Effect of High Tibial Osteotomy on the Distribution of Subchondral Bone Density Across the Proximal Tibial Articular Surface of the Knee With Medial Compartment Osteoarthritis

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Background: The effect of high tibial osteotomy (HTO) on the stress distribution across the knee joint is not completely understood. Subchondral bone density is considered to reflect the pattern of stress distribution across a joint surface.

Purpose: To assess the distribution of subchondral bone density across the proximal tibia in nonarthritic knees and in the knees of patients with osteoarthritis (OA) before and after HTO.

Study Design: Cohort study; Level of evidence, 3.

Methods: We retrospectively collected radiological and computed tomography data from 16 patients without OA (control group) and 17 patients with OA. Data from the OA group were collected before and 1.5 years after HTO. Subchondral bone density of the proximal tibia was assessed with computed tomography–osteoabsorptiometry. The locations and percentages represented by high-density areas (HDAs) on the articular surface were quantitatively analyzed.

Results: The ratio of the HDA of the medial compartment to the total HDA (medial ratio) was significantly higher in the preoperative OA group (mean, 80.1%) than in the control group (61.3%) ($P < .001$). After HTO, the medial ratio decreased significantly to 75.1% ($P = .035$ in comparison with preoperative values) and was significantly correlated with the hip-knee-ankle angle in both groups: control ($r = -0.551$; $P = .033$) and OA ($r = -0.528$; $P = .043$). The change in medial ratio after HTO was significantly correlated with the change in hip-knee-ankle angle ($r = 0.587$; $P = .035$). In the medial compartment, the HDA in the most lateral region of 4 subregions increased after HTO, but that in 3 medial subregions decreased.

Conclusion: In this exploratory study, HTO shifted the HDA of the medial compartment of the proximal tibial articular surface toward the lateral compartment. In contrast, the HDA of the most lateral region of the medial compartment increased after HTO. This change in subchondral bone density may result from the change in stress distribution.

Keywords: high tibial osteotomy; knee; osteoarthritis; stress distribution; CT-osteoabsorptiometry; alignment

Biomechanical risk factors for knee osteoarthritis (OA), such as obesity, trauma, malalignment, meniscal deficiency, and muscle weakness, increase the mechanical stress across the knee joint. Some of these are believed to be important and potentially modifiable factors that determine the site and severity of knee OA.[45] Identifying the distribution of mechanical stress across the knee joint would thus contribute to the prediction and management of OA progression.

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Malalignment of the lower limbs is a strong risk factor for progression of knee OA and one of the few risk factors that can be modified a posteriori. Valgus high tibial osteotomy (HTO) is an established surgical procedure that can be used to treat medial knee OA. HTO reduces loading of the medial compartment and thereby slows disease progression. Because it extends the healthy life expectancy of the knee, HTO is widely used as a treatment option for medial OA with varus alignment.[3,10,16] The relationships among leg alignment, medial compartment loading, and change in medial compartment loading after HTO have been examined in a cadaveric study,[1] finite element analyses,[36,52] and 3-dimensional (3D) gait analyses by assessing the knee adduction moment[7,15,29]; however, how the distribution of the actual stress within each compartment changes after HTO remains unclear.

The distribution of the subchondral bone mineral density (BMD) is thought to be correlated with the distribution of stress over the joint surface; because of the varying degrees of mineralization over the surface of a joint, a materialized field of stress is observed.[42] Computed tomography (CT)–osteoabsorptiometry was developed by Müller-Gerbl et al[34,35] as an analytical method to assess the long-term stress distribution over individual joints in living participants by measuring the subchondral BMD. This method generates a precise map of the distribution pattern of subchondral bone density over various articular surfaces. Our previous studies involving this method have evaluated the distribution of subchondral bone density to assess the pattern of stress distribution at the wrist and elbow[32] and the glenohumeral,[12,46] patellofemoral,[37] and ankle joints[41] in healthy people, those with pathological conditions, and athletes. The distribution pattern of subchondral bone density over the knee joint has been suggested to be related to the presence of knee OA[19,39]; however, it is unclear whether leg alignment affects the distribution of bone density. Furthermore, whether or how the distribution pattern of subchondral bone density changes on the articular surface across the knee joint after HTO is yet to be elucidated.

Using CT-osteoabsorptiometry, a precise map of the subchondral bone density distribution across the knee joint could provide insight into the stress distribution across the articular surface of the knee joint with and without OA and the change in the stress distribution after HTO. Thus, we hypothesized that valgus HTO leads to a reduction in the in vivo subchondral bone density on the medial compartment of the femorotibial joint in the case of varus OA of the knee. The aims of this exploratory study were (1) to evaluate the distribution pattern of subchondral bone density across the proximal tibia in patients with and without OA, (2) to assess changes in the pattern of bone density distribution in patients with OA before and after HTO, and (3) to clarify the correlation of leg alignment with changes in bone density distribution.

