Factors Associated With Unfavorable Radiological Outcomes After Opening-Wedge High Tibial Osteotomy for Varus Knees

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Background: Corrective osteotomy around the knee is based on deformity profiles of the femoral and tibial sides. Opening-wedge high tibial osteotomy (OWHTO) can be favored if the outcomes are not different, even if there is a certain degree of abnormal parameters after correction.

Purpose/Hypothesis: The purpose of this study was to identify the factors associated with unfavorable radiological outcomes after OWHTO for varus knees. Our hypothesis was that there would be an optimal situation in which double-level osteotomy (DLO) has advantages over isolated OWHTO and an optimal cutoff value of structural parameters for which DLO should be considered in patients with severe varus knees.

Study Design: Case-control study; Level of evidence, 3.

Methods: The radiological and clinical outcomes of 337 patients who underwent OWHTO were retrospectively evaluated. A subgroup analysis was performed according to the weightbearing line ratio (WBLR) (group 1: <25th percentile; group 2: 25th–75th percentile; and group 3: >75th percentile) and factors associated with unfavorable radiological outcomes. For the assessment of cutoff values of the parameters favoring DLO, unfavorable radiological outcomes were categorized as follows: (1) medial proximal tibial angle (MPTA) >95°, (2) joint-line convergence angle (JLCA) >4° (insufficient medial release), (3) JLCA <0° (medial instability), (4) recurrence of a varus deformity, and (5) lateral hinge fracture.

Results: The mean follow-up period was 66.2 ± 19.1 months. A low preoperative WBLR was related to a larger preoperative to postoperative change (Δ) in the WBLR, a larger reduction in coronal translation, a larger ΔMPTA, a wide preoperative lateral joint space, and a narrow preoperative medial joint space (P < .001, P < .001, P < .001, P = .016, and P = .003, respectively). However, only an MPTA >95° was significantly related to a low WBLR in the subgroup analysis according to unfavorable radiological outcomes (P = .038). The cutoff value of ΔWBLR causing an MPTA >95° was 46.5%, which showed a good area under the curve of 0.800, with a sensitivity of 74.4% and a specificity of 82.7%. The clinical outcomes significantly improved at the final follow-up compared with those preoperatively, with no significant differences between the WBLR groups.

Conclusion: A ΔWBLR ≥46.5% led to an MPTA >95°. However, clinical outcomes were not affected. DLO should be considered if the surgeon desires a postoperative MPTA <95°.

Keywords: knee; opening-wedge high tibial osteotomy; double-level osteotomy; unfavorable radiological outcome; medial proximal tibial angle; cutoff value

Opening-wedge high tibial osteotomy (OWHTO) has been reported to have good surgical outcomes, and the evidence is expanding in varus, aligned early osteoarthritic knees.18,20,23 It generally shifts excessive medial loading to the lateral compartment by changing the alignment and is mostly determined at the proximal tibia by changing the medial proximal tibial angle (MPTA).18,35 Therefore, increases in the MPTA are often unavoidable because mild overcorrection is recommended to prevent recurrence and can yield nonanatomic knee joint configurations, such as abnormally increased MPTAs beyond the normal range (85°–90°).

Abnormally increased MPTAs after OWHTO can be more prominent in patients with severe varus deformities than in
other patients. Nonanatomic joint-line obliquity (JLO) can result in joint subluxation, increased shear force, and subsequently unfavorable effects on cartilage. In an experimental study, an MPTA >95° adversely affected cartilage, owing to shear stress.23 In other studies, a postoperative MPTA >95° also consequently adversely affected functional and clinical outcomes.1,15

Release or cutting of the superficial medial collateral ligament (MCL) is often required to resolve contracture of medial soft tissue. However, in patients with a large correction angle, sufficient and exact management of the MCL can be difficult as the opening gap increases. Consequently, the joint-line convergence angle (JLCA) may not recover accordingly. A large JLCA may result in the recurrence of a varus deformity, and overrelease of the medial side can cause medial instability.16 A lateral hinge fracture (LHF) is also an important factor associated with unsatisfactory outcomes by causing inappropriate correction.1,19

Corrective osteotomy is based on deformity profiles, and double-level osteotomy (DLO) of the distal femur and proximal tibia is recommended if the deformity is located on both the femoral and tibial sides. However, it can also be performed to prevent abnormal JLO and other possible complications, such as LHF and delayed union or nonunion in knees with overcorrection.29 However, less invasive, isolated proximal tibial osteotomy may be advantageous if the results are not different, even with some abnormal parameters after correction. Patients who had mildly increased JLO did not necessarily have a poor outcome and exhibited steady alignment at serial follow-up, in contrast, excessively increased JLO led to poor outcomes.15

The purpose of this study was to identify the factors associated with unfavorable radiological outcomes after OWHTO for varus knees by analyzing structural parameters and determining cutoff values favoring the application of DLO. The hypothesis of this study was that there would be an optimal situation in which DLO has advantages over isolated OWHTO and an optimal cutoff value of structural parameters for which DLO should be considered in patients with severe varus knees.

