Finite Element Analysis Considering Material Inhomogeneousness of Bone Using “ADVENTURE System”*

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Mechanical property of bone is inhomogeneous and its variation depends on individual. It influences on the total stiffness and stress condition of the bone. Therefore, mechanical analysis considering inhomogeneous property is necessary for patients oriented evaluation of bone in clinic. If the finite element method is used, the inhomogeneous analysis is possible by giving a material property to an element one by one. So that, extreme fine meshing is required. In this study, we improved the “ADVENTURE system”, which had developed by JSPS (Japan Society for the Promotion of Science) as a large-scale finite element analysis system, to be applicable to stress analysis of inhomogeneous bone problems. We applied the improved program to a composite beam model with graded material property and ensured its validity by comparing between the theoretical and calculated results. Furthermore, it was applied to stress analysis of proximal femur based on CT images and its efficiency was discussed.

Key Words: Biomechanics, Finite Element Method, Image Processing, Computational Mechanics, Bone, Individual Modeling, Inhomogeneousness, Large-Scale Analysis, X-Ray CT

1. Introduction

In clinical application of computational biomechanics, mechanical analysis considering only standard or normal patient models is not sufficient to discuss clinical problems. Analysis based on individual or patient specific modeling considering characteristics of organ shape and tissue construction is indispensable. There are two specific method to make patient oriented computational models noninvasively based on cross-section images obtained from X-ray CT or MRI and so on: one is making finite element models using CAD/CAE based on outline extracted from two dimensional images^{(1),(2)}, another one is making voxel finite element models directly obtained from voxel data of three dimensional image processing^{(3),(4)}. In these days, the latter method is apt to be noticed because it is easy to make models, but huge finite elements are needed to make a precise model and it faces problems causing difficulties in computational time and its cost. It also has dif-

ficulty in clinical application, because resolution of voxel depends on amount of beam of X-rays. Dosage from X-ray CT scanner to patients increases to raise the precision of modeling. On the contrary, although the former method needs a lot of CAD operation from image processing data to making solid models, it seems reasonable method at this moment for clinical application such as whole bone analysis in orthopedic.

In conventional CAD/CAE modeling method of bone, cortical and cancellous region were determined, and constant mechanical property of both regions was usually defined respectively⁽⁵⁾. However, mechanical property of bone (especially Young's modulus) is essentially inhomogeneous related to variation of bone density distribution. Range of mechanical property variation of a bone depends on individual, and it influences on the total stiffness and stress condition of the bone. Therefore, mechanical analysis considering inhomogeneous property of bone is necessary for patients oriented evaluation in clinic. In this study, we used “ADVENTURE system”⁽⁶⁾ which had developed as a large-scale finite element analysis system. We improved it to be applicable to stress analysis of inhomogeneous bone problems by giving a material property to

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an element one by one. Then the improved program was applied to stress analysis of clinical problems and its efficiency was discussed.

Finite element analysis software specialized bone problems is rare. Many biomechanics researchers use general finite element analysis (FEA) software for biomechanics subjects with inconvenience. Program source codes of commercial FEA software are not open to the public, and their customization features are not sufficient, so it is difficult to improve them specializing for bone analysis. At the same time, program sources of ADVENTURE system are open for free and its analysis capabilities is comparable to commercial FEA software such as not only solid elastic analysis but also rigid-plastic analysis, impact-contact analysis, thermal conduction analysis, thermal-fluid analysis, and optimum design analysis. Furthermore, it can solve faster the large-scale problem by using PC cluster with parallel processing. If ADVENTURE system is expended to be applicable bone analysis, it will be a extremely useful tool for solving various bone biomechanics problems. It is important to use the ADVENTURE system in this study.

2. Method

2.1 ADVENTURE system and its improvement

If Young's modulus is given to an element one by one in the finite element analysis, mechanical analysis considering the bone inhomogeneity is possible. It is based on the premise that bone mass density distribution is obtained from pixel value of X-ray CT images. Young's modulus of each element can be calculated using relationship between mass density and Young's modulus provided by earlier studies. However there is no such function as giving a material property to an element one by one automatically in general FEA software. This operation is possible by hand but it is not realistic for application in clinical problems in view of a lot of costs due to manual work and hand time. And again, fine meshing is preferable as far as possible to reflect detailed Young's modulus distribution of bone because Young's modulus is defined for each element. It is also desirable to use fine meshing at the interface between cortical and cancellous region of bone since mass density distribution is precipitous and high stress is expected in the region. ADVENTURE system is a computational mechanics system for large-scale analysis and design developed by Japan Society Promotion Science (JSPS) released from May 2001. It enables to solve more than a few million degree of freedom problems on the PC cluster with parallel processing adopting domain decomposition method⁽⁷⁾. The system consists of plural modules for pre-processor, solver, and post-processor and program sources of the system are open for free. In this study, we improved "ADV_BCtool (version number: 0.81)" module and "ADV_Solid (ver-

sion number: 0.81)" module. ADV_BCtool sets boundary conditions and material property to finite element models, and make an all-in-one finite element model. ADV_Solid runs structure analysis to subdivided computational models. The system was improved to be able to give a material property to an element one by one making an element-to-material property table, however, all material of finite element models was assumed as a isotropic elastic in this study.

