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Changes in the Microstructural and Mechanical Properties in the Medial Condyle of Human Distal Femur in Advanced Osteoarthritis

Kwang-Kyoun Kim[1], Myong-Hyun Baek[2], Ye-Yeon Won[3]

[1]Department of Orthopaedic Surgery, Konyang University Hospital, Daejeon,
[2]Dedical Devices Clinical Trial Center, Ajou University Hospital, Suwon,
[3]Department of Orthopaedic Surgery, Ajou University Hospital, Suwon, Korea

Objectives: The purpose of this study is to analyze and compare the micro-structural and mechanical properties of subchondral trabecular bone of non-osteoarthritic and osteoarthritic distal femur using micro-images based on finite element analysis.
Materials and Methods: Twenty distal femurs were harvested from 10 cadavers. The subchondral trabeculae were obtained from the middle of the articular surface of the medial femoral condyle of distal femurs. A total of 20 specimens were scanned using the micro-CT system. Micro-CT images were converted to micro-finite element model using the mesh technique, and micro-finite element analysis was then performed for assessment of the mechanical properties.
Results: According to the results, trabecular bone of osteoarthritic distal femur showed a decrease in trabecular thickness, bone volume fraction, structure model index, and yield stress and an increase in trabecular separation and structure model index.
Conclusions: Results of bone morphometry index and strength showed greater deterioration of microstructure and decreased mechanical strength in subchondral trabeculae of the osteoarthritic group.

Key Words: Trabecular bone, osteoarthritis, FE-model, Micro-CT

Osteoarthritis is the result of mechanical and biological events that destabilize the normal processes of degradation and synthesis of articular cartilage chondrocytes, extracellular matrix, and subchondral bone. Subchondral bone changes in bone turnover, mineralization, and volume result in altered apparent and material density of bone that may adversely affect the joint's biomechanical environment. Distal femur is the most common site of the osteoarthritis in human body. Recently, the knee joint replacement for osteoarthritis is propagated more universally, and implants of various designs and material properties for joint replacement being developed. Although there are numerous studies for gross anatomy and cartilage for operation, the study for micro-structural and mechanical properties of distal femur are rare. The purpose of this study is to analysis and compare the micro-structural and mechanical properties of subchondral trabecular bone of osteoarthritic distal femur using a micro-images based on finite element analysis. We began to study after institutional review board (IRB) approval.

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Corresponding Author: Myong-Hyun Baek, Medical Devices Clinical Trial Center, Ajou University Hospital, San 5, Wonchon-dong, Yeongtong-gu, Suwon 443-721, Korea
Tel: +82-42-600-6902, Fax: +82-42-545-2373
E-mail: ajouos@hanmail.net

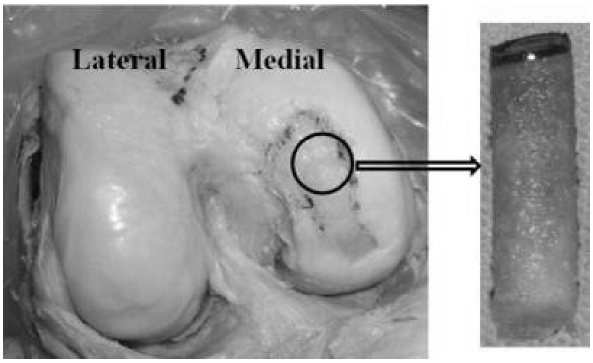

Fig. 1. Cylindrical specimen from the medial femoral condyle of distal femur.

METERIALS AND METHODS

1. Specimen preparation

Distal femur were obtained from ten donors, seven women and two men with a mean age of 65 years (53 to 79), with OA. As controls, we removed normal distal femur from ten age and gender matched donors, seven women and three men with a mean age of 67 years (58 to 81). The area of interest was the central weight-bearing portion of the medial condyle of the femur. Specimens were classified with OA group and Non OA group. Visible inspection showed the typical features of advanced osteoarthritis. These feature included erosion of cartilage down to exposed subchondral bone, osteophytes. Normal femur had no macroscopical pathology or history of musculoskeletal disease, and they had intact cartilage surface. The subchondral trabeculae were obtained using a trephine with an inner diameter 10 mm (Fig. 1). The cancellous bones were further cut 2.5 mm below the subchondral bone plate to avoid cortical plate and diameter of 7 mm and length of 7.5 mm.

