Simulation of adaptive bone remodeling by using cellular automata

J. Sakamoto, J. Oda

Department of Mechanical Systems Engineering, Kanazawa University, 2-40-20 Kodatsuno, Kanazawa 920, Japan

Abstract

In this study, a new computer simulation model of the bone remodeling adapting to mechanical environment by using the cellular automata is proposed. Finite-elements of FEM are further subdivided into smaller cells which are stated as bone tissue, bone cell or empty space. States of the cells are changed automatically by a set of rules as similar as bone remodeling rules. While the set of rules is changed due to stress level of each element, the bone density is changed adapting to the stress. Efficiency of the simulation model is demonstrated applying it to a bone remodeling problem of a human femoral head.

1 Introduction

The adaptive bone remodeling in which the bone changes its shape, topology and composition itself adapting to mechanical environment is very interesting phenomena in viewpoint of not only medical science but engineering. In the area of structural optimum design, it has been often investigated in order to develop a more creative structural optimization technique. On the other hand, the optimization techniques have been applied to simulate the adaptive bone remodeling in the area of biomechanics. Although these optimization methods and obtained optimum structures suggest the adaptive bone remodeling, almost all of them are mere variations of usual optimality criteria method. Shape or material property distribution of structures is changed directly to satisfy a stress or strain criterion in the methods. In the real bone remodeling, activities of living bone cells and their biochemical reactions play most essential role to achieve the mechanical adaptation[1]. It is difficult to represent the adaptive bone remodeling adequately by using the ordinal optimization method ignored the
biological effect. In this study, a concept of the cellular automata is adapted in order to introduce the autonomic bone cell’s activity into the bone remodeling. A cellular automata’s system regulating the bone remodeling is defined by considering the bone apposition and resorption process in the method. It is expected that time dependency and cyclic behavior of the bone remodeling would be represented by using the cellular automata. This method is applied to a bone remodeling problem of a human femoral head, and its efficiency is discussed.

2 The cellular automata for representing the bone remodeling

Adaptive bone remodeling is achieved by the bone cells which are called as "osteoclast" and "osteoblast". The osteoclasts resorb bone tissues and then they decompose themselves. After the osteoclast decomposition, the osteoblasts appear around the bone resorption parts and work to create bone tissues. Once a osteoblast is included by new bone tissues, it changes the cell called "osteosyte" and stop the bone creation until bone resorptions occur again. The bone structure is maintained by constant cycle between the bone resorption and deposition in the remodeling process. Adaptive bone remodeling is a result of which the cell's activities are varied according to mechanical environment.

It is considered that the bone cells are influenced each other and change their state or activity autonomically due to circumstance inside the bone. The sequential actions of the bone cells and their interactions characterize the bone remodeling essentially. So that, it is need to consider the dynamic and autonomic character caused by the bone cells. The cellular automata are supposed effective for our purpose. It is an artificial system constructed of many cells in which a state of a cell change automatically due to conditions of surrounding cells under a certain transition rule[2]. Where, the cell means a unit that represents a condition but doesn’t mean a biological cell. It is known that cell's pattern changing is too complicated to expect even if the cell takes only two states as 0 or 1. Furthermore, chaostic transformation pattern also can be seen the cellular automata on a special condition[3].

We define a cellular automata's system corresponding to the bone remodeling as two-dimensional cells which take three states and four transition rules. Each cell takes one state among three states as "osteoblast (osteocyte)", "bone tissue" or "lacunae". Original mean of lacunae is small hole resorbed by the osteoclast, but it means just empty space in this model. The states of the cells are kept the condition or changed to the other condition at next time step shown as Figure 1. The transition rules are defined as follows;

<Rule A>: If the number of neighboring cells corresponded to the bone tissue is larger than $L_b$ and less than $U_b$, then the concerned lacuna cell change to the osteocyte.

<Rule B>: If the number of lacuna cells in neighbor is larger than $L_i$ and less than $U_i$, then the concerned osteocyte cell change to the bone tissue.

<Rule C>: The bone tissue cell is changed to the lacuna when time step over $M_b$ steps since the bone tissue appearing.
Figure 1: The transition rule diagram of cellular automata of bone remodeling

Figure 2: Examples of changing cell state in bone remodeling
<Rule D>: The osteocyte is changed to the lacuna when time step over $M_o$ steps since the osteocyte appearing.

For example, a cell transition of the rule A on case $L_b=3$ and the rule B on case $L_t=3$ are shown in Figure 2. Transition rule A is corresponded to the osteoblast appearing at bone resorption surface. The rule B is considered as the bone apposition caused by the osteoblast, and the rule C corresponds to resorption of old bone tissue. The rule D is needs to prevent that whole cells are occupied by only osteocyte. The set of rules has six control parameters as $L_b$, $U_b$, $L_t$, $U_t$, $M_b$ and $M_o$. Although the cells change their states autonomically if once the parameters of the rules are given, whole tendency is able to be controlled indirectly by changing the parameters.

