The effect of the inverted V-shaped osteotomy on the patellofemoral joint and tibial morphometry compared to the medial opening wedge high tibial osteotomy.

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Footnotes

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ABSTRACT

Background: Recent studies have reported that medial opening wedge high tibial osteotomy (OW-HTO) induces patella baja, resulting in the degenerative change of the patellofemoral (PF) joint. The authors have developed an inverted V-shaped (iV) HTO, which is classified as a neutral wedge osteotomy.

Hypothesis: The study hypotheses were as follows: (1) The patellar height, the posterior tibial slope, and the tibial length will not change between pre- and post-operative evaluations after iV-HTO. (2) The lateral shift ratio of the patella and the distance between the tibial tubercle and the trochlear groove (TT-TG) may be significantly decreased after iV-HTO.

Study Design: Retrospective comparative study; Level of evidence, 3.

Methods: 191 patients (220 knees) who underwent HTO for medial osteoarthritis (OA) were enrolled retrospectively in this study. In the OW group, 107 knees underwent OW-HTO. In the iV group, 113 knees underwent iV-HTO. Clinical and radiological evaluations were performed before and at least 3 years after surgery.

Results: Postoperatively, the mean Caton-Deschamps ratio was significantly decreased ($p<0.0001$) from 0.95 to 0.79 in the OW group, while there were no significant changes in the iV group. The mean posterior tibial slope was significantly increased ($p<0.0001$)

from 8.5° to 10.5° in the OW group, while there were no significant differences in the iV group. Although the entire leg length was significantly increased ($p<0.0003$) after both groups, there were no significant differences in the tibial length between the pre- and post-operative periods in the iV group. Regarding the congruity of PF joint, the mean lateral shift ratio did not significantly change in the OW group, whereas it was significantly decreased ($p=0.0012$) from 11.5% to 8.8% in the iV group. The mean TT-TG distance was significantly decreased ($p<0.0001$) from 12.8 mm to 9.7 mm in the iV group, while it was significantly increased in the OW group ($p<0.0001$). Concerning the clinical outcome, the Japanese Orthopaedic Association (JOA) score and the Lysholm knee scores were significantly increased ($p<0.0001$) at the final follow-up (JOA score: 91.2 points and 90.1 points, in the OW and iV groups, respectively; Lysholm score: 92.5 points and 89.0 points, in the OW and iV groups, respectively) compared with the preoperative value (JOA score: 68.3 points and 66.8 points, in the OW and iV groups, respectively; Lysholm score: 67.9 points and 61.0 points, in the OW and iV groups, respectively) in both groups.

Conclusion: The patellar height, the posterior tibial slope, and the tibial length did not change after the iV-HTO, while they were significantly changed after the OW-HTO. Although the preoperative degrees of varus knee and PF-OA were more severe in the iV group than those in the OW group, the iV group led to an altered PF joint congruity.

Key words: high tibial osteotomy; open wedge; patellofemoral joint, Osteoarthritis

INTRODUCTION

Recently, medial opening-wedge (OW) high tibial osteotomy (HTO) has been widely performed since the improved procedure was introduced,[8,13,25,50-53,61,74] which included biplanar osteotomy and fixation with a locking plate system.[40,68] Recently, however, it has been reported that the OW-HTO has several disadvantages.[10,23,43,46,72,74] First, it is technically difficult to obtain a valgus correction of 15° or greater without any surgical problems. [46,72,74] Second, the patellar height decreases after surgery.[10,23,31,32,43,73,74] Third, the length of the lower limb increases after surgery.[35,42,74] Fourth, the posterior tibial slope (PTS) angle of the tibial plateau increases after surgery. [7,12,16,17,18,28,32,49,63] On the other hand, lateral closing-wedge (CW) HTO does not have any of these disadvantages. However, the CW-HTO has different types of disadvantages. First, the length of the lower limb decreases after surgery.[35,42,] Secondly, the bone mass is reduced in the lateral tibial plateau, resulting in difficulty of potential total knee arthroplasty (TKA).[5,36,76] Thirdly, several investigators have reported that the complication rate of the CW-HTO is high, such as a delayed union, correction loss, and compartment syndrome.[5,66,70] Therefore, an alternative HTO procedure without these disadvantages should be developed for knee osteoarthritis (OA) with moderate or severe varus deformity.

Inverted V-shaped HTO (iV-HTO), which is classified as a neutral (hemi-closing and hemi-opening) wedge osteotomy, is a potential HTO procedure to solve these disadvantages (Figure 1).[5,36,76] Namely, in this procedure, the centre of tibial alignment correction (hinge point) of the HTO is located approximately at the centre of rotation of angulation (CORA) of the lower limb deformity.[36] According to the principle of the bone deformity correction,[55] it is expected that this procedure does not affect the patellar height, the tibial length, or the bone mass of the tibial plateau. The first clinical outcome of the iV-HTO, in which an external fixator was used to fix the osteotomized tibia, was reported by Aoki et al[5] in 2006. They reported that the 10-year follow-up results were significantly better than CW-HTO. However, this procedure had a few disadvantages. First, it was technically difficult for surgeons to precisely perform the iV osteotomy. Secondly, 10 to 12 weeks were needed to allow for weight-bearing after surgery. To solve these disadvantages, the authors recently modified the original procedure by developing cutting guide devices to precisely perform the biplanar osteotomy and a locking plate system for lateral tibial fixation.[36] However, the influence of the iV-HTO procedure to the patellar height, the PTS, or the tibial length has not been clinically evaluated as of yet. Moreover, clinical results of the modified iV-HTO procedure have not been reported.

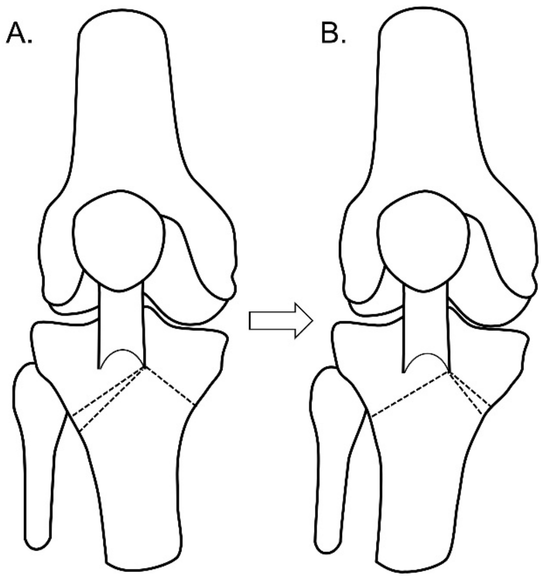

Figure 1. Diagrams of an inverted V-shaped osteotomy showing (A) a wedge of bone resected from the tibia beneath the lateral plateau in the shape of an inverted 'V' and (B) valgus correction and grafting of the resected wedged bone block into the triangular gap created beneath the medial plateau.

Thus, the authors have conducted a comparative study to compare the influence of HTO to the patellofemoral (PF) joint and the tibial dimension between the modified iV-HTO and the OW-HTO procedures, based on comparison of the radiological and clinical results of these procedures. The following hypotheses have been made in this study: (1) The patellar height, the PTS, and the tibial length will not change between pre- and post-operative evaluations after the iV-HTO, while they may significantly change after OW-HTO. (2) The tilting angle and the lateral shift ratio of the patella, and the distance between the tibial tubercle and the trochlear groove (TT-TG) may be significantly decreased after the iV-HTO in comparison with the preoperative values, while they may not change after OW-HTO. The purpose of this study is to test these hypotheses.

