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A Biomechanical Study of Osteoporotic Vertebral Trabecular Bone: The Use of Micro-CT and High-Resolution Finite Element Analysis

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Abstract

Osteoporosis is one of the most dangerous skeletal diseases in relation to the highest fracture risk in vertebral bones. A considerable amount of work has been done to investigate the biomechanical characteristics of osteoporotic vertebral trabecular bone. Previous researchers studied the elastic characteristics using a micro-finite element (micro-FE) model, used to analyze realistic trabecular architectures in full detail, based on micro-computed tomography (μCT). Since osteoporotic compression fracture is closely associated with the mechanical characteristics of the vertebral trabecular bone and there were few micro-FE models to account for all of the elastic and plastic characteristics in vertebral trabecular bone, this study analyzed the effect of voxel resolution on the plastic characteristics as well as the elastic characteristics of three-dimensional (3D) osteoporotic lumbar trabecular bone models. Also, we evaluated the effect of specimen geometry on this problem. It has been reported that a cubic specimen with side length 6.5mm was suggested as standard specimens for the experimental test of trabecular bone. Current study examined whether or not the effect of the specimen geometry on the experimental test may be also applied to the simulated compression test of trabecular bone specimens. The experimental test employing the rapid prototyping (RP) technique and INSTRON test machine is performed to indirectly validate the results of the simulated compression test by micro-FE analysis. The review finished with the verification about the effects of the simulated compression test.

Keywords: Finite element model; Vertebral trabecular bone; Osteoporosis; Micro-CT; Mechanical characteristics

1. Introduction

Osteoporosis is defined as a systemic skeletal disease characterized by low bone mass and micro-structural deterioration of bone (Frost, 1997; Marcus, 1996). Wasnich *et al.* (1999) has shown that human bone mass increases during growth, and after about 30 years it begins to decrease. It is also reported that about 30% of caucasian women after menopause present evidence of osteoporotic vertebral fractures (Melton, 1995). Osteoporotic vertebral fractures are a major health care problem world wide.

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At present, several methods are reported to investigate physical characteristics of osteoporotic vertebrae (Lis, 1989; Kabel, 1999; Keaveny, 1999). Keaveny *et al.* (1999) studied the mechanical characteristics of human trabecular bone after over-loading. They quantified the reductions in modulus and strength and the development of residual deformations and determined the dependence of these parameters on the applied strain and apparent density. Many researchers have investigated the elastic characteristic of trabecular bones using the micro-finite element (micro-FE) models based on micro-computed tomography (μCT) and experimental tests. With these FE model techniques, the detailed three-dimensional (3D) architecture of bone samples can be digitized and converted to large-scale FE models from which bone tissue stresses can be calculated. Ulrich *et al.* (1998) analyzed the elastic characteristics of 4mm cubic specimens of trabecular bones using 3D micro-FE models, in which the pixels of μCT images were changed to hexahedral finite elements (voxels).

Frank *et al.* (1992; 1994) and Dong *et al.* (2004) also tested the effect of specimen geometry on the mechanical characteristics of trabecular bone specimens. Frank *et al.* (1992; 1994) suggested a cubic specimen with side length of 6.5mm as a standard specimen for the experimental tests of trabecular bones. Dong *et al.* (2004) reported short trabecular bone cylinders (7 mm diameter and 5 mm length) should be used in the mechanical analysis of trabecular bones.

It is believed that vertebral fractures are closely associated with the plastic characteristics of trabecular bones. However, previous FE models for trabecular bones did not take account of the effects of specimen geometry and the voxel resolution on the plastic characteristics of trabecular bones. In this study, micro-FE analyses were carried out to analyze the plastic characteristics as well as the elastic characteristics of vertebral trabecular bones and to evaluate the effect of the specimen geometry on the plastic characteristics of trabecular bones. In addition, in order to elucidate the voxel resolution required to produce accurate results of the plastic characteristics of vertebral trabecular bones, we investigated the effect of the voxel resolution on the plastic characteristics of osteoporotic trabecular bone models in a simulated compression test.

