MECHANICAL PROPERTIES OF A SINGLE CANCELLOUS BONE TRABECULAE TAKEN FROM BOVINE FEMUR

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The increase of patients with osteoporosis is becoming a social problem, thus it is an urgent issue to find its prevention and treatment methods. Since cancellous bone is metabolically more active than cortical bone, cancellous bone is often used for diagnosis of osteoporosis and has received much attention within the study of bone. Bone is a hierarchically structured material and its mechanical properties vary at different structural levels, therefore it is important to break down the mechanical testing of bone according to the various levels within bone material. Mechanical properties of cancellous bone is said to be depended on quantities and orientation of trabecular bone. It is supposed that mechanical properties of trabecular bone are constant without depending on any structural arrangement and parts. However, such assumption has not been established in studies of trabecular bone. Furthermore test results have a large margin of error caused by insufficient shape assessment. In this study, three point bending tests of single cancellous bone trabeculae extracted from bovine femur were conducted to evaluate the effects of directions to the femur major axis direction on the mechanical properties. X-ray μ CT was used to obtain shape of trabecular bone specimens. Furthermore compression tests of cancellous bone specimens, which were extracted in 10mm cubic geometry, were conducted for evaluation of directional properties. There were small difference in the elastic modulus of the trabecular bones which were extracted in parallel and in perpendicular to the major axis of femur. Considering from the results that the cancellous bone specimens, which were extracted in 10mm cubic geometry, have different elastic properties depending on the tested directions; the bone structure has larger influence than bone material property on the mechanical properties of cancellous bone.

Keywords: Trabecula; cancellous bone; cortical bone.

1. Introduction

The rising incidence of osteoporosis is becoming a major public concern within the aging society, thus it is necessary to find its prevention and treatment methods. At present the clinical assessment of osteoporosis is mainly on bone mineral density (BMD) measurements, such as dualenergy X-ray absorptiometry (DXA¹), quantitative X-ray computed tomography (QCT²) and others. According to the Institute of Health (NIH) in 2000, osteoporosis is known to be a skeletal disease characterized not only by low bone mass but also by microarchitectural deterioration of bone tissue, making it necessary to seek for alternative bone quality parameter as the indicator of bone strength³. Bone is classified into cortical bone and cancellous bone. Since cancellous bone is metabolically more active than cortical bone, cancellous bone is often used for the diagnosis of osteoporosis and has received much attention within the study of bone⁴. Mechanical properties of cancellous bone is said to be depended on quantities and orientation of trabecular bone^{5,6}. It is supposed that mechanical properties of trabecular bone are constant without depending on any structural arrangement and parts. However, such assumption has not been established in studies of trabecular bone. Furthermore elastic modulus have a large margin of error caused by insufficient shape assessment^{7,8}.

In this study, three point bending tests of single cancellous bone trabeculae extracted from bovine femur were conducted to evaluate the effects of directions to the femur major axis direction on the mechanical properties. X-ray μ CT was used to obtain shape of trabecular bone specimens. Furthermore, compression tests of cancellous bone specimens, which were extracted in 10mm cubic geometry, were conducted for evaluation of directional properties.

2. Materials and methods

2.1. Specimen

2.1.1 Trabecula specimen

Cancellous bones were obtained from the bovine femur as indicated in Fig.1. Single trabecula specimen on each axis was extracted from the cancellous bone in length of 2mm to 3mm and in diameter of 200 μ m to 500 μ m. 8 specimens were prepared for each of X, Y and Z axis. Specimens were polished with Speed Lap (Maruto, ML-521-d) at diamond lapping (600grit) to a thickness of 100 μ m and with sandpaper (600grit) on outer surfaces. For these specimens, there is a $\pm 10\%$ difference for their average width. Made up trabecula specimen is shown in Fig2.

Fig.1 Trabecula on each axis obtained from the right distal femur of a bovine.

Fig.2 μ CT-imaged of trabecular bone specimen.

2.1.2 Cancellous bone specimen

Specimens of cancellous bone were obtained from the right femur of a bovine. As shown in Fig.3, cancellous bone was extracted in a 10mm cubic geometry in femoral long axis as Z axis by using a bandsaw. Bone marrow within specimens of cancellous bone was removed by saturating in hot water and removed by running through jet water. 30 specimens were prepared.

Fig.3 Cancellous bone specimen.

2.2 Experimental method

2.2.1 X-ray μ CT

Three dimension images of each cancellous bone specimen (3D images) was obtained by using micro focus X-ray system (Shimadzu, SMX-160CTS) with a voxel size of $5\mu\text{m}$. Measurement of specimen geometry that is width and thickness was obtained from the average value of 3 section of 3D image.

2.2.2 Micro three point bending test

Mechanical tests were performed by using Micro Material Tester (Shimadzu, MMT-11NV-2) with a load cell capacity of 10N. Each specimen was placed on the jig as shown

in Fig.4 and span length was set to 1.1mm. Knife-edge indenter of 0.1mm in tip radius was used as an indenter within the three point bending test. The positioning of specimen was conducted by XY stage in resolution of 0.01mm.

Fig.4 Three point bending tester.

Elastic bending test was carried out at a crosshead speed of 0.001mm/sec, and maximum displacement was 0.02mm. The following equation⁹ was used to calculate the elastic modulus for each specimen.

$$E = \frac{(P/\delta)L^3}{4bh^3} [1 + 2.85(h/L)^2 - 0.84(h/L)^3]$$

E : Elastic modulus P/δ : Load displacement curve L : Distance between the fulcrum
 b : Width of the specimen h : Thickness of the specimen

2.2.3 Compression test

Compression tests in elastic area were performed by using universal testing machine with a load cell of 1kN at a crosshead speed of 0.017mm/sec below the elastic limit strain of cancellous bone specimens. Elastic compression test was carried out to X, Y and Z axis with each cancellous bone specimens shown in Fig.3.