METHODS

Study Design

This retrospective comparative study involved 234 knees of 203 patients who underwent HTO from April 2010 to March 2017 in our hospital. The following study protocol was approved by an institutional review board, and each participant provided their informed consent. The indication for HTO was a medial OA knee or a varus knee with spontaneous osteonecrosis of the knee (SONK) in the medial compartment, and pain which was not reduced by conservative treatment for 3 months or more. Exclusion criteria for HTO were (1) patients who had an extension loss of >15°; (2) patients who had a range of knee motion <130°; (3) patients who had a history of infection in the knee before surgery; (4) patients who had anteroposterior insufficiency or varus/valgus instability of >10°. There were no age restrictions.[22]

In the present study, HTO was performed using the iV-HTO procedure (iV group) or OW-HTO procedure (OW group), according to the following indications. The indication of the iV-HTO included (1) a knee in which a valgus correction of 15° or more was needed to change the mechanical axis of the lower limb to 65%, or (2) a knee having PF-OA of stage 3 or more.[54] On the other hand, the indication of the OW-HTO involved

(1) a knee in which a valgus correction of 14° or less was enough to change the mechanical axis to 65%, and (2) a knee having PF-OA of stage 0, 1 or 2. Two senior orthopaedic surgeons (E.K. and K.Y.), who were sufficiently trained concerning the procedures, performed all operations. Each knee was radiologically evaluated 3 times, preoperatively, immediately after surgery, and at 3 years after surgery. Each knee was clinically evaluated twice, preoperatively and at 3 years after surgery.

Preoperative Planning

Preoperative planning with an appropriate correction angle of the tibia was performed by a standing full length lower limb anteroposterior radiograph. The surgical planning methods have been previously described.[36,74] In the OW group, the hinge point 'P' is located at approximately 5 mm medial from the proximal tibiofibular joint (Figure 2A). In the iV group, the hinge point 'P' is located at approximately at the medial edge of the tibial tubercle (Figure 2B). First, a 'line A' is drawn from the centre of the femoral head through the point 65% lateral from the medial edge of the tibial plateau on the lateral tibial plateau, because sufficient valgus correction is needed to obtain excellent 10-year results.[48,60,67,77] Second, a 'line B' is drawn from hinge point P to the centre of the talar dome. Then an arc C, the centre and the radius of which are the hinge point P and line B, respectively, is drawn so that the arc is across line A. Next, a 'line D' is drawn from hinge point P to the crossing point between line A and arc C. The angle formed between line B and line D provides the correction angle. However, double-level osteotomy should be considered for varus knees with the preoperatively anticipated medial proximal tibial angle (MPTA) of more than 95°.[47]

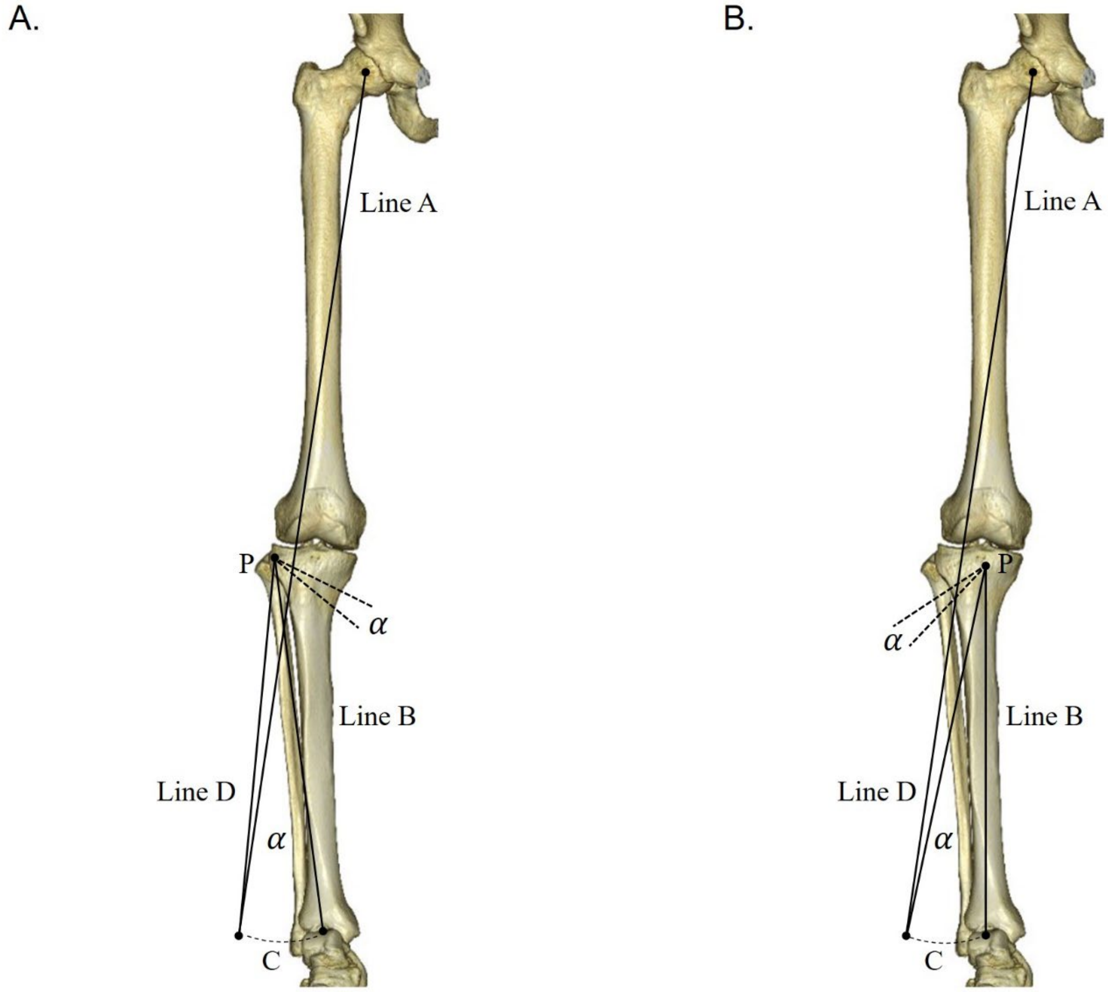

Figure 2. Preoperative planning

In the OW group, the hinge point ‘P’ is located at approximately 5 mm medial from the proximal tibiofibular joint (A). In the iV group, the hinge point ‘P’ is located at approximately at the medial edge of the tibial tubercle (B). First, a ‘line A’ is drawn from the centre of the femoral head through the point 65% lateral from the medial edge of the tibial plateau on the lateral tibial plateau. Second, a ‘line B’ is drawn from hinge point P to the centre of the talar dome. Then an arc C, the centre and the radius of which are the hinge point P and line B, respectively, is drawn so that the arc is across line A. Next, a ‘line D’ is drawn from hinge point P to the crossing point between line A and arc C. The angle (alpha) formed between line B and line D provides the correction angle.

Arthroscopy and additional treatment

Diagnostic arthroscopy was performed with standard anterolateral and anteromedial parapatellar portals to confirm that there was an isolated medial compartment OA or SONK. Concomitant procedures can be performed to address medial compartment chondral injury or meniscal disease.

Surgical Procedure of OW-HTO

This surgery was performed with the original procedure.[52] The proximal tibia was exposed through a 7-cm medial longitudinal incision. Then, after the complete release of the distal attachment of the superficial medial collateral ligament (sMCL),[62] guidewires were inserted into the tibia so that each guidewire precisely reached the proximal tibiofibular joint. In several biomechanical studies, release of the sMCL is essential for osteotomy procedure when performing OW-HTO.[2,6,40,56] This procedure is necessary to avoid not only an increase in medial joint pressure and the PTS, but also neurovascular injury by inserting a protector to the posterior tibia during surgery. Next, an ascending biplanar osteotomy of the tibial tubercle was performed. The oblique osteotomy site was then gradually opened using a specially designed spreader (Olympus Terumo Biomaterials, Tokyo, Japan) based on preoperative planning. Then, two wedge-shaped beta-tricalcium phosphate spacers (Osferion 60, Olympus Terumo Biomaterials) were implanted into the opening space. Finally, the tibia was fixed with a locking plate system (Tomofix, DePuy Synthes, West Chester, PA or TriS Medial HTO plate system, Olympus Terumo Biomaterials) (Figure 3).

