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AN ALGORITHM FOR COMPUTATIONAL SIMULATION OF MANDIBLE BONE MODELING AND REMODELING AROUND DENTAL IMPLANTS

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Abstract: *Clinically, dental implants induce diverse stresses on surrounding bone; however, when excessive forces are applied implant failure can occur. The stress and strain fields around dental implants are affected by the bone quality and quantity and the remodeling processes at the bone-implant interface. Computational simulation of the bone remodeling around dental implants still remains a challenge. In this study, a microCT-based 2-D geometry of mandibular segment is used to simulate the remodeling of bone in response to contact with a screw implant. The remodeling process is simulated using an adaptive feedback algorithm which is based on "Mechanostat" strain thresholds, i.e. the initial trabecular architecture changes depending on the loading and boundary conditions and results in the final distribution of the trabeculae within the cancellous bone. The aim of this study is to introduce a novel computational FE model for the simulation of trabecular bone remodeling around dental implants. Computational simulation of the bone remodelling process is strongly dependent on the boundary conditions and thus performing 3-D simulations with more sophisticated boundary conditions is necessary.*

Keywords: Mandible, Bone, Dental implant, Mechanostat theory, FEM.

1. Introduction

Modeling and remodeling of bone tissue is a biomechanical phenomenon that is currently still not fully understood. Furthermore computational simulation of bone remodeling is still at a very early stage of development. The first study that described structural changes in bone caused by mechanical stimuli was presented by Julius Wolff in 1892 (Wolff, 1892). Wolff described the implications of external loading on the trabecular architecture in long bones. In 2004 an American orthopedist and surgeon Harold M. Frost (Frost, 2004) explored how mechanical stimuli can influence the remodeling of bone.

In dental implantology, after the placement of an implant, the surrounding bone tissue undergoes changes in its architecture. The inserted implant is typically in contact with both cortical and cancellous bone tissues. Post-operatively, when the implant is loaded the surrounding bone changes its shape and structure according to Wolff's law. That is, the stresses transferred by the loaded implants induce strain in the adjacent bone which stimulates the modeling/remodeling processes. Additionally, an ideal post-operative healing would involve the osseointegration of the implant into the bone matrix. This process creates a firm/stable connection at the bone-implant interface without mutual relative movement/displacement.

The aim of this study is to model the adaptive changes that the cancellous bone undergoes in response to external loading of an adjacent dental implant. The following sections describe the bone modeling/remodeling algorithm based on the Mechanostat theory and developed using principles of dental biomechanics and computational simulation procedures. Special attention is paid to the level of

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detail of cancellous bone and the critically important bone-implant interface. The micro-level approach used in this study is not commonly undertaken within the field; thus the results presented in this paper, to the best of our knowledge, have not yet been published in the literature.

2. Methods

In this preliminary study, the 2D model of a mandibular section with the inserted dental implant was based on a single micro-CT (μCT) cross-sectional image (Fig. 1a). The appropriate image was selected from a tomographic image volume dataset of a mandibular segment with missing teeth. The imaged mandible was obtained from a patient who had bequeathed his body to the Anatomical Institute of Masaryk University in Brno for medical-scientific research and training purposes. The μCT images of the bone segment were acquired using a unique μCT device TOMOLAB (Synchrotron Elettra, Trieste, Italy (Bernardini et al., 2012)); with a17 μm pixel size. Using an in-house software - ROI Analysis (Valášek et al., 2010), the bone volume fraction (BVF) of the cancellous bone was determined to be 0.377±0.056, which corresponds to groups D2 and D3 of the bone density classification according to Misch (Prášilová et al., 2012).

Subsequently, a 2D geometric model was manually created in ANSYS 14 by a simple tracing of the cortical bone boundary. Thus, bone tissue was segmented into two regions - cortical bone and cancellous bone (Fig. 1b)). The cross-section of a typical dental implant was inserted into the model geometry using Boolean operations and the appropriate commands in ANSYS. It should be noted that the implant geometry is not associated with any specific implant brand, rather it is a general representation of a screw implant. This generalization aids in the qualitative study of the developed method and thus, is in keeping with the scope of this paper. All three areas are glued together. The geometry was discretized using quadratic element PLANE183 with an approximate size of 0.08 mm. The fine mesh consisted of approximately 60 000 elements and 160 000 nodes. The trabecular architecture was created on the final FE mesh by defining the material properties as explained below.

All components of the model were defined as linear isotropic material. Young's moduli of the bone tissues, inter-trabecular pores, and dental implant was 13 700 MPa, 5 MPa and 110 000 MPa, respectively (Mellal et al., 2004; Natali et al., 2003). Poisson's ratio was set in all cases at 0.3. The pores were segmented as a separate region consisting of zero pixel intensities in the processed μCT image. This region was correspondingly meshed into elements and the material properties defined (Fig. 1c). The plane stress assumption was adopted in the 2D analysis.

The FE model of a unit thickness was loaded by a force of 36 N acting on the dental implant in the axial direction. The value was determined to be "the 2D-equivalent" of 200 N acting on the 3D assembly of bone with implant (Marcián et al., 2013).

