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Alteration of Bone Strength in Osteoporosis of Mouse Femora: Computational Study Based on Micro CT Images

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***Abstract*—**The purpose of the study is to develop a finite element model based on 3D bone structural images of Micro-CT and to analyze the stress distribution for the osteoporosis mouse femora. In this study, results of finite element analysis show that the early osteoporosis of mouse model decreased a bone density in trabecular region; however, the bone density in cortical region increased.

***Keywords*—**Micro-CT, finite element analysis, osteoporosis, bone strength.

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I. Introduction

THE musculoskeletal system and the related diseases have been studied and highlighted due to the rapid increases of the expectancy of life span and the expansion of working age. Among the musculoskeletal related diseases, osteoporosis has been the central point of the public interests. Osteoporosis is defined by a decrease in bone mass and density which can cause an increased risk of bone fracture [1], [2]. Especially in the elderly population, osteoporosis is treated as the significant medical problem, because the bone fracture from osteoporosis can lead to a fatal issue for patients. Therefore, the biomechanical understanding of osteoporosis has been extensively investigated [3], [4].

Previous studies of osteoporosis using medical images, such as DEXA scan and Micro-CT, mainly focused on the changes of bone density [5], [6]. However, the bone density analysis based on two-dimensional (2D) images can limit the prediction of the alteration of bone strength, because each bone has inhomogeneous distributions of bone density in a 3D structure. In particular, to precisely understand the bone fracture, it is required to analyze the mechanical behaviors with bone density and bone strength in a 3D structure. Experimental methods to understand structure and mechanical behavior of bone, such as, mechanical compression test have technical limitations to understand internal stress and strain distributions of bone. Therefore, finite element (FE) method has been effectively utilized to better understand a much sophisticated type of bone structure in a spatial manner. For simulating an advanced FE model with accurate bone geometry, a biomedical imaging technique has been developed. The Micro scale tomography imaging technique provides a 3D structure and density distributions of bone. Image reconstruction technique using the Micro-CT image enables a visualization of a 3D architecture of the bone and provides an accurate morphological model for FE analysis.

The purpose of this study is to utilize the finite element analysis based on 3D bone structural images of Micro-CT to understand the spatial degradation of bone strength in the osteoporosis mouse femora.

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II. Method

A. Osteoporosis Mouse Model

A surgical removal of ovaries (Ovariectomy, OVX) in mouse was used for osteoporosis animal model (Osteoporosis, OP, N=3) in this study. For the comparison, non-surgical mouse was included in a separate group (Control, Con, N = 3). At the 4 and 8 weeks after ovariectomy, mice from each group were anesthetized for Micro-CT imaging.

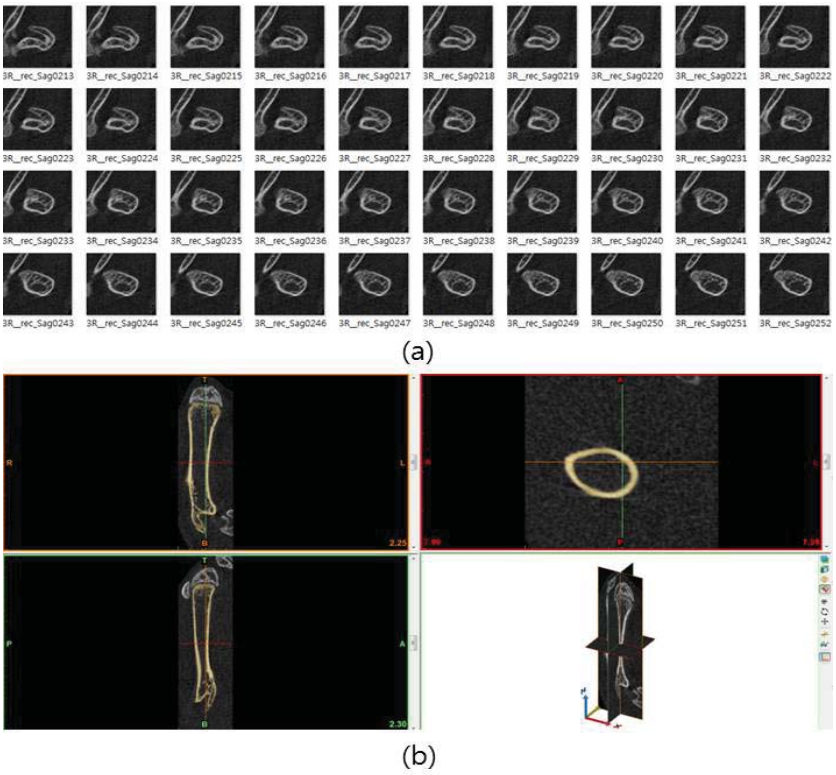


Fig. 1 (a) Examples of Micro-CT images, (b) An example of image segmentation process