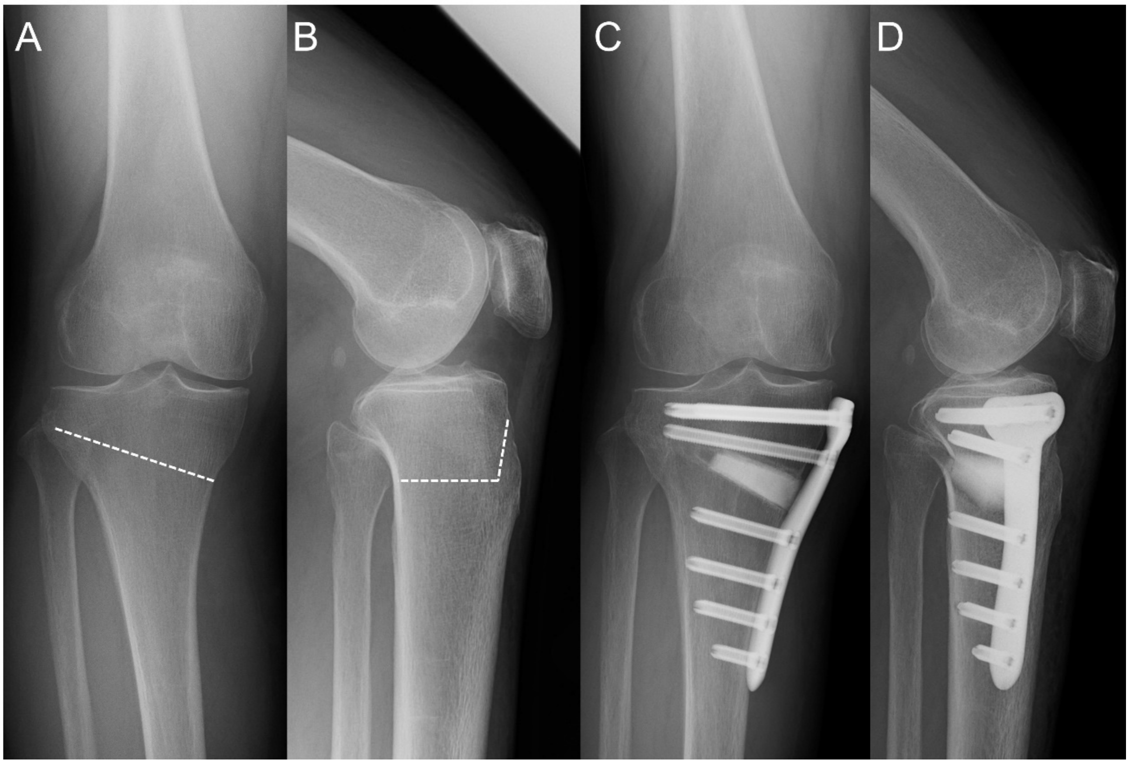

Figure 3. Pre- and post-operative radiographs in OW-HTO.
(A) Anteroposterior radiograph before OW-HTO. (B) Lateral radiograph before OW-HTO. (C) Anteroposterior radiograph after OW-HTO. (D) Lateral radiograph after OW-HTO. Dotted line: Osteotomy line

Surgical Procedure of iV-HTO

The details of the iV osteotomy procedure have been previously described.[36,76] A longitudinal incision was made at the posterolateral aspect of the mid lower leg. A long oblique osteotomy was made at the central portion of the fibula.[76] A 10-cm anterolateral curved skin incision was made at the proximal tibia. The anteromedial and posterolateral periosteums were peeled from the tibia along the medial and lateral osteotomy lines. The surgeon determined the apex point of the iV osteotomy, which was located approximately at the point where the medial edge of the patella tendon was attached to the tibial tubercle. A guidewire was then inserted at this point. The Wedge Cutting Guide (Olympus Terumo Biomaterials) was attached to the apex wire. The 2 pairs of guidewires were inserted into the tibia toward the apex wire. First, a coronal ascending osteotomy was made. Second, a lateral hemi-wedge bone resection was performed along the guidewires. Third, a Parallel Drill Guide (Olympus Terumo Biomaterials) was attached to the apex wire and the medial aspect of the tibia. Parallel holes were drilled into the tibia along the medial osteotomy line. Then, the medial side of the tibia undergoes an osteotomy along the previously drilled holes. The surgeon performed a valgus correction of the tibia by manually applying a valgus force to the knee. The locking plate (TomoFix Lateral High Tibia Plate; DePuy Synthes, or Tris lateral tibia plate, Olympus Terumo Biomaterials) was fixed on the lateral side of the tibia. Finally, the resected bone block was implanted in the medial opening space (Figure 4).

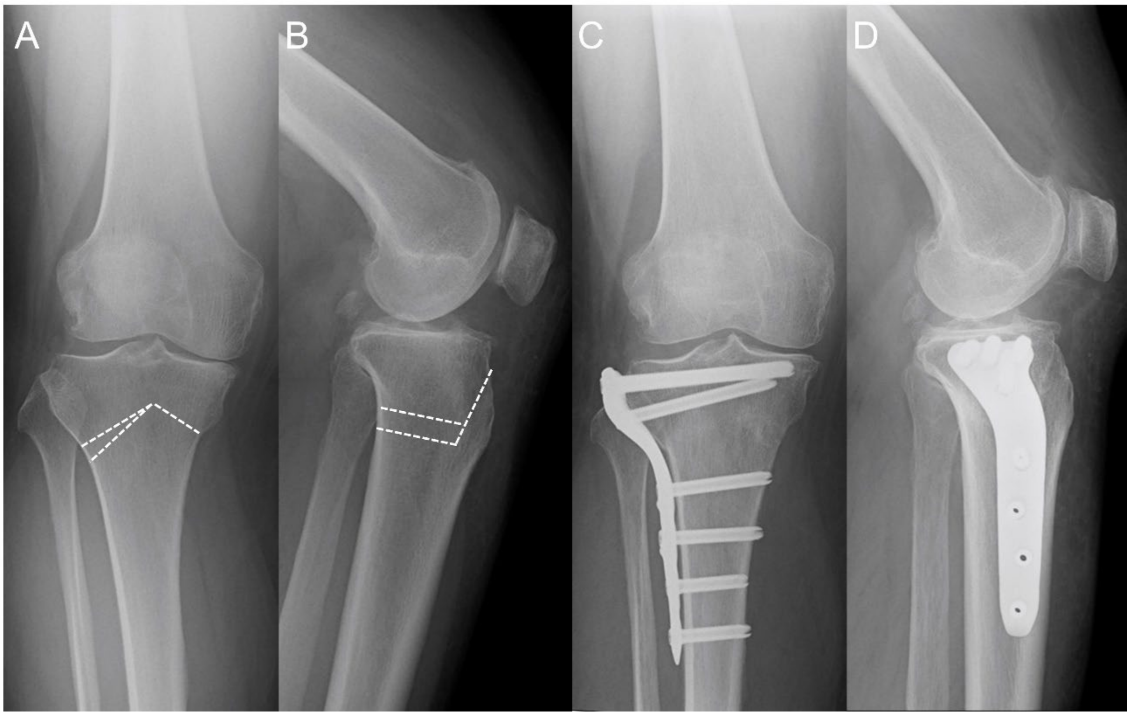

Figure 4. Pre- and post-operative radiographs in iV-HTO.
(A) Anteroposterior radiograph before iV-HTO. (B) Lateral radiograph before iV-HTO. (C) Anteroposterior radiograph after iV-HTO. (D) Lateral radiograph after iV-HTO. Dotted line: Osteotomy line

Postoperative rehabilitation

After surgery, all the patients underwent postoperative management using the same rehabilitation protocol reported previously.[36,52] Straight leg raising and quadriceps setting exercises as well as active and passive knee motion exercises were encouraged from the day after surgery. Partial weight-bearing on the tibia was permitted with crutches at 2 weeks after surgery. Full weight-bearing was allowed at 4 weeks after surgery.