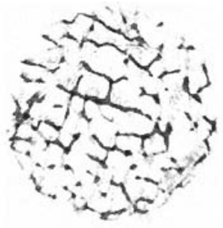
Finally, to validate the results of micro-FE analysis, several rapid prototype models were manufactured using computer-aided design (CAD) systems and rapid prototyping (FDM TITAN, Stratasys U.S.A) techniques (Iwan, 2002; Denis, 2001; Hutmacher, 2001; Yang, 2002; Werner, 2000), also known as solid free-form fabrication (SFF) technology, and were tested using the INSTRON machine (8874 series, Instron, USA) (Frank, 1992; Jensen, 1990; Olov, 1976; Keaveny, 1994).

2. Methods

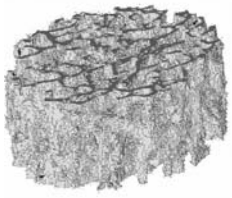
2.1 Acquisition of bone specimens

The second lumbar vertebral bodies (L2) were taken from two cadavers (females, age 85) to generate the micro-FE and rapid prototype (RP) models. Trabecular cylinders of 11 mm diameter were obtained by drilling the central part of L2, as shown in Fig. 1. Three types of specimens (two cubic specimens: side lengths of 4 mm and 6.5 mm; one cylindrical specimen: 7 mm diameter and 5 mm length) were generated from the cylinders. All the specimens were scanned through the μCT system (Skyscan-1076, Skyscan, Belguim).

Fig. 1. Bone cylinders from vertebral bone.



(a) 2D image (Micro-CT)

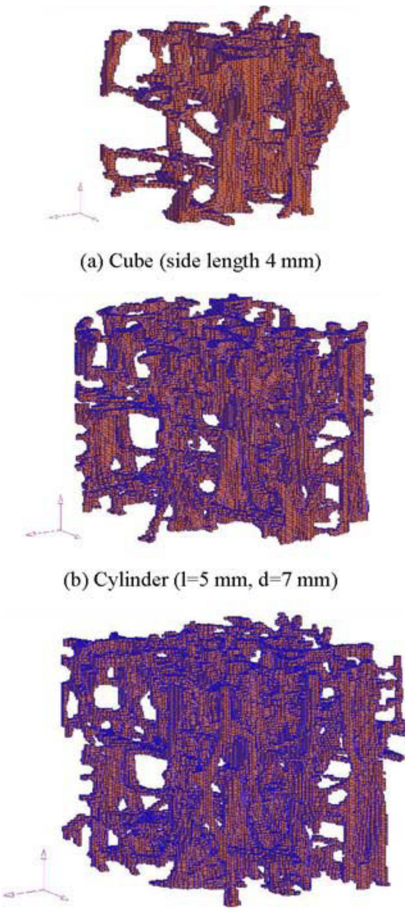


(b) 3D image (voxel)

Fig. 2. Images captured from a typical vertebral trabecular bone specimen.

2.2 Simulated compression test for trabecular bone models

The scanned images were transferred to the BIONIX system (CANTiBio Co., Korea) and converted to 3D voxel images (Fig. 2).



(a) Cube (side length 4 mm)

(b) Cylinder (l=5 mm, d=7 mm)

(c) Cube (side length 6.5 mm)

Fig. 3. 3D FE models of vertebral trabecular specimens created at a 63 μm voxel resolution using hexahedral meshing.

To compare the results of the present study with those of the elastic characteristics reported by Ulrich *et al.* (1998), a trabecular bone cubic specimen with the same side length of 4mm as used by them was generated and analyzed. Two additional specimens were also generated, a cylindrical specimen (with 7 mm diameter and 5 mm length) similar to the ones used by Mosekilde and coworkers (Jensen, 1990; Mosekilde, 1987; Dong, 2004) and a cubic specimen of the same size (side length of 6.5 mm) that was suggested by Frank *et al.* (1992; 1994), to investigate the effect of the specimen geometry and voxel resolution on the plastic characteristics of micro-FE models (Fig. 3) (Kim, 2003).

In the present study, we examined whether the effect of the specimen geometry on the mechanical characteristics in the simulated compression test is similar to that in the experimental test.

Table 1. Microstructural parameters for osteoporotic vertebral trabecular bones.

