ORIGINAL PAPER

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Finite memory model of bone healing in analysis of moving interface between mandible tissue and bone substitute material after tooth implant application

Abstract A previous bone remodelling model was presented elsewhere [30], and in the present paper, the same model was tested with new conditions; an interaction between bone tissue, bone substitute material and a dental implant was considered. The bone substitute material was assumed to be dead tissue, which does not synthesizes neither absorbs bone tissue, and it was considered, as well, resolvable. A moving border between the bone substitute material and the bone tissue was studied. The border moved as the newly synthesised bone tissue took over the bone substitute material. After the numerical calculations of time-steps, the whole bone substitute material was replaced by normal bone tissue and the implant was fixed in place only by bone tissue. Dynamical studies of the interaction of bone tissue and implant are used to improved implant design considering different factors, in this case, the presence of bone substitute material helping to fix the implant.

1 Introduction

Recently, several authors have investigated the osteointegration of dental implants using finite element analysis [4,7,12,18,19,29,33,37]. Mainly the relevance of osteointegration in the implant's longevity as well as in the mechanical stimulation of bone is studied [14,28,33].

Authors mainly considered a static scenario, i.e. an implant is inserted on the bone and loaded in different forms, or the bone tissue mechanical characteristics were tested, or different implant materials were tried, and the stress, strains or displacements were investigated [7,9,12,25,29,33,37,37].

It has been widely observed the importance of implant's design on the osteointegration, implying that "one implant fits all" is not possible anymore [32,37]. So, more studies on the influence of different parameters involved in the mechanics of dental implant are needed, for example, considering implant material as metamaterials [2,6,15,16,26]

Our study concentrates on the bone's natural remodelling process and the interaction with the implant in the case where a bone substitute material is used to improve fixation. A moving interface between the mandible and the bone substitute material is considered. The bone substitute material will be absorbed, and bone will take over and replace it with new bone tissue after some time. The bone substitute material will eventually disappear, and the bone tissue will finally have a grip on the implant. New mathematical relations will be established to control the velocity, and the way the interface moves as new bone tissue is built. This kind of study is very dynamic in the sense of biomechanical effects and not only considers loading the implant but as well takes into account the stimulus on bone remodelling to overtake the whole bone substitute material. The stimulus itself was considered dynamic by decaying exponentially not only in distance, but in time as well. In our formulation, the mechanical inertia effects are neglected.

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The model was tested against X-rays from dental practice elsewhere [30], and it was shown to be consistent with the actual biomechanical changes in bone's density in different scenarios. In the present study, the model is extended to examine the case where a bone substitute material is used to fill the space between the dental implant and the mandibular bone. That procedure is often used when the quality of the bone is not optimal and bone's density is increased artificially to improve the probability of good implant fixation. Often the actual patient's bone taken from another site in the mouth, or even body, is used as bone's substitute material.

2 Materials and Methods

Detail considerations about the mathematical simulation of bone remodelling are given elsewhere [30], and an alternative version was given in [22,23,27], but a summary formulation is reported in the following.

It is assumed that an osteocyte feels a density of strain stimulus and produce a signalling E_x defined as:

$$E_x = \int_0^t \int_\Omega \Psi\left(W_s(\xi, \tau)\right) R(\xi, x) X(\xi, \tau) \Phi(t, \tau) d\xi d\tau \tag{1}$$

where the following notation was introduced:

ξ describes the position of the osteocyte, i.e. the point where the signalling is produced; x describes the position of the osteoclast or the osteoblast, i.e. the point where the signalling is received; Ψ is the stimulus which depends on the density of strain energy and time; R is the distance from where the signalling is produced; X describes the bone's tissue mass density or bone's quality at the point ξ where the signalling is produced and Φ describes how signalling decays with time, in our case we considered to be exponential. As well, signalling was considered to decay exponentially with the distance from the point where is produced. For a given point, at a given time, the signalling could be written as:

$$E_{x,t} = \int_0^t \int_\Omega \Psi\left(W_s(\xi, \tau)\right) e^{-\|x-\xi\|} \rho\left(\xi, \tau\right) e^{-(t-\tau)} d\xi d\tau \tag{2}$$

where ρ denotes tissue mass density.

