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Numerical Analysis of Bone Forming Process and Phenomenon by using iBone Model

Mamtimin Geni[1], Xamxinur Abdikerem[2],Hazirti Eli[1]
Lihua Jia[1] and Masanori Kikuchi[3]

Summary

In this paper, the iBone (Imitation Bone) model which is coupled with Turing reaction-diffusion system and FEM, is used. The numerical simulation of bone forming process by considering the osteoclasts and osteoblasts process are conducted. The results shown, that the bone mass is increased with increase of the initial load value, then fibula and femur bones are obtained respectively by keeping the required bone forming value. The different bone shapes are obtained by changing the both bone keeping value and the compressing force value. When set larger bone keeping value by keeping larger constant compressing force value, bone shape as a pipe with hole just like femur, when set smaller bone keeping value by keeping the smaller constant compressing force value, it is close to solid pillar as like fibula.

keywords: Reaction-Diffusion System, Imitation Bone, Numerical Simulation, Osteoblasts, Osteoclasts

Introduction

Bone continuously remodeled by bone formation cells (osteoblasts) and resorption cells (osteoclasts) in order to normally balance bone mass and requites alternative changes of the body structure. Bone formed by its intrinsic gene as will as genetic transcription factors, and then optimizes its whole and local structure under the naturally biomechanical boundary condition. The metabolism of bone by osteoblast and osteoclast is the main factors of bone reconstruction processes, and bone optimize its stabilized shape and structure under naturally dynamic loading condition by using these two factors. In this way, bone ceaselessly makes its best optimized shape for adapting natural environments.

However, the bone forming process is fully pre-programmed in the genes, and it is important to understand what kind of bone shape and structure are needs, which direction bone cells will be osteoblasts or osteoclasts, how are the bone cells informed in about these rules, which so obviously dictate architecture, etc.

The earlier study for bone structure and its mechanics are conducted. Wolff[1], Springer, Berlin, 1892, based on the Meyer[2] (Wissenschaften in Medicin 27, 1867, 1389-1394) work introduce the bone micro structure matching to the stress track

[1]School of Mechanical Engineering, Xinjiang University, 21 Youhaobeilu, Urumqi, China
[2]School of Geography and Tourism, Xinjiang Normal University, 102 Xinyilu, Urumqi, China
[3]Department of Mechanical Engineering, Tokyo University of Science, Noda, Chiba, Japan

theory. Turing[3] (Phil. Trans. R. Soc. 1952, B237, 37-72) introduce an reaction diffusion system and its widely used in chemistry and biology[4]−[6]. This model has two supposed factors called activator and inhibitor.

Mullender, Huiskers[7] (J. Biomechanics, 1994: 27(11): 1389-1394) and Forst[8] (J Bone Miner Metab, 2000; 18: 305-316) also conduct for the bone biomechanics, and introduce bone mechanical control system. Huiskers[9] (Nature, 2000, 405, 704-706) introduce bone cell play a mechanical sensor role and it can be transform the stress information to osteoblast and osteoclast.

Ken-ichi Tezuka[10] (Key Engineering Materials. 2003, 243-244, 601-606) introduce a iBone model based on the reaction-diffusion system coupling with osteoblast(activator) and osteoclast(inhibitor), and implemented to finite element method. Recently, Stefanie Sick et al.[11], Science Vol. 315, 1 December(2006), 1447-1450. investigated the regulation of hair follicle patterning in developing murine skin. These results confirm predictions of a WNT/DKK-specific mathematical model and provide in vivo corroboration of the reaction-diffusion mechanism for epidermal appendage formation[11].

However, the numerical modeling and simulation method for bone forming process by considering the genetic bone supplement factors, osteoblast and osteoclast and mechanisms of bone complex patterns are not clear yet. Despite recent advances in biotechnology and mathematical modeling, this still remains a largely open question.

In this study, the iBone model based on the Turing reaction-diffusion system implemented in supposed bone, and numerical simulation of bone forming process under the compressing and bending load condition are conducted by changing the reaction-diffusion parameters and the load value in order to investigate some biomechanical phenomenon of bone shape forming process. The metabolic bone forming processes are considered by using FEM cell elimination and adding method which is assumed as osteoclasts and osteoblasts and governed by feedback process from mechanical load transfer capacity in each element. The osteoclasts and osteoblasts parameter related with numerical analysis are obtained from evaluating the local strength distribution as distributions of inhibiter and activator in bone.

