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Modelling dental implant extraction by pullout and torque procedures

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ABSTRACT

Dental implants extraction, achieved either by applying torque or pullout force, is used to estimate the bone–implant interfacial strength. A detailed description of the mechanical and physical aspects of the extraction process in the literature is still missing.

This paper presents 3D nonlinear dynamic finite element simulations of a commercial implant extraction process from the mandible bone. Emphasis is put on the typical load-displacement and torque-angle relationships for various types of cortical and trabecular bone strengths. The simulations also study of the influence of the osseointegration level on those relationships. This is done by simulating implant extraction right after insertion when interfacial frictional contact exists between the implant and bone, and long after insertion, assuming that the implant is fully bonded to the bone. The model does not include a separate representation and model of the interfacial layer for which available data is limited.

The obtained relationships show that the higher the strength of the trabecular bone the higher the peak extraction force, while for application of torque, it is the cortical bone which might dictate the peak torque value. Information on the relative strength contrast of the cortical and trabecular components, as well as the progressive nature of the damage evolution, can be revealed from the obtained relations. It is shown that full osseointegration might multiply the peak and average load values by a factor 3–12 although the calculated work of extraction varies only by a factor of 1.5.

From a quantitative point of view, it is suggested that, as an alternative to reporting peak load or torque values, an average value derived from the extraction work be used to better characterize the bone–implant interfacial strength.

1. Introduction

Osseointegration is defined as "direct structural and functional connection between ordered, living bone and the surface of a load-carrying implant" (Albrektsson et al., 1981; Stanford and Keller, 1991). This process can be regarded as a bone healing process, which creates a biological fixation through continuous bone apposition and remodeling towards the implant.

This dynamic process, that takes place at the interface between the solid implant and the biological hard tissue, depends on various factors, such as the implant's biomaterial and surface composition, topography, implant geometry, fixation type, and of course healing time after implant placement. In addition, several patient factors also contribute to the success of the process, such as the patient's medical condition (diabetes, bone disease, medication), oral habits (clenchers and bruxers), and of course the surgical protocol.

Several methods exist in order to evaluate the quality and quantity of osseointegration and the interfacial bond between the implant and the host bone (Atsumi et al., 2007). Although histological analysis is regarded as the gold standard to evaluate the degree of osseointegration, several biomechanical test methods have been developed, such as the "push out", "pullout" and "torsion" tests. These can be used to test the *ex vivo* mechanical state of biological fixation of the implant through the evaluation of the shear strength of the bone implant interface (Chang et al., 2010).

The "push out/pullout test" is also a commonly used approach to investigate the interfacial stiffness. In a typical test, a cylindrical implant is placed in bone structures, and then removed after predetermined healing time by applying a force along the implant's longitudinal axis. The interfacial stiffness can be approximated using the force–displacement curve obtained during the test (Brunski et al., 2000; Chang et al., 2010a, 2010b). This method is more suitable to cylindrical type implants. The pullout test is recommended by ASTM F543-07 (American Society for Testing and American Society for Testing and Materials, 2009), as the standard method to simulate the axial withdrawal of a screw from the cadaveric or synthetic bone. The screw

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withdrawal process is recorded as a load–displacement curve, and the holding power is defined as the peak value of the load–displacement curve (Hou et al., 2004; Hsu et al., 2005; Huja et al., 2005). This peak value is considered as an estimate the bone–screw interfacial strength (Hoshaw et al., 1994).

During a "torque test", the implant is unscrewed and the removal torque values are recorded (Trisi et al., 2011). Using this approach, interfacial shear properties are measured (Atsumi et al., 2007; Chang et al., 2010), and a torque–angle curve is obtained. This method is more suitable to screw type implants.

These mechanical tests have been used in implant dentistry to investigate the healing capabilities at the bone implant interface, with emphasis on the effect of healing time (Brånemark et al., 1997, 1998; Kraut et al., 1991), or the effect of the surface treatment (condition) (Ferguson et al., 2008).

Brånemark et al. (1997, 1998) were among the first to evaluate the biomechanics of titanium implants in animal models (rats and dogs) after varying periods of healing without loading (submerged), by *ex-vivo* torsion tests, pull-out tests, and histological analysis. Their detailed studies showed a clear correlation between the shear stresses and shear moduli in the bone tissue (pull-out test), and at the interface (torque test), and bone-implant contact area. As the duration of the bone healing increases, a substantial improvement in the mechanical shear response could be observed.