Tb.Th (mm)	Tb.Sp (mm)	Volume (mm^3)	Surface (mm^2)	Surface/ Volume (mm^{-1})	BV/TV (%)	DOA	SMI	Tb.N
(Cube : 188 voxels, side length 4mm)								
0.194	0.789	6.939	107.616	15.508	10.662	0.112	2.315	1.017
(Cube : 290 voxels, side length 6.5mm)								
0.168	0.860	23.275	397.477	17.077	9.647	0.131	2.227	0.973

BV/TV (%) of a cylindrical specimen with 7 mm diameter and 5 mm length is similar to that of a cubic specimen with side length of 6.5 mm.

Ulrich *et al.* (1998) stated that 'mass-compensated hexahedral meshing techniques' can reduce the loss of connections and produce better results than the plain hexahedral meshing techniques. In their mass-compensated hexahedral meshing techniques, the threshold is selected such that the best possible agreement between the relative bone volume (BV/TV) in the FE-model and that of every voxel image is obtained (Table 1).

The relative BV/TV of osteoporotic vertebral trabecular bones was obtained from morphological characteristics measured by μCT. The tissue volume (TV, mm^3) and the trabecular bone volume (BV, mm^3) were measured by the direct method available on μCT. Trabecular thickness (Tb.Th, mm), trabecular separation (Tb.Sp, mm) and trabecular number (Tb.N) were measured directly on 3D image data. The plate-rod characteristic of the bone structure can be measured by using the structure model index (SMI). For an ideal plate, the SMI value is zero and three for rod structure. The degree of anisotropy (DOA) is a relative measure of orientation within the trabecular bones. Values for the DOA vary from 0 to 1. The higher the DOA, the more the bone is aligned in the principal direction (on-axis direction) relative to other directions.

Several FE-models were generated from the gray-scale images. Six micro-FE models (21 μm, 42 μm, 63 μm, 84 μm, 105 μm, and 126 μm resolution) with the same BV/TV were constructed with hexahedral elements to examine the effect of μCT image resolution on the plastic characteristics of micro-FE models (Table 2).

In the present study, as Ulrich *et al.* (1998) suggested, the models of 42μm voxel resolution consisted

Table 2. Mass-compensated voxel bone models using BV/TV (Cube (l = 4 mm): 10.7%, Cylinder (Φ = 7 mm, l = 5 mm) and Cube (l = 6.5 mm): 9.7%).

		Voxel size					
		21 µm	42 µm	63 µm	84 µm	105 µm	126 µm
Cube (l = 4 mm)	*BV/TV(%)	10.6%	10.7%	10.7%	10.6%	10.6%	10.6%
	Number of Elements	734013	92048	27451	11479	5869	3397
Cylinder (l = 5 mm, Φ = 7 mm)	BV/TV(%)	9.7%	9.6%	9.7%	9.6%	9.6%	9.7%
	Number of Elements	2021163	250357	74252	31298	16031	9331
Cube (l = 6.5 mm)	BV/TV(%)	9.6%	9.7%	9.7%	9.7%	9.6%	9.7%
	Number of Elements	2457568	307713	91214	38410	19489	11386

*BV/TV (%) indicates the relative bone volume after removal of unconnected parts. Each of BV/TV (%) was the best possible agreement with those of reference models (Table 1).

Table 3. Material properties of vertebral trabecular bone and acrylonitrile–butadiene–styrene (ABS) (Ulrich, 1998, Gibson, 1988).

Property	Value: trabecular bone	Value: ABS
Young's modulus (E)	10 GPa	3 GPa
Compressive strength (σ)	136 MPa	65 MPa
Poisson's ratio (υ)	0.3	0.3

of 2×2×2 voxels with 21 μm voxel resolution, and the models of 63 μm, 84 μm, 105 μm, and 126 μm voxel resolutions were composed of 3×3×3, 4×4×4, 5×5×5, and 6×6×6 voxels, respectively. For all models, the same material properties as those reported in Ulrich *et al.* (1998) were utilized to compare the present results with those for the elastic characteristics of their cubic specimens (side length 4 mm). The trabecular material in this FE analysis was assumed to be isotropic and elastic-perfectly plastic. Table 3 shows Young's modulus, compressive strength and Poisson's ratio used in the present study (Ulrich, 1998; Gibson, 1988).