Biomechanical processes were assumed quasistatic. Therefore, the linear static elastic equations used were: equilibrium equation:

$$\sigma_{ji,j} + F_i = 0 \tag{3}$$

Linear strain tensor:

$$\varepsilon_{ij} = \frac{1}{2}(u_{j,i} + u_{i,j}) \tag{4}$$

General stress-strain tensor of material parameters, C_{ijkl}, was considered to depends on tissue mass density:

$$\sigma_{ij} = C_{ijkl}\varepsilon_{kl} \tag{5}$$

As a finite number of osteoblast and osteoclast work on the bone, either building or absorbing tissue, an upper and a lower limits for the bone's density were defined. An equilibrium state with a particular density of strain energy associated was assumed to exist in which the bone absorbed is equal to the bone produced. It was considered that the osteocyte emits a signalling ordering an action according to the strain felt, this signalling decayed exponentially to the distance from the osteocyte. Moreover, the signalling produced at any moment decays not only in space but also in time, which means that all past states are considered to determine the actual value of the signalling and stimulus. Osteoclast and osteoblast were considered to react to the total signalling emitted by all the osteocytes and either synthesise or absorb bone tissue or stay without action according to the difference between the biomechanical equilibrium density of strain energy and the actual density of strain energy at the point where the osteoblast or osteoclast is located.

In the bone substitute material region, no bone is neither absorbed not produced as the biomaterial is considered dead tissue. However, at the interface between bone tissue and biomaterial, the biomaterial is absorbed and new bone tissue is produced according to the remodelling rules discussed in the following paragraphs.

The ratio of change in bone's density was considered as an optimization of the difference between a function of the local density of strain energy and the equilibrium density of strain energy. The function of the

Table 1 Similar values have been reported in the literature [3,8,10,20]

	Young's Modulus (GPa)	Density g/cm^3	Poisson's ratio
Bone	11.2	1.8	0.306
Teeth	22.4	3.6g/cm	0.3
Implant	113.8	4.43g/cm	0.342
Biomaterial	11.2	1.8	0.306

local density used was the total stimulus E_s. The ratio of change in bone's density was calculated using the relationship:

$$dF_a = (E_s - W_0)/a \tag{6}$$

Where dF_a is the ratio of density change given as percentage and a is a constant that regulated density increment steps. A similar idea was used previously in the literature [31].

The density of strain energy that maintains the equilibrium between absorption and deposit of bone was represented by W_0, and it was calculated with the following relationship:

$$W_0 = \frac{1}{\Omega} \int_\Omega W_s \, d\Omega \tag{7}$$

Where W_s is the average of the density of strain energy. The integral is calculated over the whole mandible Ω. W_0 was calculated only in the first cycle, and it was maintained constant in calculations throughout the 150 time-steps.

As it was already mentioned, the stimulus does not disappear instantly but decreases with time, i.e. the stimulus at any time will contribute to the stimulus of the future time-steps. From equation (2), the total stimulus E_s is calculated by:

$$E_s = \int_0^t \int_\Omega W_s \rho e^{-R} e^{-(t-\tau)} d\Omega d\tau \tag{8}$$

With the mathematical justification given elsewhere in more detail [1,5,13,21,24,30] using the Prony series, $\sum_{i=1}^N \alpha_i e^{\frac{-t}{\gamma}}$ to expand the time-dependent factor in 8 with finite memory of four time-steps, and coefficient of relaxation, γ, equal to 1, the total stimulus could be written as:

$$E_s(t) = \int_\Omega W_{s0} \rho_0 e^{-R} d\Omega + \sum_{i=1}^4 \int_\Omega \alpha_i W_{si} \rho_i e^{-R} e^{-i} d\Omega + \varepsilon \tag{9}$$

where α_i is a constant. We consider ε to be small enough to be neglected so we keep only the first two terms, which consider the current stimulus plus the stimulus of previous 4 cycles decaying exponentially. The contribution of the 5th element was calculated to affect less than 1% of the total value which is small enough to be neglected.

A lazy zone was considered where stimulus is so low that no remodelling takes place. Considering the lazy zone limits, the signalling had the following relationship:

$$\delta\rho = \begin{cases} \rho F_a & for \quad E_s > dzp, \ E_s < dzn \\ 0 & for \quad dzn \leq E_s \leq dzp \end{cases} \tag{10}$$

very similar to the one used previously in the literature [31], where dzp is the lazy zone upper limit, and the dzn is the lazy zone lower limit. More details about this relationship are given elsewhere[30].

In numerical finite element simulation, the following relation was assumed between the tissue mass density and Young's modulus:

$$E = b\rho^2. \tag{11}$$

where ρ denotes the tissue mass density and E the Young's modulus. The parameter b was chosen to give the values collected in Table 1 for a normal bone characteristics.