METHODS

Study Design

This study was approved by the institutional review board of Hokkaido University Hospital (017-0163). We retrospectively recruited all patients who underwent HTO for medial compartment OA between April 2013 and March 2017 at our institution. All operations were performed by a senior orthopaedic surgeon (E.K.) who had >20 years of experience in performing knee surgery. The OA group included patients who underwent medial open wedge HTO for medial compartment OA. Indications for open wedge HTO in our hospital were moderate varus leg alignment (hip-knee-ankle [HKA] angle $> -10°$) and absence of OA in the patellofemoral joint (Kellgren-Lawrence [KL] grade[21] ≥ 2) or anterior knee pain. Exclusion criteria were as follows: lateral knee OA (KL grade ≥ 2) or lateral knee pain, not completing a follow-up period of at least 1 year, having no metal removal after HTO, loss of $>15°$ of knee extension before and after HTO, knee range of motion $<130°$ before and after HTO, anterior cruciate ligament insufficiency or varus/valgus instability $>10°$, medial meniscal injury grade ≥ 3 (per the magnetic resonance imaging [MRI] grading system of Lotysch and Mink[5,30]) or any tear of the medial meniscus for which partial meniscectomy or other repair was performed, and any lateral meniscal injury. Finally, we evaluated 17 knees in 16 patients in the OA group (Figure 1).

For a control group, we collected the data of 16 patients who underwent simultaneous radiological and CT examinations of both knees for comparison of ipsilateral knee trauma between April 2013 and March 2017. The uninjured contralateral knee was used as control. Inclusion criteria for the control group were knee OA of KL grade ≤ 1 in the contralateral knee and patients aged 15 to 30 years at the time of CT scanning. Exclusion criteria for the control group were current pain in the contralateral knee and previous surgery in the contralateral knee.

Postoperative clinical and radiological evaluations were performed around 1.5 years (mean, 17.4 months; range, 14-25 months) after open wedge HTO and immediately after removal of the locking plate.

Preoperative Planning

The Miniaci method[31] was used for preoperative planning as previously reported.[43,49] To calculate an appropriate angle of the medial opening wedge, a long line, A, was drawn from the center of the femoral head through the 65% lateral from the medial edge of the tibial plateau on the whole tibial plateau. Another line, B, was then drawn from the hinge point, P, to the center of the talar dome, and its length was measured. An arc, C—the center and the radius of which are the hinge point P and line B, respectively—was then drawn so that the arc crossed line A. A line, D, was then drawn from the hinge point to the

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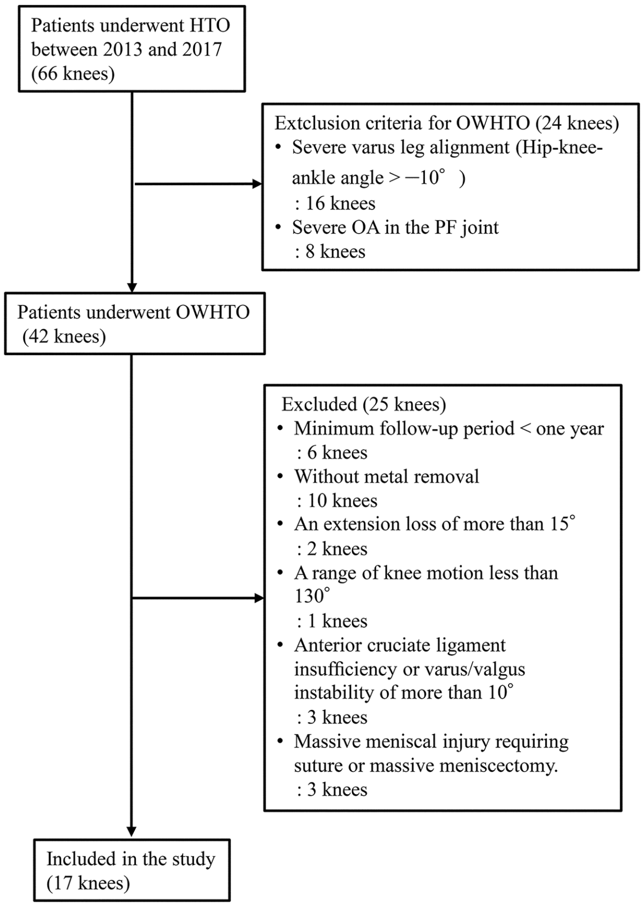

Figure 1. Flowchart of study enrollment. HTO, high tibial osteotomy; OA, osteoarthritis; OWHTO, open wedge HTO; PF, patellofemoral.

crossing point between line *A* and the arc *C*. The angle formed between lines *B* and *D* provides the medial opening angle, which is identical to the correction angle of the lower limb alignment.