Displacement boundary conditions were applied to the specimens to simulate a uniaxial compression test. For the elastic characteristics of micro-FE analysis, the effective modulus was measured by applying a compressive displacement (strain: 0.5%) to specimens. For the plastic characteristics, reaction force and strength of specimens were evaluated by imposing compressive displacement. In the present study, to obtain reliable results, two-commercial FE softwares

(a) Cubic specimens with side length of 4 mm

(b) Cylindrical specimens with diameter 7 mm and length 5 mm

(c) Cubic specimens with side length of 6.5 mm

Fig. 4. 3D ABS plastic models fabricated by using RP machine.

Fig. 5. Experimental compression test with INSTRON test machine.

(ANSYS 10.0; ANSYS, Inc., Abaqus 6.4; HKS, Inc) were utilized to analyze the elastic and plastic characteristics of the trabecular bone specimens.

2.3 Experimental compression test for the rapid prototype models

Acrylonitrile–butadiene–styrene (ABS) copolymerization plastic has been a popular material in rapid prototyping and manufacturing (RP&M) processes (Weihong, 2001; Klasterman, 1997; Calvert, 1994). We utilized ABS plastic to produce human vertebral trabecular bone specimens for experimental testing (Weihong, 2001). In order to perform the experimental compression test, three types of specimens (two cubic specimens; l = 4 mm and 6.5 mm; one cylindrical specimen; Φ = 7 mm, l = 5 mm) were reconstructed by fused deposition modeling (FDM) as shown in Fig. 4 (Iwan, 2002).

Material properties of ABS plastic specimens were obtained by tensile and compression tests with an INSTRON test machine (Table 3). Actual trabecular bone specimens were too small to fabricate prototype models of actual size. Therefore, in this study, trabecular bone-shaped specimens were scaled up to 20 times to fabricate the RP models. 3D FE models were also scaled up to the same size (20 times) as RP models. 3D trabecular bone models fabricated by RP technology were compressed on an INSTRON test machine (Fig. 5).

The simulated compression test was also performed for micro-FE models with the material properties of ABS.

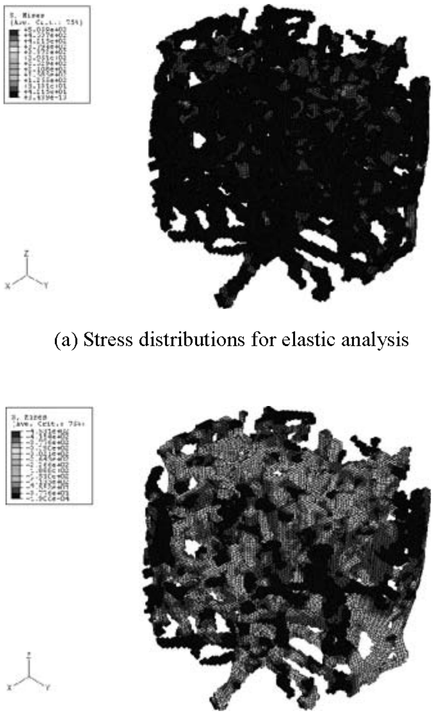
2.4 Comparison of experimental compression test and simulated compression test

The results on both the experimental and the simulated compression tests with ABS material property were compared with those of the simulated compression test with trabecular property. In the present study, the experimental test using the rapid prototyping technique and INSTRON test machine was performed to indirectly validate the results of the simulated compression test using micro-FE analysis.

3. Results

Vertebral trabecular bone models with six resolutions (21 μm, 42 μm, 63 μm, 84 μm, 105 μm, 126 μm) were generated and analyzed by the FEM. The relative effects of the μCT image resolution on the plastic characteristics as well as the elastic characteristics of the micro-FE models were evaluated. Figure 6 illustrates the typical stress distributions in the cylindrical specimens with 7 mm diameter and 5 mm length among various specimens for the elastic and plastic analyses.