2.2 Development of the software to calculate Young's modulus distribution of bone

We also developed the program to calculate Young's modulus of each element based on CT images of individual bone. We called the program "ADV_CTBone" regarding it as a one of the modules of ADVENTURE system. In the program, the coordinate of the element's center of gravity is calculated first, then the CT value at the point is linearly interpolated from two values on CT planes which sandwich the point as shown in Fig. 1. When a center of gravity of element is sandwiched between pixel A and pixel B, CT value P_G of the center of element G is interpolated as follow:

$$P_G = \frac{nP_A + mP_B}{m + n} \quad (1)$$

where the pixel value of pixel A and B are P_A and P_B respectively, and the distance between the pixels and the center of gravity are m and n respectively. Based on the CT value calculated in that way, mass density and Young's modulus of bone are calculated respectively using the relationship described in next section. In this study, we used 8-bit images transformed from 16-bit CT images. So 256 values of Young's modulus was prepared and a value of each element was corresponded to any one of them. Flow of bone analysis using ADVENTURE system is shown in Fig. 2. We used MSC/Patran software for meshing pre-process, and FE data related with nodes and elements were converted from MSC/Patran format to ADVENTURE system format. Relationship between CT value and mass density⁽⁸⁾ in this study are as follows:

Fig. 1 An interpolation of the CT value at the center of gravity of the element from CT images

Fig. 2 Process flow of the bone analysis using the ADVENTURE system

Fig. 3 A beam model and its material properties

$$\rho = (\text{CT value} + 1.4246) \times 0.001 / 1.0580$$

$$(-1 < \text{CT value})$$

$$\rho = 1.0 \times 10^{-8} \quad (\text{CT value} \leq -1) \quad (2)$$

where ρ [g/cm³] is mass density of bone. We also use relationship between Young's modulus and mass density provided by Carter⁽⁹⁾ as follows:

$$E = 0.001 \quad (\rho \leq 1.0 \times 10^{-8})$$

$$E = 2875\rho^3 \quad (1.0 \times 10^{-8} < \rho) \quad (3)$$

2.3 An example for program evaluation

We applied the improved program to a composite beam model with graded material property and compared between the theoretical and numerical results for program evaluation. Boundary condition and material property distribution of the beam model is shown in Fig. 3. Origin of coordinates of the model was set the center of fixed end and z axis was set in the longitudinal direction. Distribution of Young's modulus was depended on only y direction and Poisson's ratio was constant. Distributed load of 1 N/mm was added at the edge of the beam. In finite element (FE) analysis, Young's modulus was constant in an element. We used axial stress of the center of element to evaluate results. FE model and Mises stress contour of the beam model are shown in Fig. 4, and axial stress dis-

Fig. 4 FE model and Mises stress contour of the beam

Fig. 5 Axial stress distribution at $x = 0$ mm and $z = 15.1$ mm along y direction

tribution at $x = 0$ mm and $z = 15.1$ mm along y direction is shown in Fig. 5. FE model was meshed by hexahedral elements and number of nodes and elements were 38 656 and 33 750 respectively. Good correspondence between both results was observed, so efficiency of the improved program was confirmed.

3. Application to Clinical Problems

3.1 Subjects

The improved ADVENTURE system was applied to an example of clinical problems that is stress analysis of a proximal femur. We prepared CAD model of 24-year-old male proximal femur from based on CT images at 2 mm intervals. CAD model, its boundary condition and FE models meshed by tetrahedral elements (average element length were 10 mm, 5 mm, or 3 mm) were shown in Fig. 6. Simple boundary condition was assumed as standing still by one leg: hip joint force of 1 500 N was applied to the femoral head with an angle 13 degree relative to the femoral axis, the greater trochanter was loaded with 1 000 N, the angle of 20 degree with the femoral axis, and distal edge face of the model was fixed⁽¹⁰⁾. On the other hand, the volumetric proportion of mass density of the femur calculated to the 3 mm elements model is shown in Fig. 7. We prepared 2 types FE models that were "inhomogeneous type" and "homogeneous type". Inhomogeneous type was that Young's modulus of each element was calculated due to mass density distribution, and homogeneous type was that constant Young's modulus was defined for cortical and cancellous region respectively like as conventional model. When a threshold value of mass density between cortical and cancellous bone was defined in homo-