METHODS

Patients

We retrospectively evaluated patients who underwent OWHTO between March 2014 and July 2019. The inclusion criteria were as follows: (1) medial unicompartmental knee osteoarthritis, (2) genu varum deformity of the lower limb, and (3) completion of >2 years of follow-up after OWHTO. Initially, 355 knees were examined. Meanwhile, the exclusion criteria were as follows: (1) revision OWHTO (4 knees), (2) DLO including distal femoral osteotomy (8 knees), and (3) simultaneous ligament reconstruction that required concomitant sagittal-plane modification (6 knees). Finally, 337 knees were included in this study. Institutional review board approval was obtained before the evaluations.

Surgical Technique and Rehabilitation

All surgical procedures were performed by a single senior surgeon (Y.S.L.). A longitudinal incision was made in the anteromedial aspect of the tibia. The superior border of the pes anserinus was incised, and the superficial MCL was mobilized and released. Under C-arm imaging, a protective cutting system (Trademedics and Corentec) was applied to the lateral cortical hinge located just below the tip of the fibular head.21 Osteotomy was performed from the medial to lateral side until reaching just 5 to 10 mm before the lateral cortex. The amount of distraction or control of the tibial slope was adjusted according to preoperative planning at the most posterior gap. The target point of correction was at approximately 62% (Fujisawa point) of the weight-bearing line.29 The target weight-bearing line was adjusted after considering the meniscus (complex tear, root tear, and remaining meniscus after previous meniscectomy) and cartilage (degree and width of the cartilage defect) through preoperative magnetic resonance imaging as well as the difference in the preoperative medial and lateral joint space width (MJSW and LJJSW, respectively) on varus-valgus stress radiographs. The difference between varus-valgus stress radiographs (VVD) was then subtracted to reflect the soft tissue imbalance, which could be resolved with MCL release.14 Fixation was performed using locking plates devised for OWHTO.

Isometric quadriceps exercises and range-of-motion exercises were started on the first postoperative day. Partial weightbearing with crutches was allowed for the first 2 weeks after surgery. Weightbearing as tolerated was allowed from 2 weeks postoperatively. Single or double crutches were used for 6 weeks after surgery. For 3 months postoperatively, climbing up and down stairs or sudden shifting from a sitting position to a standing position was prohibited if possible.31

Radiological Evaluation

Radiological outcomes were assessed preoperatively; at 6 weeks, 3 months, 6 months, and 1 year postoperatively;
and at 1-year intervals thereafter. Whole-leg radiographs, anteroposterior weightbearing radiographs of the knee, and varus-valgus stress radiographs were obtained. Radiological measurements were performed using picture archiving and communication system digital radiographic software (version 5.0.9.2; INFINITT). There were 2 orthopaedic surgeons (S.J.S. and H.W.J.) who conducted the measurements twice with a minimum 6-week interval between measurements.

Measurements were made focusing on radiological parameters related to unfavorable radiological outcomes, including MPTA, JLCA, recurrence of a varus deformity, and LHF. The weightbearing line ratio (WBLR), mechanical lateral distal femoral angle (mLDFA), and MPTA were measured on whole-leg radiographs. The WBLR was calculated as the distance from the medial edge of the plateau to the weightbearing line divided by the width of the plateau and then multiplied by 100 (Figure 1A). The mLDFA was defined as the angle formed by a line of the mechanical femoral axis and a line tangent to the joint surface of the distal femur (Figure 1B), and the MPTA was defined as the medial angle formed by a line of the mechanical tibial axis and a line tangent to the joint surface of the proximal tibial plateau (Figure 1B). Coronal translation and JLCA were measured on anteroposterior weightbearing radiographs. Coronal translation was expressed as the distance between the lines perpendicular to the ground through the most lateral margins of the lateral femoral condyle and lateral tibial condyle. A positive value indicated that the line through the lateral tibial condyle was lateral to the line through the femoral condyle (Figure 1C). The JLCA was defined as the angle between the lines tangential to the articular surface of the distal femur and the proximal tibia (Figure 1D). A positive value was recorded when the apex of the JLCA was medial. Conversely, a negative value was recorded when the apex of the JLCA was lateral.

