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EVALUATION OF MECHANICAL ROBUSTNESS OF A VERTEBRAL BONE

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ABSTRACT
This paper deals with a numerical analysis and the experiment to investigate risk of fracture. We propose an evaluation index, "stress/strength," for the robustness of a bone. Validity of the index is examined by the following steps. First, the index is calculated by an individual modeling method using vertebral bodies of a rat. Second, compression tests with the specimen of bone are performed for measuring the loading conditions in fracture. Finally, high values of the index and fracture lines in the bones are compared. To perform these steps, we devise an individual modeling method for effective numerical analyses, prepare the specimen of bone, and design the measuring system for the compression tests. The proposed numerical method predicts the initiation site of the fracture.

KEY WORDS
Computational Biomechanics, Finite Element Method, Osteoporosis, Individual Modeling.

1 Introduction

Osteoporosis is a musculoskeletal disease characterized by progressive decrease in the bone density that results in increase of fracture risk. Bone mineral density (BMD) is used as an index to determine the degree of osteoporosis. However, diagnosis just based on BMD is not sufficient to evaluate the robustness of bones. This is because if the stress created at a certain portion is too large, a bone fracture may occur even when the bone density is high. Namely, it is necessary to consider not only the BMD, but also the mechanical characteristics of bones.

For this reason, several studies on computational analyses considering the structure of bones have been published [1][2]. These studies are mainly concerned with the strength of femoral neck portion and analytical results have high correlation with the mechanical testing. However, the failure location at femoral neck is relatively predictable. The loading condition for the analysis should be set up more exactly to examine other bones such as vertebrae.

In our previous paper, we discussed the robustness of a bone from the viewpoint of structural mechanics [3]. This paper focuses on a method to obtain proper loading conditions for numerical analyses. We propose a measuring device including four load cells. The device is applied to compression tests of vertebral bodies of rats. Then, we reports a comparison between the results of compression tests and the analytical results obtained from an individual model.

Figure 1 shows the procedure for evaluating the analysis. First, a specimen of a rat's vertebral body is prepared (A). After taking a CT image of this specimen (B), a compression test is performed and a loading condition at the onset of failure is measured (C). In parallel with the compression test, an individual model of each specimen is produced based on the CT image (D), and stress analysis is performed using the measured loading condition (E). The part of the fracture observed in the specimen (F) and a section with high fracture risk obtained from the analysis (G) are compared (H).

2 Compression test of rat's vertebral body

In this study, we compare fracture locations predicted by numerical analyses with the results of compression tests of bones. We used vertebral bodies of rats in the comparative verification. The vertebral bones of rats have a fairly similar structure to that of the human, and are easily obtainable. The vertebral bone of a rat is roughly divided into two sections: the vertebral body and the vertebral arch. Only the vertebral bodies of rats were used for compression tests, after removing the vertebral arch using a micro-saw. The only vertebral body is difficult to sustain its posture dur-

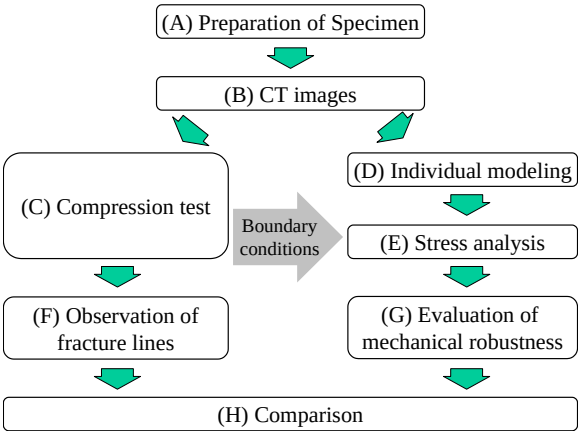
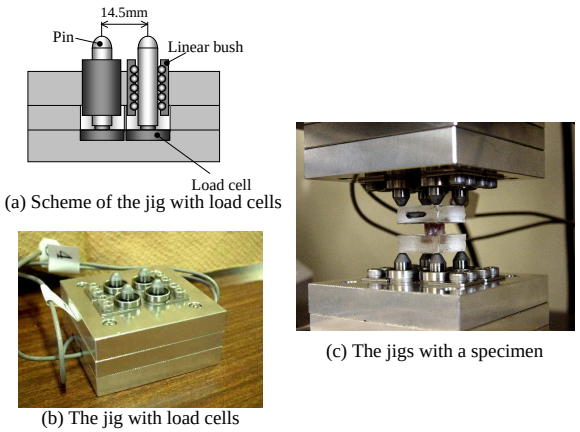


Figure 1. Procedure of the evaluation.



