

The Constructure Alteration Simulation of A Type of Self-growth Material of Whistar Rat

Yu ZHOU, Chao-Jie WAN and Tong-Tong GUO*

Harbin Institute of Technology, ShenZhen,518000, China

* tongtong.guo@hitsz.edu.cn

Keywords: Bone growth, Surface Remodeling Simulation, Rat Femur, Finite Element Method.

Abstract. Bone is a special composite material with excellent performance. This paper carries out numerical simulation of bone growth of femur in Wistar rat based on bone adaptive remodeling theory, integrated into the physiological regulation of bone growth. Proximal femur was scanned by Computed Tomography(CT) to collect the image data which can be translated into recognizable format in software Mimics. The middle cross-sections of the femur at different stages were found out with Mimics. The coordinates of the points on inner and outer contours of the cross-sections were extracted with software Matlab and saved in specified files which were used as the initial model and comparable data. Base on the contour data of the initial cross-section and the loads(torque and bending moment) applied on bones, stress states of the nodes on the bone surface can be determined with the program written in Fortran language. Daily stress stimulus were computed by definition. Surface remodeling rate which was governed by daily stress stimulus was determined. Based on the local modeling rate and the temporal length of the simulation time step, the locations of all points on the bone surface were moved the appropriate distance in a direction normal to the bone surface. The coordinates of the points after moved were saved for next cycle. Repeating the above processes, the growth of cross-section of diaphysis can be simulated. After adjusting the magnitudes of torque and bending moment, cross-sections closed to real ones were simulated. To research the effects caused by initial model and the direction of the bending moment applied on the bone, another two simulations were taken in this paper. One was taken using the hollow circle as the initial model, and the other was simulated under the bending moment which was turned 30° clockwise. Comparative analysis were taken between the real contours of the cross-sections and the results simulated under three different conditions above. The results of analysis corroborated the theory that bone remodeling was governed by the mechanics environment. This study also found that the results simulated from real cross-section of femur in one month rat were more closer to the actual shape at following stages and verified the rationality that the bending moment was applied about middle-lateral axis.

Introduction

Bone is a special composite material with excellent performance. Bone tissue of organic and inorganic orderly combination of permutation makes the bone with strong bending resistance and high tensile strength, determines the unique bone load characteristics[1]. Bone special is that it is different from the general engineering materials, it is a living "life" of the material, in life, its internal structure and composition is always based on changes in the external environment and constantly changing. Bone is a biological material that grows itself and changes its mechanical properties over time[2].The simulation of bone remodeling is an intersecting subject of continuum mechanics, finite element technology and bone physiology[3]. It plays an important role in prosthesis design, disease diagnosis, preventive and curative of bone disease[4]. As a result, research on bone remodeling is of great academic and technical value. This paper carries out numerical simulation of bone growth of femur in Wistar rat based on bone adaptive remodeling theory, integrated into the physiological regulation of bone growth.

Finite element model

Through the CT scan to obtain complete bone digital data, according to the establishment of bone finite element model. The finite element analysis is based on this.

Selection of Femoral Modeling Methods

Bone modeling method is generally divided into the following categories: three-dimensional measurement, histological method, based on medical image modeling method. Because this project requires 1~9 months femur shaft cross-section profiles geometry data, taking into account the existing lab equipment, therefore, in this study using the third methods. Using micro computed tomography (Micro-CT) rat bone scan data obtained, then Mimics refactoring and find it in middle of the femur cross-section, used Matlab's graphics tool cross section profiles the key points on coordinates extracted.

Extraction of Profile Data of Femur Cross Section

Acquisition of CT Image data. In this study, we selected 1 to 9 months old female Wistar rat left femur as a sample, the femur around the soft tissue such as muscle removal, the use of our laboratory SKYSCAN-1174 series Micro-CT scan. Remove the Wistar rat femur until it is thawed and place the distal end of the Wistar rat cartilage over the tray, keeping it vertically upwards (Fig1-1). And then placed in the Micro-CT in the scan window. Setting the number of scans to 3 eliminates the effects of metal shadows. The scanning direction is from the distal femoral head to the distal bone end of the mouse. We performed three-dimensional reconstruction of CT scan images. The resulting pattern is shown in Fig1-2.