The model's dimensions and more details concerning the position of the forces considered and other mechanical requirements were taken from the model described previously [30]. The considered 2D model is presented in Figure 2.
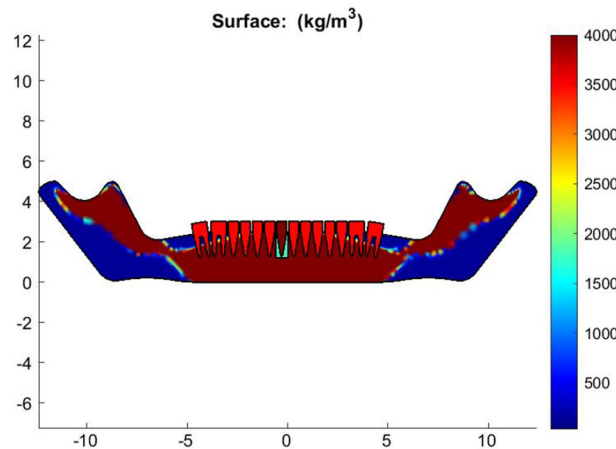
Fig. 1 Initial model before the beginning of the remodelling process

The boundary between the biomaterial and the bone was defined with the used of 150 points with moving coordinates. For those points, the parameter given in equation 6 was calculated; the negative value indicated motion of the point away of the implant if it was positive towards the implant. To calculate the displacement, we used the following relation:

$$disp = F_d/\gamma \tag{12}$$

where $disp$ was the displacement of the point, F_d a parameter proportional to the total stimulus strength at the border point at a particular time given by equation (9), and γ a parameter to regulate how fast the boundary moves. The actual displacement vector was normalized, and its direction was calculated as the bisector of the angle formed with the two points that were beside the point considered; one to the left and one to the right. Points at the edge of the mandible were considered to move along the mandible border.

After the border displacement was calculated, the new density was calculated using equations (6), (9) and (10) for those new points located inside the bone's area. The correspondent Young's modulus was calculated using equation (11).

To perform the numerical testing of the model, the mathematical relations were implemented in a FEM software, COMSOL Multiphysics®, to solve a set of differential equations. To control the iterations representing time, MATLAB ver. R2018b was used.

While the mathematical simulations were run at COMSOL Multiphysics®, the Dirichlet boundary conditions were kept. The placement of the static forces over the model and other mechanical characteristic of the model are giving elsewhere [30].

The following material characteristics were considered for the mathematical simulation:

The Comsol Multiphysics® model was controlled by a MATLAB ver. R2018b script according to the flow diagram shown in Fig. 1.

3 Results

The initial configuration of the model is shown in Fig. 2. After running the model 50 time-steps, the boundary changed to a new position:

The bone tissue in the mandible was very close to a biomechanical state of equilibrium at the beginning of the simulation, and no significant changes in bone density were noticed. The small picture at the right portraits a magnified region close to the implant to show in more detail the interface between bone tissue and bone substitute material. After 100 time-steps, the model changed to:

At this stage, the border moved the middle position between the initial configuration and the implant. After 150 time-steps, the model configuration changed to:

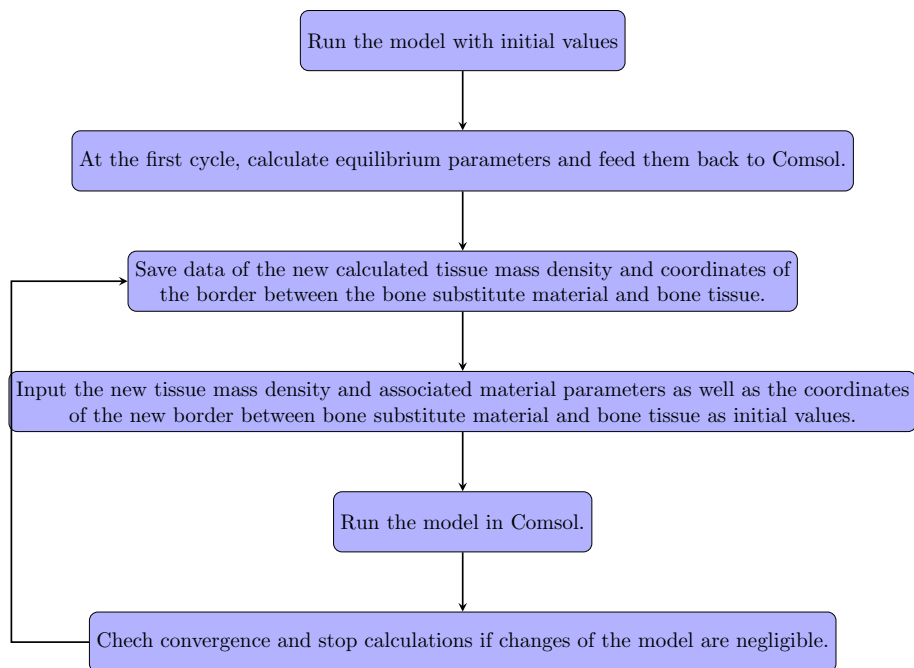At this stage, the whole bone substitute material was absorbed and replaced by healthy normal bone.