Radiological evaluation

The following radiological outcomes were evaluated preoperatively, immediately after surgery, and at 3 years after surgery. The degree of OA at the FT and PF joints was evaluated using the Kellgren–Lawrence classification.[34] The hip–knee–ankle angle (HKA), defined as the angle between the femoral mechanical axis and the tibial mechanical axis, the FTA, defined as the angle between the anatomical axis of the femoral shaft and the axis of the tibial shaft on the fibular side, and the MPTA, defined as the angle between the proximal tibial joint line and the mechanical axis of the tibial shaft, were measured on an anteroposterior radiograph of the whole lower limb taken with a long cassette in the one-leg standing position with the knee joint in extension (Figure 5). To calculate the mechanical axis, a line was drawn from the centre of the femoral head to the middle point of the proximal talar joint surface. The mechanical axis percentage was defined as the horizontal distance from the mechanical axis to the medial edge of the tibial plateau, divided by the width of the tibial plateau. The entire leg length was defined as the distance between the top of the femoral head and the centre of the tibial plafond. The tibial length was defined as the distance between the centre of the proximal tibia and the centre of the medial tibial plafond. The Insall-Salvati (IS) ratio,[29] the Caton-Deschamps (CD) ratio[11] and the PTS[4] were estimated on lateral radiographs. The PTS was measured as the angle between the line perpendicular to the mid-diaphysis of the tibia and the posterior inclination of the medial tibial plateau on the lateral view. The patellar tilting angle and lateral shift ratio[9,75] were estimated in the skyline view with the knee flexed to 30°. The tilting angle was defined as the angle between the line intersecting the widest bony structure of the patella and the line tangentially passing the anterior surface of the femoral condyles. The lateral shift was defined as the ratio of the distance between the summit of the lateral femoral condyle and the point at which a line from the lateral edge of the patella that is perpendicular to the line that passes through the summits of the femoral condyles crosses that line to the distance between the summits of the medial and lateral femoral condyles of the femur.

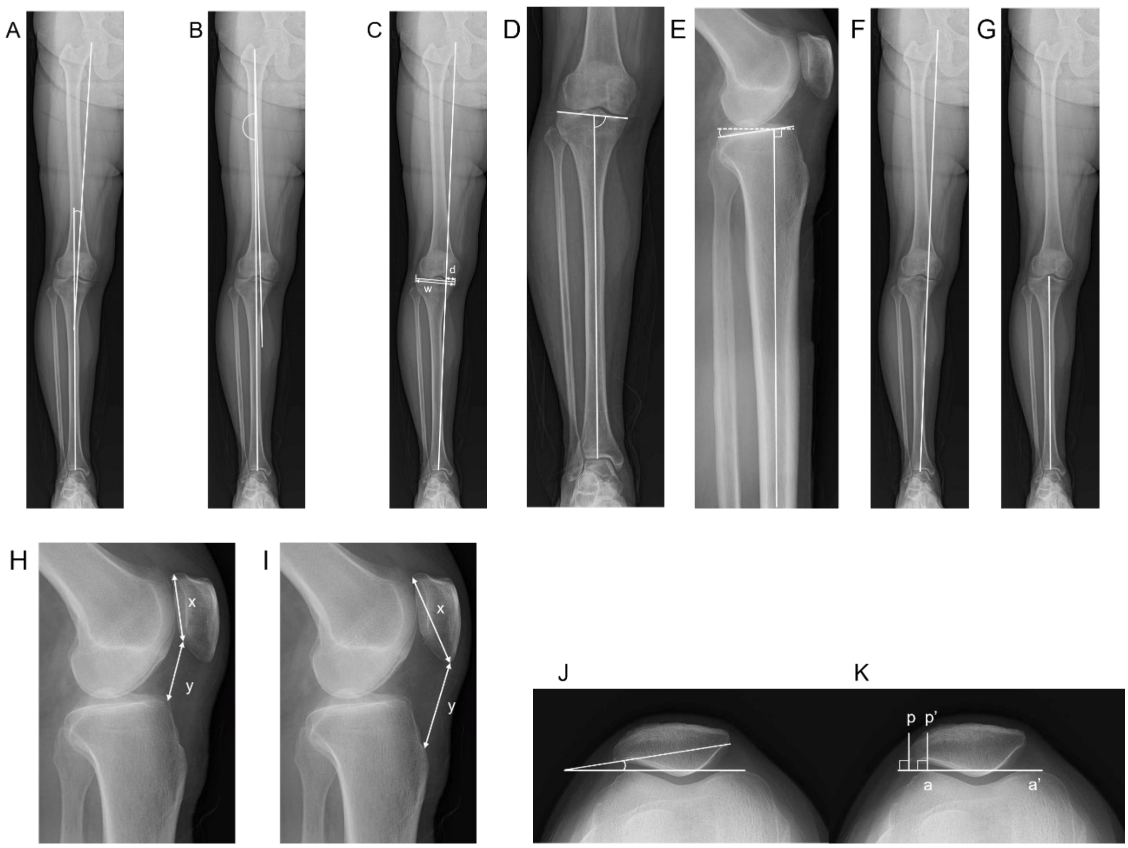

Figure 5. Radiographic assessments.

(A) Hip–knee–ankle angle (HKA). The HKA was defined as the angle between the femoral mechanical axis and the tibial mechanical axis. (B) Femorotibial angle (FTA). The FTA was defined as the angle between the anatomical axis of the femoral shaft and the axis of the tibial shaft on the fibular side. (C) Mechanical axis of the lower limb. A mechanical axis line was drawn from the centre of the femoral head to the middle point of the proximal talar joint surface. The mechanical axis percentage was defined as the horizontal distance from the mechanical axis line to the medial edge of the tibial plateau (d), divided by the width of the tibial plateau (w). (D) Medial proximal tibial angle (MPTA). The MPTA was defined as the angle between the proximal tibial joint line and the mechanical axis of the tibial shaft. (E) Posterior tibial slope (PTS). The PTS was defined as the angle between the line perpendicular to the mid-diaphysis of the tibia and the posterior inclination of the medial tibial plateau. (F) Entire leg length. The entire leg length was defined as the distance between the top of the femoral head and the centre of the tibial plafond. (G) The tibial length was defined as the distance between the centre of the proximal tibia and the centre of the tibial plafond. (H) Caton-Deschamps (CD) ratio. The CD ratio was defined as a ratio of the distance (x) between the inferior pole of the patella and the antero-proximal edge of the tibial plateau divided by the patellar length (y). (I) Insall-Salvati (IS) ratio. The IS ratio was defined as a ratio of the length of the patella tendon (the distance between the inferior pole of the patella and the tibial tubercle (x)) divided by the patellar length (y). (J) Tilting angle. The tilting angle was defined as the angle between the line intersecting the widest bony structure of the patella and the line tangentially passing the anterior surface of the femoral condyles. (K) Lateral shift ratio. The lateral shift ratio was defined as the ratio of the distances pp'/aa'. aa' is defined as the distance between the summits of the medial and lateral femoral condyles. pp' is defined as the distance between the summit of the lateral femoral condyle and the point where a line from the lateral edge of the patella perpendicular to the line that passes through the summits of the femoral condyles crosses that line.

The TT-TG distance[24] was measured from 2 superimposed CT slices, one through the floor of the groove where the intercondylar notch has a Norman arch shape, and the other through the middle of the tibial tubercle (Figure 6).

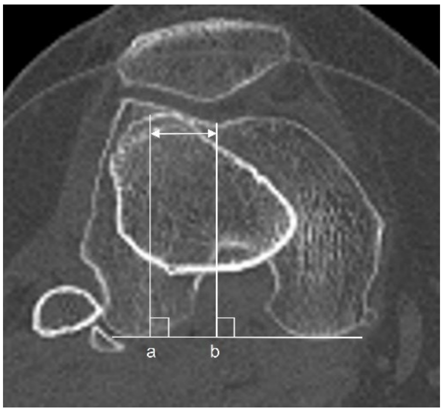

Figure 6. The distance between the tibial tubercle and the trochlear groove (TT-TG). The TT-TG distance was measured from 2 superimposed CT slices, the distance was defined between the centre of the tibial tubercle (a) on one image and the trochlear groove perpendicular to the posterior femoral condyles (b) on a second image.

Clinical evaluation

The patients were evaluated by use of the Japanese Orthopaedic Association (JOA) score[5,77] and Lysholm knee score[41] at preoperative and final follow-up periods in our outpatient clinic. The JOA score is the standard knee function scale in Japan. Based on a previous study,[5,77] the results were graded as good for total JOA scores of 85 to 100 points, fair for 70 to 84, and poor for 69 or less.

