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BK메디텍㈜ 기술연구소, 아주대학교 의과대학 정형외과학교실[1], 가톨릭대학교 의과대학 정형외과학교실[2],
단국대학교 기계공학과[3], 건양대학교 의과대학 정형외과학교실[4]

· [1] · [2] · HR Girish[1] · [3] · [4] · [3]

Bone Strength of the Primary Compression Trabeculae in Human Calcaneus

Myong-Hyun Baek, Ye-Yeon Won[1], Yang-Guk Chung[2], Girish Halasinanagenahalli Rudrappa[1],
Jung Ho Seo[3], Kwang-Kyoun Kim[4], Young Eun Kim[3]

Technical Institute, BK Meditech Co., Ltd, Hwasung,
Department of Orthopaedic Surgery, Ajou University School of Medicine[1], Suwon,
Department of Orthopaedic Surgery, College of Medicine, The Catholic University of Korea[2], Seoul,
Department of Mechanical Engineering, Dankook University[3], Yongin,
Department of Orthopaedic Surgery, Konyang University School of Medicine[4], Daejon, Korea

Objectives: The accuracy of bone strength can be improved for medically treating osteoporosis by diagnosing and predicting fracture risk. In this study, we calculated the material properties of calcaneus bone and evaluated the statistical correlation of the bone mineral density (BMD) with morphometry indices and bone strength.

Materials & Methods: Twelve cored bone samples were obtained from the primary compressive trabeculae of human calcaneus. All samples were scanned with a Lunar PIXImus®, and two-dimensional serial section images were obtained on a μ-computed tomography system. A mechanical test was performed with an Instron universal testing machine and finite element analysis (FEA) to determine material properties and bone strength.

Results: The material property of the samples was 2.97 GPA. BMD was significantly correlated with bone strength and morphometric indices except for Tb.Sp, DA, and Tb.N. The statistical relationship between bone strength and the morphometric indices was significant except for DA.

Conclusions: FEA based on *in vivo* high resolution serial section images can be used to directly evaluate bone strength and will be a useful tool in clinical practice for diagnosing osteoporosis and predicting fracture risk.

Key Words: Bone strength, Finite element analysis, Morphometric indices, BMD, Trabecular bone

(calcaneus) 7
,
(tibia) (talus)
(navicular bone) (cuboid)
.

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Corresponding Author: Young Eun Kim, Department of Mechanical Engineering, Dankook University, Yongin
Tel: +82-31-8005-3520, Fax: +82-31-8005-3509
E-mail: yekim@dankook.ac.kr
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10,000 .

(primary compression trabeculae)
(primary tensile trabeculae) [1]
.

,
. (bone strength)

. 2000 NIH Consensus Statement
(BMD, bone mineral density) 70%

.[2]
(bone quantity)
DXA BMD
,
X-ray , (*in vivo*)
. BMD
(g/cm^2)
. Mosekilde [3]
(fluoride)
(vertebral body)
(volume density)
(compressive strength)
.
(bone quality)
(CT, computed tomography),
(pQCT, peripheral quantitative CT),
(hrCT, high resolution CT),
(μ-MRI, micro magnetic resonance imaging),
(μ-CT)
. CT, pQCT and hrCT
in vivo ,
500 μm

X-ray
.
μ
-MRI 500 μm
. μ-CT
20 μm

(*in vitro*)
,
.
X-ray
in vivo
.
(bone strength)

,
(fracture risk)
. (Instron, universal testing machine)
.
(FEA, finite element analysis) CT, MRI, μ-CT
.
, (material property) (boundary condition)
.
Instron FEA
BMD, ,
.