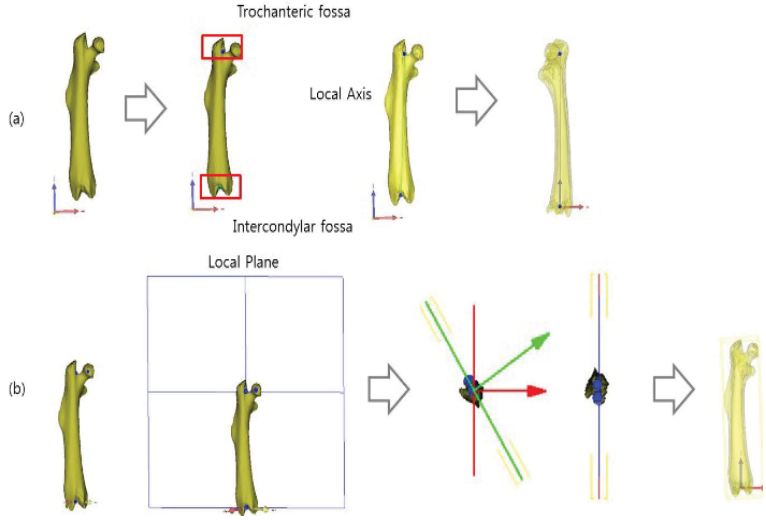


Fig. 2 The schematic illustrations of the re-arrangement of a femur for conducting finite element analysis (a) Aligned the local z-axis was aligned with the global Z-axis, (b) The local x-z plane was aligned with the global X-Z plane

B. Micro-CT Imaging 3D Reconstruction

Femora from each group were scanned by Micro-CT (SKYSCAN 1076, Bruker, Germany) (Fig. 1). Image resolutions were 18*18 μm. Bone densities were estimated based on Micro-CT images for entire femoral and local regions between trabecular and cortical bone.

A 3D femur reconstruction was conducted by using a 3D image process software (Materialise Mimics 16.0) (Fig. 1).

The grey value (GV) of each pixel was linearly converted to the Hounsfield Units (HU). For the simplicity, the average Hounsfield Units was calculated for the 3D reconstructed entire femoral model for the analysis. The average Young's Modulus was finally calculated based on the conversion formula from the previous study [3].

$$\rho = 1.067 \times \mathrm{HU} + 131 \quad (1)$$

$$\mathrm{E} = 0.004 \times \rho^{2.01} \quad (2)$$

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C. Finite Element Analysis

For conducting finite element analysis with the same boundary conditions among samples, each femur was re-arranged in consideration of anatomical features. First of all, the connected straight line of trochanteric fossa and intercondylar fossa was set to a local z-axis and aligned with the global Z-axis (Fig 2 (a)). Secondly, the plane made up of three points of trochanteric fossa, intercondylar fossa and the center of femoral head was defined as local base plane and then matched with the global X-Z plane (Fig. 2 (b)).

Finite element analysis was conducted on the entire femur bone structure using a commercial solver (ANSYS, Version 12). A 10 N of external load was applied to the femoral head for the entire femur model (Fig. 3). Femoral condylar areas were fixed for the simplicity of the boundary conditions.

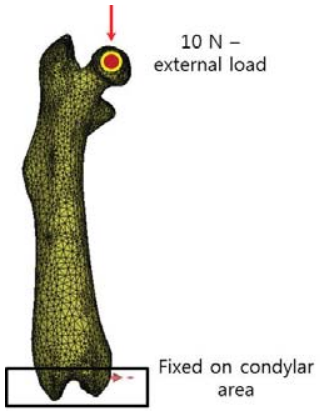


Fig. 3 Boundary conditions for finite element analysis

III. Results

At 4 weeks after ovariectomy in mouse model, there is no large difference on average bone density for the entire femur (Fig. 4). However, the bone density in the trabecular bone decreased and that in the cortical bone increased (Fig. 5). At 8 weeks after ovariectomy in mouse model, average bone densities for the entire femur tend to decrease. Under a 10 N of external load on the femur, osteoporosis group at 8 weeks had more displacement and less stress compared to zero week (Fig. 6 and 7).

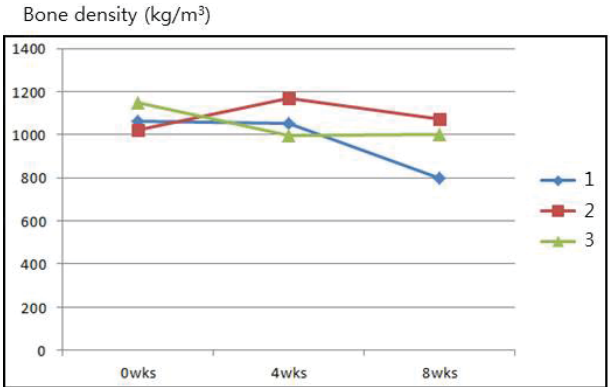


Fig. 4 Bone densities at 4 and 8 weeks after ovariectomy compared to 0 week in each specimen