When a complication was clinically or radiologically detected during surgery or follow-up, it was recorded in the electronic medical record system.[66,74] Intraoperative lateral hinge fractures were evaluated according to Takeuchi et al.[72]

Statistical analysis

An a priori power analysis was performed. Based on our previous studies,[5,31,52,62] a sample size of 191 patients (220 knees) was calculated to have greater than 85% power to test the hypothesis. All data are shown as means with a standard deviation. The paired Student t-test was used to assess the clinical and radiological differences between before and after surgery. The Mann–Whitney U test and the chi square test were used to assess the demographic parameter, the clinical and radiological differences between the OW and iV groups. JMP Pro10.0 for Windows (SAS Institute Japan) was used for statistical analyses. The significance level was set at $p = 0.05$.

RESULTS

Follow-up examinations

Consequently, in the 234 knees, 118 knees underwent iV-HTO and 116 knees underwent OW-HTO (Figure 7). The authors tried to follow up these knees for 3 years or more after surgery in the outpatient clinic. However, 12 patients (14 knees) were lost to follow-up. Therefore, a total of 220 knees of 191 patients were subjects in this study. Among the subjects, 113 knees of 93 patients underwent iV-HTO (iV group), while 107 knees of 98 patients underwent OW-HTO (OW group). Patients underwent follow-up at an average of 65.7 months (range, 40.1-132.1 months) and 67.2 months (range, 39.9-135.5 months) in the OW and iV groups, respectively.

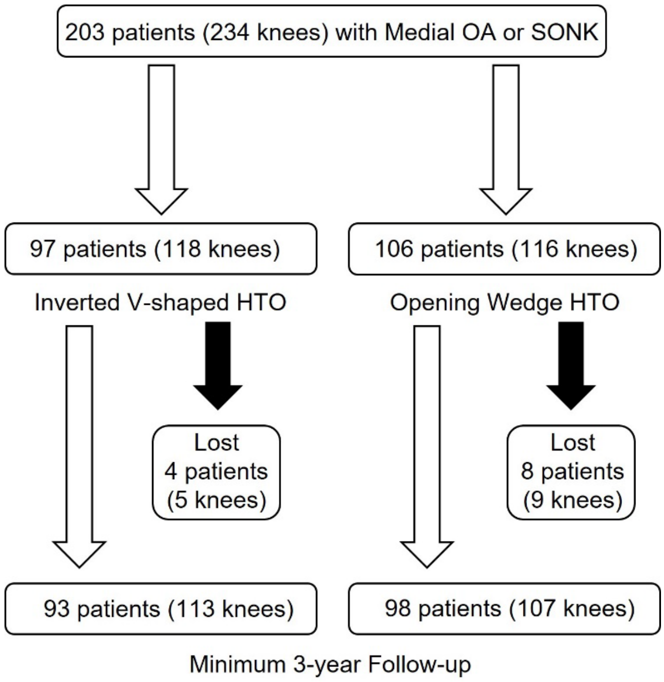

Figure 7. Follow-up examinations.
HTO, high tibial osteotomy; OA, osteoarthritis; SONK, spontaneous osteonecrosis of the knee.

Patient Demographics

There were 65 men and 126 women with a mean age of 61.0 years (range; 41 to 81) at the time of surgery. Their background characteristics are shown in Table 1.

TABLE 1. Background characteristics and Radiographic OA grade of the patients[a]

	OW group (n=98, 107 knees)	iV group (n=93, 113 knees)	p value
Age (years)	62.5 (6.6) (range: 42-78)	59.9 (9.1) (range: 41-81)	0.0366
Male/Female (patients)[a]	28/70	37/56	0.1021
Rt/ Lt[a]	47/60	61/52	0.1105
Unilateral/ Bilateral[a]	89/9	73/20	0.0177
Height (cm)	157.3 (7.9)	160.1 (9.0)	0.0244
Weight (kg)	64.7 (10.9)	67.5 (12.9)	0.0891
Body mass index (kg/m²)	26.1 (3.9)	26.2 (3.9)	0.9840
Femorotibial grade[a,b] (No. of Knees)			< 0.0001[c,d]
Preoperative/Final Follow-up			
Grade 0	0/0	0/0	
Grade 1	2/1	2/1	
Grade 2	30/29	15/11	
Grade 3	71/72	61/63	
Grade 4	4/5	35/38	
Patellofemoral grade[a,b] (No. of Knees)			< 0.0001 [c,d]
Preoperative/Final Follow-up	*		
Grade 0	22/17	10/7	
Grade 1	75/67	29/27	
Grade 2	10/18	39/41	
Grade 3	0/5	26/29	
Grade 4	0/0	9/9	
Length of follow-up periods (Mo)	65.7 (21.8) (range:40.1-132.1)	67.2 (17.6) (range: 39.9-135.5)	0.1902

[a]Data except for patient sex, rt/lt, uni/bilateral, and femorotibial and patellofemoral grades are reported as mean (standard deviation).

[b]Determined via the Kellgren-Lawrence grading system.

[c]Preoperative OW group vs iV group.

[d]Postoperative OW group vs iV group.

*Significant difference between pre- and post-operative values.

Additional Treatment

Degenerative findings were observed in the medial menisci of all cases. Partial meniscectomy was performed for unstable meniscal tears in 127 knees. Debridement was performed for fragmentation of the cartilage. No treatment was administered for softening or fissuring of the articular cartilage. Osteochondral autograft transfer was carried out in 14 knees using the OATS system (Arthrex, Naples, FL, USA). A donor graft was harvested from the lateral femoral trochlea.

TABLE 2. Arthroscopy and Additional treatment

	OW group (n=98, 107 knees)	iV group (n=93, 113 knees)	p value
Partial menisectomy Medial meniscus	68 knees	59 knees	0.0888
Suture Medial meniscus	4 knees	6 knees	0.5760
Osteochondral autograft transfer Medial femoral condyle	9 knees	5 knees	0.2260

Radiological evaluation

The demographic parameters and the results of the radiographic measurements are listed in Tables 1, 3 and 4. Concerning the preoperative OA grades at FT and PF joints, the iV group was significantly higher than the OW group (p<0.0001) (Table 1). In the iV group, no significant differences were seen between the pre- and postoperative radiographic FT- and PF-OA grades (Table 1). In the OW group, significant PF-OA progression was found at the final follow up ($p=0.0388$). Regarding preoperative coronal lower leg alignment, the iV group had severe varus deformity (Table 3). The preoperative values for the HKA, FTA, mechanical axis, and MPTA were significantly higher in the iV group than in the OW group ($p<0.0001$). Postoperatively, the HKA, FTA, mechanical axis, and MPTA changed significantly ($p <0.0001$) compared with the preoperative values in both groups. There were no significant differences in the postoperative HKA, FTA, mechanical axis, and MPTA between the two groups. There was no significant difference in each parameter between the immediately after surgery and final follow-up periods in both groups.

Postoperatively, the PTS was significantly increased in the OW group ($p<0.0001$), while there were no significant differences in the iV group (Table 3). The postoperative PTS was significantly higher ($p<0.0031$) in the OW group than in the iV group.

Concerning the leg length, the postoperative entire leg length and tibial length were significantly increased after surgery compared with the preoperative values in the OW group ($p<0.0001$) (Table 3). Although the entire leg length was significantly increased ($p=0.0003$), there were no significant differences in the tibial length between the pre- and post-operative periods in the iV group.