Fig. 6 Femur CAD model with its boundary condition and FE models meshing by tetrahedral elements (length of element are 10 mm: left, 5 mm: middle, 3 mm: right)

Fig. 7 Mass density distribution of the femur model

geneous type, we chose some points in the vicinity of the border by visual observation, then calculated the average of their mass density. Then we got the value as 1.1 g/cm^3 . If mass density value was more than 1.1 g/cm^3 , the point was assumed cortical bone, and it assumed cancellous bone if not. Mass density of cortical bone: 1.9 g/cm^3 is defined as the value corresponded to high volumetric proportion in Fig. 7. A mass density value of cancellous bone is defined as 0.8 g/cm^3 that is provided by Evans⁽¹¹⁾. These are shown in piles in Fig. 7. In addition, we approximated the mass density of canal parts by the value less than $0: 3.3 \times 10^{-4} \text{ g/cm}^3$ (Young's modulus is $1.0 \times 10^{-7} \text{ MPa}$) because the CAD model was created without considering inside canal surface and the canal part was divided by elements. Poisson's ratio was set all constant 0.4.

3.2 Stress analysis

Femur Mises stress of whole region and cross-section at the neck of caput are shown in Fig. 8 for three different mesh models comparing between inhomogeneous type and homogeneous type respectively. It was noticed Mises stress distribution became clearer as FE mesh of the model was finer in inhomogeneous models. High stress area was observed wider at the neck of femur (part A in Fig. 8) and the region between greater trochanter and third trochanter (part B in Fig. 8) especially in the fine mesh model. On the other hand, in homogeneous models, high stress area was not so wide on the lateral side (part B in Fig. 8) even if FE mesh of the model was finer. In stress distribution

Fig. 8 Mises stress contour of the whole model and the cross-section at the neck of caput of three models (A, B: large stress region)

of the cross-section at the neck of caput, differences of the stress between cortical and cancellous bone are clear in fine meshing models in inhomogeneous models, but are not in homogeneous models. The reason is considered that realistic Young's modulus was set with higher accuracy as finer FE meshing in inhomogeneous models, but it is ineffective in homogeneous models. Though mass density would be changed exponentially in interface of cortical and cancellous bone, one finite element certainly straddled the interface. So that, it is difficult to represent the exponential change by homogeneous model or coarse mesh model. Availability of the improved system, which can represent accurate inhomogeneous property of bone, was suggested on the clinical analysis.

3.3 Evaluation of stress-strength ratio

We estimated stress-strength ratio using the same

models. Stress-strength ratio is a ratio of stress to its corresponding strength. We use it as one of the index of bone fracture risk. It is given by:

$$k = \frac{\sigma}{\sigma_r} \quad (4)$$

where k is stress-strength ratio, σ is major principal stress, and σ_r is yield stress. In Eq. (4), we assumed tensile yield stress was equal to compressive one, and principal stress was adopted larger value of tensile or compressive stress. σ_r is also given as:

$$\sigma_r = \begin{cases} 1.0 \times 10^{20} & (\rho \leq 0.2) \\ 51.6\rho^2 & (0.2 < \rho) \end{cases} \quad (5)$$

provided by Carter⁽⁹⁾. The low density region ($\rho \leq 0.2$) was out of evaluation. Stress-strength ratio was calculated by Eq. (4) substituting major principal stress obtained from ADVENTURE system and yield stress of Eq. (5). Stress-strength ratio contour viewing from medial side is shown in Fig. 9 and maximal stress-strength ratio at the neck of caput is shown in Fig. 10. Considerable difference between two of the result, homogeneous and inhomogeneous model, was observed. These results have not always given us exact prediction of bone fracture risk because of some analysis limitations that is linear elastic analysis and the too simple boundary condition, nevertheless maximal stress-strength ratio exceeded 1.0 in the vicinity of the neck of caput and it means local bone failure occurs in analysis of the homogeneous models. In Eq. (4), yield stress

was proportional to square of mass density due to Eq. (5), in contrast, principal stress strongly depended on cube of mass density due to Eq. (3). It was considered that stress-strength ratio calculated in the homogeneous models tends to be higher because mass density was set to be higher totally. Stress-strength ratio of medial and front side in inhomogeneous models are shown in Fig. 11 by changing contour scale. Mass density distribution and stress-strength ratio contour in frontal plane section around the femoral neck of inhomogeneous models are also shown in Fig. 12. It is noticed that stress-strength ratio was less than 1.0: principal stress was less than yield stress. It is also noticed that high stress-strength ratio i.e. high failure risk was specified at the place between greater trochanter and third trochanter. In Fig. 12, mass density distribution of bone