1.
3
10 mm (trephine)

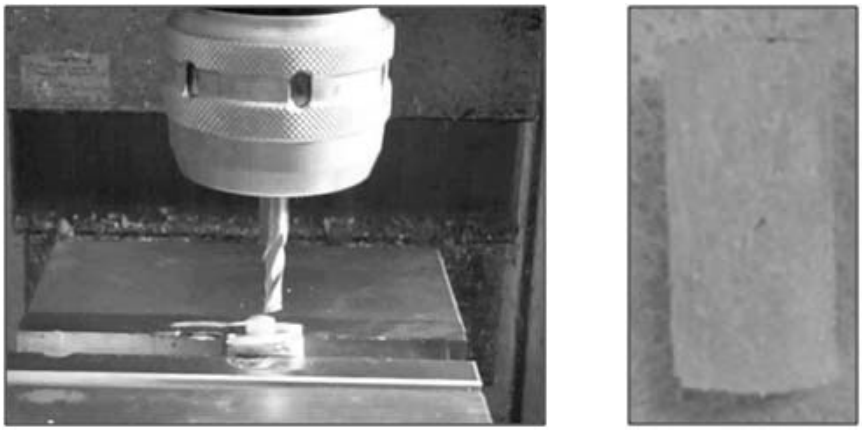

Fig. 1. Cutting edge of the top and bottom surface of bone sample by milling machine (Lt) and cored bone sample (Rt) in the primary compression trabecular bone in human calcaneus.

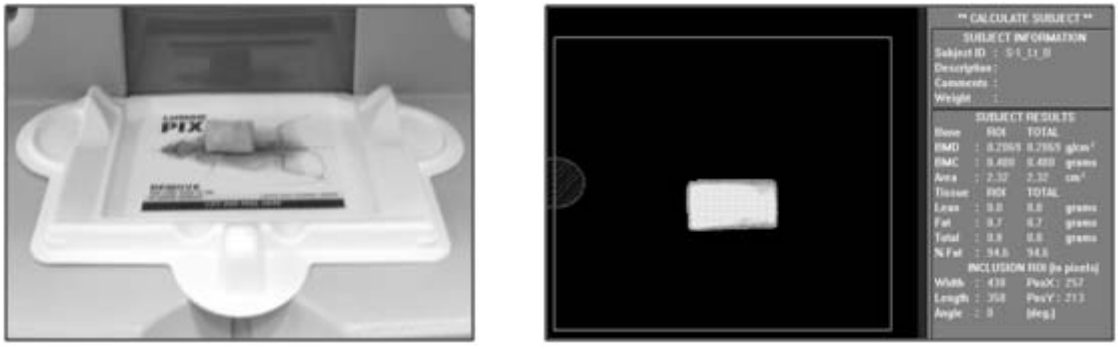

Fig. 2. Scanning of the bone sample using the PIXImus2 densitometry (Lt) and total region of interest in bone sample (Rt).

. , (QC, quality control) (end-artifact)[4] (phantom) (milling machine) 3 (coefficient of variation) 1% BMD . 10 mm, 20 mm 12 (interobserver error) (Fig. 1). 70% , . (ROI, region of interest) FEA . Fig. 2 .

(No.0812-070).

3.

2.

BMD , (μ-CT Lunar μm (spatial resolution) , PIXImus2 (GE Medical System, Madison, WI, USA) 80 kV 100 μm . 2 (BMD, bone mineral density) TomoNT™ (SKYSCAN, Belgium)

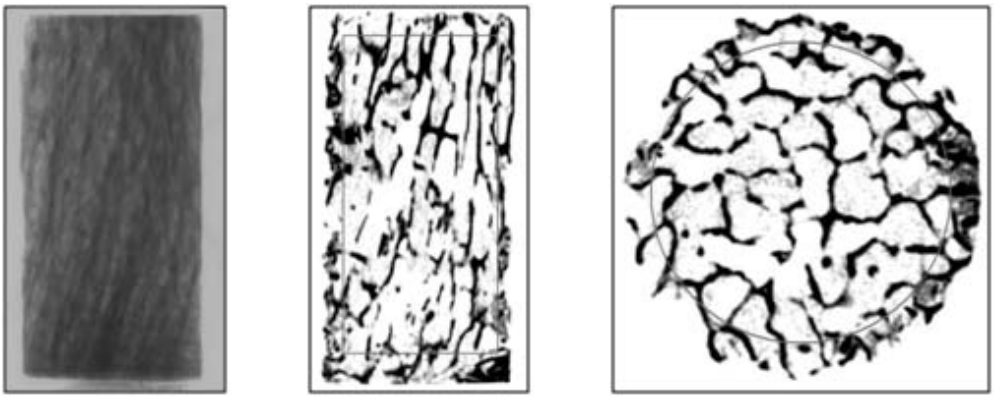

Fig. 3. Two-dimensional micro-images of the bone sample (Lt: X-ray transmission image, Middle: sagittal image and Rt: 2D cross-section image). The specific region of interest is defined square and circle.

Fig. 4. Three-dimensional reconstruction models of the primary compression trabeculae. Morphometric parameters were calculated from this 3-D models.

Fig. 3 2 Fig. 4 8 mm, 17 , (range: 0.025～0.283) mm 3 , . (bone morphometry) ROI (Table 1).[5-7]

4. (Instron) Fig. 3 ROI ANT^{TM} (SKYSCAN, Belgium) μ-CT

Table 1. BMD and bone morphometry indices of calcaneus trabecular bone

	BMD (g/cm^2)	Tb.Th (mm)	Tb.Sp (mm)	BS (mm^2)	BV (mm^3)	BS/BV (1/mm)	BS/TV (1/mm)	BV/TV (%)	SMI	DA	TBPf (1/mm)	Tb.N (1/mm)
AVE	0.198	0.314	0.700	3311.677	274.841	12.822	3.855	31.995	1.711	0.533	1.073	1.010
STDEV	0.076	0.086	0.163	509.346	102.764	2.658	0.593	11.956	0.362	0.128	2.532	0.165

AVE and STDEV means average and standard deviation. Tb.Th: trabecular thickness, Tb.Sp: trabecular separation, BS: bone surface, BV: bone volume, BS/BV: surface-to-bone volume ratio, BS/TV: ratio of surface to tissue volume, BV/TV: bone volume fraction, SMI: structure model index, DA: degree of anisotropy, TBPf: trabecular pattern factor, and Tb.N: trabecular number.

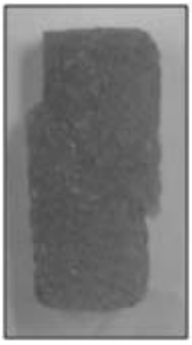

Fig. 5. Fractured bone after the compression test using Instron system. The compression test is used to determine yield stress, yield strain and Young's modulus.

(Instron 8501, INSTRON Inc., USA) Fig. 5 .

Ladd [8]

0.01 s^{-1} (displacement rate) (uni-axial compression)

- (stress-strain curve) .

0.2% (offset) ,

(E_a, apparent modulus of elasticity) - (slope) (1) .

$$E_a = \sigma_y / \varepsilon_y \quad \cdots\cdots (1)$$

E_a=apparent modulus of elasticity

σ_y=Yield stress

ε_y=Yield strain

5. (FEA)

(FE-model) μ-CT 2 BIONIX 3.1 (CANTIBio, Suwon, Korea) (edge detection) Fig. 6 (hexahedron mesh model) . (element size) 84 μm^3 , (VOI, volume of interest)

8 mm, 17 mm . FE-model (isotropic) (linear elastic) , (ν, Poisson's ratio) 0.3, E_a

(E_t, tissue modulus of elasticity) (Table 2).

Table 2. Mechanical properties of calcaneus trabecular bone

	σ_y (MPa)	ε_y (%)	E_a (MPa)	E_t (MPa)
Average	7.951	1.498	453.072	2970.963
STDEV	9.390	0.459	397.652	1443.210.

σ_y: yield stress, ε_y: yield strain, E_a: apparent modulus of elasticity, and E_t: tissue modulus of elasticity.

(BV/TV) (BV/TV_E) BIONIX (threshold value) (element) .[9]

(2) BV/TV BV/TV_E .

$$BV/TV = BV/TV_E = E_N/T_N \quad \cdots\cdots (2)$$

BV/TV: bone volume fraction

BV/TV_E: element volume fraction

E_N: tissue element number

T_N: total element number

FEA (simulation) ANSYS

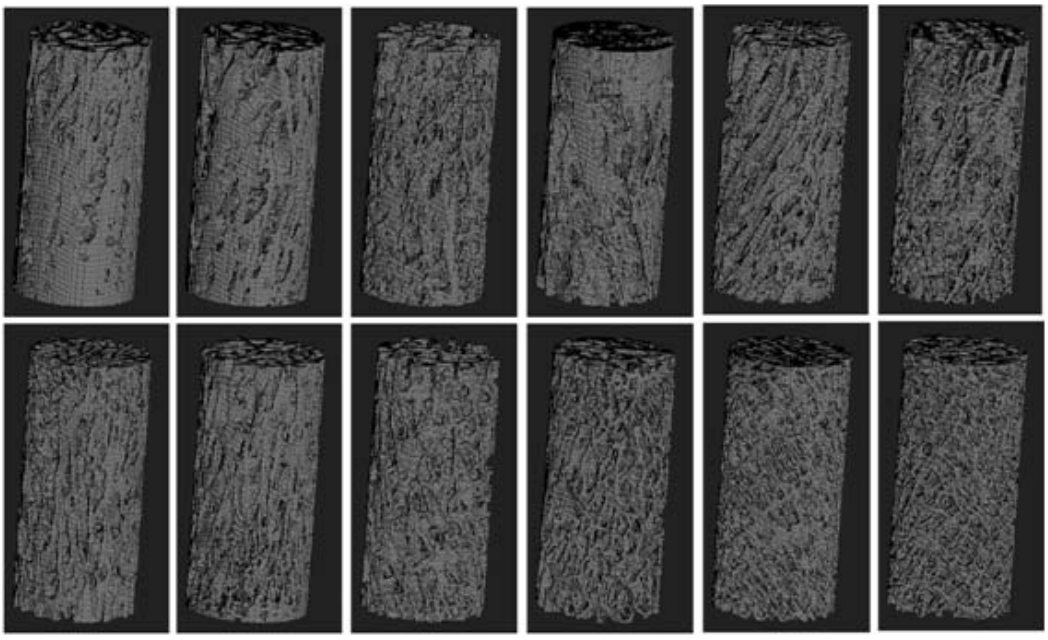

Fig. 6. Hexahedron mesh models of the primary compression trabeculae in human calcaneus. The element size is 84 μm.

10.0 (ANSYS. Inc) ,
(boundary condition)

(strain) .[9]
FE-model
(σ_y, yield stress) E_t
. (ε_y, yield
strain) 1.50 (±0.46)% ,
2.59% , 0.93% (Table 2).

6.

(bivariate correlations
analysis) (person's cor-
relation coefficient) (significant level)
BMD,
. 5%
,
SPSS Ver. 17.0 (SPSS Inc., Chicago, USA)
.

1.

BMD 0.198 g/cm^2 (±0.076)
(Table 1).
BMD Tb.Th,
BV, BS, BV/TV BS/TV
, BS/BV, SMI TBPf
. Tb.Sp,
DA Tb.N .
BMD (σ_y and E_a) σ_y E_a
0.958 0.942
(Table 3).

2.

(Tb.Th) 0.314 mm,
(Tb.Sp) 0.7 mm, (BV/TV)
31.995%,
(SMI) (DA) 1.711 0.533
(Table 1). SMI 0～3 0
(plate-like structure), 3
(rod-like structure) , DA

Table 3. Bivariate correlations analysis with BMD, bone morphology and mechanical strength