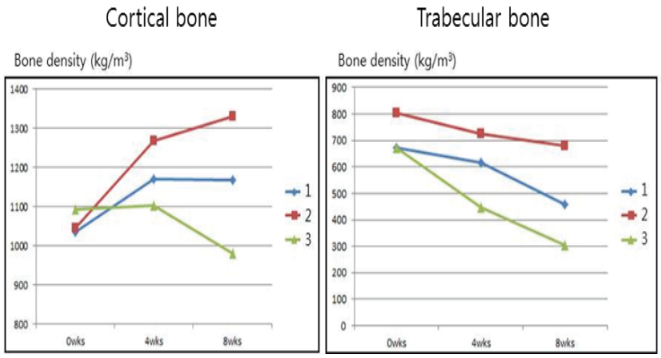


Fig. 5 Bone densities at 4 and 8 weeks after ovariectomy compared to zero week in each specimen for cortical and trabecular bones

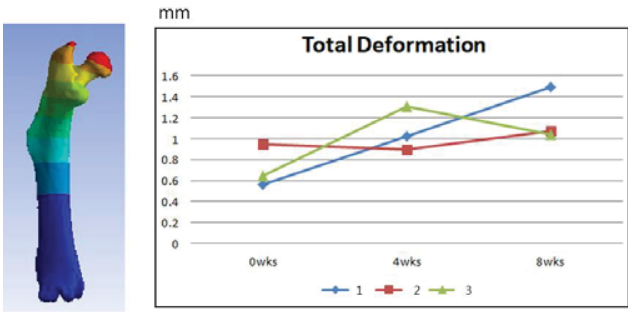


Fig. 6 (a) Result of finite element analysis for axial displacement (b) Displacement at 4 and 8 weeks after ovariectomy compared to zero week in each specimen

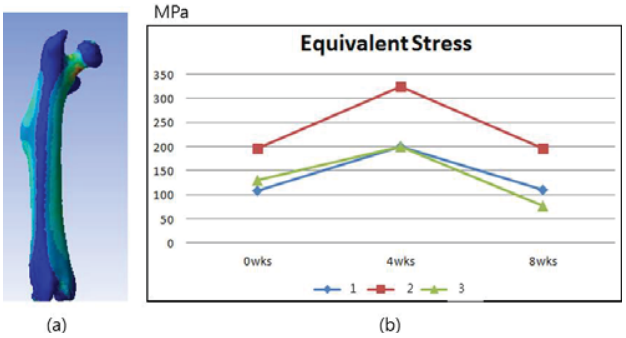


Fig. 7 (a) Result of finite element analysis for equivalent stress (b) Equivalent stress at 4 and 8 weeks after ovariectomy compared to 0 week in each specimen

IV. Conclusion

This study demonstrated that ovariectomy in mouse was used for an osteoporosis animal model, and a 3D reconstruction of bone structure was made by using Micro-CT images as done previously. 3D Micro-CT images provided high resolution of bone density distributions which are highly inhomogeneous. FE analysis estimated that the local alterations of bone strength in osteoporosis.

Based on the results, the early osteoporosis of mouse model decreased a bone density in trabecular region but increased them in cortical region. Therefore, we anticipated that osteoporosis model using mouse should consider its bone

degradation behavior at measuring time point. Early osteoporosis in mouse model may have compensation effect on cortical bone, while trabecular bone loses its bone density. As a next step, we will plan to investigate the bone density conditions using a mouse femur at 8~12 weeks after ovariectomy as a moderate osteoporosis model.

Although bone density is highly inhomogeneous, an average bone density was used in this study for the simplicity of numerical calculations. In additions, the effect of trabecular structure on the bone strength, such as the porosity of trabecular bone, was not modelled in this study. The homogeneous bone model used in this study can limit the results. Further study will aim to implement inhomogeneity of bone density to represent the intrinsic behavior of material properties and structure of bone.

Osteoporosis is considered as a high risk health problem especially for the elderly population [7]. Bone fracture caused by osteoporosis may not be solely related by bone mass loss, but more related to the bone strength possibly depending on both bone density and bone structure. In order to simulate bone fracture analysis, further study will be aimed to simulate bone fracture problem and more realistic boundary and loading conditions, such as, facture analysis and dynamic load. Furthermore, since the osteoporosis and the related bone health have been investigated extensively, a variety of medical treatments of osteoporosis have been introduced [8]-[10]. For monitoring the effects of these medical treatments on osteoporosis, the most of common methods is to exam 2D bone density images. As we introduced this study, 3D FE model based on high resolution of bone images could provide a relevant prediction of bone strength measurement. Therefore, we plan to utilize a FE method for quantifying the improvement of bone strength after medical treatment of osteoporosis including local regions between trabecular and cortical bones where the effect of osteoporosis treatment mostly occurs in the future studies.

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