Ferguson et al. (2008) performed a biomechanical study evaluating the effect of various surface treatments, conventional (sandblasting and etching, CaP coated and anodized), and alternative treatments (coating with bisphosphonate or artificial extracellular matrix) on osseointegration. The healing process was evaluated using in-vivo animal sheep model. Peri-implant bone density and removal torque were compared at 2, 4, and 8 weeks after implantation. A torque-rotation curve was constructed and the maximum removal torque (N-mm) value was recorded. Interestingly, bone-implant interfacial failure could be qualitatively distinguished by 3 different kinds of torque-angle relationship, with each surface treatment characterized by a specific tendency.

Here, one should note that the force needed to either push out or pull out an implant specimen is mostly borne by the interfacial area. Therefore, while the assumption of an "average shear stress" may be applicable to a regular cylindrical specimen, the more complex realistic implant geometry with its threads renders this notion questionable for the simple reason that neither the interfacial stresses or strains are homogeneous anymore.

From the above-mentioned references, it seems that because of variability in test conditions and parameters, the reported test results are quite scattered, so that one cannot *systematically* compare the interfacial stiffness or shear properties and draw firm conclusions.

Numerical models are used extensively in medicine and in dentistry in order to simulate a medical device and evaluate its behavior in a tested environment, under a predetermined set of selected model parameters. These "in silico" methods, which are more controlled and unlimited in terms of test/model parameters, provide valuable insight on mechanical behavior of the device. While there is a very large number of papers about numerical modeling of the bone-implant interaction, with emphasis on local strains, stresses and bone remodeling to some extent, papers reporting models of implant pullout, pushout or torque tests, with emphasis on the bone-implant interface are still quite scarce.

Dhert et al. (1992) used finite element modelling to evaluate the interfacial stress distribution on a stem implant used in orthopedics and placed solely in the cortical bone. This early frictionless numerical model used rather simplistic assumptions to calculate the mean interfacial strength without showing the evolution of the process at the bone level in terms of damage for instance.

Hansson et al. (2011) developed an analytical model for the interfacial strength of a rough cylinder based on strength of materials considerations, into which surface roughness elements were included to enhance the physical aspects of the problem. This study did not account for the geometry of a real dental implant with its threads. Mathieu et al. (2012) recently evaluated experimentally, and then modelled the interfacial strength and fracture behavior of the bone-implant system, for a coin-shaped implant, using analytical fracture mechanics concepts. This work addressed specifically torque tests to which mode III fracture is particularly suitable, while paying attention to the cohesive/adhesive nature of the failure process which is seldom addressed in this context. Additional studies reported a high correlation between the numerical indices and measured holding power, see e.g. (Hou et al., 2004; Hsu et al., 2003, 2005).

This literature survey shows that the few experimental studies are essentially aimed at estimating an averaged value of the bone-implant interfacial strength based on homogeneity assumptions that may be questionable. The few available analytical studies correlate the experimentally measured parameters to the interfacial strength and failure parameters of geometrically simplified models. Moreover, there is an even greater scarcity of numerical models for those complex tests, in which a minimal number of assumptions are made, that could provide information on both the mechanical strength parameters and also on the evolution of the physical damage processes that lead to implant total extraction. The complete simulation of a *real implant geometry* being pulled or torque-extracted is still missing.

This numerical study addresses the extraction process of a dental implant by pullout and torque procedures. Specifically, we study the effect of osseointegration on the extraction process by modeling two limit cases: 1) Extraction immediately after insertion (no osseointegration). 2) Extraction after a long time, where the implant is fully osseointegrated and thus fully bonded to the bone.

The pullout results for a wide range trabecular bone parameters, right after insertion are presented first. The results by pulling and torque of an osseointegrated implant are shown next, followed by a comparative and a sensitivity analysis of the torque to various material parameters. A discussion and conclusion section end this manuscript.

2. Material and methods

The extraction process of the representative commercial implant (shown in Fig. 1) from the mandible bone, was simulated numerically (Simulia, 2014a). Two extraction procedures were modelled:

1) Straight implant pullout (pullout).
2) Rotational un-screwing (torque).

The following two cases were considered:

a) The implant was extracted immediately after insertion. In that case, the only interaction between the bone and the implant is frictional.
b) The implant was extracted "sufficiently long" after insertion, so that full osseointegration had taken place. Here, perfect bonding was assumed.

The two cases and their associated extraction procedures are summarized in Table 1. The torque process was not simulated for case (a) because the calculated torque value is very small, and thus of limited interest.

2.1. Pullout of a rigid implant right after insertion

This simulation is a direct continuation of our previous work (Dorogoy et al., 2017), in which the *insertion* process was modeled in detail. Here too, the model is three-dimensional, and the analyses are dynamic, continuous and non-linear. The implant is modeled as a rigid structure. The simulations were performed in three steps: