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Mechanobiological model of bone remodeling for orthodontics

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1. Introduction

Orthodontic tooth movement, a key aspect of treatment, involves applying forces to shift teeth within the jaws. This process is linked to bone remodeling, where bone adjusts its structure in response to mechanical stimuli. Orthodontic forces transmit to surrounding bone, triggering cellular activities by osteoclasts to resorb bone on the compression side and osteoblasts to form bone on the tensile side.

Bone remodeling models, like those by (Hamanaka et al., 2017; Zargham et al., 2016), predict tooth movement, while others by (Bonfoh et al., 2011; Komarova et al., 2003) explore bone cell evolution and mechanical properties during remodeling cycles.

This study aims to develop a finite element model to simulate alveolar bone remodeling subjected to mechanical constraints, to be applied after during the levelling phase of orthodontic treatment. Since the model of (Bonfoh et al., 2011) incorporates the biological mechanism on cellular level subjected to external loadings, it is chosen as a first modeling attempt. The temporal evolution parameters such as osteoclast/osteoblast numbers, bone density, and mechanical properties align closely with the findings of (Bonfoh et al., 2011).

2. Methods

2.1 Bone remodeling model

The considered bone remodeling model is based on the work of (Bonfoh et al., 2011) that relates the mathematical model provided by (Komarova et al.,

2003) to the mechanical stimuli applied for a long time period resulting a bone remodeling cycle.

The mechanical stimulus strain energy density is sensed by the osteocytes residing in bone matrices and transformed to signals transmitted to pre-osteoclasts and pre-osteoblasts that convert them into autocrine and paracrine factors. Based on those factors, the differential equations of (Komarova et al., 2003) can be solved to elucidate the dynamic interactions within cell populations in the Basic Multicellular Unit. Since bone is made up of different cells, the change in bone mass is directly related to the number of active cells at the remodeling site. Furthermore, apparent bone density evolution can be computed due to the resulted competition between osteoclasts and osteoblasts. The change in density of a material typically affects its mechanical properties, as commonly used in the literature where different relationships are provided to calculate the elastic Young's modulus and Poisson's ratio based on the material density.

To simulate this bone remodeling model related to external mechanical stimuli, an Abaqus UMAT subroutine has been coded in Fortran language and applied on a simple parallelepiped ($10 \times 10 \times 50 \text{ mm}^3$) under four points bending test as done in (Bonfoh et al., 2011) using the same model parameters, initial and boundary conditions, to be able to validate it as a first step.

2.2 Segmentation and preparation of the FE Model

The geometry of the maxillary bone and teeth shown in *Figure 1,d* were obtained by post-processing of cone-beam computed tomography scans of an anonymous patient using the software 3D Slicer (Version 5.6.0). The FE Model (*Figure 1,e*) is created and prepared for further simulations using Autodesk Fusion 360 and Abaqus® (Version 2019). The average thickness of the cortical layer was approximated to 2-mm and assumed to remain constant throughout the model. The periodontal ligament is created all around the roots with a constant thickness of 0.2 mm.

3. Results and discussion

As bone density evolves with strain energy density from Abaqus, the resulting apparent density distribution is closely linked to stresses and strains.

The results shown in *Figure 1,a* are computed in the external fiber of the parallelepiped beam and then compared to Bonfoh's results. During the 10 first days, the bone density decreases slightly corresponding to bone resorption. After that, the density increases corresponding to bone formation. The final value after 150 days is highly dependent on the external stimulus and cells population that are activated in the influence zone.

The number of osteoclasts decreases almost instantaneously from 15 to 0 after 30 days (*Figure*

1,b). However, 650 osteoblasts are activated after 12 days to compensate the resorption caused by osteoclasts and go into bone formation (Figure 1,c).

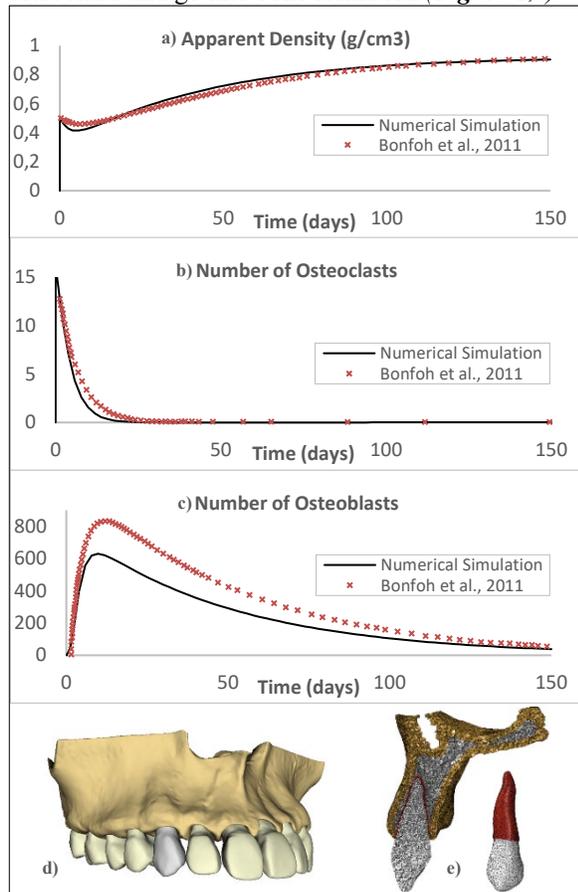


Figure 1- Evolution of a) bone density. b) number of osteoclasts. c) number of osteoblasts compared to (Bonfoh et al., 2011). d) Geometry of maxillary bone and teeth. e) FE Model.

To summarize the effectiveness of this approach, during the initial phases of remodeling, it consistently anticipates bone resorption and if the stimulus is insufficient, it becomes challenging to rectify during the subsequent apposition phase.

Applying an orthodontic force consistently for a long period exerts a light force that is sufficient to induce bone remodeling process and then a tooth movement. Simulating the previous approach for a duration of one week will give us resorption in both sides of tooth because this approach does not differentiate between compressive and tensile stresses. For that, this model should be modified to have a resorption in compression zones and apposition in tension zones.

4. Conclusions

This study represents a development of numerical coupled mechanobiological model based on the work of (Bonfoh et al., 2011) allowing for the simulation of alveolar bone remodeling based on the evolution of

osteoclasts and osteoblasts. This model has been tested and validated for simple loading and in the near future, the mechanical stimulus will be adapted and modified to differentiate between tensile and compression external loads applied by orthodontic appliances using the prepared finite element model (Figure 1,e).

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Conflict of Interest Statement

The authors declare no conflicts of interest associated with the work reported in this paper.

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