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Title

Paradoxical change in subchondral bone density in the medial compartment of the proximal tibial articular surface after high tibial osteotomy: A detailed subchondral bone density analysis

Abstract

Background: High tibial osteotomy (HTO) aims to realign the varus knee to alleviate stress in the medial compartment. However, a detailed information on the impact of HTO on stress distribution across the tibiofemoral joint surface is not completely elucidated. Hence, this notion should be further investigated.

Hypothesis/Purpose: This study hypothesized that there is a paradoxical stress change in the medial compartment beyond a specific threshold for lower limb realignment after HTO. The current study aimed to analyze the subchondral bone density distribution to validate the alignment threshold causing paradoxical changes.

Study Design: Cohort study; level of evidence: 3.

Methods: A retrospective clinical study of 32 knees from 30 patients who underwent medial open-wedge HTO between 2015 and 2019 was conducted at ###. The subchondral bone density across the tibiofemoral joint was analyzed on computed tomography-osteoabsorptiometry before and after HTO. The high-density area (HDA) within the medial and lateral compartments and its subregions were specifically examined.

Results: The hip–knee–ankle angle, medial proximal tibial angle (MPTA), joint line obliquity (JLO), and joint line convergence angle significantly changed after HTO ($P < .01$). The HDA of the medial compartment-to-the total HDA ratio decreased by 8%. Paradoxically, the HDA in the M4 region of the medial compartment increased. There were significant differences in MPTA and JLO between with or without paradoxical changes in HDA. MPTA and JLO cutoff values causing paradoxical changes in HDA were 94° and 4°, respectively.

Conclusion: There was a paradoxical stress increase in the M4 region at the medial compartment, which is associated with MPTA and JLO beyond specific thresholds. Therefore, surgical planning should be cautiously carried out to prevent overcorrection, which can possibly lead to adverse stress distribution changes.

Key terms: High tibial osteotomy, stress distribution, CT-osteoabsorptiometry, osteoarthritis

Clinical relevance: The current study can provide significant implications for surgical planning in HTO, which aims to achieve optimal realignment to decrease adverse stress distribution. MPTA cutoff value of 94° can provide a more precise surgical guidance to prevent overcorrection that can potentially exacerbate stress on the medial compartment. Further long-term follow-up studies are required to confirm clinical outcomes and validate the proposed MPTA threshold in broader HTO candidate subsets.

What is known about the subject: High MPTA and JLO after valgus HTO are associated with deterioration in clinical outcomes and increased shear stress in the medial compartment as shown by simulations.

What this study adds to existing knowledge: In living participants, MPTA of >94° and JLO of 4° after HTO lead to a paradoxical stress increase in the medial compartment. This finding harbor significant implications for surgical planning in HTO, which aims to achieve optimal realignment to decrease adverse stress distribution. MPTA cutoff value of 94° can provide a more precise surgical guidance to prevent overcorrection, which can possibly exacerbate stress in the medial compartment.

Introduction

Valgus high tibial osteotomy (HTO) is a surgical procedure that corrects varus alignment to the valgus to reduce stress in the medial compartment. Three-dimensional gait analysis revealed that knee adduction moment, which is a surrogate for mediolateral force distribution,[14] decreased after HTO.[11] Therefore, the force on the medial compartment shifted toward the lateral compartment.

In a finite element analysis, if the joint line obliquity (JLO) exceeded 5°, shear stress in the medial compartment of the proximal tibial articular surface can possibly increase.[22] However, the changes in lower limb alignment caused by high tibial osteotomy (HTO) correction and the stress distribution on the living joint surface remain unclear.