Surgical Technique

Surgery was performed as previously described.[40,43,49] The proximal tibia was exposed through a 7-cm medial longitudinal incision. Furthermore, after the complete release of the distal attachment of the superficial medial collateral ligament, 3 pairs of Kirshner wires were inserted into the tibia so that each wire precisely reached the proximal tibiofibular joint using the parallel guide. We then performed a biplanar osteotomy of the tibia, after which the oblique osteotomy site was gradually opened—according to the preoperative planning angle—using a specially designed spreader (Olympus Terumo Biomaterials). Under fluoroscopic control, we set a long straight metal rod to connect the center of femoral head and ankle and then measured the transection point of the rod through the tibial plateau. This was expressed as a percentage of the tibial width from medial to lateral. We confirmed the transection point of 65%.[11] Two wedged beta-tricalcium phosphate spacers (Osferion 60; Olympus Terumo Biomaterials) were implanted into the anterior and posterior parts of the opening space in a parallel fashion. We fixed the tibia with a locking plate (Tomofix [DePuy Synthes] or TriS Medial HTO plate system [Olympus Terumo Biomaterials]) by inserting 8 locking screws.

Each patient underwent an additional procedure approximately 1 year (mean, 13.4 months; range, 12-15 months) after the initial surgery to remove the locking plate. Arthroscopic evaluation was performed simultaneously to evaluate the status of the meniscus after HTO.

Evaluation Criteria

Clinical Evaluation. Patients were evaluated according to the Japanese Orthopaedic Association (JOA) knee scoring system (total, 100 points),[4,50] which is the standard knee subjective score used in clinics in Japan. The JOA knee score consists of 4 categories: pain on walking (0-30 points), pain on ascending and descending stairs (0-25 points), range of motion (0-35 points), and joint effusion (0-10 points).

Meniscal Status Evaluation. To compare meniscal status before and after HTO, an examiner (K.I.) evaluated the arthroscopic images at HTO and plate removal and the MRI scans before HTO and after plate removal according to the MRI grading system of Lotysch and Mink.[5,30] The change in meniscal status after HTO was graded according to 3 categories: deterioration, no change, and improvement.

Radiological Evaluations. Standing anteroposterior and lateral radiographs of the knee and full-length anteroposterior radiographs of the whole lower limb with the knee in full extension were acquired. The radiological stage of OA was assessed according to the KL grading system.[21] We measured the HKA angle on anteroposterior radiographs of the whole lower limb, taken with a long cassette in the 1-leg standing position. We also calculated the percentage of mechanical axis (%MA) as follows: a line was drawn between the center of the femoral head and the center of the tibial plafond; the medial edge of the tibia plateau was defined as 0% and the lateral edge as 100%; and the %MA was the point at which the line passed across the tibial plateau.[8,20,33,38,51] The posterior tibial slope (PTS) was measured as the angle between a line perpendicular to the mid-diaphysis of the tibia and the posterior inclination of the medial tibial plateau on the lateral view.

CT-Osteoabsorptiometry. A high-resolution helical CT scanner (Aquilion One/ViSION Edition; Toshiba Medical Systems) was used to acquire axial images of the knee. Patients rested in a supine position with their knees extended during imaging. Slice thickness and interval were set at 0.5 mm. Acquired CT data were transferred to a personal computer. Sagittal and coronal slices at 1.0-mm intervals and 3D bone models were generated from axial CT data with the use of commercial software (Ziocube; Ziosoft, Inc). We determined the sagittal and coronal axes by reference to the epicondylar axis of the distal femoral condyle at the axial slice. By reference to sagittal and coronal CT images and a 3D CT image of the articular