Fig.1-1 The rat femur was fixed with trays in a rubber plaster

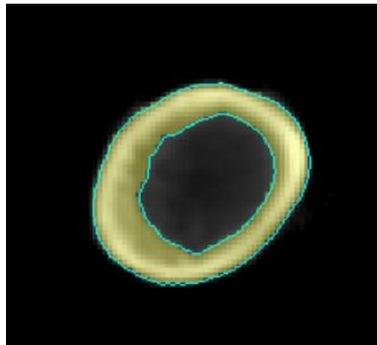


Fig 1-2 Reconstructed cross - section images of murine femur

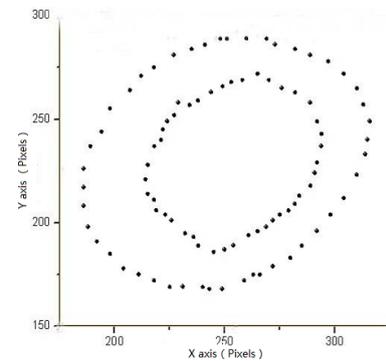


Fig 1-3 The internal and external contours of the femur cross section

Coordinate Extraction of Inside and Outside Contour. The purpose of this study was to simulate the growth pattern of the Wistar rat femoral cross-section. In order to make the simulation closer to the real state, the cross-sectional profile of the 1-month Wistar rat femur was used as the initial data. The simulation interval is set to 1 to 9 months (30 days per month), while the data of 2, 4, 6, and 9 months are used as the comparison data. In order to make the simulation results more consistent with the actual shape, in this unified selection of the backbone of the rat femoral section of the simulation object.

The use of Matlab's graphics processing tools, the outline of the internal and external coordinates of the key points extracted. When the key points are extracted, adjust the interval appropriately to ensure the uniformity of the points. The internal and external contours of the obtained femur cross section are shown in Fig1-3.

Simulation of Cross - section Growth of Femur

Combined with bone surface reconstruction algorithm to the node of the daily stress stimuli for the bone growth rate of the control volume, through the cycle of the various stages of the simulation results, and the simulation results compared with the true shape.

In the laboratory, Wistar rats can be measured during the growth of body weight data, which data can be bending moment and torque associated with the same time. Measured in the laboratory, 9-month-old Wistar rat femur in the middle section of the cross-sectional size of 4.2mm×2.8mm, in this condition, the torque and bending moment with the weight of the scale factor is selected for the 6.1 and 7.1. The torque acting on the femur is $T = (6.10 \times BW)N \cdot mm$.

The direction of action of the bending moment is along the inner and outer axes, so that compressive stresses are generated on the anterior side of the cross section of the bone, and tensile stresses are generated at the posterior side. The torque is applied in the direction of the central axis of the cross section.

Wistar Cross-section of rat femur growth simulation algorithm flow chart is as follows:

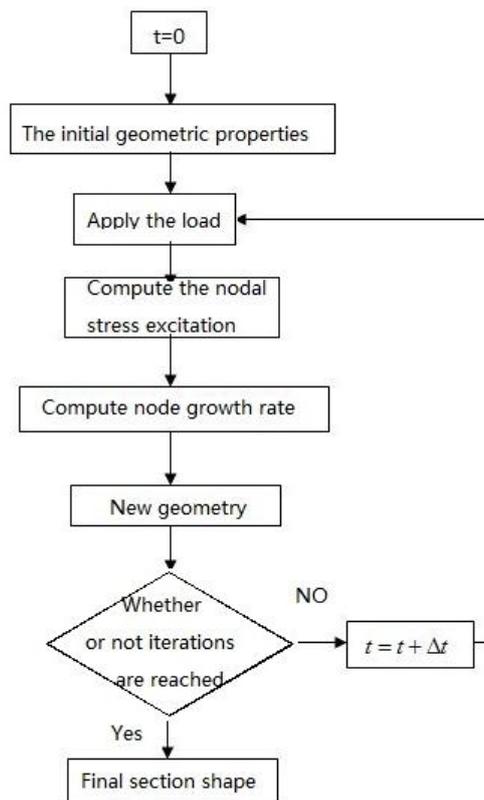


Fig.2 Cross-section growth simulation flow chart

Stimulation of Stress on the Inner and Outer Membrane of Bone

When applied the bending moment and torque, the inner and outer membrane of bone will produce stress, stress on the periosteum determines the growth rate of bone. From the local strain energy density, an invariant can be obtained. Here, it is called the energy equivalent stress $\bar{\sigma}$. The energy equivalent stress can represent the stress state at any point in the bone tissue[5]. The energy equivalent stress does not differentiate what the component of the stress tensor is, and it only provides a measure of the magnitude of the strain energy stored in the bone tissue[6]. In the model, assuming that the bone tissue is isotropic material under the premise of any point in the bone tissue stress state can be expressed as energy equivalent stress $\bar{\sigma}$ to the following form:

$$\bar{\sigma} = \sqrt{\sigma_{zz} + \left(\frac{E}{G}\right)\tau^2} \text{MPa} \quad (1)$$

where σ_{zz} is normal stress of bone tissue, τ is shear stress of bone tissue, E is the elastic modulus of bone, G is the shear modulus of bone.

The growth rate of the inner and outer membranes of the bone is determined by daily stress stimulation on the periosteum and the daily stress stimulus can be defined as follows:

$$\Psi = \left(\sum_{\text{day}} n_i \bar{\sigma}_i^m \right)^{1/m} \text{MPa/day} \quad (2)$$

Where n_i is the number of cycles per day at the i th load level, $\bar{\sigma}_i$ is the energy equivalent stress at the i th load level in the bone, m is the empirical constant, in the range of 2 to 8.