The distribution of subchondral bone density across the articular surface can reflect the stress distribution in the living joint.[20] Computed tomography (CT)-osteoabsorptiometry aims to analyze the stress distribution on the living joint surface based on the distribution of the subchondral bone density across the articular cartilage.[20] This method was previously utilized to analyze the stress distribution across various joint surfaces.[7, 8, 17, 19, 23, 25] Our previous study demonstrated that the high density area (HDA) decreased on the medial side and increased on the lateral side before and after HTO. These changes were correlated with the hip–knee–ankle (HKA) angle.[6] Further, a detailed analysis revealed that HDA in the medial compartment changed with increased high bone density in the central region of the medial compartment. Therefore, there is increased stress in the central region of the medial compartment.[6] The stress in the medial compartment commonly decreases by changing the lower limb alignment toward the valgus alignment. Thus, increased stress in the central region of the medial compartment was a paradoxical change. These findings were consistent with the results showing that excessive correction increased shear stress on the medial compartment, based on a previous finite element analysis.[22] However, the factors associated with the development of the paradoxical change are not elucidated.

This study hypothesized that there was a paradoxical change in stress in the medial compartment beyond a specific threshold for lower limb alignment alteration. The current study aimed to examine the detailed changes in the distribution of subchondral bone density on the tibiofemoral joint surface before and after HTO to identify the lower limb alignment threshold at which paradoxical change occurs after HTO.

Material and Method

Study design

This clinical study was performed at ### and was approved by the institutional review board (IRB) of ### (IRB number: ##). The patients who underwent HTO for medial compartment osteoarthritis (OA) between 2015 and 2019 at our institution were recruited retrospectively. The inclusion criteria were patients who underwent medial open-wedge HTO (OWHTO). The indications for OWHTO at our hospital were moderate varus leg alignment (HKA of ≥ 10°) and absence of OA in the patellofemoral joint (Kellgren–Lawrence [KL] grade[9] of ≥ II) or anterior knee pain. The exclusion criteria were patients with lateral knee OA (KL grade of ≥ II) or lateral knee pain, those who did not complete the follow-up period of at least 1 year, those who did not undergo metal removal after HTO, those who did not undertake CT scan and clinical evaluation before and after metal removal, those with loss of >15° of knee extension before and after HTO, those with a knee range of motion of < 130° before and after HTO, those with anterior cruciate ligament insufficiency or varus/valgus instability of >10°, and those with a medial meniscal injury of ≥ grade 3 (Lotysch and Mink's magnetic resonance imaging grading system[2, 16]) or massive tear in the medial meniscus managed with massive meniscectomy or other repair procedures, and any lateral meniscal injury. The indication for open-wedge HTO and the inclusion and exclusion criteria of this study were similar to those of the previous study.[6] Finally, 32 knees in 30 patients in the OA group were evaluated (Figure 1).

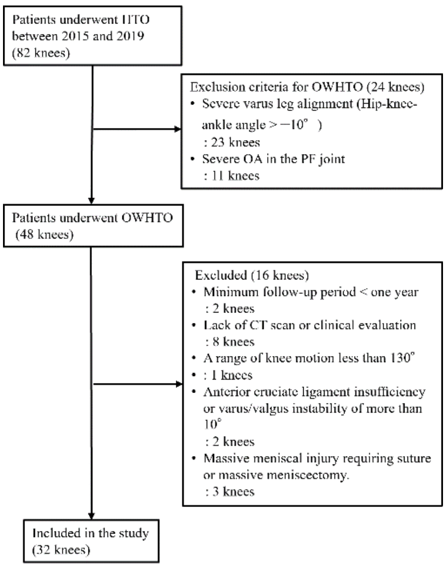

Figure 1. Flow chart of study enrollment

Surgical procedure

The Miniaci's method was used for preoperative planning, as reported in previous studies.[6, 18, 24, 28, 32] The target alignment was 65% of the mechanical axis. All surgical procedures were performed by two surgeons (E.K. and K.I.) using the same principle and technique, as described in a previous study.[6] After the complete release of the distal attachment of the superficial medial collateral ligament, biplanar osteotomy of the tibia was performed. According to the preoperative planning angle, the oblique osteotomy site was gradually opened. Two wedged beta-tricalcium phosphate spacers (Osferion 60; Olympus Terumo Biomaterials) were implanted into the anterior and posterior parts of the opening space. The tibia was fixed with a locking plate (TriS Medial HTO Plate System; Olympus Terumo Biomaterials) by inserting eight locking screws.

Each patient underwent an additional procedure at approximately 1.5 years (mean: 18.3 [range: 14–25] months) after the initial surgery to remove the locking plate.