Displacements and reaction forces for the simulated compression tests are given in Tables 4~6. The elastic characteristics were analyzed for a 0.5% uniaxial strain (0.02 mm displacement for the cubic specimen with side length of 4 mm) and the results are given in



(a) Stress distributions for elastic analysis

(b) Stress distributions for plastic analysis

Fig. 6. Stress distribution in 3D models at 84 μm resolution (cylindrical specimen with 7 mm diameter and 5 mm length)

Table 4. Mechanical characteristics of cubic specimens with side length of 4 mm.

	Mechanical characteristics			
	Elastic characteristics		Plastic characteristics	
Voxel size	Reaction Force (N)	Displaceme nt (mm)	Reaction Force (N)	Displacement (mm)
21 μm	37	0.02	78	0.07
42 μm	37	0.02	77	0.07
63 μm	38	0.02	81	0.07
84 μm	36	0.02	74	0.07
105 μm	38	0.02	77	0.07
126 μm	36	0.02	67	0.06

Table 5. Mechanical characteristics of cylinders with 7 mm diameter and 5 mm length.

	Mechanical characteristics			
	Elastic characteristics		Plastic characteristics	
Voxel size	Reaction Force (N)	Displaceme nt (mm)	Reaction Force (N)	Displaceme nt (mm)
42 μm	69	0.025	157	0.096
63 μm	67	0.025	152	0.096
84 μm	66	0.025	146	0.090
105 μm	59	0.025	122	0.082
126 μm	56	0.025	107	0.089

Table 6. Mechanical characteristics of cubic specimens with side length of 6.5 mm.

	Mechanical characteristics			
	Elastic characteristics		Plastic characteristics	
Voxel size	Reaction Force (N)	Displacement (mm)	Reaction Force (N)	Displacement (mm)
42㎛	66	0.0325	140	0.1000
63㎛	66	0.0325	139	0.0980
84㎛	62	0.0325	127	0.1010
105㎛	58	0.0325	114	0.0976
126㎛	56	0.0325	105	0.0931

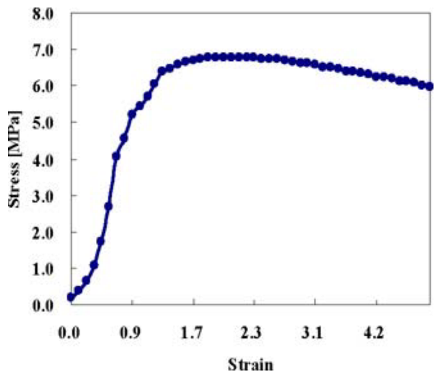


Fig. 7. Compressive stress-strain curve for a typical 3D microstructural model of vertebral trabecular bone.

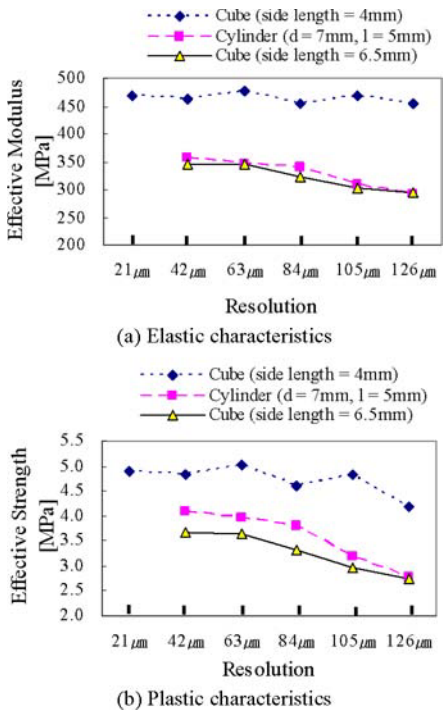


Fig. 8. Effective modulus and strength for several resolutions in uniaxial compression test