(a) Scheme of the jig with load cells

(b) The jig with load cells

(c) The jigs with a specimen

Figure 2. Measuring device for loading condition.

ing compressive application. Therefore, the two end surfaces of the vertebral body were embedded in epoxy resin to provide mechanical restraint. Twelve specimens were prepared using the vertebral bodies of healthy rats fixed with alcohol. The specimens were stored in a physiological salt solution until the start of the experiment.

To perform stress analysis under the loading conditions at the measured onset of fracture, accurate loading conditions must be applied to the analytical model. However it is difficult to measure the load distribution on the end surface of a specimen using the universal testing machine. Therefore, we designed a measuring device including four load cells. As shown in Figs. 2 (a) and (b), the cells measure the load distribution on one end surface. The specimen is compressed by pins whose tips have been processed into a spherical shape. The load cells with a rated capacity of 200 N (9E01-L42-200N, NEC San-ei Instruments, Ltd.) were selected based on a preliminary experiment.

Figure 2 (c) shows the setup for the compression test. An instron-type universal testing machine (AutoGraph AG-2000E, Shimadzu Corp.) was used for the compression test in which the actual measuring devices are placed at the top and bottom of a specimen. Compression was performed under displacement control at 0.1 mm/sec, and loads at each measurement point were measured at a sampling frequency of 0.15 sec. A moving average method was applied for the elimination of noises during compression.

Figure 3 shows the load histories at 8 points measured with the upper and lower measuring devices during compression of a vertebral body until complete breakage. The histories indicate that the unbalanced load is applied to the specimen. This is an important information to set up the boundary condition in the analysis.

For the comparison of these experimental results with analytical results, the load must be removed immediately after the occurrence of fracture. We terminated the application of a load on confirming the fracture of a specimen by visual inspection. In this study, twelve specimens are subjected to compression testing.

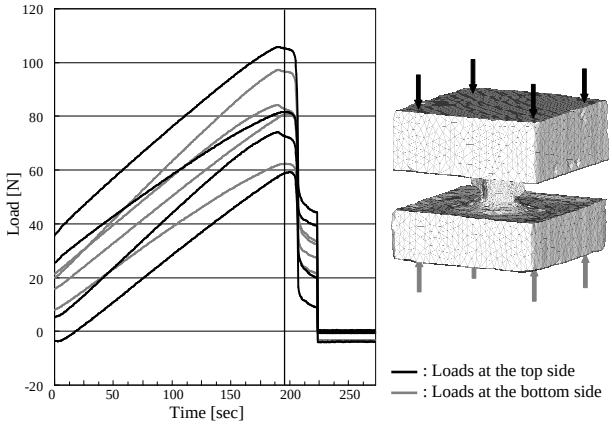


Figure 3. Load histories.

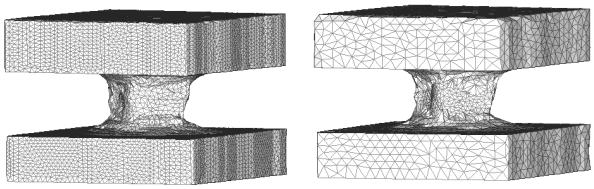
3 Individual finite element modeling

For the numerical analysis, an individual model of the specimen is generated based on our proposed modeling method [4]. To generate the individual analytical model, slice images of the specimen are taken before compression tests, using a pQCT device (XCT Research SA, Stratec Medizintechnik GmbH).

pQCT images were taken including the resin-embedded parts (resin parts) for individual modeling of the whole specimen. The resolution is 0.05 mm/pixel, the slice thickness is 0.11 mm, and the number of images is approximately 80.