Evaluation criteria

Clinical evaluation

Patients were evaluated according to the Japanese Knee Injury and Osteoarthritis Outcome Score (KOOS),[21] which is the modified version of KOOS[26] for the Japanese population. The KOOS questionnaire comprises five distinct dimensions, each assessed separately: pain (nine items), symptoms (seven items), daily life function (17 items), sports and recreational activities (five items), and quality of life related to knee health (four items). All individual items were rated on a scale of 0–4, and the total score for each of the five dimensions was calculated as the sum of its respective items. Subsequently, these scores were transformed onto a scale of 0–100, with zero indicating severe knee issues and 100 indicating the absence of any knee issues.

Radiological evaluations

Standing anteroposterior and lateral radiography of the knee and full-length anteroposterior radiography of the whole lower limb with the knee in full extension were performed. The radiological stage of OA was assessed according to the KL grading system.[9] The HKA angle, mechanical lateral distal femoral angle (mLDFA), mechanical medial proximal tibial angle (MPTA), JLO[31], and joint line convergence angle (JLCA) were measured on the anteroposterior radiography of the whole lower limb taken with a long cassette while in the one-leg standing position. The posterior tibial slope (PTS) was defined 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

CT-osteoabsorptiometry was performed using the same protocol in our previous study.[6] A highresolution helical CT scanner (Aquilion One/ViSION Edition; Toshiba Medical Systems, Japan) was used to acquire axial images of the knee. The patients rested in the supine position with their knees extended during imaging. Slice thickness and interval were set at 0.5 mm. The acquired CT scan data were transferred to a personal computer. Sagittal and coronal slices at 1.0-mm intervals and three-dimensional bone models were generated using axial CT scan data with the use of a commercial software (Ziocube®; Ziosoft Inc., Tokyo, Japan). The sagittal and coronal axes were determined based on the epicondylar axis of the distal femoral condyle at the axial slice. According to the sagittal and coronal CT scan images and a three-dimensional CT scan image of the articular surface of the proximal tibia, an outline of the medial and lateral compartment of the proximal tibial articular surface was manually selected to include the whole subchondral bone layer of the articular surface in all slices.[3] Then, the subchondral bone density of each generated sagittal slice was analyzed with a noncommercial software (OsteoDens 4.0) developed at our institution.[3, 5, 23, 25, 30] The maximum increment point in Hounsfield units from the joint surface was 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. The radiodensity of the identified subchondral bone region at each coordinate point at 1-mm intervals was determined. Then, a two-dimensional image that mapped the distribution of the subchondral bone density was obtained by stacking sagittal slices (Figure 2A, 2B). The differences between the maximum and minimum values in Hounsfield units on the mapping images were divided into nine grades. A surface mapping image was generated via the use of these grades to produce a color scale, in which red and violet colors indicated the greatest and lowest bone densities, respectively. The selected areas of the medial and lateral plateaus included the cortical bone or bony spur at the periphery of the articular surface because the cortical bone or bony spur could not be excluded using the software. However, these features were cautiously removed manually from the target area of analysis in the subsequent quantitative analysis.[3]

Quantitative analysis of the obtained mapping data focused on the location of the HDA of the articular surface. The HDA was defined as the region containing the coordinate points representing the top 20% of the Hounsfield unit values 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 four subregions of equal width in the coronal direction, referred to as M1–M4 from the medial to lateral sides. The lateral compartment was divided equally, referred to as L1–L4 from the medial to lateral sides (Figure 2C). The percentage of each subregion represented by the HDA was calculated (%HDA).