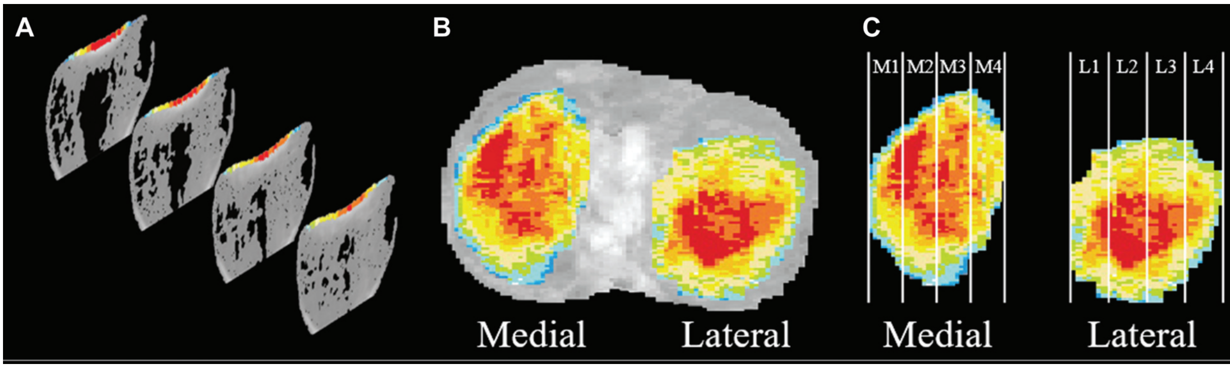

Figure 2. Identification of the subchondral bone regions of the proximal tibia using customized software. (A, B) Subchondral bone density of the selected region was automatically measured at each coordinate point in each 1.0-mm sagittal slice. (C) Images of the areas used for quantitative analysis of the bone density mapping data for the medial and lateral compartments of the proximal tibia. L1-L4, subregions of the lateral compartment, divided equally from the medial to lateral side. M1-M4, subregions of the medial compartment of the proximal tibia, divided equally from the medial to lateral side.

surface of the proximal tibia, outlines of the medial and lateral compartments of the proximal tibial articular surface were manually selected to include the entire subchondral bone layer of the articular surface in all slices.[12] Then the subchondral bone density of each generated sagittal slice was analyzed with noncommercial software (OsteoDens 4.0) developed at our institution.[12,17,37,41,46] The maximum increment point in Hounsfield units from the joint surface was selected as the starting point of the region of interest, and the maximum point in Hounsfield units was selected automatically in the 2.5-mm region of interest from the starting point (Appendix, available in the online version of this article). We determined the radiodensity of the identified subchondral bone region at each coordinate point at 1-mm intervals. Then, a 2-dimensional image that mapped the distribution of subchondral bone density was obtained by stacking sagittal slices (Figure 2, A and B). The differences between the maximum and minimum values in Hounsfield units on the mapping images were divided into 9 grades, and a surface mapping image was generated through the use of these grades to produce a color scale in which red and violet indicated the greatest and lowest bone densities, respectively. Selected areas of the medial and lateral plateaus included the cortical bone or bony spur at the periphery of the articular surface because it was impossible to exclude either using the software. However, these features were carefully removed manually from the target area of analysis in subsequent quantitative analysis.[12]

Quantitative analysis of the obtained mapping data focused on the location of the high-density area (HDA) of the articular surface. The HDA was defined as the region containing the coordinate points representing the top 20% of Hounsfield units out of the total area of the medial and lateral compartments. The medial ratio was calculated as the ratio of the HDA of the medial compartment to the total HDA of both compartments. The medial compartment of the proximal tibia was divided into 4 subregions of equal width in the coronal direction, denoted M1 to M4 from the medial to lateral sides. The lateral compartment was divided equivalently, denoted L1 to L4 from the medial to lateral sides (Figure 2C). The percentage of each subregion represented by the HDA was calculated (%HDA).

Statistical Analysis

Statistical analyses were performed using JMP Pro Version 14.0 (SAS Institute Inc). The significance level was set at P = .05. Means and 95% CIs for the changes after surgery in patients with OA were calculated. We compared controls and patients with OA before and after surgery by using the Student t test, and we compared the patients with OA before and after surgery by using a paired t test. Pearson correlation was used to evaluate the relationship between the medial ratio and other factors (age, body mass index [BMI], HKA angle, %MA, and PTS) to compare controls with preoperative patients. In addition, we compared changes from pre- to postoperative values (denoted by Δ) of the medial ratio and other variables using Pearson correlation. These factors were selected because they are believed to influence the distribution of subchondral bone density[19,45,47] or the biomechanics of the knee joint.[44]

The reproducibility of data was evaluated using our noncommercial software (OsteoDens 4.0). Intra- and interobserver reliability was assessed on 3 randomly selected knees from the control group and each OA group. Two observers (K.I. and S.M.) independently measured %HDA in these 6 knees; a total of 48 subregions were measured twice in a blinded manner at 1-month intervals. The intraclass correlation coefficients for intraobserver reliability were 0.922 (K.I.) and 0.913 (S.M.), and the intraclass correlation coefficient for interobserver reproducibility was 0.917.