The modeling method is composed of the following four processes.

1. A voxel space of the specimen is determined from the CT images.
2. Nodal points are distributed within the voxel space.
3. Tetrahedral elements are generated between the nodal points by use of Delaunay triangulation.
4. The model is completed by removing excessive elements.



(a) Model A: Without element size control (b) Model B: With element size control

Figure 4. Individual models of the specimen.

Table 1. Number of elements of the analytical models.

	Model A	Model B
Vertebral body	23,815	25,630
Parts of Resin	354,517	46,778
Total	378,332	72,408

It is necessary to model the entire specimen including the resin parts since the mechanical conditions of compression tests should be included in the analyses. The amount of the resin parts in the specimen is significantly larger than the vertebral body itself. That is, if elements of identical size are used for both the resin part and the bone part, the number of elements becomes huge in the attempt to model the bone part with sufficient analytical accuracy. Huge model requires a lot of time for stress analysis. Therefore, we used different nodal distances between the bone part and the resin part in Step 2, so that model with different size elements can be produced.

Figure 4 (a) shows the result of modeling with element of identical size in the bone and resin parts. Figure 4 (b) shows the result of modeling in which the element size in the resin parts is larger than that in the bone part. Table 1 compares the numbers of elements of the models with and without the element size control. In the former model with identical size elements, the number of elements in the resin parts is nearly 15 times that in the bony part, and a total of over 370,000 elements were necessary in the model. In contrast, in the model with different size elements, the difference in the number of elements in both parts was twofold or less. Therefore, the total number of elements in the entire model was 1/5 of that in the former model.

Material properties of the model are assigned based on the CT value. The CT value obtained by the pQCT device is equivalent to the amount of hydroxy-apatite $[Ca_{10}(PO_4)_6OH_2]$ in each pixel, and is proportional to the BMD (g/cm^3). The following relationship holds between the CT value (V_{CT}) and bone density (ρ).

$$\rho = 828.1 \times \frac{V_{CT}}{1000} - 200 \tag{1}$$

In the analysis, the Young's moduli of the bone part (E) and the bone strength (σ_b) are calculated using following equations, in reference to the reports by Carter et al. [5][6].

$$E = 3790\rho^3 \tag{2}$$

$$\sigma_b = 68\rho^2 \tag{3}$$

In the resin parts, the Young's modulus of 2.06 GPa, which was obtained from a preliminary material test, was assigned.

4 Evaluation of reliability in the analysis

The equivalent stress distribution was analyzed using FEM, and the evaluation index of bone fracture risk, "stress/strength," was obtained. In the analysis, we assumed that no slipping between each pin and specimen occurs, and the loads measured by the 8 load cells in the experiment were applied as point loads.

One of the analytical and experimental results are shown in Figs. 5 and 6. Fracture lines are observed at both the anterior and posterior regions as shown in Figs. 5 (A) and (B). Figure 5 (C) illustrates loading condition at the measured onset of bone fracture. Figure 6 shows analytical results only with the bony parts of the models. In the figures, value of the maximum BMD and approximately 1/2 or more for the maximum equivalent stress and for the maximum "stress/strength" are expressed in black.

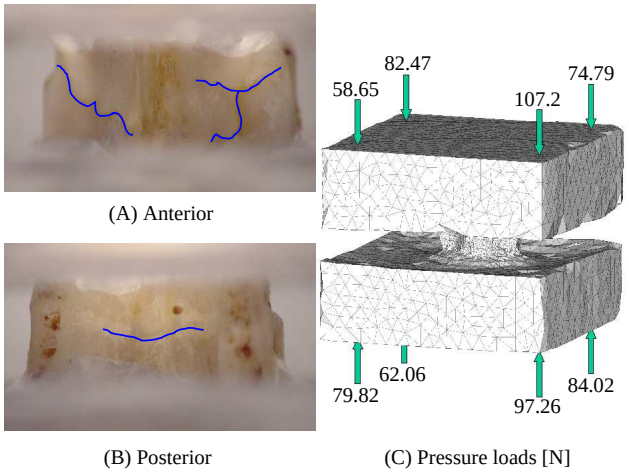
High equivalent stresses are distributed in the center of the anterior bone part, and no clear correlation is observed between the stress distribution and the position of fracture. In contrast, in the "stress/strength" distribution, values of 1 or more are distributed in the anterior part from the upper left to the lower, central section and a "J" shaped section at the right-hand side. This computational result qualitatively agrees with the fracture line of the specimen obtained in the compression test. Also in the posterior section, the position of the fracture partially agrees with the values of "stress/strength," though these values are small. This suggests that "stress/strength" is effective in the prediction of bone fracture risk.