Varus-valgus stress radiographs were checked preoperatively using a Telos device with a 15-lb (6.8 kg) varus and valgus force on a fully extended knee. Then, 2 lines connecting the distal femoral articular surface and proximal tibial

Figure 1. Measurements of radiological parameters: (A, B) The weightbearing line ratio was calculated as \( \frac{A - B}{A} \), the mechanical lateral distal femoral angle was calculated as \( B - \alpha \), and the medial proximal tibial angle was calculated as \( B - \beta \). (C) Coronal translation, (D) joint-line convergence angle, (E) lateral joint space width, and (F) medial joint space width (indicated by arrows).
articular surface were drawn. The length of the perpendicular line from the proximal tibial articular surface to the lowest point of the medial femoral condyle on varus stress radiographs was defined as the varus-LJW (Figure 1E). The length of the perpendicular line from the proximal tibial articular surface to the lowest point of the lateral femoral condyle on valgus stress radiographs was defined as the valgus-MJSW (Figure 1F). The VVD was defined as the absolute difference between the varus-LJW and valgus-MJSW.

Subgroup Analysis

The patients were classified according to the severity of varus alignment. The preoperative WBLR was used, and the patients were divided into 3 groups (group 1: <25th percentile; group 2: 25th-75th percentile; and group 3: >75th percentile). For the assessment of cutoff values of the parameters favoring the application of DLO, unfavorable radiological outcomes were initially determined. Unfavorable radiological outcomes were based on previously reported parameters and were categorized as follows: (1) MPTA >95°;7,13,15,39 (2) JLCA >4° (insufficient medial release);11,16,33 (3) JLCA <0° (medial instability);16,17,22 (4) recurrence of a varus deformity,18 and (5) LHR.5,19,34 The recurrence of a varus deformity was defined as a WBLR <55% on whole-leg radiographs at 1 year after surgery because our target point for the WBLR was adjusted as 55% to 65% (~62%) according to the status of the medial compartment of the knee joint. All patients were also classified into 2 groups (unfavorable outcomes and favorable outcomes) according to the presence of unfavorable radiological outcomes, and comparisons were performed between them.

Clinical Evaluation

Clinical outcomes were evaluated using the American Knee Society Score (AKSS) and Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) score preoperatively and at the final follow-up. A physical assistant blinded to the surgical details assessed these outcomes. In the clinical evaluation, the AKSS was subdivided into clinical and functional scores, with higher scores on the 0- to 100-point scale indicating better outcomes. The WOMAC score includes pain (0-20 points), stiffness (0-8 points), and function (0-68 points) subscores, with lower scores on the 96-point scale indicating better outcomes.

Statistical Analysis

The intrarater and interrater reliabilities of the radiological measurements were assessed by the intraclass correlation coefficient. Normality testing for continuous variables was performed using the Shapiro-Wilk test. The chi-square test was used for the analysis of categorical variables. One-way analysis of variance was used for the subgroup analysis according to the preoperative WBLR. When there was a difference between the 3 study groups, the Scheffé analysis was used as a post hoc test. The paired t test was used to compare radiological changes from preoperatively to 1 year postoperatively (Δ), parameters between favorable and unfavorable radiological outcomes, and clinical outcomes between preoperatively and the final follow-up. Using receiver operating characteristic (ROC) curve analysis, the best cutoff value was selected by the Youden index ([sensitivity + specificity] − 1). Statistical significance was set at P < .05. Data were analyzed using SPSS version 28.0 (IBM).

A post hoc power analysis of the study was performed using G*Power version 3.1.9.7, with an effect size of 0.40 and an alpha value of 0.05. For the sample size calculation using the F test, G*Power software provided conventional effect size values of 0.40, for a large effect size.

RESULTS

The interobserver and intraobserver reliabilities for the measurements of radiological parameters were satisfactory, with intraclass correlation coefficient values of 0.88 (range, 0.86-0.90) and 0.90 (range, 0.88-0.92), respectively. According to the post hoc power analysis, the statistical power of this study was 0.99, with an effect size of 0.40 and an alpha value of 0.05. All continuous variables were normally distributed.

The preoperative demographics, radiological data, and clinical outcomes are summarized in Table 1. The mean follow-up period was 66.2 ± 19.1 months. Of the 337 knees, 84, 169, and 84 knees were allocated to groups 1, 2, and 3, respectively; the mean preoperative WBLR was 5.8% ± 6.5%, 20.3% ± 2.4%, and 32.0% ± 3.1%, respectively. There were no significant differences between the 3 groups in terms of the preoperative demographic data.

The preoperative mLDFA in group 1 (87.8° ± 1.3°) was significantly smaller than that in group 2 (88.7° ± 1.6°), while that in group 2 was significantly smaller than that in group 3 (89.7° ± 2.4°) (P = .019). Nevertheless, these values were within the normal range of mLDFAs (85°–90°). The clinical outcomes, including the AKSS and WOMAC scores, significantly improved at the final follow-up compared with those preoperatively but with no significant differences between the groups.