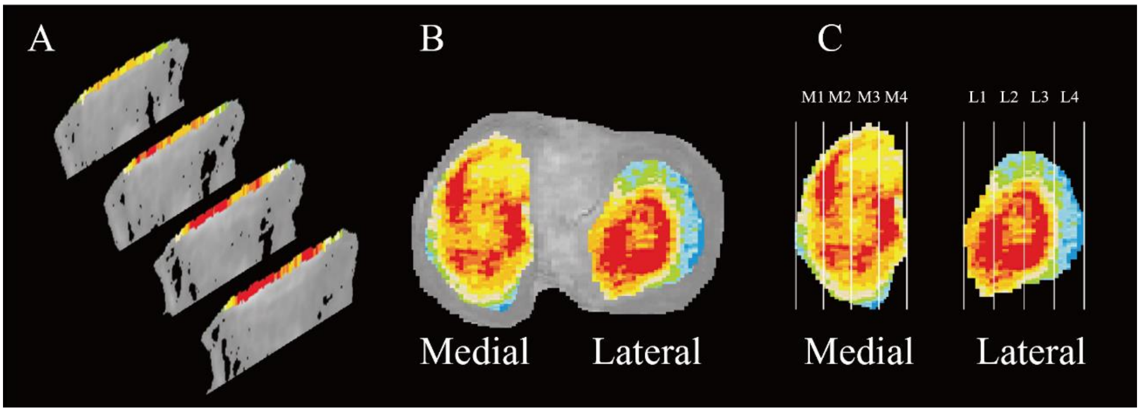

Figure 2. Measurement of the subchondral bone density of the proximal tibia using a customized software. (A) Subchondral bone density of the selected area was automatically measured at each coordinate point in each 1.0-mm sagittal slice. (B) The map including the subchondral bone density was created by stacking the sagittal slice data. (C) M1–M4, subregions of the medial compartment of the proximal tibia, divided equally from the medial to lateral side. L1–L4, subregions of the lateral compartment, divided equally from the medial to lateral side in the same manner.

Statistical analysis

Statistical analyses were performed using JMP Pro 16.0 (SAS Institute Inc., Cary, NC, the USA). A p value of 0.05 was considered statistically significant. The means and 95% confidence intervals (CIs) for the changes before and after OA surgery were calculated. The patients were compared before and after surgery using the paired *t*-test. Paradoxical change was defined as increased HDA at the subregion of the medial compartment or decreased HDA at the subregion of the lateral compartment. Further, the characteristics, clinical outcomes, and radiographic parameters between patients with or without paradoxical changes were compared using the unpaired *t*-test and the chi-square test. The cut-off value of radiographic parameters for the paradoxical change was derived from the receiver operating characteristic curve.

Post-hoc power analysis revealed that an alpha value of 0.05 and a power of 0.96 in a sample size of 31 knees was achieved for medial ratio differences before and after surgery.

The data reproducibility was evaluated using a noncommercial software (OsteoDens 4.0). Intra- and interobserver reliabilities were assessed using three randomly selected knees in the control group and each OA group. Two observers (YF and KI) independently measured %HDA in six knees. In total, 48 subregions were measured twice in a blinded manner at an interval of 1 month. The intraclass correlation coefficients for intraobserver reliability were 0.9003 (YF) and 0.920 (KI), respectively. The intraclass correlation coefficient for interobserver reproducibility was 0.910.

Results

There were significant differences in HKA angle, MPTA, JLO, and JLCA before and after HTO ($P < .01$). The medial ratio decreased by 8% after HTO. The KOOS of the symptom, pain, ADL, sports/recreation, and QOL subgroups improved by 32%, 45%, 39%, 54%, and 96%, respectively (Table 1).

Table 1. Demographic Characteristics of the Patients and Preoperative and Postoperative Findings

	Preoperative findings	Postoperative findings	*P* value
Age, years	59.5 (56.0–63.0)	61.2 (57.8–65.0)	< .01
Male:female	15:17		N/A

BMI, kg^2 × m	27.1 (25.5–28.7)	27.3 (25.6–29.0)	.93
HKAA, degree	−5.6 (−4.5 to −6.7)	4.8 (4.1–5.5)	< .01
mLDFA, degree	88.0 (87.1–88.8)	88.3 (87.4–88.9)	.87
MPTA, degree	84.9 (84.2–85.6)	94.5 (93.6–95.5)	< .01
PTS, degree	11.8 (10.6–14.0)	11.7 (10.4–13.1)	.89
JLO, degree	−0.8 (−2.1–4.5)	2.4 (1.3–3.6)	< .01
JLCA, degree	2.5 (1.9–3.0)	1.4 (0.8–1.9)	< .01
Medial ratio (%)	83.1 (78.6–87.8)	76.7 (70.9–82.5)	< .01
KOOS, points			
Symptoms	62.8 (55.3–70.2)	83.2 (78.1–88.4)	< .01
Pain	57.5 (48.9–66.1)	83.5 (77.3–89.7)	< .01
ADL	63.1 (53.4–72.8)	87.8 (83.2–92.4)	< .01
Sports/recreation	37.7 (27.1–48.3)	57.9 (45.5–70.2)	< .01
QOL	35.5 (25.8–45.2)	69.4 (58.6–80.3)	< .01