2. Micro-CT imaging

Total 20 specimens were scanned using micro-CT (SkyScan-1172, SKYSCAN, Belgium) at 24.9 ㎛ of spatial resolution under 70㎸'s voltage and current of 141㎂. For each bone core, total of 1,024 consecutive microtomographic slices were acquired. 2-D images with $1,024^{\times 1.024}$ pixels were established by an imaging software as shown in Fig. 2. Bone tissues were segmented from the bone marrow at thresholds ranged from 0.552 to 0.17. By employing the micro-CT scanner's built-in software, the two dimensional structural parameters, including the trabecular number (Tb.N), the trabecular thickness (Tb.Th) and the trabecular seperation (Tb.Sp), and the three dimensional structural parameters including the bone volume fraction (BV/TV), the structure model index (SMI), and degree of anisotropy within the three VOIs were calculated by the ANT software (ANT, SKYSCAN, Belgium).[1]

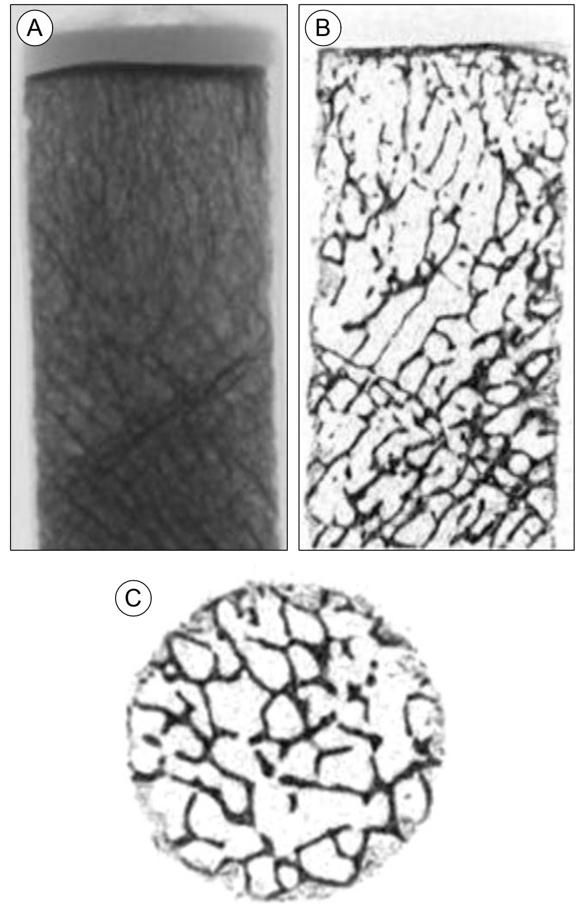

Fig. 2. Micro-images taken from a micro-CT (A) x-ray transmission image (B) sagittal image (C) cross section image.

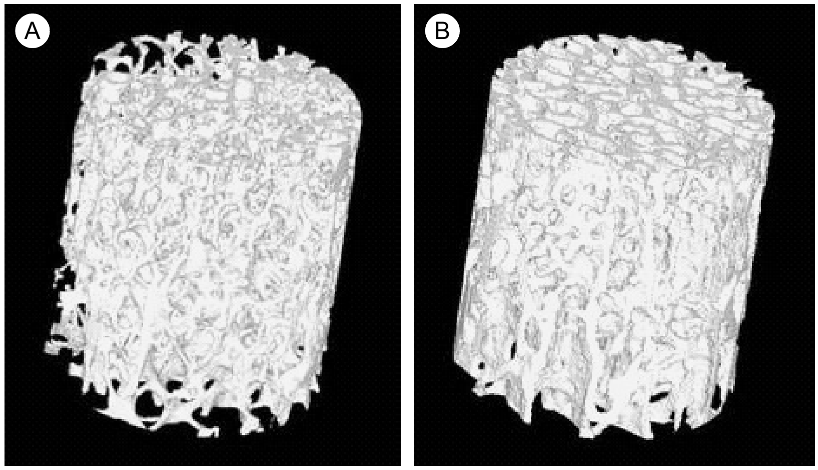

Fig. 3. 3D micro-CT reconstruction images (A) Osteoarthritis group (B) Non-osteoarthritis group.

