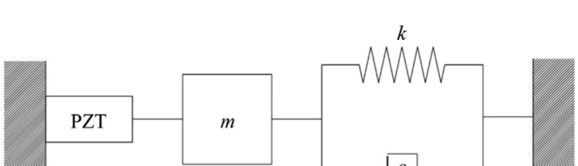

Fig. 1. Scheme of a 1-D electromechanical impedance model (adapted from Park et al. (2006)).

(Liang et al., 1994)

$$\bar{Y} = \omega j \frac{w l_p}{h}\left(\bar{\varepsilon}_{33}^T - d_{31}^2 \bar{Y}^E\right) + \left(\frac{Z_P}{Z_S + Z_P}\right) d_{31}^2 \bar{Y}^E \left(\frac{\tan k_p l}{k_p l}\right) \tag{2}$$

where l_p, w and h are the length, width and thickness of the PZT, respectively, d_{31} is the piezoelectric strain coefficient, $\bar{Y}^E$ is the complex Young's modulus of the PZT at a constant electric field, and $\bar{\varepsilon}_{33}^T$ is the complex electric permittivity at a constant stress. The expressions of $\bar{Y}^E$ and $\bar{\varepsilon}_{33}^T$ are given by

$$\bar{Y}^E = Y^E(1 + \eta j) \tag{3a}$$

$$\bar{\varepsilon}_{33}^T = \varepsilon_{33}^T(1 - \delta j) \tag{3b}$$

where η and δ denote the PZT's mechanical and dielectric loss factor, respectively, Y^E is Young's modulus of the PZT, and ε_{33}^T is the electric permittivity. Z_s and Z_P are the mechanical impedance of the structure and the PZT, respectively, obtained as the ratio of a harmonic excitation force at an angular frequency to the velocity response. Z_P can be expressed as

$$Z_P = \frac{k_p w h \bar{Y}^E}{\omega j \tan(k_P l_P)} \tag{4}$$

In Eq. (4) k_P is the wave number $k_P = \omega\sqrt{\frac{\varrho_P}{\bar{Y}^E}}$ of the patch, related to the angular frequency of excitation ω, and ϱ_P is the density of the PZT.

A few researchers used ANSYS to predict the interaction between the PZT patch and its host structure. Some authors used a pair of known harmonic forces applied to the patch to derive the mechanical impedance of the host structure (Tseng and Wang, 2004; Bhalla and Bajaj, 2008).

The CFA can be also adopted to model mechanical behavior and electrical field (Moharana and Bhalla, 2012). CFA was used in some EMI-based engineering applications (Liu and Giurgiutiu, 2007; Moharana and Bhalla, 2012; Yang et al., 2008; Zhang et al., 2011) but was never applied to model the electromechanical response of PZT in biomechanics.

3. Validation of the model

Prior to applying the CFA to the clinical problem, a few preliminary simulations were performed in order to validate the model.

3.1. 1-D electromechanical system

The electromechanical system schematized in Fig. 2(a) was studied. It consisted of a $2 \times 2 \times 100$ m^3 PSI-5A4E transducer, from Piezo Systems, Inc., bonded to a $2 \times 2 \times 100$ mm^3 aluminum beam. The material properties of the transducer are the same of those presented in Table 1 > of La Malfa Ribolla et al. (2015), whereas for the aluminum we considered density and Young's modulus equal to 2700 Kg m^{-3} and 70 GPa, respectively. The Solid-5 element, a 3D couple-field brick with 8 nodes, and the Solid-185, a 3D structural brick with 8 nodes, were used for the PZT and the metallic beam, respectively (ANSYS, 2009b). A 5 mm cuboid element was adopted and a three-dimensional analysis was performed.

For the particular case of a fixed 1-D beam, Z_s becomes

$$Z_S = \frac{k_S m n E_S}{\omega j \tan(k_S l_S)} \tag{5}$$