A comparison of preoperative and postoperative structural parameters is summarized in Tables 2 and 3. The preoperative WBLR in group 1 (5.8% ± 6.5%) was significantly smaller than that in group 2 (20.3% ± 2.4%), while that in group 2 was significantly smaller than that in group 3 (32.0% ± 3.1%) (P < .001). The postoperative WBLR showed no significant differences between the 3 groups. The ΔWBLR in group 1 (50.1% ± 8.8%) was significantly larger than that in group 2 (36.1% ± 10.2%), while that in group 2 was also significantly larger than that in group 3 (26.1% ± 8.8%) (P < .001). The preoperative coronal translation in group 3 (5.3 ± 1.2 mm) was significantly smaller than that in group 2 (6.2 ± 1.8 mm) and group 1 (6.5 ± 1.8 mm) (P < .001). However, there was no significant difference between groups 1 and 2. Meanwhile, the postoperative coronal translation showed no significant differences between the 3 groups. The absolute values of Δcoronal translation in group 1 (1.8 ± 0.8 mm) and group 2 (1.6 ± 0.9 mm) were significantly larger than that in group 3.
Table 1: Preoperative Demographic, Radiological, and Clinical Characteristics

| Patient characteristics              | Group 1 (WBLR <25%; n = 84) | Group 2 (WBLR 25%-75%; n = 169) | Group 3 (WBLR >75%; n = 84) | P Value |
|---------------------------------------|------------------------------|----------------------------------|------------------------------|---------|
| Age, y                                | 56.4 ± 6.9                   | 56.1 ± 6.1                       | 56.3 ± 7.1                   | 56.7 ± 7.2 | .876 |
| Sex, male/female, n                   | 107/230                      | 26/58                            | 54/115                       | 27/57    | .983 |
| BMI, kg/m²                             | 26.8 ± 3.5                   | 27.1 ± 3.6                       | 26.6 ± 3.2                   | 26.8 ± 3.8 | .544 |
| Side, right/left, n                   | 168/169                      | 34/50                            | 84/85                        | 50/34    | .066 |
| Follow-up, mo                         | 66.2 ± 19.1                  | 63.7 ± 17.0                      | 67.1 ± 20.7                  | 65.6 ± 15.1 | .204 |

Radiological findings

| WBLR, %                               | 19.6 ± 10.1                  | 5.8 ± 6.5                        | 20.3 ± 2.4                   | 32.0 ± 3.1 | <.001 |
| mLDFA, deg                            | 89.1 ± 2.2                   | 87.8 ± 1.3                       | 88.7 ± 1.6                   | 89.7 ± 2.4 | .019 |
| MPTA, deg                             | 84.6 ± 3.3                   | 83.9 ± 4.0                       | 85.0 ± 2.7                   | 84.4 ± 3.4 | .046 |

Clinical outcomes

| AKSS clinical score                   |                             |                                 |                             |         |
| Preoperative                          | 49.7 ± 15.6                 | 50.6 ± 15.3                      | 49.5 ± 15.5                 | 49.2 ± 16.2 | .825 |
| Final follow-up                       | 91.5 ± 8.6                  | 92.3 ± 7.8                       | 90.5 ± 9.8                  | 92.9 ± 6.3 | .064 |
| AKSS functional score                 |                             |                                 |                             |         |
| Preoperative                          | 57.1 ± 12.8                 | 57.7 ± 11.7                      | 56.0 ± 13.2                 | 58.9 ± 12.9 | .198 |
| Final follow-up                       | 87.8 ± 10.9                 | 87.7 ± 10.8                      | 87.1 ± 11.4                 | 89.2 ± 9.7 | .372 |

WOMAC total score

| Preoperative                          |                             |                                 |                             |         |
| Final follow-up                       |                             |                                 |                             |         |
| WOMAC pain score                      |                             |                                 |                             |         |
| Preoperative                          |                             |                                 |                             |         |
| Final follow-up                       |                             |                                 |                             |         |
| WOMAC stiffness score                 |                             |                                 |                             |         |
| Preoperative                          |                             |                                 |                             |         |
| Final follow-up                       |                             |                                 |                             |         |
| WOMAC function score                  |                             |                                 |                             |         |
| Preoperative                          |                             |                                 |                             |         |
| Final follow-up                       |                             |                                 |                             |         |

| P Value                                |                             |                                 |                             |         |