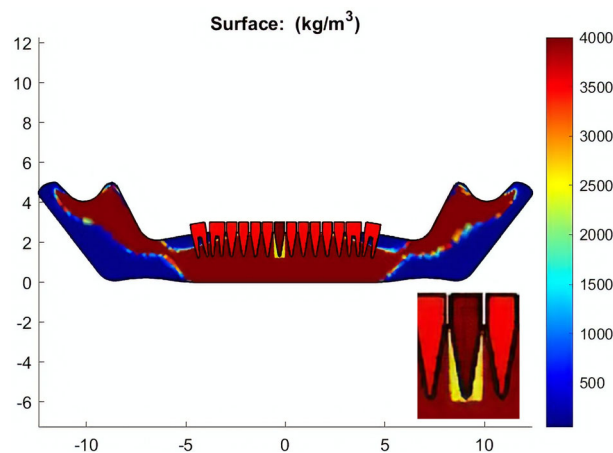**Fig. 2** Flow chart of the script

Fig. 3 Model after 50 time-steps, the bone in other regions of the mandible is in equilibrium

4 Discussion

Finite element method has been used to examine interactions between bone and dental implants [4,7,12,17,29, 33,37]. Some authors concentrated on the prosthesis design [9,29]. Others focused on the stress distribution in the bone after the implant [4,11]. The distribution of stress on the implant was also tested [33], and the interaction between bone and implant was as well studied [7,37].

In the present paper, the relationship between bone tissue, bone substitute material and an implant was investigated. The border between the bone substitute material and bone tissue was considered dynamic in the sense that bone tissue, due to a stimulus to grow, takes over the bone substitute material. In our investigation, the bone effectively advances over the bone substitute material and fix the implant in place.

This examination of the bone tissue, bone substitute material and implant complements our previously presented model and proves finite element method and mathematical modelling as a strong tool to study complex and dynamic cases of bone remodelling in the presence of an implant and a bone substitute material.
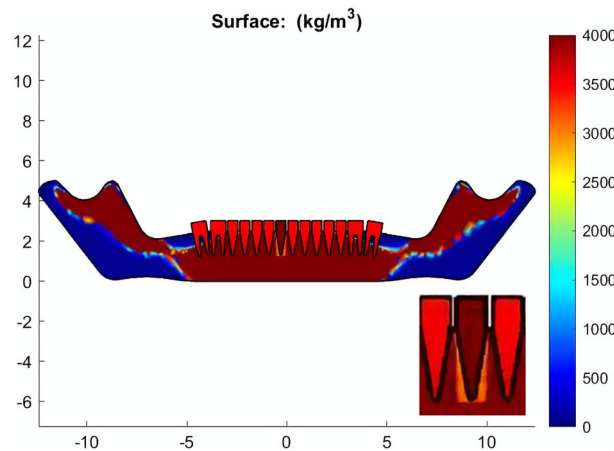
Fig. 4 Model after 100 time-steps, the bone is already taking over the bone substitute material
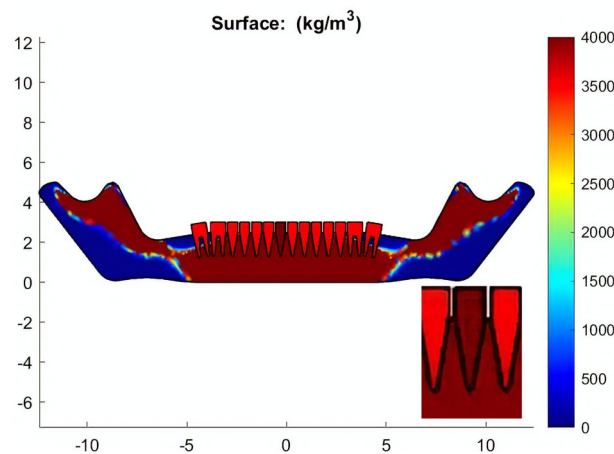

Fig. 5 Model after 150 time-steps, the bone took over the bone substitute material completely

As noted previously by some authors, the future design of implant should consider actual conditions of patient's bone to improve osteointegration [32,37]. More investigation is needed on the influence of several mechanical parameters of the implant design on osteointegration in the presence of bone tissue weakened by disease, i.e. osteoporosis, osteoarthritis, etc [15,34–36].

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