iBone Model

Reaction-diffusion model was firstly proposed by Turing and has been studied in various fields, such as chemistry and biology. A basic Turing's model consists of two hypothetical molecules, activator and inhibitor, which interact with each other and diffuse independently. These molecules spontaneously generate stable periodical patterns, so called Turing patterns. In each stripe or dot, activator and inhibitor shows typical distribution. Activator shows a sharp peak while the inhibitor shows a diffuser distribution. Testuka observed the cell condensation patterns in his previous work and the results shown similar to these Turing patterns, and then introduce iBone model. This model was made by assumption of bone remodeling as shown in Fig. 1 and assumed that bone formation and resorption are proportional to local concentrations of activator and inhibitor in reaction-diffusion system, respectively. The local stress was introduced into the differential equation of the activator to make the entire reaction respond to it. In this model bone formation occurred near the stress center and bone resorbing activity surrounded it. This model required only one global parameter that determined the balance between total bone formation and resorption. All the other information was obtained locally and the cells communicated each other via diffusion of local factors.

The hypothetical bone remodeling behaves as a shape adaptation system to the given stress in iBone model, and by using a simple two dimensional model considering the reaction-diffusion system by using following partial equation with main variables activator A and inhibitor I.

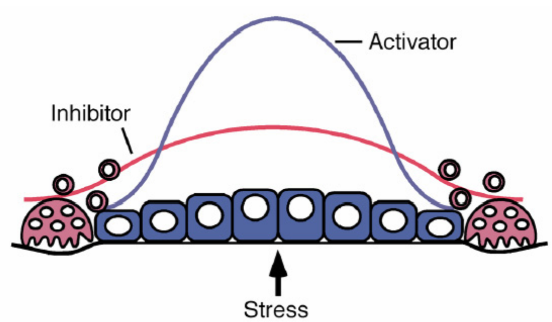


Figure 1: A iBone Model for Bone Remodeling Based on a Reaction-diffusion System

$$dA/dt = C_1A + C_2I + C_A + D_A(d^2A/d^2x) - g_A + C_S\sigma_e \quad (1)$$

$$dI/dt = C_3A + C_I + D_I(d^2I/d^2x) - g_I \quad (2)$$

where, σ_e local von Mises stress, D_A and D_1 are diffusion coefficient for activator and inhibitor respectively. C_1, C_2, C_3 are feedback parameters.

When an external mechanical stress was applied, stimulated bone formation and subsequent activation of bone resorption efficiently adapted the shape of sample models to the given stress. iBone model could also repair fractures which caused uneven stress distribution. The advantage of this model is how bone cells can form a cooperative system that adapts the microstructure of bone to voluntary mechanical loads.

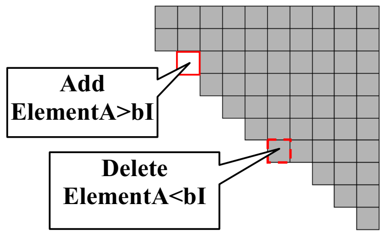


Figure 2: Reaction-diffusion and Imitation Bone Formation-Absorption by Adding and Deleting Element

The element is added if $A > bI$ or deleted if $A < bI$, b calculated by using following equation.

$$b = \sum A / \sum I \tag{3}$$

Here b is the ratio between mean concentrations of activator and inhibitor of every element.

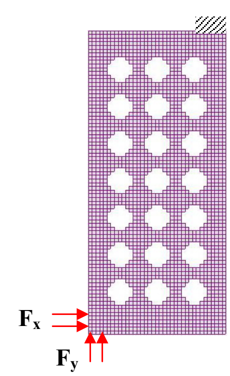
Numerical Modeling of Bone Forming

Much amount of bone type can be found and bone is a verity of remarkable material. In this study only two types of bone are analyzed according to the bone cross section type. Type I bone is it's cross section with solid comparable to pine as shown in Fig.3(a), and type II bone is it's cross section with hole comparable to bam book as shown in Fig.3 (b).

(a) Type I (b) Type II

Figure 3: Two Typical Bone Type

Two kinds of simple compressible bone and both compressible and bending bone are considered and the boundary conditions are set for the numerical simulation as shown in Fig.4(a) and (b). The 2D numerical initial tissue structure bone modeled with uniform distributed small hole respectively. The aspect ratio of two models (width/length) are chosen by using same value as 0.25 and the radius of small hole also same. The following assumption are used for the numerical simulation of bone: (1) it is always continuous and close-grained material; (2) it made



(a) Compression Boundary Condition (b) Compression and Bending Boundary Condition

Figure 4: FEM Numerical Model for Two Different Boundary Condition

by same materials in all position; (3) it is isotropic homogenize materials; (4) it's structure forming does not affected by temperature and (5) no initial stress.