Table 2: Preoperative and Postoperative Structural Outcomes

| WBLR, %                               | Group 1 (Post Hoc) | Group 2 (Post Hoc) | Group 3 (Post Hoc) | P Value | P Value (Post Hoc) |
|---------------------------------------|--------------------|--------------------|--------------------|---------|--------------------|
| Preoperative                          | 5.8 ± 6.5          | 20.3 ± 2.4         | 32.0 ± 3.1         | 921.56  | <.001 (1 < 2 < 3)  |
| Postoperative                         | 55.9 ± 8.1         | 56.4 ± 9.8         | 58.1 ± 9.3         | 1.42    | .244               |
| Δ                                     | 50.1 ± 8.8         | 36.1 ± 10.2        | 26.1 ± 8.8         | 135.47  | <.001 (1 < 2 < 3)  |
| JlCA, deg                             | 3.0 ± 1.6          | 3.3 ± 2.0          | 3.0 ± 1.9          | 1.14    | .321               |
| Postoperative                         | 2.1 ± 1.5          | 2.3 ± 2.0          | 2.2 ± 1.8          | 0.39    | .679               |
| Δ                                     | -0.9 ± 1.6         | -1.0 ± 1.9         | -0.9 ± 2.0         | 0.26    | .261               |
| Coronal translation, mm               | 6.5 ± 1.8          | 6.2 ± 1.8          | 5.3 ± 1.2          | 15.26   | <.001 (1, 2 > 3)   |
| Postoperative                         | 4.7 ± 1.6          | 4.7 ± 1.4          | 4.5 ± 1.1          | 0.27    | .765               |
| Δ                                     | -1.8 ± 0.8         | -1.6 ± 0.9         | -0.7 ± 0.6         | 53.74   | <.001 (1, 2 < 3)   |
| MPTA, deg                             | 83.9 ± 4.0         | 85.0 ± 2.7         | 84.4 ± 3.4         | 3.11    | .046 (1 < 2, 3)    |
| Postoperative                         | 92.2 ± 3.3         | 91.5 ± 3.1         | 90.0 ± 4.0         | 9.47    | <.001 (1 < 2, 3)   |
| Δ                                     | 8.3 ± 4.3          | 6.6 ± 3.6          | 5.8 ± 4.6          | 9.56    | <.001 (1 < 2, 3)   |
| Varus-LJSW, mm                        | 9.9 ± 1.5          | 9.5 ± 1.8          | 9.2 ± 1.4          | 4.21    | .016 (1 < 3)       |
| Valgus-MJSW, mm                       | 7.1 ± 1.3          | 7.2 ± 1.1          | 7.6 ± 1.2          | 5.78    | .003 (1, 2 < 3)    |
| VVD                                   | 2.8 ± 1.9          | 2.4 ± 2.2          | 1.6 ± 1.2          | 0.41    | .667               |

Data are presented as mean ± SD unless otherwise specified. Boldface P values indicate a statistically significant difference between groups (P < .05; one-way analysis of variance). AKSS, American Knee Society Score; BMI, body mass index; mLDFA, mechanical lateral distal femoral angle; MPTA, medial proximal tibial angle; WBLR, weightbearing line ratio; WOMAC, Western Ontario and McMaster Universities Osteoarthritis Index.

Table 3: Unfavorable Radiological Outcomes After OWHTO

| Value (Post Hoc) | Group 1 | Group 2 | Group 3 | P Value |
|------------------|---------|---------|---------|---------|
| WBLR, %          | 19.6 ± 10.1 | 5.8 ± 6.5 | 20.3 ± 2.4 | 32.0 ± 3.1 | <.001 (1 < 2 < 3) |
| mLDFA, deg       | 89.1 ± 2.2 | 87.8 ± 1.3 | 88.7 ± 1.6 | 89.7 ± 2.4 | .019 |
| MPTA, deg        | 84.6 ± 3.3 | 83.9 ± 4.0 | 85.0 ± 2.7 | 84.4 ± 3.4 | .046 |

*Data are presented as mean ± SD unless otherwise specified. Boldface P values indicate a statistically significant difference between groups (P < .05; one-way analysis of variance). AKSS, American Knee Society Score; BMI, body mass index; mLDFA, mechanical lateral distal femoral angle; MPTA, medial proximal tibial angle; WBLR, weightbearing line ratio; WOMAC, Western Ontario and McMaster Universities Osteoarthritis Index.*
Table 3  
Unfavorable Radiological Outcomesa

|                | Group 1 (n = 84) | Group 2 (n = 169) | Group 3 (n = 84) | P Value |
|----------------|-----------------|------------------|-----------------|---------|
| MPTA >95°      | 17 (20.2)       | 18 (10.7)        | 8 (9.5)         | .038    |
| JLCA >4°       | 10 (11.9)       | 26 (15.4)        | 14 (16.7)       | .659    |
| JLCA <0° (valgus progression) | 2 (2.4)     | 16 (9.5)         | 6 (7.1)         | .119    |
| Recurrence of varus deformity (WBLR <55%) | 23 (27.4) | 34 (20.1)        | 18 (21.4)       | .416    |
| LHF            | 26 (30.9)       | 44 (26.0)        | 11 (13.1)       | .313    |

aData are presented as n (%). Boldface P values indicate a statistically significant difference between groups (P < .05). JLCA, joint-line convergence angle; LHF, lateral hinge fracture; MPTA, medial proximal tibial angle; WBLR, weightbearing line ratio.

