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Original article

Impact of Mechanical Axis Correction, Coronal Plane Alignment Phenotype, and Joint-Line Obliquity on Clinical Outcomes Following Lateral Closing-Wedge High Tibial Osteotomy: A Retrospective Cohort Study of 350 Knees

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High Tibial Osteotomy, Lateral Closing-Wedge Osteotomy, CPAK, Constitutional Alignment, Joint-Line Obliquity, Mechanical Axis, Osteoarthritis.

ABSTRACT

High tibial osteotomy (HTO) is an established joint-preserving procedure for the treatment of medial compartment osteoarthritis associated with varus malalignment. While correction of the mechanical axis remains the primary objective of osteotomy planning, recent concepts of constitutional alignment and the Coronal Plane Alignment of the Knee (CPAK) classification suggest that restoration of native alignment may influence postoperative function and patient satisfaction. To evaluate the influence of postoperative mechanical axis correction, CPAK phenotype restoration, and joint-line obliquity (JLO) on clinical outcomes following lateral closing-wedge high tibial osteotomy (LCWHTO). A retrospective cohort study was conducted on 350 knees in 220 consecutive patients who underwent LCWHTO for symptomatic medial compartment osteoarthritis with varus deformity between January 2016 and December 2021. Clinical outcomes were assessed using the Hospital for Special Surgery (HSS) Knee Score. Standardized standing hip–knee–ankle radiographs were obtained preoperatively and at a minimum follow-up of three years. Radiographic parameters included hip-knee-ankle angle (HKA), weight-bearing line (WBL) ratio, medial proximal tibial angle (MPTA), lateral distal femoral angle (LDFA), arithmetic HKA (aHKA), joint-line obliquity (JLO), and CPAK phenotype. Associations between radiographic correction and clinical outcomes were analyzed. At a mean follow-up of 3.2 ± 0.6 years, the mean HSS score improved significantly from 61.3 ± 8.7 preoperatively to 88.5 ± 7.4 postoperatively ($p < 0.001$). Knees corrected to a postoperative WBL between 60% and 70% of the tibial plateau achieved significantly higher HSS scores than those corrected outside this range (92.4 ± 5.6 vs. 83.4 ± 8.0, $p < 0.001$). Acceptable postoperative JLO was associated with superior outcomes, with 78% of patients achieving excellent or good results compared with 61% among those with excessive JLO ($p = 0.002$). Patients whose postoperative alignment closely approximated their constitutional CPAK phenotype demonstrated significantly higher functional scores and greater satisfaction. Clinical outcomes following LCWHTO are influenced not only by mechanical axis correction but also by restoration of constitutional alignment and preservation of physiological joint-line orientation. Optimal outcomes were achieved when the postoperative WBL passed through 60–70% of the tibial plateau while maintaining acceptable JLO. CPAK-guided planning may provide an effective framework for individualized osteotomy correction.
Level III, retrospective cohort study.

Introduction

Medial compartment osteoarthritis associated with varus malalignment remains a common source of pain and functional limitation among active middle-aged individuals. High tibial osteotomy (HTO) has long been established as an effective joint-preserving procedure that redistributes load from the diseased medial compartment to the relatively preserved lateral compartment, thereby reducing symptoms and delaying the need for total knee arthroplasty. Historically, successful HTO has been closely linked to accurate correction of the mechanical axis. Following the pioneering work of Coventry and Fujisawa, most correction strategies have targeted placement of the weight-bearing line at approximately 62–67% of the tibial plateau width. Achievement of this target has consistently been associated with improved pain relief, functional recovery, and long-term survivorship. Recent advances in alignment theory have challenged the concept of universal correction targets.

Constitutional alignment studies have demonstrated considerable variation in native lower-limb alignment among individuals. The Coronal Plane Alignment of the Knee (CPAK) classification introduced by MacDessi et al. provides a comprehensive framework for characterizing both limb alignment and joint-line orientation. This classification suggests that restoration of a patient's constitutional phenotype may be more physiologically appropriate than correction toward a standard valgus alignment. Joint-line obliquity has emerged as another important determinant of postoperative biomechanics. Excessive obliquity may increase shear stresses across the tibiofemoral joint, alter ligament tension, and

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potentially compromise clinical outcomes despite satisfactory mechanical-axis correction. Consequently, contemporary osteotomy planning increasingly incorporates both constitutional alignment and preservation of physiological joint-line orientation. Although these concepts have been extensively investigated in medial opening-wedge HTO, limited evidence exists regarding their influence on outcomes following lateral closing-wedge high tibial osteotomy. Therefore, the purpose of this study was to evaluate the relationship between postoperative mechanical-axis correction, CPAK phenotype restoration, joint-line obliquity, and clinical outcomes following LCWHTO. We hypothesized that superior clinical outcomes would be achieved when correction restored a physiological alignment pattern characterized by a postoperative WBL within the Fujisawa zone and preservation of acceptable joint-line obliquity.

Materials And Methods

Study Design

This retrospective cohort study was approved by the Institutional Review Board. Consecutive patients who underwent LCWHTO between January 2016 and December 2021 were identified from a prospectively maintained institutional database.

Patient Selection

Inclusion criteria were:

- Symptomatic medial compartment osteoarthritis.
- Varus malalignment confirmed on standing long-leg radiographs.
- Failure of non-operative treatment for at least six months.
- Age between 40 and 65 years.
- Minimum follow-up of three years.

Exclusion criteria included inflammatory arthritis, lateral compartment osteoarthritis, severe patellofemoral degeneration, previous major ligament reconstruction, flexion contracture greater than 15°, and incomplete radiographic data. A total of 220 patients (350 knees) met the study criteria.