5 Discussion

From the comparison of fracture lines obtained by analysis with those obtained by experiment, we have showed that the value of "stress/strength" is effective as an index for evaluating the robustness of bones. We can predict sections where bone fracture may easily occur using this index.

We employed the relationship that Young's modulus is proportional to the third power of bone mineral density in this study. Some researches report the exponent for Young's modulus as a smaller number than three [7]. The smaller exponent will produce more blurred stress distribution compared with the present one. Further research is needed for clarifying the quantitative effect on the computational results.

The proposed index of "stress/strength" is the inverse of "Factor Of Safety (FOS)". While FOS becomes infinite,



(A) Anterior

(B) Posterior

(C) Pressure loads [N]

Figure 5. Fracture lines and loading condition.

our index is 0 in regions without stress. This means calculation of FOS requires considering of the element that generates zero stress in the analysis. In addition, a value of "stress/strength" greater than 1 indicates the presence of a bone fracture, and thus, easy intuitional understanding is possible.

6 Conclusions

In this study, we pointed out that the measurement of the BMD is not sufficient for evaluation of bone-fracture risk in the diagnosis of osteoporosis. We reported a method for predicting bone-fracture risk based on mechanical analysis using individual models, as well as experimental verification.

In the verification experiment, we used specimens of rats' vertebral bodies, of which two end surfaces were embedded epoxy resin; their load history was measured using 8 load cells. In the mechanical analysis, we devised an efficient modeling method in which the resin part and bone part were modeled with elements of different sizes, taking into consideration their different volumes. By the comparison of fracture lines observed in compression tests with fracture risks obtained from mechanical analyses, we demonstrated that the proposed index of "stress/strength" can predict bone-fracture risks with high accuracy.

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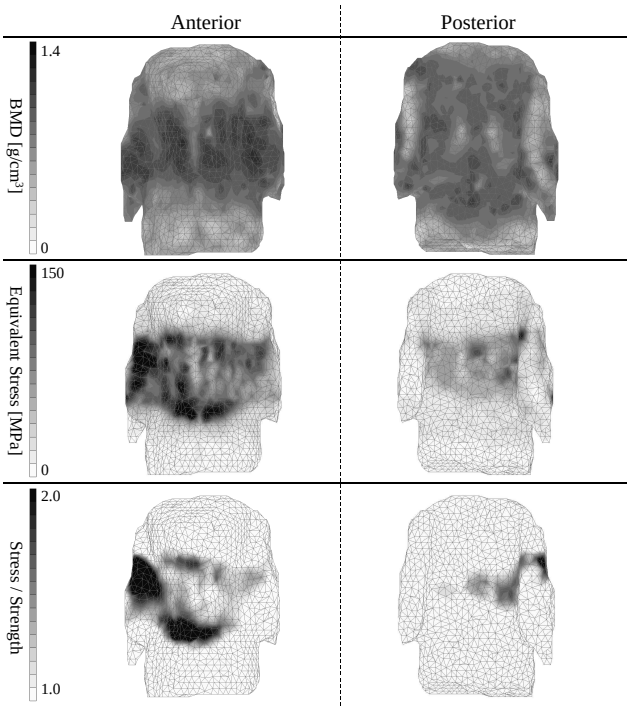

Figure 6. Distributions of BMD, equivalent stress and "Stress/Strength".

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