In order to estimate the effect of changing the parameters for the cell's behavior, computational experiments are carried out for a two-dimensional matrix cell the size is 50X50 varying the parameters. The calculations are started from a condition in which the bone tissue ratio to the whole cells is 50% and both of the osteocyte and lacunae ratios are 25% respectively. The initial arrangements of cells are defined at random and 100 transition steps are carried out. We only focused on parameter $L_t$ because effect of changing the parameter is most considerable of all parameters. The other parameters are fixed as $L_b=3$, $U_b=6$, $U_t=6$ and $M_b=M_o=10$. Figure 3 shows ratio of the bone, osteocyte and lacunae cells to whole cells versus transition time steps on case $L_t=2$ and $L_t=4$. Cell patterns obtained after 100 transitions are shown in Figure 4. In the case of $L_t=2$, the osteocyte ratio is almost constant and the bone and lacunae ratios show periodical changes. The orderly behavior is cause of that the transition by the rule B is frequently occurred when the $L_t$ number is low, so that the bone tissue's formation turn out many times. On the other hand, more complicate behavior is seen in the case of $L_t=4$ in which the osteocyte ratio does not keep constant. This is because the change to the bone tissue from the osteocyte is hard to occur. At the mention of Figure 4, clusters of the bone tissues and lacunae can be seen. It is similar as trabecula structure of cancellous bone in fact.

It is confirmed that the bone tissue ratio tends to increase in according to $L_t$ number is larger. We apply this features to develop the simulation model of the bone remodeling.

3 The simulation method of the adaptive bone remodeling

Finite-elements for stress analysis are subdivided to smaller cells of cellular automata described in previous section. The states of cells are defined at random in initial condition and the states are changed by the transition rules explained before. The simulation procedure is described as follows.

1. calculate the stress or strain on each element by FEM,
2. determine the cellular automata's transition rules on each element in according to the stress or strain level,
3. change the cell states a certain time using the transition rules,
4. determine the material property of elements on account of the bone tissue ratio, and then return to step (1). In practice, number of $L_t$ on the rule B is determined based on the element stress level in step (2). Young's modulus of the
Figure 3: Histories of bone, osteocyte and lacunae ratio

(a) $L_i=2$
(b) $L_i=4$

Figure 4: Cells array patterns after a hundred state changing iterations
elements are calculated in proportion with the bone density that is the bone tissue ratio in step (4). If $L_i$ is given as smaller at higher stress elements, the bone density becomes higher and the stress can be reduced. On contrary this, $L_i$ is set lower for elements in which the stress is low. We provide a mechanical adaptive function to the bone remodeling simulation by applying above strategy.

4 Numerical Example

The proposed method is applied to a bone remodeling problem of a human femoral head changing the bone density distribution. Two-dimensional finite element model of plane strain condition is used for the calculation as shown in Figure 5. Each element is subdivided to 30X30 cells. Equivalent stress based on strain energy is used for index to determine parameter $L_i$. Equivalent stress is given as $\sigma = \sqrt{2EW}$ where $E$ is Young's modulus and $W$ is strain energy density. We define the six stress levels between the maximum and the minimum equivalent stresses, and correspond the $L_i$ number that is 1 through 6 to these stress levels. Time of changing cell's state between stress analyses is given as 30. Iteration of bone remodeling through step (1) to (4) is carried out 20 times. History of the bone, osteocyte and lacunae cells ratio is shown in Figure 6. It shows the convergence is obtained by 10 times iterations. Distributions of the bone tissue are shown in Figure 7 for the initial and after 10 times iterations. The bone density is higher around loading axis that corresponds to a part called "compressive trabecula" in real femoral head. It is considered that the result is consist real femoral head well.

5 Conclusion

Computer simulation model of the adaptive bone remodeling is proposed by applying the cellular automata's system. It is applied to the remodeling problem of the human femoral head to confirm efficiency of the method. We obtain a result in which the bone topology is similar as the real femoral head. It is considered that the autonomic and dynamic adaptation is an essence of the bone remodeling. These essential factors are taken into the proposed simulation model by using cellular automata. It is expected that the strategy is applicable to the structural optimization in which an element changes the property itself autonomically.

Reference

Figure 5: An example problem of adaptive bone remodeling simulation on a femoral head

Figure 6: Histories of bone, osteocyte and lacuna ratio in adaptive remodeling process of the example
Figure 7: Adaptive bone remodeling simulation of femoral head by using cellular automata