RESULTS

Age, BMI, HKA angle, and %MA were significantly different between the control and preoperative OA groups

TABLE 1
Patient Characteristics, OA Grade, Leg Alignment, Clinical Outcomes, and Medial Ratio[a]

	Controls (n = 16)	Patients With OA (n = 17)		Preop vs Control, *P* Value	Preop vs Postop		Preop vs Control, *P* Value
		Preop	Postop		Change	*P* Value	
Age, y	20.8 (18.1 to 23.4)	58.9 (54.8 to 63.0)		<.001			
Male:female ratio	8:8	6:11		.393			
BMI	24.0 (21.8 to 26.2)	27.0 (25.1 to 28.9)		.026			
KL grades 3 and 4		16:1	16:1			.99	
HKA angle,[b] deg	−1.5 (–3.4 to 0.4)	−6.1 (–8.0 to –4.2)	5.0 (4.1 to 5.8)	<.001	9.9 (7.6 to 12.2)	<.001	<.001
MA, %	43.8 (37.3 to 50.3)	22.8 (14.9 to 30.7)	68.8 (65.3 to 72.3)	<.001	45.4 (36.7 to 54.0)	<.001	<.001
PTS, deg	9.9 (8.2 to 11.6)	11.5 (9.7 to 13.7)	13.1 (10.8 to 15.4)	.191	1.6 (0.3 to 2.8)	.019	.025
JOA knee score							
Total		68.8 (61.3 to 76.2)	91.6 (86.6 to 96.5)		22.7 (17.3 to 28.3)	<.001	
Pain on walking		19.6 (17.2 to 21.9)	29.1 (27.7 to 30.5)		9.6 (6.8 to 12.3)	<.001	
Pain on ascending and descending stairs		13.6 (11.0 to 16.3)	22.7 (21.0 to 24.5)		9.1 (6.5 to 11.6)	<.001	
Range of motion		28.6 (26.5 to 30.8)	30.9 (28.4 to 33.4)		2.3 (0.5 to 4.0)	.02	
Joint effusion		6.8 (4.6 to 9.1)	8.3 (7.1 to 10.2)		1.8 (0.1 to 3.5)	.04	
Medial ratio,[c] %	61.3 (55.7 to 66.9)	80.1 (72.3 to 85.6)	75.1 (67.8 to 83.5)	<.001	4.4 (0.6 to 8.1)	.035	.008

[a]Data are reported as mean (95% CI) or ratio. Blank cells indicate *not applicable*. BMI, body mass index; HDA, high-density area (ie, 20% highest area in Hounsfield units out of the sum of the medial and lateral compartments); HKA, hip-knee-ankle; HTO, high tibial osteotomy; JOA, Japanese Orthopedic Association (total, 100 points); KL, Kellgren-Lawrence; MA, mechanical axis; OA, osteoarthritis; postop, 1 year after HTO; preop, before HTO; PTS, posterior tibial slope.

[b]Varus alignment was a negative value of HKA angle and valgus alignment, a positive value.

[c]Medial ratio: the ratio of HDA of the medial compartment in relation to the total HDA of both compartments.

TABLE 2
Pearson Correlation Between the Medial Ratio and Patient Data in Controls and Patients With Osteoarthritis[a]

	Controls		Patients	
	r Value	*P* Value	*r* Value	*P* Value
Age	0.122	.670	0.671	.009
BMI	−0.144	.609	−0.077	.785
HKA angle	−0.551	.033	−0.528	.043
% MA	−0.558	.031	−0.432	.108
PTS	−0.126	.654	−0.217	.438

[a]Medial ratio: the ratio of HDA of the medial compartment relative to the total HDA of both compartments. BMI, body mass index; HDA, high-density area (ie, 20% highest area in Hounsfield units out of the sum of the medial and lateral compartments; HKA, hip-knee-ankle; MA, mechanical axis; PTS, posterior tibial slope.

($P < .001$, $P = .026$, $P < .001$, and $P < .001$, respectively) (Table 1). The medial ratio was 31% higher in the preoperative OA group than the control group ($P < .001$).

After HTO, JOA score improved by 33% ($P < .001$). The sum of the "pain on walking" and "pain on ascending and descending stairs" subcategory scores improved by 56% ($P < .001$). There were significant differences in HKA angle, %MA, and PTS between the pre- and postoperative OA groups ($P < .001$, $P < .001$, and $P = .019$, respectively). The medial ratio decreased by 6% after HTO ($P = .035$) (Table 1).

In the comparison between the patients with OA after surgery and the controls, leg alignment was significantly more valgus in the patients (5.0° valgus in HKA angle) as compared with the controls (1.5° varus; $P < .001$). The medial ratio was 21% higher in the patients than in the controls ($P = .008$).