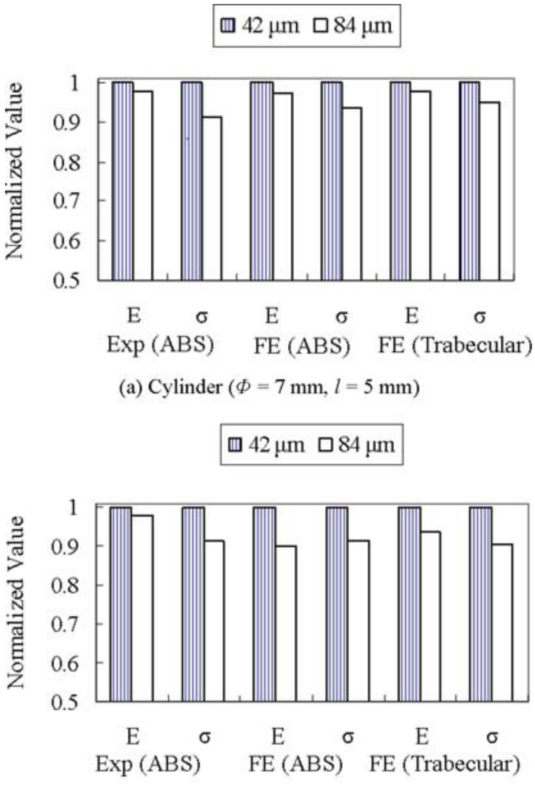
Tables 4~6. The displacements and reaction forces for the plastic characteristics were obtained from the values of the maximum stress in stress-strain curves during nonlinear simulations (Fig. 7).

In these simulated compression tests, the results of ABAQUS 6.4 were consistent with those of ANSYS 10.0. For the cubic specimen with side length of 4 mm, as shown in Fig. 8, there was no major difference between the results for 21 ㎛-voxel revolution and those for 42 ㎛-voxel revolution. This result was also confirmed in the experimental test using the INSTRON test machine. Therefore, for other specimens, only five models (42 ㎛, 63 ㎛, 84 ㎛, 105 ㎛, 126 ㎛) were generated and analyzed. In Tables 4~6, as the image resolution improves, the reaction force has a tendency to increase for elastic and plastic cases. Tables 4, 5 and 6 give the results for the mechanical characteristics of two cubic (side length 4 mm, 6.5 mm) and a cylindrical (7 mm diameter and 5 mm length) specimens, respectively.

The values for the modulus (elastic characteristics) and strength (plastic characteristics) in Fig. 8 were calculated from the data in Tables 4~6. Figure 8 illustrates the elastic and plastic characteristics of osteoporotic vertebral trabecular bone models. The result showed that the 'mass-compensated voxel meshing techniques' suggested by Ulrich *et al.* (1998) were effective up to 105 ㎛ resolution for the cubic specimen with side length of 4 mm but up to only 84 ㎛ resolution for both a cylindrical specimen (diameter= 7 mm, length=5 mm) and a cubic specimen with side length of 6.5 mm.

In the effective modulus and strength of mechanical characteristics considering the effect of specimen geometry, when the values of cylindrical specimen (diameter=7 mm, length=5 mm) were compared with those of the cubic specimen (side length 6.5 mm) on each resolution, we found that the results on both the specimens were similar. It was also shown that the effective modulus and strength of the cubic specimen (side length 6.5 mm) and cylindrical specimen (diameter=7 mm, length=5 mm) were in contrast to those of the cubic specimen (side length 4 mm). The values of the cubic specimen (side length 6.5 mm) and the cylindrical specimen (diameter=7 mm, length=5 mm) were less than those of the cubic specimen (side length 4 mm).

In the experimental test, novel 3D ABS plastic models were fabricated by FDM with RP technology and were compressed by using the INSTRON test



(b) Cube (side length 6.5 mm)

Fig. 9. Results for the compression test with material properties of ABS plastic and vertebral trabecular bones through the use of experimental RP models and simulated FE models (E: Effective modulus, σ: Strength).

machine. The effective modulus and strength of experimental RP models were in good agreement with the results of the micro-FE element models with material properties of ABS plastic and vertebral trabecular bones (Fig. 9). Results are presented as relative values, normalized by the values for the 42 μm voxel resolution bone models. There was no serious difference in the results between 42 μm and 84 μm-voxel revolution (Fig. 9). In both the experimental & the simulated compression tests with ABS material property and the simulated compression test with trabecular property, the errors of less than 7 percent were investigated. The results of the experimental compression test support the results of the simulated compression test.

4. Discussion

The current study is the first attempt to take account of the effects of voxel resolutions and the specimen geometry in micro-FE analysis, studying the plastic characteristics as well as the elastic characteristics of the osteoporotic vertebra trabecular bones.