Refer to the data given by Carter D R^[6], the relationship between bone growth rate and daily stress stimuli is expressed as a function of the following

$$\dot{r} = \begin{cases} 0.125\psi - 5, & 0 \leq \psi \leq 40 \\ 0.008\psi - 0.4 & 40 < \psi \leq 60 \\ 0.3987\psi - 23.84 & 60 < \psi \leq 120 \\ 260 & 120 < \psi \leq 140 \end{cases} \quad (3)$$

Calculation of New Contour

After each cycle, the internal and external contours of the bone cross section are changed accordingly. In order to facilitate the calculation, this is only selected inside and outside the outline of some key points on the move, and use these key points to define the new bone contour. Since each cycle needs to be meshed, the distribution of nodes on the inner and outer contours is uniform, and the coordinate values, the stress components at this point, and the unit normal vectors of the inner and outer contours at this point are stored in the memory. Node selection as the definition of internal and external contours of the key points, this can be a very good program to improve operational efficiency.

The point is moved along the normal direction of the inner and outer contours, and the new position of the point is easily determined after finding the moving distance of the node according to Eq. (3). These moved points become the geometry data for the next cycle.

Determination of basic Parameters

The parameters in the model are as follows: Elastic Modulus of Bone Tissue $E = 17\text{GPa}$. Shear modulus $G = 3.28\text{GPa}$. Cycle time increment $\Delta t = 1 \text{ day}$, As well as the number of cycles $n_i = 10000$ and Empirical constant $m = 4$.

Simulation Results and Analysis

According to the initial model and loading conditions, the simulation content of this paper can be divided into three parts.

Result Analysis

The results of the above three different conditions and the real section of the mechanical properties of the calculation of the area, made of the Table 4-1 and 4-2.

Table4-1 The mechanical properties of the cross-section at different stages

Days	Actual cross section				Real initial model			
	I_x	I_y	I_p	S	I_x	I_y	I_p	S
30	1.12	1.73	2.86	2.54				
60	1.69	2.95	4.65	3.23	1.95	3.44	5.39	3.77
120	3.49	5.40	8.90	5.36	3.94	6.55	10.49	6.52
180	3.73	6.87	10.06	5.83	4.33	8.72	13.05	7.11
270	4.06	8.06	12.13	6.47	5.14	10.08	15.22	8.73

Table4-2(Continued)

Days	Change the direction of bending moment				Hollow circular model			
	I_x	I_y	I_p	S	I_x	I_y	I_p	S
30					0.64	1.04	1.69	2.47
60	2.79	3.01	5.79	4.50	2.19	3.67	5.87	5.16
120	5.94	5.04	10.98	6.98	4.06	7.15	11.22	7.64
180	7.23	5.88	13.11	8.15				

In Table 4-1, I_x, I_y —The moment of inertia of the section to the x and y axes(mm^4); I_p —The Moment of the Moment of the Moment to the Center of the Section(mm^4); S —Sectional area(mm^2).

Discussion & Conclusion

Observe the results of the simulation process can be found, whether it is from the initial model of the initial hypothetical hollow circle, the final is a group of similar to the contour of the ellipse. This is due to the fact that, after applying the bending moment, the point on the cross section is farther away from the bending moment line, where the larger the normal stress is, the more the calculated daily stress is. According to the relationship between the daily stress stimulus and the growth rate, it can be seen that this point grows faster, and this point farther away from the axis.

When the axis of action of the moment of rotation of the homeopathic needle rotation 30° found that over time, the entire cross-section in the slow clockwise rotation, when to 6 months, found the final rotation of the cross-section angle is also similar Equal to 30° .

From the comparison chart, it can be observed that the simulated outer contours are close to the true contours, but the inner contours are quite different. This may be due to the fact that the inner contour curves are not very smooth, and there may be individual points Of the stress and other points of the difference is too large, resulting in simulation of the contour is not very regular.

It can be seen from the comparison, bending moment and torque with the weight ratio of the internal and external contours of the shape and size of the more obvious impact. Overall, the bending moment and torque are great, the larger the cross-sectional area, the ratio of bending moment and torque on the shape of the inner contour of a greater impact.

References

- [1] Wang Kun. *Simulation and analysis of bone reconstruction and cross-section growth of the backbone*[D]. Master's thesis ,Harbin University of Technology, 2010.(In Chinese)
- [2] Van Der Meulen, Beaupre G S. and Carter D R. *Mechanobiologic Influences in Long Bone Cross-sectional Growth*[J]. Bone, 1993, 14(4): 635-642.
- [3] Huiskes R. *Effects of Mechanical Forces on Maintenance and Adaptation of form in Trabecular bone*[J]. Nature, 2000, 405 (6787): 704-706.
- [4] Frost H M. *Bone Mass and The Mechanostat: A proposal*[J]. The Anatomical Record, 1987, 219(1): 1-9.
- [5] Carter D R. *Mechanical Loading History and Skeletal Biology*[J]. Journal of Biomechanics, 1987, 20(11-12): 1095-1109.
- [6] Carter D R, Beaupre G S. *Skeletal Function and Form: Mechanobiology of Skeletal Development, Aging, and Regeneration*[J]. England: Cambridge Univ Pr, 2007.