The model was simulated under three different boundary conditions (Fig. 2a, b, c):

1. The segment is constrained in the middle of buccal as well as lingual cortical bone boundary;
2. The segment is constrained around the whole bone perimeter except at the alveolar region;
3. The segment is constrained in the basal boundary only.

In the first step, the bone has the initial cancellous bone architecture (and therefore the material properties distribution) as described above. In the following steps, the Mechanostat-based algorithm is employed to predict the trabecular architecture changes throughout the loading (Fig. 3). The algorithm is as follows: After each step, the strain intensity distribution in the bone is determined and the values in all elements are compared to the Mechanostat strain thresholds (Frost, 2004). Strain intensity (ε_{int}) is an invariant defined as the largest of the maximum values of $|\varepsilon_1-\varepsilon_2|$, $|\varepsilon_1-\varepsilon_3|$, $|\varepsilon_2-\varepsilon_3|$, where ε_1, ε_2, and ε_3 are the principle strains. Three cases may arise (the thresholds are proposed by Frost): 1. If $\varepsilon_{int} < 250\ \mu\varepsilon$ then the element acquires the properties of pores; 2. If $250\ \mu\varepsilon < \varepsilon_{int} < 4000\ \mu\varepsilon$ then no change in the element properties occurs; 3. If $4000\ \mu\varepsilon < \varepsilon_{int}$ then the element acquires the properties of bone. These cases represent the bone atrophy, bone maintenance, and bone growth, respectively. The solution was performed for 100 steps (cycles) which were identified to be sufficient for the stabilization of the structure. It should be emphasized that this is a preliminary study and the quasistatic character of solution may be questioned. Nevertheless, the work presented in this paper is a springboard to the more sophisticated applications of the Mechanostat-based algorithm which take into account the time factor, typical chewing record etc.

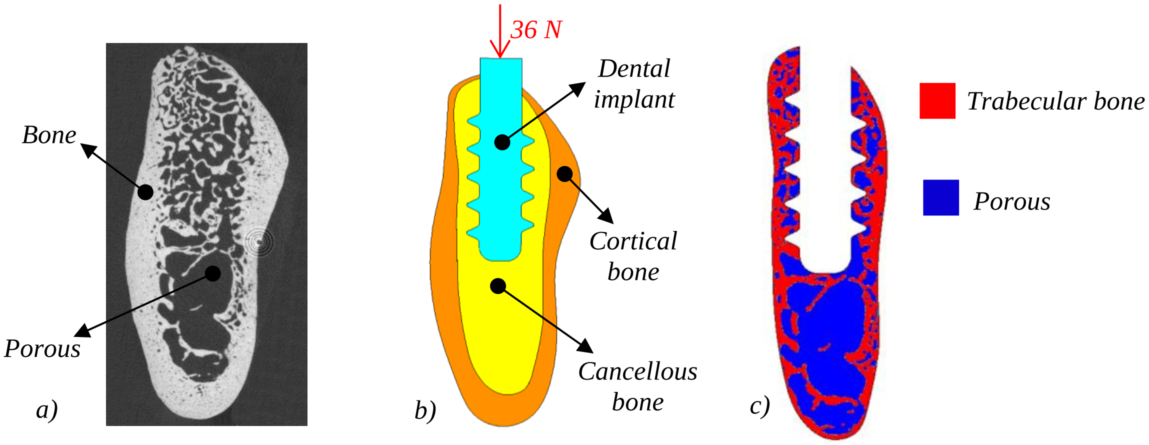

Fig. 1: a) Micro-CT slice; b) Geometry model; c) Trabecular architecture of cancellous bone.

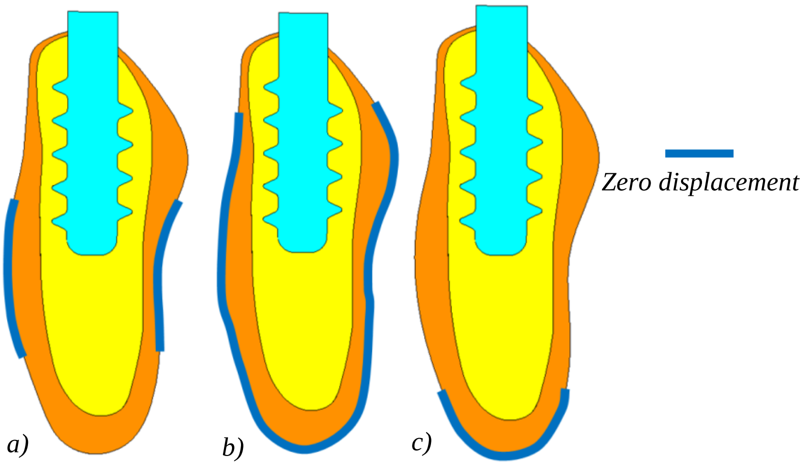

Fig. 2: Three different variants of boundary conditions.