TABLE 3. Pre- and Post-operative radiographic measurement of OW- and iV-HTOs

	Pre-operative	Immediately	Post-operative	p value
HKA (°)				
OW group	-5.4 (3.1)	4.3 (2.4)	4.4 (2.4)	<0.0001[a]
				0.1301[b]
iV group	-8.7 (4.1)*	3.5 (3.8)	3.6 (3.9)	<0.0001[a]
				0.0793[b]
FTA (°)				
OW group	179.8 (2.6)	170.1 (2.1)	170.3 (2.4)	<0.0001[a]
				0.0827[b]
iV group	183.2 (4.1)*	168.8 (3.1)	169.9 (3.5)	<0.0001[a]
				0.2669[b]
Mechanical axis (%)				
OW group	25.9 (12.2)	65.8 (10.3)	66.0 (10.6)	<0.0001[a]
				0.0966[b]
iV group	10.2 (18.9)*	64.6 (14.9)	65.9 (11.9)	<0.0001[a]
				0.9548[b]
MPTA (°)				
OW group	84.8 (2.5)	93.4 (2.1)	93.5 (2.0)	<0.0001[a]
				0.1377[b]
iV group	82.3 (2.9)*	93.9 (1.9)	94.0 (2.3)	<0.0001[a]
				0.5216[b]
PTS (°)				
OW group	8.5 (2.9)	10.5 (3.8)	10.5 (3.6)	<0.0001[a]
				0.3477[b]
iV group	8.4 (3.0)	8.8 (4.0)*	8.9 (4.0)*	0.0736[a]
				0.0777[b]
Whole leg length (mm)				
OW group	730.5 (40.1)	739.4 (39.8)	739.9 (39.6)	<0.0001[a]
				0.7552[b]
iV group	768.9 (58.9)*	771.4 (58.6)*	771.3 (59.0)*	0.0003[a]
				0.6309[b]
Tibial length (mm)				

OW group	322.7 (20.0)	331.5 (19.9)	331.7 (20.1)	<0.0001[a]
				0.4782[b]
iV group	341.1 (29.8)*	340.6 (30.0)	341.5 (29.4)	0.3692[a]
				0.1288[b]

Data are reported as mean (standard deviation). HKA, the hip-knee- ankle angle; FTA, the lateral femorotibial angle; MPTA, the medial proximal tibial angle; PTS, the posterior tibial slope.

[a]Preoperative vs final follow-up data.

[b]Immediately after surgery vs final follow-up data.

*Significant difference between the OW and the iV groups.

For the CD ratio, the OW group showed a significant decrease after surgery compared with the preoperative value (p<0.0001), while there was no significant difference in the iV group (Table 4). The postoperative CD ratio was significantly smaller (p<0.0001) in the OW group than in the iV group. Regarding the IS ratio, there were no significant differences in the pre- and postoperative values between the two groups.

Regarding changes in the axial view of the PF joint, the tilting angle was significantly decreased after surgery compared with the preoperative values in both groups (p<0.0001) (Table 4). For the lateral shift ratio, the iV group showed significant medial translation after surgery compared with the preoperative value (p=0.0012), while there was no significant change in the OW group. There were significant differences (p<0.0001) in the postoperative lateral shift ratio between the two groups. Postoperatively, the TT-TG distance was significantly decreased in the iV group (p<0.0001), while this value was significantly increased in the OW group (p<0.0001). The postoperative TT-TG distance was significantly smaller (p<0.0059) in the iV group than in the OW group. There were no significant differences in the tilting angle, the lateral shift ratio, and the TT-TG distance between the immediately after surgery and the final follow-up data in both groups.

TABLE 4. Change in patellofemoral joint congruity with OW- and iV-HTOs

	Pre-operative	Immediately	Post-operative	p value
Carton-Deschamps ratio				
OW group	0.95 (0.12)	0.80 (0.12)	0.79 (0.12)	<0.0001[a]
				0.3715[b]
iV group	0.88 (0.13)*	0.89 (0.12)*	0.88 (0.12)*	0.6297[a]
				0.2643[b]
Insall-Salvati ratio				
OW group	1.02 (0.13)	1.00 (0.13)	1.00 (0.13)	0.0262[a]
				0.1458[b]
iV group	0.99 (0.12)*	0.96 (0.13)	0.97 (0.13)	0.1083[a]
				0.1065[b]
Tilting angle (°)				
OW group	7.4 (3.2)	7.2 (3.1)	7.1 (3.1)	<0.0001[a]
				0.4043[b]
iV group	8.4 (4.6)	6.4 (3.6)	6.5 (3.3)	<0.0001[a]
				0.1992[b]
Lateral shift ratio (%)				
OW group	12.1 (4.5)	12.1 (4.6)	12.1 (4.7)	0.8164[a]
				0.5039[b]
iV group	11.5 (6.7)*	9.0 (8.4)*	8.8 (9.1)*	0.0012[a]
				0.6181[b]
TT-TG distance (mm)				
OW group	10.5 (2.8)	11.5 (3.2)	11.6 (3.3)	<0.0001[a]
				0.3365[b]
iV group	12.8 (3.9)*	9.5 (4.2)*	9.7 (4.1)*	<0.0001[a]
				0.2871[b]

Data are reported as mean (standard deviation).

TT-TG, the tibial tubercle and the trochlear groove.

[a]Preoperative vs final follow-up data.

[b]Immediately after surgery vs final follow-up data.

*Significant difference between the OW and the iV groups.

Clinical evaluation

Concerning the clinical outcome, the JOA score and the Lysholm knee scores were significantly increased at the final follow-up compared with the preoperative value in both groups ($p<0.0001$) (Table 5). There were no significant differences in the pre- and post-operative JOA score and Lysholm score between the 2 groups. The functional gradings of the JOA scores are presented in Table 5. At the final follow-up, the results were graded as good in 96 knees (89.7%), fair in 8 knees (7.5%) and poor in 3 knees (2.8%) in the OW group. In the iV group, the results were good in 93 knees (82.3%), fair in 16 knees (14.2%) and poor in 4 knees (3.5%) (Table 5). There was no significant difference in the functional grading of the JOA score between the two groups.

TABLE 5. Change in clinical outcomes with OW- and iV-HTOs

	Pre-operative	Post-operative	p value
JOA score (points)			
OW group	68.3 (10.6)	91.2 (8.3)	<0.0001
iV group	66.8 (10.0)	90.1 (6.4)	<0.0001
Good			
OW group	10 knees	96 knees	<0.0001
iV group	3 knees	93 knees	<0.0001
Fair			
OW group	42 knees	8 knees	
iV group	48 knees	16 knees	
Poor			
OW group	55 knees	3 knees	
iV group	62 knees	4 knees	
Lysholm score (points)			
OW group	67.9 (13.8)	92.5 (6.7)	<0.0001
iV group	61.0 (16.2)	89.0 (9.5)	<0.0001

Data are reported as mean (standard deviation).
JOA; Japanese Orthopaedic Association

Complications

In the OW group, lateral hinge fractures occurred in 28 knees (26%) (Table 6). After surgery, 2 knees had superficial infections around the skin incision, although no patients had deep infections. Unacceptable over-correction (< FTA 160°) occurred in 1 knee, correction loss greater than 5° occurred in 2 knees, and nonunion occurred in 3 knees. In the patient with unacceptable overcorrection, we performed revision OW-HTO at 1 week after the first surgery. In the 2 patients with correction loss, TKA was performed 12 months after surgery. In the 3 patients with nonunion, after 6 months a revision OW-HTO and iliac bone graft was performed by use of bilateral plate fixation.

In the iV group, no patients had superficial and deep infections. Unacceptable over-correction occurred in 1 knee, correction loss occurred in 1 knee, and nonunion occurred in 3 knees. In the 3 patients with unacceptable overcorrection or nonunion, we performed revision iV-HTO and iliac bone graft was performed by use of bilateral plate fixation. No cases of popliteal vascular injury, peroneal nerve injury, tibial tubercle fracture, or compartment syndrome were noted in both groups.

Each patient underwent an additional procedure approximately 1 year (mean, 13 months; range, 10-32 months) after the initial surgery to remove the implanted plate and screws. During the plate removal surgery, implant failure was found or occurred in 9 knees and 2 knees in OW and iV groups, respectively (Table 6). We confirmed that 14 locking screws were broken. In these cases, we removed the inserted screw by hollowing out the bone tissue with a core reamer. There were no significant differences in the complication rate without implant failure between the two groups.

TABLE 6. Complications in Opening Wedge and inverted V-shaped High Tibial Osteotomies.