Numerical Results

Fig. 5 shows the final bone forming under compressed loading condition with different bone keeping value. The compressed forces are set 100N in all cases. The results show that the bone formed as a solid pillar in all cases. There is much unwanted bone stack on it, just like strange grotesque, in all of the cases. The unwanted bone positions not only undefined during the bone forming process, but also changed before or after the convergence of the strain energy. However, the unwanted bone stacks is gradually decreased by decreasing the bone keeping volume and nearly close to fibula.

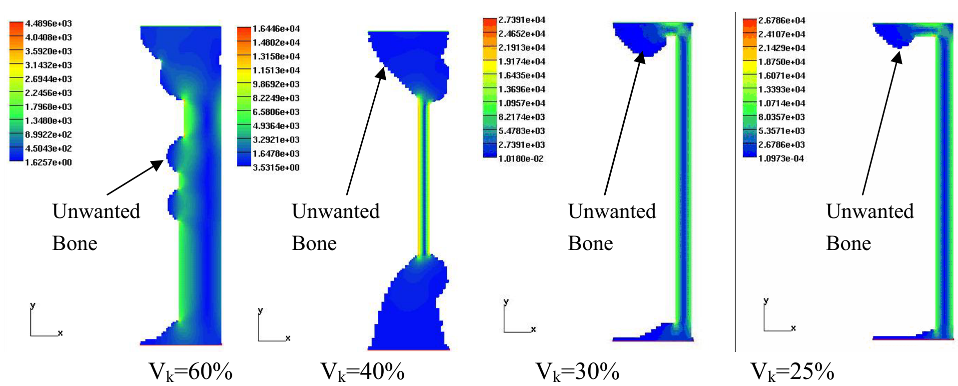


Figure 5: Bone Final Formation under Compressed Load (F=100N) in Different Bone Keeping Volume

Fig. 6 shows the final bone forming under compressed loading condition with different bone keeping value, and the compressed forces are set 200N in all cases.

The results show that the bone formed largely changed with Fig.5, and bone shape as a pipe with hole in bone keeping volume are V_k=60%, V_k=40%, V_k=30% models. But in V_k=25% models, it is also appear the same results with Fig.5 results and show solid pillar. There is much unwanted bone stack on it too in all of the cases. The unwanted bone positions not defined and go round and round along the pipe wall. The unwanted bone stacks gradually decreased by decreasing the bone keeping volume from 60% to 30% and nearly close to femur, in 25% close to fibula.

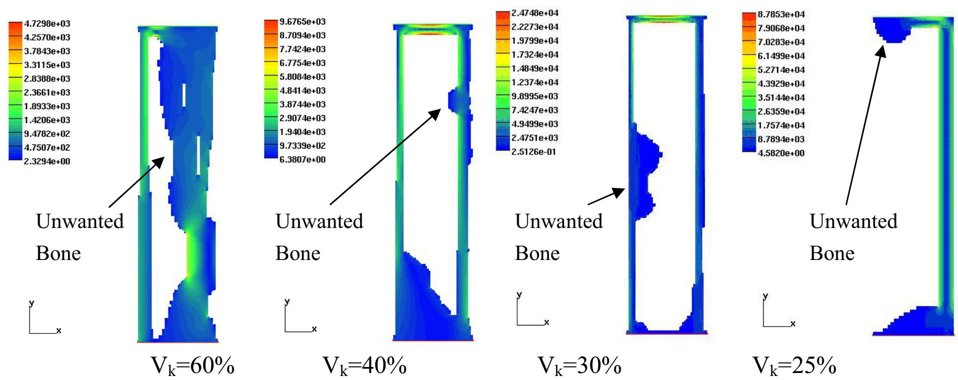


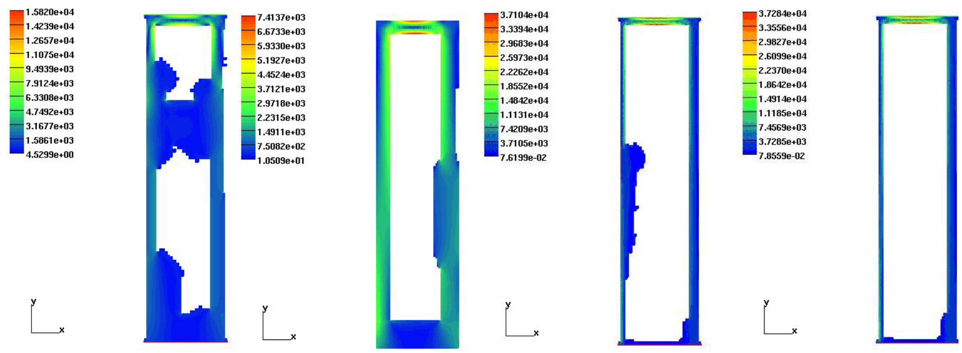
Figure 6: Bone Final Formation under Compressed Load (F=200N) in Different Bone Keeping Volume