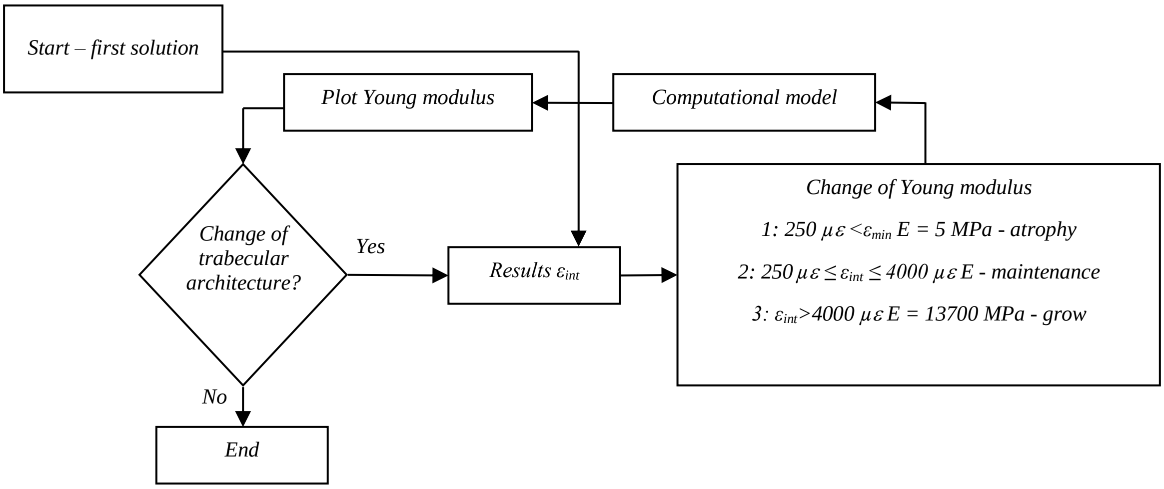

Fig. 3: Algorithm of bone modeling and remodeling.

3. Results

Fig. 4 shows the final shape of the trabecular architecture for all three variants of boundary condition. It is apparent that in cases 1 and 2 the trabecular network, which initially was present in the basal part of the segment, erodes after 100 cycles. In these cases, the cancellous bone adapted to the specific boundary conditions constraining the sides of the segment, i.e. the trabeculae developed in close proximity to the implant only. In case 3, the segment is simply supported in the basal region and the results indicate this to be favorable for the modeling of the trabecular bone.

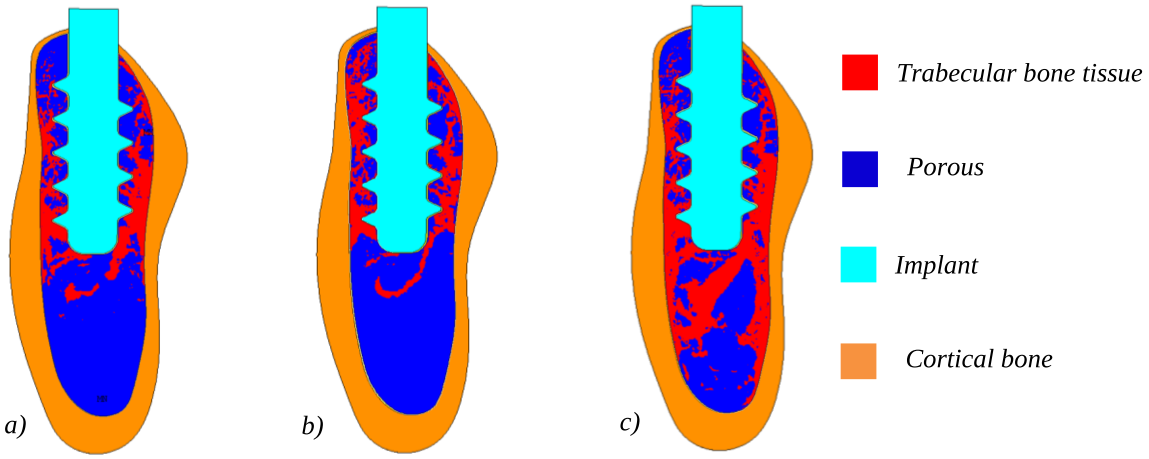

Fig. 4: Finish shape of trabecular bone architecture.

4. Conclusion

This paper describes an initial study of the simulation of bone adaptation to the loading of a dental implant inserted in its proximity. The tissues and regions within the bone are modeled at the micro-structure level. Using the Mechanostat-based algorithm the cancellous bone architecture is modeled for 100 cycles over the simulation-adaptation loop under static loading of the implant. Per literature review, the Mechanostat-based algorithm was already applied in bone adaptation prediction. However, to the best of our knowledge, there are no published studies which apply this on a detailed bone and dental implant assembly. The authors are aware that this is the very first step in this specific research direction. The time aspect of the bone modeling/remodeling, the typical loading record, the proper boundary conditions, and other relevant factors must be thoroughly discussed and implemented into the model in order to provide a reliable prediction of the bone adaptation to the external loading. In the near future we aim to integrate all these factors into a 3D geometrical model to develop a more realistic simulation.

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