3. Results and Discussions

Figure5 shows the elastic modulus of trabecula specimen on each X, Y and Z axis obtained from elastic bending test. Elastic modulus of each axis was $7.70 \pm 1.13\text{GPa}$, $8.43 \pm 1.03\text{GPa}$ and $7.57 \pm 1.00\text{GPa}$. There were small differences in the elastic modulus of the trabecular bones which were extracted in parallel and in perpendicular to the major axis of femur. As a reason for that, bone is a composite material consisting of living hydroxyapatite(HAp) and collagen fiber¹⁰ and orientation of collagen fiber coincides with

the long axis of the trabecular bone¹¹. Additionally, HAp are oriented in such a way that the c-axis coincides with collagen long axis as shown Fig.7, and the c-axis orientation of HAp is stiff and hard, and shows significant anisotropy in properties. Figure6 shows the elastic modulus of cancellous bone specimen on each of X, Y and Z axis obtained from compression test. Elastic modulus of each axis was 695.6 ± 316.9 GPa, 301.7 ± 205.1 GPa and 791.9 ± 241.1 GPa. The cancellous bone specimens, which were extracted in 10mm cubic geometry, have different elastic properties depending on the tested directions. Mechanical properties of cancellous bone are influenced by the difference in bone density, elastic modulus of single trabecula and trabecular bone structure, e.g. orientation of trabecula bone. However, there was no influence of bone density to the results because the same cancellous bone specimen was used in X, Y and Z axis direction tests. Furthermore, it is thought that there is little influence of elastic modulus of single trabecula to mechanical properties of cancellous bone, because orientation of single trabecula had little influenced on the elastic modulus as confirmed by Fig.5. Therefore, trabecular bone structure has larger influence than bone density of cancellous bone and elastic modulus of single trabecula on the mechanical properties of cancellous bone.

Fig.5 Elastic modulus of trabecula specimen on each X, Y, and Z axis obtained from elastic bending test.

Fig.6 Elastic modulus of cancellous bone specimen on each X, Y, and Z axis obtained from compression test.

Fig.7 Orientation direction of HAp Crystal and collagen.

4. Conclusion

In this study, three point bending tests of single trabecula specimens extracted from bovine femur were conducted to evaluate the effects of directions to the femur major axis direction on the mechanical properties. X-ray μ CT was used to obtain shape of trabecular bone specimens. Furthermore compression tests of cancellous bone specimens, which were extracted in 10mm cubic geometry, were conducted for evaluation of directional properties. The investigation yielded the following conclusions.

- 1) There were small difference in the elastic modulus of the trabecular bones which were extracted in parallel and in perpendicular to the major axis of a femur.
- 2) Considering the results obtained from cancellous bone specimens, which were extracted in 10mm cubic geometry, different elastic properties depend on the tested directions.
- 3) Trabecular bone structure has larger influence than bone material property on the mechanical properties of cancellous bone.

References

1. Kanis, J.A., Diagnosis of osteoporosis and assessment of fracture risk , Lancet 359, pp. 1929-1936(2002)
2. Ch. Muschitz, L. Milassin, J. Patsch, P. Deman, K. Brown, T. Pirker, L. Pollhammer, H.barden, L. Weynand, R. Waneck, H. Resch, DXA and QCT Geometric Structural Measurements of Proximal Femoral Strength, Journal of Japanese Society of Bone Morphometry 17(3), 27-34, (2008)
3. Mary L, Bouxsein, *Bone quality, where do we go from here?* Osteoporosis International Volume 14, Supplement 5(2003)
4. Parfitt, A.M., Misconceptions (2): Turnover is always higher in cancellous than in cortical bone, bone 30 (6), pp. 807-809(2002)
5. Morgan, E.F., Keaveny, T.M., *Dependence of yield strain of human trabecular bone on anatomic site*, Journal of Biomechanics 34 (5), pp. 569-577(2001)
6. Ito, M., Nishida, A., Koga, A., Ikeda, S., Shiraishi, A., Uetani, M., Hayashi, K., Nakamura, T., *Contribution of trabecular and cortical components to the mechanical properties of bone and their regulating parameters*, Bone 31 (3), pp. 351-358(2002)
7. K. Choi. J. L. Kuhn, M. J. Ciarelli and S. A. Goldseint,, *The elastic moduli of human subchondral*,” J. B-knus Vol 23. No. 23. pp. 1103-1113(1990)
8. Jungmann, Ralf, Schitter, Georg, Fantner, Georg E., Lauer, Matthias E., Hansma, Paul K. and Thurner, Philipp J., *Real-time microdamage and strain detection during micromechanical testing of single trabeculae*, Experimental and Applied Mechanics: SEM Annual Conference and Exposition, pp.11(2007)
9. S. P. Timoshenko, *Theory of elasticity*, CORONA PUBLISHING CO.,LTD pp. 117-125(1973)
10. N. Sasaki and Y. Sudoh,, X-ray Pole Figure Analysis of Apatite Crystals and Collagen Molecules in Bone, Calcified Tissue International, pp. 361-367(1997)
11. B. Viswanath, R. Raghavan, U. Ramamurty and N. Ravishankar,, *Mechanical properties and anisotropy in hydroxyapatite single crystals*, Scripta Materialia 57 pp.361–364(2007)