Table 4  
Factors Associated With Unfavorable Radiological Outcomesa

|                | Favorable | Unfavorable | P Value |
|----------------|-----------|-------------|---------|
| MPTA >95°      | Preoperative WBLR 20.0 ± 10.0 | 16.6 ± 10.3 | .039    |
| MPTA <95°      | Postoperative WBLR 55.4 ± 8.6 | 65.4 ± 9.2 | <.001   |
| JLCA >4°       | AWBLR 35.4 ± 12.1 | 48.8 ± 11.1 | <.001   |
| JLCA <0°       | Postoperative MPTA 90.5 ± 2.9 | 96.4 ± 0.8 | <.001   |
| LHF            | AMPTA 6.0 ± 3.7 | 11.4 ± 3.4 | <.001   |
| Recurrence of varus deformity (WBLR <55%) | Postoperative WBLR 57.2 ± 9.5 | 53.7 ± 7.3 | .004    |
| LHF            | AWBLR 37.8 ± 12.6 | 33.0 ± 12.9 | .017    |
| Preoperative JLCA 2.9 ± 1.8 | 4.5 ± 1.7 | <.001   |
| Preoperative JLCA 1.7 ± 1.3 | 5.0 ± 0.7 | <.001   |
| LHF            | DjLCA –1.3 ± 1.8 | 0.5 ± 1.6 | <.001   |
| VVD            | AMPTA 6.9 ± 4.1 | 5.4 ± 3.8 | .011    |
| VVD            | Varus-LJSW 9.1 ± 1.6 | 10.4 ± 1.8 | <.001   |
| VVD            | VVD 1.7 ± 1.8 | 3.1 ± 2.2 | <.001   |
| LHF            | Preoperative WBLR 21.9 ± 10.4 | 18.6 ± 9.7 | .032    |

aData are presented as mean ± SD. Boldface P values indicate a statistically significant difference between groups (P < .05). JLCA, joint-line convergence angle; LHF, lateral hinge fracture; LJSW, lateral joint space width; MPTA, medial proximal tibial angle; VVD, difference between varus and valgus stress radiographs; WBLR, weightbearing line ratio.

(0.7 ± 0.6 mm) (P < .001). However, there was no difference between groups 1 and 2. The preoperative MPTA in group 1 (83.9° ± 4.0°) was significantly smaller than that in group 2 (85.0° ± 2.7°) and group 3 (84.4° ± 3.4°) (P = .046). However, there was no significant difference between groups 2 and 3. The varus-LJSW in group 1 (9.9 ± 1.5 mm) was significantly larger than in group 3 (9.2 ± 1.4 mm) (P = .016). However, the varus-LJSW in group 2 did not significantly differ from that in groups 1 and 3. The valgus-MJSW in group 3 (7.6 ± 1.2 mm) was significantly larger than that in group 1 (7.1 ± 1.3 mm) and group 2 (7.2 ± 1.1 mm) (P = .003). However, there was no difference between groups 1 and 2. The JLCA and VVD also did not significantly differ between the 3 groups. The incidence of an MPTA >95° showed a significant relationship with the WBLR between group 1 (20.2%), group 2 (10.7%), and group 3 (9.5%) (P = .038). However, the incidence of a JLCA >4°, a JLCA <0°, the recurrence of a varus deformity, and an LHF showed no significant relationships between the groups.