In arthroscopic evaluation after HTO, meniscal status was graded "no change" in the medial and lateral compartments in all cases. Similarly, MRI grading of meniscal status per Lotysch and Mink[5,30] was unchanged in the medial and lateral compartments after HTO.

Of the parameters that differed significantly between the control and preoperative OA groups, age, HKA angle, and %MA were significantly correlated with the medial ratio (Table 2). Only HKA angle was significantly correlated with the medial ratio in the control and OA groups (Figure 3).

Of the patients' characteristics, including age, BMI, sex, and JOA knee score, none showed a significant correlation with Δmedial ratio. In contrast, of the parameters that were changed after HTO, only ΔHKA angle was significantly correlated with the Δmedial ratio ($P = .035$) (Table 3). In addition, there was no significant correlation between ΔHKA angle and functional knee score.

Subregional %HDA analysis revealed %HDA of the M2 and M3 regions to be significantly higher among patients with OA than controls ($P = .011$ and $P < .001$, respectively). The %HDA of all 4 subregions of the lateral compartment was significantly lower in patients with OA than controls (L1, $P < .001$; L2, $P = .013$; L3, $P = .005$; L4, $P = .005$) (Table 4). After HTO, the %HDA of M2 and M3 decreased by 23% ($P = .009$) and 20% ($P = .017$), whereas that of M4 increased by 19% ($P = .014$). In the lateral compartment, the %HDA of L2 and L3 increased by 52% ($P = .026$) and 74% ($P = .006$).

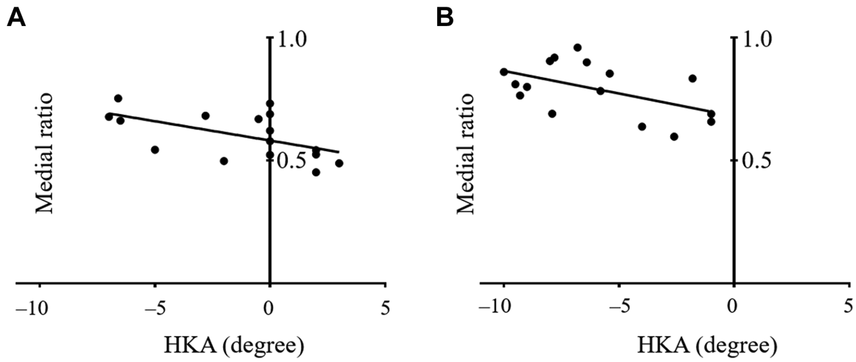

Figure 3. Relationship between hip-knee-ankle (HKA) angle and medial ratio. (A) Control group: Pearson correlation analysis shows a significant negative correlation between HKA angle and medial ratio (Pearson $r = -0.551$; $P < .033$). (B) Osteoarthritis group: Pearson correlation analysis shows a significant negative correlation between HKA angle and medial ratio (Pearson $r = -0.528$; $P < .043$). Medial ratio: the ratio of high-density area (HDA) of the medial compartment in relation to the total HDA of both compartments. HDA: 20% highest area in Hounsfield units out of the sum of the medial and lateral compartments.

TABLE 3
Pearson and Partial Correlation Coefficients Between ΔMedial Ratio and Patient Data in Patients With Osteoarthritis Before and After HTO[a]

	Correlation Coefficient	*P* Value	Partial Correlation Coefficient
Pre-HTO			
HKA angle	−0.338	.259	−0.431
PTS	0.0002	.999	0.151
Post-HTO[b]			
HKA angle	0.432	.140	0.415
PTS	0.009	.999	0.031
Δ Pre- vs post-HTO			
HKA angle	0.587	.035	0.539
PTS	0.018	.930	0.151

[a]Medial ratio: the ratio of the HDA of the medial compartment to the HDA of both compartments. HDA, high-density area (ie, 20% highest area in Hounsfield units out of the sum of the medial and lateral compartments); HKA, hip-knee-ankle; HTO, high tibial osteotomy; PTS, posterior tibial slope.
[b]1 year after HTO.

DISCUSSION

In this study, we demonstrated that the medial ratio, defined as the ratio of the medial HDA to the total HDA of the proximal tibia, was increased among patients with OA and varus deformity but decreased significantly after valgus HTO. Furthermore, we discovered that leg alignment was significantly correlated with medial ratio in healthy individuals as well as patients with OA and that the degree of correction of alignment after HTO was correlated with the change in medial ratio.

According to the results of previous studies involving dual-energy x-ray absorptiometry (DEXA), leg alignment was correlated with BMD of the proximal tibia,[2,25,47] as well as with the decrease in BMD of the medial compartment after HTO.[2,25] These findings are similar to the results of our study. However, DEXA is used to evaluate the BMD of periarticular bone but does not distinguish the subchondral bone plate from trabecular bone of the articular surface or from bone spurs or cortical bone. In addition, according to the results of 1 experimental study, the BMD of subchondral bone and trabecular bone changed differently over time,[6] which suggests the difficulty of evaluating the change in the BMD of subchondral bone precisely with DEXA. In contrast, in CT-osteoabsorptiometry, bone spurs can be hidden in the region of interest so that the focus is on the subchondral bone plate of the articular surface. This was believed to be an advantage in our study.

Previous studies involving CT-osteoabsorptiometry indicated that the distribution pattern of subchondral bone density reflects the distribution of the resultant stresses acting on a joint surface under actual loading conditions.[¶] We found the medial ratio to be higher in patients with OA than in healthy individuals, decreasing after HTO in the former. Moreover, the JOA knee scores improved

[¶]References 12, 17, 18, 32, 34, 35, 37, 41, 46.

TABLE 4
Subregional Analysis of Percentage HDA[a]

Subregion	Controls	Patients With OA[b]		*P* Value	
		Preoperative	Postoperative	Preoperative vs Control	Pre- to Postoperative Change
M1[c]	6.2 (4.6-7.9)	9.5 (6.5-12.6)	7.0 (3.9-10.2)	.051	.112
M2	18.9 (16.4-21.3)	23.4 (20.8-26.0)	18.1 (13.8-22.5)	.011	.009
M3	21.6 (19.8-23.3)	29.0 (26.5-31.6)	23.2 (18.5-28.0)	<.001	.017
M4	16.1 (13.0-19.1)	18.1 (15.1-21.0)	21.6 (18.3-24.9)	.323	.014
L1[d]	12.1 (9.9-14.3)	5.4 (3.5-7.3)	8.1 (4.0-12.1)	<.001	.132
L2	13.5 (11.4-15.6)	9.1 (6.3-12.0)	13.8 (9.4-18.3)	.013	.026
L3	9.0 (6.6-11.4)	4.2 (1.8-6.6)	7.3 (3.7-10.9)	.005	.006
L4	2.7 (1.2-4.2)	0.5 (0.1-0.8)	1.6 (0.2-3.0)	.005	.095

[a]Data are reported as mean (95% CI). HDA, high-density area (ie, 20% highest area in Hounsfield units out of the sum of the medial and lateral compartments); HTO, high tibial osteotomy; OA, osteoarthritis.
[b]Preoperative (before HTO) and postoperative (1 year after HTO).
[c]M1-M4: subregions of the medial compartment of the proximal tibia, divided equally from the medial to lateral side.
[d]L1-L4: subregions of the lateral compartment, divided equally from the medial to lateral side.

after HTO, particularly in the pain subcategories. These results indicate that HTO reduces the stress distribution pattern across the medial compartment of the proximal tibial articular surface.

The correlation between ΔHKA angle and Δmedial ratio was weak (r = 0.587), which indicates that the change in leg alignment explained the small variance (~35%) in the Δmedial ratio. Other factors not evaluated in this study, including physical characteristics (eg, muscle strength, pelvic width), kinetics (ie, dynamic alignment), and postoperative activity, might explain the rest of the variance in the Δmedial ratio. Our results demonstrated that HKA angle, but not age and BMI, was significantly correlated with the medial ratio in healthy individuals and patients with OA and that only ΔHKA angle was significantly correlated with the Δmedial ratio among variances (age, sex, BMI, and JOA knee score, as well as preoperative, postoperative, and Δvalues of HKA angle and PTS). In addition, a 3D motion analysis study demonstrated that among the changes in the mechanical axis angle, PTS, gait speed, and lateral trunk lean, only the change in the mechanical axis angle was significantly correlated with the change in knee adduction moment during level walking before and after HTO.[28] Thus, we can conclude that leg alignment is an important factor influencing the stress distribution pattern across the proximal tibial articular surface.

The comparison between the patients postoperatively and the controls revealed that although the patients had valgus alignment more than did controls, the medial ratio was still higher in the patients postoperatively. A possible explanation for this dissociation between the alignment and the medial ratio is the influence of OA itself on the subchondral bone density.[19,39] Another possible explanation is that the distribution of bone density 1.5 years after HTO was not the final distribution of bone density after HTO, inasmuch as the DEXA study mentioned earlier demonstrated that a medial-to-lateral ratio of femoral and tibial condyle BMD was still changing 1 year after HTO.[25] Further study is needed to clarify when the final distribution of subchondral bone density is established.