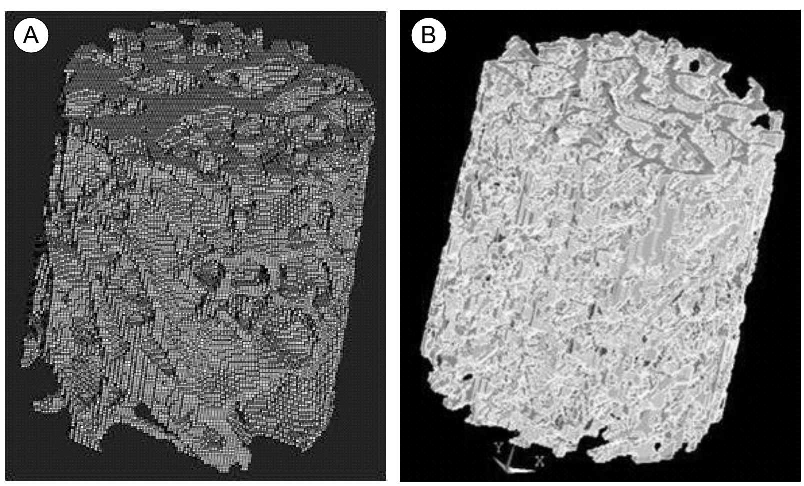

Fig. 4. FE-Analysis of trabecular bone (A) 8 node hexa-hedron mesh model (B) Distribution of stress.

3. Reconstruction of Finite element model

The segmented reconstructions of the VOI were converted to micro-FE models by converting the voxels that represented the equally shaped bony tissue 8-node brick elements with using a mass-compensated, hexahedron-meshing technique (Fig. 3). The tissue element properties were chosen to be liner, elastic and isotropic with a Young's modulus of 10 Gpa and a Poisson's ratio of 0.3 for the all models. Finite element analysis was done using ANSYS 6.1 (ANSYS. Inc) software. Boundary condition is applied at a strain (E) of 1%, in which at the bottom face the displacements in the vertical direction were constrained, but all other faces of the cube were unconstrained (Fig. 4). Mechanical parameters, reaction force (R_f) and Yield stress (MPa) were calculated with ANSYS 10.0 (ANSYS, Inc).

4. Statiscal analysis

We used SPSS version 17.0 (SPSS, Chicago, USA). Due to the limited number of samples in each group and the consequent wide variance, data was analyzed using non-parametric method. For comparison between the groups, the Mann-Whitney U test was used. For all statistical analyses, exact p values were given and a *P* value <0.05 was considered to be significant.

Table 1. Histomorphometry and mechanical property indexes of trabecular bone with osteoarthritis and non-osteoarthritis

	Tb.Tn (mm)	Tb.Sp (mm)	BV/TV (%)	DOA	SMI	TB.N (mm)	R_f (N)	Yield Stress (MPa)
Non-Osteoarthritis	0.263 (±0.041)	0.578 (±0.139)	30.372 (±7.018)	0.432 (±0.091)	0.666 (±0.382)	1.347 (±0.220)	344.292 (±125.849)	9.068 (±2.314)
Osteoarthritis	0.242 (±0.021)	0.653 (±0.105)	22.898 (±4.802)	0.415 (±0.098)	0.867 (±0.304)	1.076 (±0.228)	186.657 (±78.479)	4.916 (±1.594)
P-value	0.124	0.024	0.174	0.131	0.004	0.022	0.0004	0.0006

RESULTS

Although no significant difference was found in Tb.Th, DOA, There was a significant difference in BV/TV, Tb.N and Tb.Sp, DOA, SMI, Rf, Yield stress between the two groups as shown in Table 1. Trabecular thickness was lower in the OA groups than in the normal groups, but this result was statistically meaningless (P=0.124). Medial OA specimen had a decrease of 7% in the trabecular thickness compared with that of the normal medial. Trabecular number was lower in the OA groups than in the normal groups (P=0.022). Medial OA specimen had a decrease of 20% in trabecular number compared with that of the normal medial. Trabecular spacing was greater in the OA groups than in the normal groups (P=0.024). Medial OA specimen had an increase of 12% in trabecular spacing compared with that of the normal medial. Bone volume fraction was lower in the OA groups than in the normal groups, but this result was statistically meaningless (P=0.174). Medial OA specimen had a decrease of 22% in compared with that bone volume fraction of the normal medial. Structure model index was increase in the OA groups than in the normal groups (P=0.004). Medial OA specimen had a increase of 30% in the structure model index compared with that of the normal medial. Degree of anisotropy was lower in the OA groups than in the normal groups, but this result was statistically meaningless (P=0.131). Medial OA specimen had a decrease of 3% in compared with degree of anisotropy that of the normal medial. Yield stress was lower in the OA groups than in the normal groups (P=0.0006). Medial OA specimen had a decrease of 45% in Yield stress compared with that of the normal medial. Reaction force was lower in the OA groups than in the normal groups (P=0.0004). Medial OA specimen had a decrease of 42% in Yield stress compared with that of the normal medial.