Data were presented as mean (95% CI) or ratio. HKA, hip–knee–ankle; mLDFA, mechanical lateral distal femoral angle; MPTA, medial proximal tibial angle; PTS, posterior tibial slope; JLO, joint line obliquity; JLCA, joint line convergence angle; KOOS, Knee Injury and Osteoarthritis Outcome Score

Subregional analysis of subchondral bone density showed that %HDA decreased significantly from 34.8% to 30.0% in the M2 region (P = .02) and significantly increased from 23.6% to 30.2% in the M4 region (P = .01) in the medial compartment. The %HDA in the L4 region significantly increased from 1.0% to 2.7% (P < .01). A paradoxical change occurred in the M4 region (Table 2).

Table 2. Subregional analysis of %HDA[a]

	Preoperative values	Postoperative values	*P* value
M1	19.1 (14.6–23.6)	17.5 (12.8–22.3)	.61
M2	34.8 (30.5–39.1)	30.0 (25.1–34.9)	.02
M3	33.7 (29.2–38.2)	33.4 (28.9–37.8)	.87

M4	23.6 (18.2–30.0)	30.2 (23.7–36.7)	.01
L1	13.4 (8.2–18.5)	12.5 (8.2–16.8)	.73
L2	19.9 (14.9–25.0)	20.1 (14.3–26.0)	.94
L3	6.2 (2.9–9.7)	8.8 (5.4–12.1)	.06
L4	1.0 (0.0–0.2)	2.7 (0.8–4.5)	<.01

[a]Data were expressed as means (95% CI).

The incidence of paradoxical change at the M4 region was in 50.0% (16/32 knees). There were significant differences in MPTA and JLO between patients with paradoxical changes and those without at the M4 region (both $P < .01$) (Table 3). There were no differences in the medial ratio and KOOS subscores between the paradoxical change.

Table 3. Patients with paradoxical change and those without in the subchondral bone density on the medial-compartment of the proximal tibial articular surface after HTO.

	Paradoxical change		*P* value
	(+) (n = 16)	(-) (n = 16)	
Age, years	58.4 (53.4–63.6)	60.4 (55.5–65.4)	.39
Male:female	6:10	9:7	.47
BMI, $kg^2 \times m$	27.6 (25.3–28.9)	26.6 (24.3–28.9)	.46
HKAA, degree	5.2 (4.3–6.2)	4.3 (3.4–5.3)	.20
mLDFA, degree	88.1 (86.9–89.3)	87.8 (86.6–89.0)	.69
MPTA, degree	96.0 (94.9–97.0)	92.9 (91.8–94.0)	.03
PTS, degree	11.4 (9.5–13.3)	12.1 (10.2–14.0)	.60
JLO, degree	3.5 (2.0–5.1)	1.6 (−0.2–2.9)	.04
JLCA, degree	1.6 (0.8–2.6)	1.2 (0.4–2.0)	.47
Medial ratio (%)	76.9 (68.5–85.2)	76.5 (68.2–84.9)	.95
KOOS, points			
Symptoms	81.5 (73.5–89.5)	84.5 (77.7–91.5)	.55
Pain	80.1 (70.6–89.6)	86.1 (77.9–94.4)	.34
ADL	86.7 (79.7–93.9)	88.6 (82.5–84.7)	.69
Sports/recreation	49.6 (30.8–68.3)	64.1 (47.8–80.3)	.24

QOL	66.1 (49.3–83.0)	71.9 (57.3–56.4)	.60

Data were reported as mean (95% CI) or ratio. HKA, hip–knee–ankle; mLDFA, mechanical lateral distal femoral angle; MPTA, medial proximal tibial angle; PTS, posterior tibial slope; JLO, joint line obliquity; JLCA, joint line convergence angle; KOOS, Knee Injury and Osteoarthritis Outcome Score

Receiver operating characteristic curve analysis revealed that the cutoff values for paradoxical change in %HDA at the M4 region were 94° in MPTA and 4° in JLO (Figure 3).