The results of our subregional analysis of HDA distribution pattern before and after HTO demonstrated that of the 4 subregions in the medial compartment, the %HDA of M2 and M3 decreased after HTO, whereas M4 was the only region to exhibit increased %HDA. These results suggest that stress on the most lateral region of the medial compartment increases after HTO. A finite element study reported that shear stress on the lateral region in the medial compartment increases as lateral joint line obliquity increases.[36] This might be a reason for the paradoxical observation that stress increased only in the most lateral region but decreased for all other regions. Further study is required to clarify whether this effect influences long-term clinical outcomes; however, surgeons should consider the risk of OA progression at the most lateral region of the medial compartment after HTO, owing to the increased mechanical stress, especially in cases where changes in OA have occurred in this region. In this study, the mean medial ratio was higher in the OA group (80.1%) than the control group (61.3%), which is consistent with a previous biomechanical study in which the percentage of total loading attributable to medial compartment loading was 66% in the control group (with normal alignment) as compared with 74.5% in patients with OA at the first peak of the knee adduction moment.[26] The similarity between the medial ratio of this study and the medial compartment loading ratio in the previous study[26] provides some support and verification of the reliability of CT-osteoabsorptiometry as a method for evaluating stress distribution.[#]

There are different opinions about the leg alignment after HTO. Some authors recommend HKA angles of 3° to 5° valgus,[13,14] whereas others suggest 8° to 10° valgus.[9,24] Fujisawa et al[11] suggested %MA of 65% to 70%. However, the medial compartment loading correlated with the tibiofemoral alignment in the dynamic single-limb loading

[#]References 12, 17, 18, 32, 34, 35, 37, 41, 46.

(R^2 = 0.59) with varus malalignment,[27] indicating that the same leg alignment does not indicate the same distribution pattern of the joint loading. Therefore, it is thought to be desirable that the postoperative leg alignment of each patient is decided per the distribution of the joint loading. Further investigation including the distribution pattern of subchondral bone density, as well as kinematic analysis including knee adduction moment, can be useful for elucidating the optimal leg alignment of each patient who underwent HTO.

This study has several limitations that should be acknowledged. First, we did not directly measure the stresses and overall bone density in the knee. Instead, the distribution of subchondral bone density in the knee joint was assessed according to the CT-osteoabsorptiometry method.[34,35] Furthermore, the absolute value of stress at each analysis point was not elucidated. Therefore, it should be kept in mind that the stress distribution evaluated by the CT-osteoabsorptiometry method does not reflect actual stress at the analysis points. Second, there was a significant difference in age between the OA and control groups (mean difference, 38.1 years). This study reveals that age is correlated with the medial ratio in patients with OA but not in healthy individuals. However, leg alignment was found to be correlated with the medial ratio in both groups. This indicates that age might influence the distribution of subchondral bone density as strongly as varus alignment. Third, we evaluated patients with OA after the removal of metal components. Finite element analysis has been used to demonstrate the stress shielding effect of the HTO plate on the bone around the plate[22]; however, the mechanisms underlying this effect on the articular surface are unclear. Moreover, regardless of the stress shielding effect of the HTO plate, this study reveals that the distribution of subchondral bone density differs significantly before and 1.5 years after HTO. A fourth limitation was the small sample size. We included patients who underwent open wedge HTO and excluded those with meniscal injury, joint instability, patellofemoral OA, and lateral OA. Our results may have consequently been affected by the inclusion of patients with only good outcomes, especially in view of the small sample size. At our institution, however, we perform closed HTO[23] for patients with severe varus OA (HKA angle $\leq -10°$) or patellofemoral OA (KL grade $\geq$2). In general, closed HTO necessitates fibular osteotomy, which itself might affect stress distribution across the knee joint.[48] Each exclusion criterion was believed to be a contraindication to HTO or a factor other than HTO that affects the stress distribution. We thus believed that the inclusion and exclusion criteria were necessary for this study to evaluate the influence of HTO alone on the distribution of subchondral bone density as accurately as possible. Despite these limitations, the results presented here provide fundamental clarification of the stress distribution over the knee joint.

In conclusion, we demonstrated that the distribution pattern of the HDA shifted from the medial to lateral compartment after HTO. We discovered that leg alignment was correlated with the distribution of subchondral bone density among nonarthritic individuals and patients with OA and that the degree of alignment correction after HTO was correlated with the change in the distribution of the HDA. Moreover, we found that the HDA of the most lateral region in the medial compartment increased after HTO.

These findings suggest that HTO reduces the stress on the medial compartment of the proximal tibial articular surface in knees with varus OA by shifting the stress toward the lateral compartment and that the stress on the most lateral region of the medial compartment increases after HTO, inasmuch as the change in subchondral bone density results from the change in stress distribution.

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