Ulrich *et al.* (1998) reported that, for the elastic characteristics, the best results were obtained at 168μm resolution when they used ‘mass-compensated hexahedral meshing techniques’ with the same relative BV/TV as that of a human trabecular bone cube (side length 4 mm). However, the present study indicates that, for the plastic analysis, ‘the mass-compensated hexahedral FE model’ is likely to be limited up to 105 μm image resolution for the cubic specimen (side length 4 mm), but only to 84 μm image resolution for both a cylindrical specimen (diameter=7 mm, length=5 mm) and a cubic specimen (side length 6.5 mm) in the vertebral trabecular bones. Because the voxel size of the CT and MR images in vivo (170~300 μm) is substantially larger than that obtained from micro-imaging techniques (Ulrich, 1998), FE models with 168 μm resolution, which is currently the highest available in vivo resolution, cannot produce accurate results for the plastic characteristics of osteoporotic trabecular bones.

Micro-FE models were also utilized to evaluate the effect of specimen geometry on the elastic and plastic characteristics of vertebral trabecular bone specimens. The specimen geometry has a highly significant influence on mechanical characteristics such as stiffness, ultimate strain and energy absorption. As trabecular bones are rather inhomogeneous and show a large topographical variation, the proper specimen geometry will be required to map such variations. As a result, the effective modulus and strength in cubic specimens (side length 4 mm) were significantly higher than those in cubic specimens (side length 6.5 mm). The values for mechanical characteristics of the cylindrical specimens (7 mm diameter, 5 mm length) were similar to those of the cubic specimens (side length 6.5 mm). Our results illustrate that in the simulated compression test, to exactly analyze the plastic characteristics as well as the elastic characteristics of vertebral trabecular bones, it is recommended to use a cubic specimen with side length of 6.5 mm or a cylindrical specimen with 7 mm diameter and 5 mm length rather than a cubic specimen with side length of 4 mm. A cubic specimen with side length of 6.5 mm and a cylindrical specimen with 7 mm diameter and 5 mm length are suggested as better geometries providing comparable results.

This is consistent with the experimental result obtained by Frank *et al.* (1992; 1994) and Dong *et al.* (2004) for the mechanical characteristics of their cubic and cylindrical specimens. As the mechanical test using the various specimen geometries was performed, they suggested a reasonable standard geometry for comparative studies. Frank *et al.* (1992; 1994) proposed a cubic specimen with side length of 6.5 mm and Dong *et al.* (2004) recommended a short cylindrical specimen (7 mm diameter and 5 mm length) in their observation about the effect of specimen geometry obtained from the results of the mechanical analysis of trabecular bones. The experimental results reported by Frank *et al.* (1992; 1994) and Dong *et al.* (2004) supported our observation.

5. Conclusion

Since osteoporotic compression fracture is closely associated with the mechanical characteristics of trabecular bone and there are few micro-FE models to account for the plastic characteristics of vertebral trabecular bone, we analyzed the plastic characteristics as well as the elastic characteristics of the trabecular bones and evaluated the effect of voxel resolutions and specimen geometry on them. In the present study, two cubic specimens (side lengths 4 mm and 6.5 mm) and a cylindrical specimen (7 mm diameter, 5 mm length) were generated from the central part of the second lumbar vertebral body, and analyzed by both the simulated and experimental compression test. The results show that to analyze the plastic characteristics as well as the elastic characteristics of vertebral trabecular bones, it is recommended to use a cubic specimen (side length 6.5 mm) or a cylindrical specimen (7 mm diameter, 5 mm length) rather than a cubic specimen (side length 4 mm) generally used in the mechanical compression test. For both the cylindrical specimen with 7 mm diameter and 5 mm length and the cubic specimen with side length of 6.5 mm, it was concluded that, the 'mass-compensated hexahedral meshing techniques' suggested by Ulrich *et al.* (1998) were effective up to only 84 μm resolution. For further verification, an RP machine was used to fabricate complex 3D objects of vertebral trabecular bone and the experimental compression test for RP models 'instead of real bone specimens' was performed to indirectly validate the results of the simulated compression test for the FE models in vertebral trabecular bones.

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