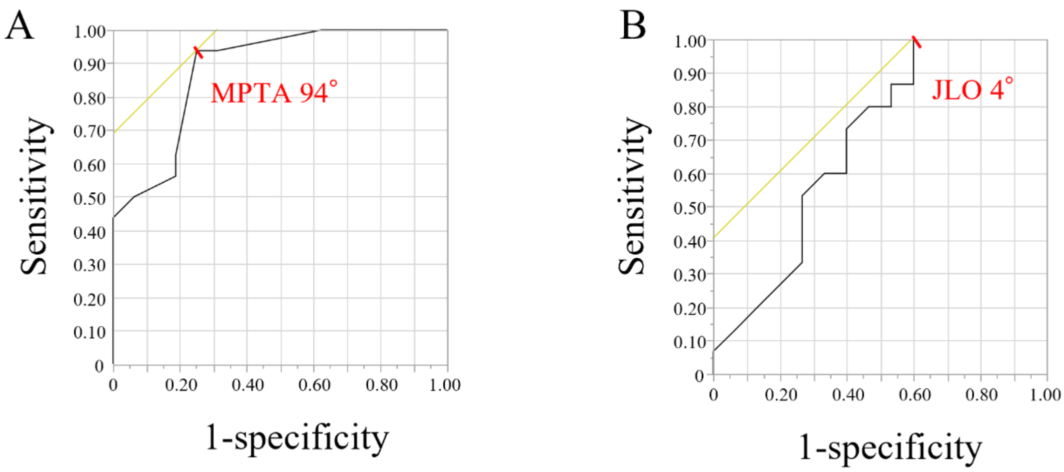

Figure 3. Receiver operating characteristic curve for the paradoxical change in %HDA at the M4 region, with a cutoff MPTA and JLO of 94° and 4°, respectively.
MPTA, medial proximal tibial angle; JLO, joint line obliquity

Discussion

This study showed that the medial ratio decreased after HTO. The average %HDA in the M4 region increased (paradoxical change) among the four regions within the medial compartment. The factors associated with paradoxical change in the M4 region were MPTA and JLO, with cutoff values of 94° and 4°, respectively.

The decreased medial ratio indicated a shift of stress from the medial to lateral compartment. Similar to our previous report,[6] paradoxical change was observed in the M4 region, and stress in the M4 region increased with MPTA of 94° or JLO of 4°. Finite element analysis showed that compressive forces did not exhibit significant changes until JLO reached 7.5°. However, shear forces increased from JLO of 5° onward.[22] In this study, JLO of 4° was as the cutoff value, which was consistent with the notion that overcorrection with HTO leads to increased stress in the medial compartment.

It was challenging to accurately predict postoperative JLO. Previous reports have shown that JLO of 3° corresponds to MPTA of approximately 93°–97° according to correlation plots. However, the correlation coefficients (r) in these studies varied from 0.42 to 0.67, [1, 4, 12, 13] thereby indicating a moderate correlation at the best. In contrast to the elusive predictability of JLO, MPTA is a surgically controllable factor. Therefore, based on the findings of this study, setting the cutoff value at MPTA of 94° can provide a valuable surgical planning indicator, thereby offering a more reliable guide for the surgeon's decision-making compared with the unpredictable JLO.

A cutoff JLO value of 6° increases the risk of narrowing of the joint space at the medial compartment within an average of 4 years after HTO.[31] However, the likelihood of increased stress in the M4 region occurs with MPTA of 94° or JLO of ≥ 4°, which is smaller than JLO of 6°. This implied that increased stress might not directly lead to the narrowing of the joint space of the medial compartment and was more likely to be associated with clinical cartilage wear caused by a greater joint surface inclination.