DISCUSSION

Subchondral bone alterations, such as bone marrow lesions and subchondral bone attrition, tend to occur more frequently in the more loaded knee compartments, and are associated with cartilage loss in the same region. Understanding the pathophysiologic sequences and consequences of OA pathology will guide rational therapeutic targeting. In our study, trabecular space, bone volume fraction, and trabecular number showed a meaningful change in the OA group. Therefore, we think that these changes influence the mechanical properties, such as the reaction force and yield stress, which affect clinical symptoms.

A volume-weighted measure of trabecular thickness has been shown to differ for the skeletal site and to decrease with aging. Ding et al[2] reported an increase of tibial trabecula thickness in early arthritis, and Boyd et al[3], in a study of distal femur structural in early oateo-arthritis, reported increasing trabecular thickness. The increase trabecular thickness indicates a process of filling trabecular remodeling cavities. This mechanism is followed by a progressive change of trabeculae from rods to plates in cancellous bone in early OA.[4] This mechanism is opposite of the normal process of ageing in trabeculae which is normally a change from plates to rods.[5] For the change of microstructure in the advanced OA, Brown et al[6] reported microstructure of advanced OA in the femoral head. But, there was not result for thrabecular thickness. No study of change in distal femur trabecular thickness in advanced osteoarthritis has been reported. In our study, trabecular thickness tended to decrease, however, this result was statistically meaningless. We thought that these different results may be due to the fact that trabecula in early OA may undergo thickening as early compensation for the decrease in mechanical strength.[7,8] However, in advanced OA, as in our study, the trabeculae directivity showed axial rearrangement against the change of mechanical stress. In the process of trabecular rearrangement, trabecular absorption occurs, resulting in a decrease of trabecular thickness, and an increase of trabecular separation, DOA, and SMI. Structure model index with degree of anisotropy best predicts the mechanical properties of normal cancellous bone.[9-11] In certain circumference, trabecular plates are perforated and connecting rods are dissolved. Development of low- density rod-like structures in regions of low stress has been demonstrated, whereas high-density plate-like structures are observed in regions of high stress.[12,13] In this study, SMI showed a statistically meaningful increase. This result differs from that reported by Ding in early OA, because, in early OA, SMI showed a decrease, causing an increase of plate-like structure as a remodeling for filling the diminution of mechanical structure of early subchondral trabecular, however, arthritis progresses, adaptation by trabecula shape reaches the limit, and then recovery of bone strength appears to occur by mineralization at the level of bone tissue.[14-16]

In our study, Yield stress and Reaction force also showed a significant decrease. Therefore, the increased amount of defective bone tissue, which may also accompany accumulation of microdamage, in both early OA and late OA could not entirely compensate for the decrease in mechanical properties.[17] The primary mechanism responsible for loss of cancellous bone strength in advanced stage experimental OA was a change in the cancellous tissue modulus rather than a change in the architecture.[18]

In our study, we used micro CT and finite element analysis for evaluation of microstructure and mechanical properties. Recently, micro-computed tomography has made it possible to obtain two-dimensional data on trabecular microstructure without destruction of bone samples. The mechanical properties, as assessed by finite element analysis, the reaction force (R_f), and Young's modulus (€), showed a significant decrease in the osteoarthritic group, compared with the non-osteoarthritic group. This result demonstrated that finite element analysis can capture other changes in trabecular microstructure to reflect the mechanical properties. Therefore, in the present study, use of the micro-FEA to calculate elastic constant rather than compression test was essential.

There are some limitations of the study that should be discussed. First, objects of research are primary OA. It has a limit in application of the result to secondary OA (eg, post-traumatic OA) by reason of the different pathogenesis of osteoarthritis. Second, in general, due to the small group size, the statistical tests used in this study should be regarded cautiously; nevertheless, statistically significant change was detected.

CONCLUSION

According to results of bone morphometry index and mechanical properties, subchondral trabeculae of the advanced osteoarthritic group showed a more degenerative structure and decreased mechanical strength, compared with the non-osteoarthritis group. In comparison of early OA, as osteoarthritis progresses, adaptation from tissue level would show more growth as compensation for change of mechanical property.

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