	OW group (n=98, 107 knees)	iV group (n=93, 113 knees)	P value
Lateral hinge fracture	28 (26%)	n/a	n/a
Infection	2 (2%)	0 (0%)	0.1443
Over correction	1 (1%)	1 (1%)	0.9691
Correction loss	2 (2%)	1 (1%)	0.5293
Nonunion	3 (3%)	3 (3%)	0.9460
Implant failure	9 (8%)	2 (2%)	0.0239

No. of Knees (%)
n/a, not available.

DISCUSSION

The main findings of the present study were that, first, even though the tibial correction angle was significantly greater in the iV group than in the OW group, the patellar height, the PTS, and the tibial length did not change in the iV group. On the other hand, the patella height was significantly reduced, and the PTS and the tibial length were significantly increased in the OW group. Second, the lateral shift ratio of the patella and the TT-TG distance were significantly decreased in the iV group, compared with the preoperative values, while the lateral shift ratio did not change in the OW group. Third, even though the preoperative OA grade and the degree of knee deformity were more severe in the iV group than in the OW group, the 3-year clinical results were significantly improved in comparison with the preoperative status in each group, and there were no differences in the 3-year results between the two groups.

Concerning the patellar height, this study showed that no changes occur in the CD ratio and IS ratio after iV osteotomy. We considered that the centre of tibial alignment correction (hinge point) of iV osteotomy was located approximately at the medial portion of the distal attachment of the patella tendon. Therefore, this osteotomy does not change the patellar height after surgery. The most frequent radiographic change seen after the OW-HTO procedure with ascending tibial tuberosity osteotomy was patella baja as a deformity of the tibia.[10,32,43,73,] Patella baja is known as an adverse deformity of the knee. Altered patellar height may induce anterior knee pain and result in long-term PF cartilage degeneration.[64] Namely, Yabuuchi et al[74] reported complications after OW-HTO. According to the measurement with the CD ratio, the patellar height was reduced under 0.6 or more in 37.6% of the patients. Recently, Goshima et al[23] reported that cartilage degeneration was frequently found in the PF joint in patients after the OW-HTO surgery. Although the patella baja induced by the OW-HTO did not result in a significant reduction of the functional results in the short-term clinical evaluation,[16] there is a risk that the functional results may be significantly reduced in the long-term follow-up evaluation. Furthermore, lower patellar height potentially increases the load of the PF joint, resulting in PF-OA and anterior knee pain.[69] Stoffel et al[69] reported that OW-HTO led to a significant elevation in PF cartilage pressure at 30°, 60°, and 90°of knee flexion in a cadaveric biomechanical experiment. Some other radiologic and biomechanical studies have indicated an increase of PF contact pressure and the progression of PF-OA after OW-HTO.[10,19,39] Kemeda et al[31] also reported that a statistically significant decrease of the patellar height and degradation of the PF cartilage after OW-HTO. Their study demonstrated that the OW-HTO procedure significantly increased stress distribution patterns of the femoral lateral trochlea and the medial portion of the patellar lateral facet using the CT-osteoabsorptiometry method. OW-HTO is often associated with decreased patellar height due to distal and lateral movement of the tibial tuberosity. Previous studies[17,19] reported that patellar height significantly increased with CW-HTO. On the other hand, in the iV-HTO, there were no significant differences in the patellar height between the pre- and post-operative periods. Recently, several authors reported descending tibial tuberosity osteotomy (DTO) in OW-HTO.[3,20,69] Biomechanically, DTO does not increase contact pressure in the PF joint. However, the long-term effect of DTO on the PF joint is little known.

With respect to PF joint congruency, Gaasbeek et al[19] reported that OW- and CW-HTOs caused the patella to tilt more medially. A systematic review and meta-analysis revealed that tilting angle was significantly decreased, but the lateral shift ratio did not differ significantly after OW-HTO.[38] Kemeda et al[31] suggested that the medial tilt of the patella occurred because of lateral and distal shifts of the tibial tuberosity forcing up the lateral side of the femur and patella. In the present study, the tilting angle and the lateral shift ratio after OW-HTO were similar to those in previous studies.[9,23,38,39] Ishimatsu et al[30] reported that the tilting angle was significantly decreased, and the lateral shift ratio showed significant translation in a medial direction after the hybrid CW-HTO. IV-HTO procedure is classified as a neutral osteotomy. The centre of tibial alignment correction is located approximately at the CORA of the lower-limb deformity, which is located at medial side of the tibial tuberosity. On the other hand, the hybrid CW-HTO is classified as a CW osteotomy. The centre of alignment correction divides the proximal oblique osteotomy line by about 2 to 1 from lateral to medial. In addition, the present study showed that the TT-TG distance was significantly decreased in the iV group between the 2 periods, while it was significantly increased in the OW group. In the OW-HTO, the hinge point is located near the proximal tibiofibular joint. After opening the osteotomy site, the patellar height was decreased because of a distal and lateral shift of the tibial tuberosity, resulting in an increase of the TT-TG distance. In the iV-HTO, the hinge point is located at medial side of the tibial tuberosity. After closing the lateral osteotomy site, this osteotomy could antero-medialize the tibial tuberosity, resulting in a reduction of the

TT-TG distance. However, these values were relatively small since it is also still within normal reference values. Therefore, clinical relevance remains unclear at mid-term follow-up.

The effects of HTO on the PTS have been widely debated.[7,12,16,17,18,28,32,49,63] It is generally thought that the PTS increases after OW osteotomy and decreases after CW osteotomy. Ducat et al[16] reported that 14% of the OW osteotomies increased PTS by 5°, whereas 12% of the CW osteotomies led to a decrease of 5° or more of the PTS. A meta-analysis[49] showed that the PTS increased 2.02° after OW-HTO and decreased 2.35° after CW-HTO. Modification of PTS is a source of instability and excessive anteroposterior tibial translation that may encourage the progression of OA.[1,27] The previous studies[1,15,21] have shown the linear relationship between the PTS and tibial translation during a monopodal stance: the more the tibial slope increases, the more the anterior tibial translation increases. On the other hand, CW osteotomy produces a decrease in the PTS, which distributes the stresses on the posterior compartment. This study showed that the PTS was increased after OW-HTO surgery. An OW osteotomy with anterior and posteromedial spaces of the same height results in an increase in the PTS.[44] Slope changes after OW-HTO may also be caused by an incomplete posterior corticotomy, whereas changes after CW-HTO may result from inadequate bony removal from the posterior part of the wedge; both of these changes may be due to surgeons' concerns about posterior neurovascular injury during OW- or CW-HTO.[65] This study showed that the PTS did not change after iV-HTO surgery. We considered that the lateral wedge volume of the iV osteotomy is smaller than that of the CW osteotomy, because the hinge point is located near the centre of the tibial condyle.

There was no general consensus about the extent to which the change in leg length could result in clinically relevant problems such as back pain and progression of knee OA due to alteration of gait kinematics.[71] Some degree (less than 2 cm) of leg length discrepancy can be allowed in humans because of a compensatory mechanism that dynamically lengthens the shorter limb and shortens the longer limb,[59] probably to minimize the displacement of the body center of mass and consequently reduce body energy expenditure.[33] However, a leg length discrepancy-whether lengthening or shortening-should be avoided as much as possible, because previous studies demonstrated that leg lengthening, even by less than 1 cm, increases the chance of developing knee OA in the longer limb,[26] and that correcting leg length discrepancy of only 5.6 mm relieved chronic low back pain.[14] Magnussen et al[42] compared leg-length change after OW- and CW-HTOs. In the OW group, entire leg length increased 5.5 mm, and tibia length increased 4.3 mm. In the CW group, entire leg length decreased 2.7 mm, and tibia length decreased 4.1 mm. The result of the meta-analysis[35] showed that the OW-HTO resulted in an 8-mm greater leg length than CW-HTO. This small difference, although less than 1 cm, could induce clinically important symptoms. Yabuuchi et al[74] reported that there was a significant correlation between the wedge-opened distance and the length of the tibia. The shift in the weight-bearing axis from the medial opening cortex to the lateral plateau offsets the effect of tibial lengthening after an OW-HTO. In the present study, although the entire leg length was significantly increased in both groups (OW; mean 9.4 mm, iV; 2.4 mm), there were no significant differences in the tibial length between the pre- and post-operative periods in the iV group. Therefore, iV osteotomy resulted in significantly smaller changes in the leg length than OW osteotomy. Therefore, orthopedic surgeons should carefully consider leg length changes when deciding the type of HTO. Thus, we consider that OW-HTO is not recommended for knees that need large alignment correction with regards to the patellar height, PTS, and leg length changes.