		BMD	σ_y	E_a	Tb.Th	Tb.Sp	BV	BS	BS/BV	BV/TV	BS/TV	DA	SMI	Tb.N	TBPf
BMD	Pearson Correlation	1	.958**	.942**	.883**	−.519	.951**	.583*	−.872**	.951**	.582*	−.547	−.713**	.523	−.985**
	Sig. (2-tailed)		.000	.000	.000	.084	.000	.047	.000	.000	.047	.066	.009	.081	.000
σ_y	Pearson Correlation		1	.969**	.857**	−.673*	.978**	.692*	−.807**	.978**	.690*	−.471	−.589*	.620*	−.930**
	Sig. (2-tailed)			.000	.000	.016	.000	.013	.002	.000	.013	.122	.044	.031	.000
E_a	Pearson Correlation			1	.781**	−.647*	.916**	.675*	−.751**	.916**	.674*	−.459	−.630*	.623*	−.896**
	Sig. (2-tailed)				.003	.023	.000	.016	.005	.000	.016	.133	.028	.030	.000
Tb.Th	Pearson Correlation				1	−.317	.903**	.343	−.958**	.903**	.342	−.554	−.370	.205	−.911**
	Sig. (2-tailed)					.316	.000	.276	.000	.000	.276	.062	.237	.523	.000
Tb.Sp	Pearson Correlation					1	−.666*	−.969**	.204	−.667*	−.969**	−.079	.348	−.919**	.456
	Sig. (2-tailed)						.018	.000	.525	.018	.000	.807	.268	.000	.136
BV	Pearson Correlation						1	.695*	−.849**	1.000**	.694**	−.457	−.549	.600*	−.946
	Sig. (2-tailed)							.012	.000	.000	.012	.135	.064	.039	.000
BS	Pearson Correlation							1	−.243	−.849**	1.000**	.079	−.506	.945**	−.534
	Sig. (2-tailed)								.447	.000	.000	.806	.094	.000	.073
BS/BV	Pearson Correlation								1	−.243	.694*	.751**	.415	−.177	.914**
	Sig. (2-tailed)									.447	.012	.005	.180	.582	.000
BV/TV	Pearson Correlation									1	−.849**	−.457	−.549	.600*	−.946**
	Sig. (2-tailed)										.000	.136	.065	.039	.000
BS/TV	Pearson Correlation										1	.081	−.504	.953**	−.534
	Sig. (2-tailed)											.803	.095	.000	.074
DA	Pearson Correlation											1	.297	−.040	.586**
	Sig. (2-tailed)												.348	.902	.046
SMI	Pearson Correlation												1	−.572	.697*
	Sig. (2-tailed)													.052	.012
Tb.N	Pearson Correlation													1	−.477
	Sig. (2-tailed)														.116
TBPf	Pearson Correlation														1
	Sig. (2-tailed)														

* Correlation is significant at the 0.05 level (2-tailed), ** Correlation is significant at the 0.01 level (2-tailed).

0～1 0 (isotropy structure), 1 (anisotropy structure) . 3. Instron σ_y, ε_y, E_a Tb.Th, 7.951 MPa, 1.498% 453.072 MPa BV, BS, BV/TV, BS/TV, Tb.N , FEA E_t 2.97 GPa , Tb.Sp, BS/BV, SMI, (Table 2, Fig. 7).

TBPf . σ_y E_a BMD DA (Table 3). DA .

FE-model (element)

.

, ,

. Baek [13]

(femoral head) 5.17 GPa , Ulrich [12] (proximal femur) 3.5～8.6 GPa, (vertebral body) Ladd [8] 5.5～7.7 GPa , Hou [14] 2.7～9.7 GPa .

,

FEA

.

BMD, ,

, BMD σ_y E_a 95.8% 94.2%

,

Tb.Sp, DA, Tb.N

. BMD

BMD

, (bone biopsy)

(soft tissue) ( )

.

, DA

,

Tb.Th, Tb.Sp, BV, BS, BS/BV, BV/TV, BS/TV, SMI, Tb.N, TBPf 80%

(Table 3).

hrCT μ-MRI

.

, BMD

,

in vivo

.

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<Appendix> Nomenclature

E_a=apparent modulus of elasticity ( )

E_t=tissue modulus of elasticity ( )

ν=Poisson's ratio ( )

σ_y=yield stress ( )

ε_y=yield strain ( )