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Journal of Biomechanics 39 (2006) 939–947

JOURNAL OF BIOMECHANICS

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The resonance frequencies and mode shapes of dental implants: Rigid body behaviour versus bending behaviour. A numerical approach

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Accepted 10 January 2005

Abstract

The purpose of this study was to evaluate the modal behaviour of the bone–implant–transducer (Osstell) system by means of finite element analyses. The influence of different parameters was determined: (1) the type of implant anchorage being trabecular, cortical, uni-cortical, or bi-cortical, (2) the implant diameter, (3) the length of the implant embedded in the bone, and (4) the bone stiffness. The type of anchorage determines the resulting modal behaviour of the implant–transducer system. A rigid body behaviour was found for a uni-cortical anchoring and for a homogeneous anchoring with low bone stiffness ($\leqslant$1000 MPa), whereas a bending behaviour was found for a homogeneous anchoring with a high bone stiffness ($\geqslant$5000 MPa) and for a bi-cortical anchorage. The implant dimensions influence the values for the resonance frequencies. Generally, an increase in implant diameter or implant length (in bone) results in higher resonance frequencies. This study also showed that resonance frequencies in case of rigid body behaviour of the implant–transducer system are more sensitive to changes in bone stiffness than resonance frequencies in case of bending behaviour. In conclusion, it seems that the Osstell transducer is suited for the follow-up in time of the stability of an implant, but not for the quantitative comparison of the stability of implants.

Keywords: Osstell™ transducer; Implant stability; Finite element method; Parametric study

1. Introduction

Bone-anchored implants, also called osseointegrated implants, are often used in dentistry to provide support for prostheses replacing missing teeth in complete and partially edentulous patients (Snauwaert et al., 2000; Naert et al., 2002a, b). Before implant placement, the risk factors that can prejudice a successful treatment are determined. These risk factors are classified into general, local, and biomechanical factors (Renouard and Rangert, 1999). Although patients at risk are detected in advance, and treatment is changed in order to decrease the risks of failure, implants fail. According to Meredith et al. (1996), failure of an implant can be characterised by (1) a clinical mobile implant, (2) a severe loss of the marginal bone surrounding the implant, or (3) a fracture of the implant. A decisive condition for implant success is the presence of a stable bone–implant contact (Duyck and Naert, 1998). On the one hand, such an osseointegration can be inhibited by several factors, e.g. infection, implant contamination, excessive micromovement, etc., which results in early implant failure. On the other hand, the integrity of an already established osseointegrated implant can be affected by a disturbance in a biological or a biomechanical equilibrium.

Therefore, in clinical practice it is important to detect an increased implant mobility before failure occurs. Implant mobility is influenced by a number of factors:

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0021-9290/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jbiomech.2005.01.035

the amount of bone surrounding the implant and its quality, the length and type of implant used, and the fact whether it engages one or two bony cortices (Meredith et al., 1997a).

Resonance frequency analysis (RFA) has been used in orthopaedics to identify the in vivo vibration modes of human tibiae (Van der Perre et al., 1983) and to determine the torsional stiffness of long bones (Lowet et al., 1993). The feasibility of the resonance frequency technique for monitoring of fracture healing (Cornelissen et al., 1987) and osteoporosis evaluation (Van der Perre and Lowet, 1994, 1996) was shown. Vibration analysis was used to assess the stability of fixation of hip stems in vitro as well as in vivo (Rosenstein et al., 1989; Li et al., 1995; Denayer and Van der Perre, 1998; Puers et al., 2000; Georgiou and Cunningham, 2001). Moreover, numerical modal analyses were performed by Qi et al. (2003) to indicate the hip prosthesis loosening in a quantitative manner.

The Osstell^{TM} transducer (Integration Diagnostics AB, Sweden) is a device to clinically monitor the stability of a dental implant. It is screw tightened onto the implant or to its transmucosal component, the abutment, and measures the resonance frequency. A transmitter element attached at one side of the cantilever beam of the device (Fig. 1) is excited by a sine wave varying in frequency from 5 to 15 kHz in steps of 25 Hz. The receiver element attached to the other side of the cantilever beam measures the response. The resonance frequency is recorded as the peak of the Bode diagram, i.e. the amplitude of the received signal plotted against the frequency. It has been shown that the Osstell^{TM} transducer is able to measure the change in implant stability over time, and can discriminate between successful implants and clinical failures. Moreover the resonance frequency measurements are related to the effective length of an implant above the level of the bone and the stiffness of the implant–tissue interface (Meredith et al., 1994, 1996, 1997a, b; Glauser et al., 2004).

Implant mobility is influenced by several factors, but the effect of these individual factors on the resonance frequency value measured by the Osstell^{TM} transducer is not yet fully known. Therefore, this study investigates the influence of different parameters, i.e. the type of implant anchorage, the implant diameter, the length of the implant embedded in bone, and the bone stiffness, on the resonance frequencies of the Osstell^{TM} transducer by means of finite element analyses.

In the past, finite element analysis was used to support the quantitative interpretation of vibration analysis measurements for the assessment of tibial fracture healing (Lowet et al., 1996). Finite element modelling (FEM) has also been used in analysing vibration behaviour of dental implants following impulse excitation (Williams and Williams, 1997; Huang et al., 2002). FEM has the advantage of simulating various conditions, i.e. each parameter can be changed individually, which is difficult to replicate in in vitro or in vivo experiments.

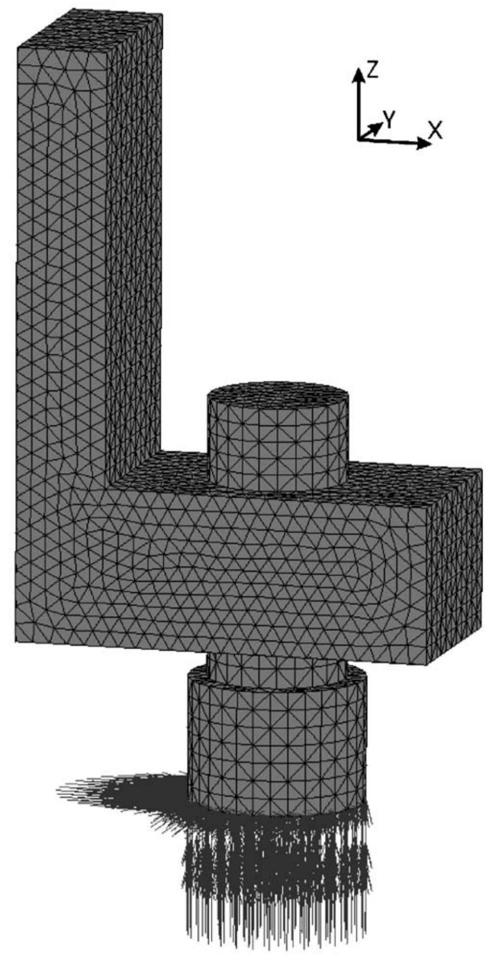

Fig. 1. Finite element model of the Osstell^{TM} transducer (element size $\approx$0.45 mm).

2. Materials and methods

This section consists of three parts. First a modal analysis of the Osstell^{TM} transducer alone, as a reference case, was performed. Then the bone–implant–transducer system was modelled and the influence of the implant anchorage on the resonance frequencies was determined. Finally a parametric study of the bone–implant–transducer system, looking at the influence of implant diameter, length of the implant in the bone, and bone stiffness was performed.

2.1. Osstell^{TM} transducer

A finite element model was made of the Osstell^{TM} transducer. The transducer was modelled by means of