The factors associated with unfavorable radiological outcomes are summarized in Table 4. For the MPTA, the preoperative WBLR, postoperative WBLR, AWBLR, postoperative MPTA, and ΔMPTA showed significant differences between the patients with an MPTA ≤95° and those with an MPTA >95° (P = .039, P < .001, P < .001, and P < .001, respectively). A representative case showing an MPTA >95° is demonstrated in Figure 2. For the JLCA, the postoperative WBLR, AWBLR, preoperative JLCA, ΔJLCA, ΔMPTA, varus-LJSW, and VVD showed significant differences between the patients with a JLCA ≤4° and those with a JLCA >4° (P = .004, P = .017, P < .001, P < .001, P < .001, P < .011, P < .001, and P < .001, respectively). A representative case showing a JLCA >4° is demonstrated in Figure 3. Additionally, the preoperative JLCA, postoperative JLCA, and ΔJLCA showed significant differences between the patients with a JLCA ≥0° and those with a JLCA <0° (P = .005, P < .001, and P < .001, respectively). The preoperative WBLR, postoperative WBLR, AWBLR, and ΔMPTA showed significant differences between the knees that developed the recurrence of a varus deformity and those that did not (P = .039, P < .001, P < .001, and P = .044, respectively). For the LHF, only the preoperative WBLR showed a significant difference between the 2 groups (unfavorable outcomes and favorable outcomes) (P = .032). A representative case showing an LHF is shown in Figure 4.

The cutoff values of the WBLR causing each unfavorable outcome are summarized in Table 5 and Figure 5. The ROC curve analysis indicated that the cutoff value of ΔWBLR causing an MPTA >95° was 46.5%, which showed a good area under the curve value of 0.800, with a sensitivity of 74.4% and a specificity of 82.7%. The ROC curve analysis between the WBLR and other
unfavorable radiological outcomes showed poor area under the curve values (<0.600).36

DISCUSSION

The principal findings of this study are as follows. First, a \(\Delta WBLR \geq 46.5\%\) predicted unfavorable radiological outcomes. Second, a low preoperative WBLR was related to a larger \(\Delta WBLR\), a larger reduction in coronal translation, a larger \(\Delta MPTA\), a wide preoperative lateral joint space, and a preoperative narrow medial joint space. However, only an \(MPTA > 95^\circ\) was significantly related to a low WBLR in the subgroup analysis according to unfavorable radiological outcomes. Third, the \(\Delta WBLR\) after OWHTO correlated with an \(MPTA > 95^\circ\), as verified in the subgroup analysis according to unfavorable radiological outcomes. In addition, more severe varus knees showed a larger preoperative coronal translation and a larger reduction in coronal translation, which can decrease excessive loading on the medial compartment by correcting varus deformities.4 Along with these changes, the JLCA decreased, which indicated that contracture of medial soft tissue was released and knee joint congruency was returned to normal.24 However, the MPTA also consequently increased.

The unfavorable radiological outcomes in our study, including an \(MPTA > 95^\circ\), a JLCA >4°, a JLCA <0°, the recurrence of a varus deformity, and an LHF, were determined on the basis of previous reports. Excessively increased MPTAs have been reported to be associated with unfavorable clinical outcomes, especially when the MPTA increases to >95°.7,13,15,30 However, in our study, there were no statistically significant differences in clinical outcomes in the subgroup analysis. Meanwhile, residual intra-articular varus is represented by the postoperative JLCA. Therefore, a large postoperative JLCA may act as an adduction moment for the medial compartment of the knee.11,16,33 On the contrary, it was also reported that as the postoperative limb alignment became more valgus, the postoperative JLCA became more parallel. This indicates that parallel or negative JLCAs after OWHTO may be associated with valgus overcorrection.16,17,22 An LHF has been reported as an important factor associated with inaccurate correction and recurrence.5,19,34

In the subgroup analysis of unfavorable radiological outcomes, \(\Delta WBLR\) was the common significant factor associated with unfavorable radiological outcomes, except for a JLCA <0° and an LHF. For a JLCA <0°, which indicates a tendency for valgus overcorrection, only the JLCA parameters were significant. This study focused on the WBLR
and reported a threshold for the correction degree of the WBLR while considering the MPTA, JLCA, recurrence of a varus deformity, and LHF. However, only the MPTA was significant in terms of the cutoff values. DLO is then suggested when $\geq 46.5\%$ of $\Delta$WBLR is predicted during preoperative planning.

In previous studies, DLO has been introduced for joint preservation in patients with severe unicompartmental osteoarthritis to avoid JLO. The concept of DLO was to restore normal joint angles at the distal femur and the proximal tibia to avoid JLO and achieve normal alignment, resulting in a good clinical outcome. Many studies have been conducted to identify the indications for DLO. Iseki et al. reported that in patients with a varus hip-knee-ankle angle $>10^\circ$, the predicted MPTA was $\geq 95^\circ$ or the wedge size was $\geq 15$ mm in the OWHTO surgical simulation, and DLO could avoid leg-length changes and non-physiological joint lines. Sohn et al. reported that a preoperative JLO $>3^\circ$ and a JLCA $>5^\circ$ were 2 significant risk factors for excessive MPTAs after OWHTO, which may require DLO. In another study, it was reported that less than one-third of patients (28%) with a mechanical tibiofemoral angle $>3^\circ$ had a tibial deformity. Therefore, if anatomic correction (MPTA $<90^\circ$) is intended, only 12% of cases can be corrected via isolated OWHTO, 63% will require DLO, and 25% are uncorrectable or will require distal femoral osteotomy. If slight overcorrection is accepted (MPTA $<95^\circ$), 57% of cases can be corrected via isolated OWHTO, whereas 33% will still require DLO. In addition, Harrer et al. reported that by performing DLO instead of isolated OWHTO, they lowered complications such as LHFs and delayed bone healing.