Recently, several techniques of combined osteotomy have been reported.[45,57,58] Papp et al[57] performed a proximal osteotomy parallel to the tibial plateau, followed by a distal osteotomy extending from the lateral part of the tibia to the line of the proximal osteotomy at the center of the tibial condyle. A combined osteotomy with lateral closing then medial opening utilizing the removed lateral bone wedge. They noted that the combined osteotomy resulted in significantly smaller changes in the PTS angle and IS values than CW osteotomy. They concluded that the combined osteotomy is better at preserving the normal or near normal condition of the knee than CW osteotomy. Porter et al[58] reported that CW osteotomies produced patellar ascent by an average of 13%, OW osteotomies produced descent by an average of 21%, and the combined osteotomy mean showed any minimal change. The combined osteotomy minimizes changes in patellar height. A combination of lateral CW and medial OW osteotomy should produce a patellar height closer to neutral. However, osteotomy line of their combined osteotomy[45,57,58] was horizontal plane. On the other hand, the iV-shaped osteotomy may increase angular stability of the post-osteotomy tibia against shear forces after valgus correction. The combined osteotomy offers some advantages over traditional types: the removed wedge is thinner, but still can tighten the medial collateral ligament and, in CW, decrease the slackness produced in the lateral collateral ligament. The combined osteotomy allows the ability to adjust the patellar height. In addition, performing TKA is easier after combined osteotomy than after OW osteotomy because the shortening of the patella tendon after combined osteotomy is smaller than after OW osteotomy. To perform the same correction during combined osteotomy, a bone wedge must be removed that is approximately 50% smaller than the removed wedge at CW osteotomy. Less bone loss after combined osteotomy eases the tibial bone resection during the subsequent TKA. Residual proximal tibial deformity affects the degree of difficulty in possible future TKAs.[37]

Concerning the clinical outcome, the JOA score and the Lysholm knee scores were significantly increased at the final follow-up after 3 years compared with the preoperative value in both groups. Although the preoperative OA grade and the degree of varus deformity were more severe in the iV group than in the OW group, there were no significant differences in the post-operative JOA score and Lysholm score between the 2 groups. Aoki et al[5] compared the results ten years after an iV-HTO using an external fixator with those of a historical series of conventional CW osteotomies. They concluded that the iV-HTO was significantly better in the postoperative clinical outcome than CW-HTO. They suggested that the iV osteotomy may offer more dependable long-term results than traditional CW osteotomy. Although there were no significant differences in the radiographic FT-OA grades between the pre- and postoperative periods in both groups, significant PF-OA progression was found in the OW group at the final follow up period. Regarding the complication rate, there were no significant differences between the two groups.

There are some limitations in this study. First, the indication of 2 HTO procedures was different as previously mentioned. A weakness of our study is its reliance on a historical control and a lack of random allocation. Therefore the outcome between the two groups cannot be attributed to a difference in the two procedures with certainty. In the future, we recommend using the iV technique for routine use. Second, retrospective nature of the study introduces a number of confounding factors and risk of selection bias, etc. Third, the follow-up period averaged only 3 years, and a longer-term follow-up is needed. Further long-term studies are needed to assess the subjective and objective patient outcomes of iV osteotomy in patients with severe varus malalignment.

In conclusion, this study demonstrated that the patellar height, the posterior tibial slope, and the tibial length did not change after the iV-HTO, while they were significantly changed after the OW-HTO. Although the preoperative degrees of varus knee and PF-OA were more severe in the iV group than those in the OW group, the iV group led to an altered PF joint congruity. Therefore, in patients with varus knee combined with PF-OA preoperatively, iV-HTO may be a more effective than OW-HTO.

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Figure Legends

Figure 1. Diagrams of an inverted V-shaped osteotomy showing (A) a wedge of bone resected from the tibia beneath the lateral plateau in the shape of an inverted 'V' and (B) valgus correction and grafting of the resected wedged bone block into the triangular gap created beneath the medial plateau.

Figure 2. Preoperative planning

In the OW group, the hinge point 'P' is located at approximately 5 mm medial from the proximal tibiofibular joint (A). In the iV group, the hinge point 'P' is located at approximately at the medial edge of the tibial tubercle (B). First, a 'line A' is drawn from the centre of the femoral head through the point 65% lateral from the medial edge of the tibial plateau on the lateral tibial plateau. Second, a 'line B' is drawn from hinge point P to the centre of the talar dome. Then an arc C, the centre and the radius of which are the hinge point P and line B, respectively, is drawn so that the arc is across line A. Next, a 'line D' is drawn from hinge point P to the crossing point between line A and arc C. The angle (alpha) formed between line B and line D provides the correction angle.

Figure 3. Pre- and post-operative radiographs in OW-HTO.

(A) Anteroposterior radiograph before OW-HTO. (B) Lateral radiograph before OW-HTO. (C) Anteroposterior radiograph after OW-HTO. (D) Lateral radiograph after OW-HTO. Dotted line: Osteotomy line

Figure 4. Pre- and post-operative radiographs in iV-HTO.

(B) Anteroposterior radiograph before iV-HTO. (B) Lateral radiograph before iV-HTO. (C) Anteroposterior radiograph after iV-HTO. (D) Lateral radiograph after iV-HTO. Dotted line: Osteotomy line

Figure 5. Radiographic assessments.

(A) Hip–knee–ankle angle (HKA). The HKA was defined as the angle between the femoral mechanical axis and the tibial mechanical axis. (B) Femorotibial angle (FTA). The FTA was defined as the angle between the anatomical axis of the femoral shaft and the axis of the tibial shaft on the fibular side. (C) Mechanical axis of the lower limb. A mechanical axis line was drawn from the centre of the femoral head to the middle point of the proximal talar joint surface. The mechanical axis percentage was defined as the horizontal distance from the mechanical axis line to the medial edge of the tibial plateau (d), divided by the width of the tibial plateau (w). (D) Medial proximal tibial angle

(MPTA). The MPTA was defined as the angle between the proximal tibial joint line and the mechanical axis of the tibial shaft. (E) Posterior tibial slope (PTS). The PTS was defined as the angle between the line perpendicular to the mid-diaphysis of the tibia and the posterior inclination of the medial tibial plateau. (F) Entire leg length. The entire leg length was defined as the distance between the top of the femoral head and the centre of the tibial plafond. (G) The tibial length was defined as the distance between the centre of the proximal tibia and the centre of the tibial plafond. (H) Caton-Deschamps (CD) ratio. The CD ratio was defined as a ratio of the distance (x) between the inferior pole of the patella and the antero-proximal edge of the tibial plateau divided by the patellar length (y). (I) Insall-Salvati (IS) ratio. The IS ratio was defined as a ratio of the length of the patella tendon (the distance between the inferior pole of the patella and the tibial tubercle (x)) divided by the patellar length (y). (J) Tilting angle. The tilting angle was defined as the angle between the line intersecting the widest bony structure of the patella and the line tangentially passing the anterior surface of the femoral condyles. (K) Lateral shift ratio. The lateral shift ratio was defined as the ratio of the distances pp'/aa'. aa' is defined as the distance between the summits of the medial and lateral femoral condyles. pp' is defined as the distance between the summit of the lateral femoral condyle and the point where a line from the lateral edge of the patella perpendicular to the line that passes through the summits of the femoral condyles crosses that line.

Figure 6. The distance between the tibial tubercle and the trochlear groove (TT-TG).
The TT-TG distance was measured from 2 superimposed CT slices, the distance was defined between the centre of the tibial tubercle (a) on one image and the trochlear groove perpendicular to the posterior femoral condyles (b) on a second image.

Figure 7. Follow-up examinations.
HTO, high tibial osteotomy; OA, osteoarthritis; SONK, spontaneous osteonecrosis of the knee.