Fig. 11 Stress-strength ratio contour of the inhomogeneous models (left: view from medial side, right: view from anterior side)

Fig. 9 Stress-strength ratio contour viewing from medial side (a: inhomogeneous models, b: homogeneous models)

Fig. 10 Maximal stress-strength ratio at the neck of caput

Fig. 12 Mass density distribution and stress-strength ratio contour in frontal plane section around the femoral neck of inhomogeneous models (length of element are 10 mm: left, 3 mm: right)

was given more precisely in inhomogeneous type than that of homogeneous type, and it was considered stress-strength ratio distribution depended on mass density distribution. At this point, it is conceivable that unexpected stress concentration occurred due to material and geometric discontinuity between elements. Stress-strength ratio showed in from Fig. 9 to 11 were results at cortical surface, so that influence of unexpected stress concentration was small comparatively. Furthermore, though stress-strength ratio in internal cancellous bone came under the influence of the stress concentration, it is considered that solution of the inhomogeneous model was more accurate than the homogeneous model because material property (both of Young's modulus and strength-ratio) distribution was correctly represented. Consequently, analysis considering bone inhomogeneity in detail is required especially for evaluation of stress-strength ratio of bone. Proposed stress-strength analysis would be effective to subject the bone fracture problems in fact.

3.4 Large-scale analysis and evaluation of computational performance

Analysis as discussed above were done by one PC. Analysis operated on the PC cluster with parallel processing is needed to make full use of the advantages of ADVENTURE system and to solve large-scale problems effectively. We improved the program of the system to accommodate for parallel computation and run the analysis using the models shown in preceding section by 2 PC cluster with parallel processing. Stress analysis with more finer FE meshing was carried out, and appropriate scale of meshing for the calculation was discussed. Computer architecture of the PC cluster is shown as Table 1. Improvement of program for parallel processing operation makes possible to solve models whose element length was 1.3 mm. The FE model, Mises stress contour of the whole model and cross-section at the neck of caput of inhomogeneous type and homogeneous type are shown in Fig. 13. It was noticed that higher stress region was found at the posterior side of femur in inhomogeneous type. It had not detected in the model whose element length was 3 mm. Accuracy of Young's modulus setting seems to be improved by finer FE meshing. On the contrary, in homogeneous models, higher stress region at the posterior of femur could not find even if FE meshing was finer. FE data and computational performance of all models men-

tioned above are shown as Table 2. If PC performance is better or scale of PC cluster scales up, more precise analysis considering inhomogeneous of bone is possible. However, limit of intervals of CT shooting is 2 mm at this time because of dosage from CT to patients. So calculation accuracy of Young's modulus has a limit, because the element values were approximated by values at CT sections. In order to improve performance of individual analysis, it is also required to consider shape errors between CT images and CAD models⁽¹²⁾, and partial volume effect⁽¹³⁾.

4. Conclusion

In this study, we developed the large-scale finite element analysis system especially for bone considering inhomogeneous material property and solve the problems with fine meshing models by improved ADVENTURE system. On that basis, following conclusions was obtained.

(1) In the analysis of a composite beam model with graded material property, good correspondence between analysis and theoretical results were obtained and validity of the improved system was confirmed.

(2) By the analysis of a proximal femur, necessary of considering inhomogeneous of bone is ensured to evaluate stress distribution and stress-strength ratio of bone.

Fig. 13 FE model (length of element is 1.3 mm), Mises stress contour of the whole model and cross-section at the neck of caput (inhomogeneous model: left, homogeneous model: right, *: large stress region)

Table 1 Computer architecture of the PC cluster

PC	PC (1)	PC (2)
CPU*	300MHz	330MHz
Memory	512MByte	512MByte
Hard Disk	3GByte	1.3GByte

* Intel Pentium II

Table 2 FE data and computational time

Element length	10mm	5mm	3mm	1.3mm
Number of elements	1972	7636	26088	245783
Number of nodes	8856	36910	135537	1387307
Number of PC	1PC	1PC	1PC	2PC
Computational time	1min.	15min.	200min.	33hr

(3) Under the parallel operation of large-scale finite element analysis of bone over million elements, it was confirmed that the improved system considering bone inhomogeneity was efficient.

ADVENTURE system will be a very valuable tool for various mechanical analysis of bone by developing having functions specialized for bone analysis in the future. For that purpose, assignments to resolve in future are an adopting of bone anisotropy, improvement of the system to consider soft tissues such as cartilages, tendon, ligament on a joint, and so on. It is necessary to extend ability of the improved system considering other various clinical application such as analysis of an artificial joint problems and strength analysis of osteoporosis.

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