The study results did not provide clear evidence on the association between paradoxical change in the M4 region and clinical outcomes. Previous studies on postoperative JLO or MPTA and their association with clinical outcomes have yielded different results. Some reports revealed that clinical outcomes were worse with a JLO of >4°[31] or MPTA of 95°,[1, 12, 29] Meanwhile, others have shown no significant association between JLO or an MPTA of >95° and clinical outcomes. Rosso et al.[27] reported that clinical outcomes did not significantly differ between cases with MPTA of >95° and those with MPTA of < 95° when they excluded cases with HKA of ≤5° or >5° as technical errors in a 10-year follow-up on HTO. Therefore, the variability in JLO, which changes based on the position of the foot, may lead to low reproducibility. Moreover, reports on the association between poor and a large JLO or MPTA might be influenced by cases with excessive overcorrection, including those with MPTA >100°. Goshima et al.[4] and Kim et al.[10] reported no significant difference in terms of clinical outcomes between cases with MPTA of ≥ 95° and those with MPTA of < 95°, even when including cases with postoperative HKA differences of ≥ 5° in the study of Goshima. Lee et al.[15] reported that the postoperative JLO was not associated with 1-year clinical outcomes after HTO. Therefore, the association between postoperative JLO, MPTA, and clinical outcomes should be further investigated. MPTA of 94°, as proposed in this study, can be a novel reference point in terms of stress changes on the joint. However, its direct association with clinical outcomes at the 1.5-year follow-up was not evident, and longer-term observations may be necessary.

In the population of the current study, MPTA can be ≤ 94° with a target HKA of 3° if the postoperative JLCA and mLDFA were 2.0° and ≤ 87°, respectively. At our hospital, cases with mLDFA of >90° (n = 6) are currently considered suitable for double level osteotomy (DLO). After excluding cases with mLDFA of >90°, 13 (50%) of 26 presented with mLDFA of >87°. In these cases, correcting the tibial side alone could result in a MPTA of >94°. By only considering the occurrence of paradoxical change, DLO may be necessary rather than HTO in half of cases. However, to correct mLDFA to the normal lower limit of 84° by DLO in cases with mLDFA of 87°, a correction of 3° was required, which may be technically challenging and invasive. Some studies[4, 10] indicating no significant difference in clinical outcomes with MPTA of ≥ 95° may imply that it is overly stringent to aim for MPTA of ≥ 94° based on our study results. Although excessive overcorrection of MPTA is not desirable, it is important to maintain a realistic approach in surgical planning.

This study had several limitations. First, the CT-osteoabsorptiometry method only estimates stress from the bone density distribution beneath the cartilage, and it does not directly measure the actual stress on the joint surface. However, currently, there is no method available for directly measuring stress on the joint surface in living organisms; hence, using this technique for stress estimation is valuable. Second, we assessed patients after the removal of metal components. A finite element analysis has been used to identify the stress shielding effect of the HTO plate on the bone surrounding it. However, the mechanisms behind this effect on the articular surface remain unclear. In addition, the stress shielding effect caused by the plate disappeared after the osteotomy site had completely healed. Therefore, in this study, the metal was removed after confirming that the bone has healed sufficiently, with an average of 1.5 years postoperatively. Consequently, the impact on load distribution to the joint surface was even smaller. Third, the small sample size, as it was limited to cases of OWHTO. However, CWHTO was excluded from this study due to the risk of different stress alterations caused by fibular osteotomy compared with OWHTO. In addition, cases that could possibly affect stress distribution, such as those with meniscal injury requiring massive meniscectomy or joint instability, were excluded in this study. Consequently, the research focused on cases with minimal preoperative varus deformity, and it analyzed a subset of the usual candidates for HTO. However, the number of cases has increased since the previous study,[6] and the reliability of the results in this study improved.

Conclusion

Although the stress shifted from the medial to the lateral side after OWHTO, a paradoxical stress increase was observed in the M4 region of the tibial joint surface. MPTA and JLO cutoff values were 94° and 4°, respectively. In knee valgus osteotomy for varus osteoarthritis, caution is required as excessive joint line obliquity can lead to increased stress on the medial joint surface.

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