Fig. 7 shows the final bone forming under compressed loading condition with different bone keeping value as V_k=60%, V_k=40%, V_k=30% and V_k=25%. The compressed forces are set 300N in all cases. The results shown, that the bone formed largely changed with Fig.5 and Fig.6, and bone shape as a pipe with hole in all models. There is some unwanted bone stack on it too in all of the cases, and the same results of with Fig. 5 and Fig.6 are observed as indefinitely unwanted bone. The unwanted bone stacks gradually decreased by decreasing the bone keeping volume from 60% to 30% and 25%, and very smoothed pipe much close to femur.

Fig. 8 shows the bone forming process under compressed and bended loading condition by keeping value V_k=25%. The compressed and bending forces are set 100N along x and y direction. The results shown, that the bone formed shape largely different with Fig.5, Fig.6 and Fig.7, and final bone shape as a solid turned pillar just like a fibula shown in Fig.8 (c).

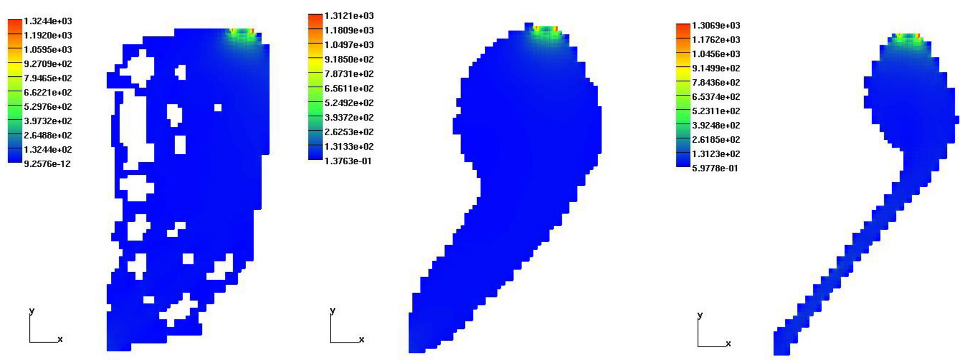
Summary

The iBone model based on the Turing reaction-diffusion system implemented in supposed bone, and numerical simulation of bone forming process under the compressed and bending loading condition are conducted by changing the reaction-diffusion parameters and the load value. For investigate the bone different type of shapes the initial modeling and remodeling processes are conducted by solving the



V_k=60% V_k=40% V_k=30% V_k=25%

Figure 7: Bone Final Formation under Compressed Load (F=300N) in Different Bone Keeping Volume



(a) Stage 5 (b) Stage 20 (c) Stage 50

Figure 8: Bone Forming Process under Compressing and Bending Load (Fx=Fy=100N, V_k=30%)

different mechanical boundary conditions.

The result shown, that the bone mass and space volume are increased with increase of the initial load value in a same bone keeping value, then fibula and femur bones are obtained respectively by keeping the required bone forming value. The different bone shapes are obtained by changing the both bone keeping value and the compressing force value. When set larger bone keeping value by keeping larger constant compressing force value, bone shape as a pipe with hole just like femur and largely increasing its space volume, when set smaller bone keeping value by keeping the smaller constant compressing force value, it is close to solid pillar as like fibula and decrease its space volume.

There is much unwanted bone stack on the bone during the bone forming process. It means that the present bone shape have much enough loading capacity to satisfy the present loading condition. If the keeping value or acting load chosen suitable one then the mature required bone shape is observed just like fibula and femur bones respectively. This is indicated that the relationship exists between bone architecture and mechanical usage and close to real vertebrate activities,—while strenuous exercise increases bone mass, disuse, as in microgravity and inactivity, reduces it.

Applying the computer simulations with iBone model, it is demonstrated that this model with control mechanism explains how the bone is modeled with different types and growth towards a mature required shape of structure with realistic characteristics in terms of morphology and biomechanics.. Eventually a homeostatic steady state is reached in which the mechanical integrity of the bone structure is maintained by ongoing resorption and formation, precisely as it occurs in mature bone.

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