**Strengths and Limitations**

This study has several strengths. It comprehensively analyzed various unfavorable radiological outcomes that can occur after OWHTO, which are associated with various parameters, such as the MPTA, JLCA, recurrence of a varus deformity, and LHF. Furthermore, these radiological outcomes were divided into categories, and the factors related to their occurrence were analyzed. We also evaluated the cutoff values of each parameter to determine the ideal indication for DLO for severe varus knees. However, only the MPTA was acceptable and was strongly related to the change in the WBLR between the preoperative status and the final target of correction.

The limitations of this study are as follows. First, this study did not directly compare DLO to OWHTO. Therefore, it has not been established whether unfavorable radiological outcomes are actually resolved or indicate better clinical outcomes after DLO. Second, although a radiographic

![Figure 3. A 58-year-old female patient who underwent opening-wedge high tibial osteotomy on her right knee. (A) The preoperative weightbearing line ratio (WBLR) was 32.1%, and the joint-line convergence angle (JLCA) was 5.4°. (B) The medial joint space width was 6.9 mm. (C) The lateral joint space width was 8.7 mm. (D) The WBLR and JLCA changed to 51.2% and 4.1°, respectively.](image-url)
evaluation was performed at 1-year intervals after surgery, in this study, radiological assessments were compared and analyzed only before and at 1 year after surgery. The reason was that alignment after OWHTO usually remains steady after 1 year.32 In addition, the patients had different follow-up periods, and it was necessary to use radiographs from the

**Figure 4.** A 58-year-old female patient who underwent opening-wedge high tibial osteotomy (OWHTO) on her right knee. (A) The preoperative weightbearing line ratio was –1.8%, and the medial proximal tibial angle was 83.7°. (B) The medial joint space width was 9.1 mm. (C) The lateral joint space width was 11.2 mm. (D) A lateral hinge fracture occurred during OWHTO, and additional fixation to the lateral hinge was performed for prevention.

**TABLE 5**

| Cutoff Values for WBLR Causing Unfavorable Radiological Outcomes<sup>a</sup> | Cutoff Value | Sensitivity, % | Specificity, % | AUC   |
|--------------------------------------------------------------|--------------|----------------|---------------|-------|
| MPTA >95°                                                    | Preoperative WBLR | –8.3           | 100.0         | 2.4   | 0.388 |
|                                                             | AWBLR        | 46.5           | 74.4          | 82.7  | 0.800 |
| JLCA >4°                                                     | Preoperative WBLR | 19.7           | 55.2          | 32.2  | 0.573 |
|                                                             | AWBLR        | 10.5           | 100.0         | 0.3   | 0.390 |
| JLCA <0°                                                     | Preoperative WBLR | 19.8           | 79.2          | 52.4  | 0.573 |
|                                                             | AWBLR        | 36.6           | 58.3          | 49.8  | 0.482 |
| Recurrence of varus deformity                               | Preoperative WBLR | 24.9           | 26.7          | 73.7  | 0.429 |
|                                                             | AWBLR        | 8.1            | 100.0         | 0.0   | 0.204 |
| LHF                                                          | Preoperative WBLR | 11.5           | 82.8          | 23.3  | 0.464 |
|                                                             | AWBLR        | 30.3           | 72.4          | 38.4  | 0.516 |

<sup>a</sup>AUC, area under the curve; JLCA, joint-line convergence angle; LHF, lateral hinge fracture; MPTA, medial proximal tibial angle; WBLR, weightbearing line ratio.
same time period for the assessment. Third, the subgroup analysis according to the WBLR was performed with 3 percentile categories, which might have resulted in bias. However, we also wanted to simultaneously determine general tendencies and cutoff values. Fourth, coronal alignment compensations of the ankle and hip joints that can affect each other were not analyzed. Fifth, the target WBLR was not the same for each patient, and the degree of correction could be different. However, the target WBLR range for all patients was limited between 55% and 65%. Finally, this study could not evaluate unfavorable outcomes due to delayed union or nonunion because the patients underwent different bone grafting methods.

CONCLUSION

A ΔWBLR >46.5% led to an MPTA >95°. However, clinical outcomes were not affected. DLO should be considered if the surgeon desires a postoperative MPTA ≤95°.

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