Surgical Technique

All procedures were performed by experienced knee surgeons using a standardized lateral closing-wedge high tibial osteotomy technique. Preoperative planning was based on standing hip–knee–ankle radiographs. After removal of the planned lateral wedge, the osteotomy was closed while preserving the medial cortical hinge. Internal fixation was achieved using a standardized fixation construct, and postoperative rehabilitation followed a uniform protocol.

Surgical Technique: The Al-Khadra Lateral Closed Wedge Osteotomy

- **Anesthesia:** General or spinal
- **Positioning:** Supine with tourniquet control
- **Incision:** Oblique, ~5 cm lateral to tibial tubercle
- **Exposure:** Subperiosteal dissection over the lateral tibial condyle
- **Osteotomy:** Lateral closed wedge (1 cm base), preserving the medial cortex
- **Fixation:** Single staple fixation; no fibular osteotomy performed
- **Post-op immobilization:** Plaster-of-Paris (POP) cylinder cast
- **Post-op imaging:** Standard AP and lateral radiographs



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Clinical Evaluation

Clinical outcomes were assessed using the Hospital for Special Surgery (HSS) Knee Score before surgery and at final follow-up. Outcomes were categorized as excellent (≥85), good (70–84), fair (60–69), or poor (<60).

Radiographic Assessment

Standing full-length weight-bearing radiographs were obtained preoperatively and postoperatively. The following parameters were measured:

- Mechanical axis position
- Weight-bearing line (WBL);
  The *WBL* is drawn from the center of the femoral head to the center of the talus. The *WBL* ratio is calculated in the tibial plateau from the medial edge
- Hip-knee-ankle angle (HKA)
- The HKA is measured on a weight-bearing, full-length AP lower limb radiograph. The first line is drawn from the femoral head to the femoral intercondylar notch, while the latter is drawn from the tibial interspinous point to the tibial mid-plafond. The HKA is defined as the angle between these two lines

* Joint line obliquity (JLO);

The angle between a horizontal line parallel to the ground and a tangent to the tibial plateau. Surgical correction targets a valgus overcorrection, typically between 8–12°, depending on patient-specific anatomy and surgeon preference [1,5,6]. Restoration of proper alignment is critical to redistributing load and optimizing long-term outcomes.

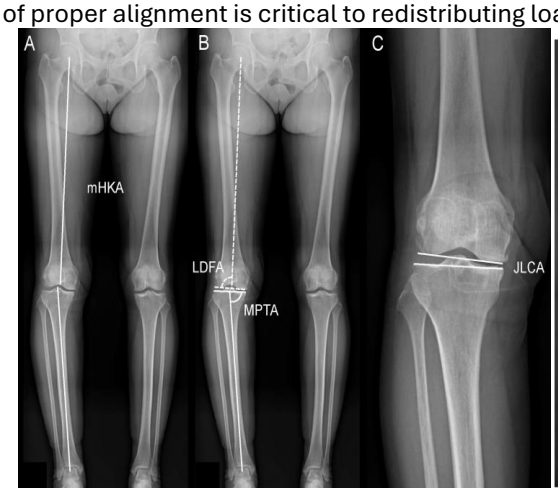


Photo 1 **Photo 2** **Photo 3**

CPAK Phenotype Analysis

Patients whose postoperative alignment remained within one CPAK category of their constitutional phenotype demonstrated higher functional scores and greater patient satisfaction than those with substantial phenotype deviation. Coronal plane alignment phenotypes were classified according to the CPAK system described by MacDessi et al. Arithmetic HKA (aHKA) was calculated as MPTA minus LDFA, while joint line obliquity (JLO) was calculated as MPTA plus LDFA. Knees

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were classified into one of nine CPAK phenotypes based on constitutional limb alignment and joint-line orientation. Phenotype distribution was analyzed preoperatively and postoperatively to evaluate restoration of constitutional alignment. Clinical Outcomes According to Postoperative CPAK Phenotype (n = 350).
Patients whose postoperative alignment most closely restored their constitutional CPAK phenotype (Types III–V) demonstrated significantly higher postoperative HSS scores and a greater proportion of excellent/good clinical outcomes compared with other phenotypes ($p < 0.05$).

CPAK phenotypes were determined according to the classification system described by MacDessi et al. Arithmetic HKA was calculated as MPTA minus LDFA, while JLO was calculated as the sum of MPTA and LDFA. Knees were categorized into one of nine CPAK phenotypes based on constitutional alignment and joint-line orientation.

Statistical Analysis
Continuous variables were expressed as mean ± standard deviation. Paired t-tests were used to compare preoperative and postoperative outcomes. Analysis of variance (ANOVA) assessed differences among WBL groups, while categorical variables were analyzed using chi-square testing. Multivariate regression analysis identified independent predictors of postoperative function. Statistical significance was defined as $p < 0.05$.

Results

The study included 220 patients (350 knees) with a mean age of 54.8 ± 7.2 years and a mean body mass index of 29.4 ± 3.8 kg/m^2. Mean follow-up was 3.2 ± 0.6 years. Clinical outcomes improved significantly following surgery. The mean HSS score increased from 61.3 ± 8.7 preoperatively to 88.5 ± 7.4 at final follow-up ($p < 0.001$). Patients whose postoperative WBL was corrected to between 60% and 70% of the tibial plateau achieved the highest functional outcomes. Significant reductions in HSS scores were observed when the correction fell outside this range. Joint-line obliquity also demonstrated a significant influence on clinical outcome.

Table 1. Clinical outcomes according to CPAK phenotypes: distribution of knees, mean HSS scores, and proportion of excellent/good results.

CPAK Phenotype	Knees (n)	Mean HSS Score	Excellent/Good Results (%)
Type I	38	84.6 ± 7.9	68.4
Type II	42	86.1 ± 7.2	71.4
Type III	55	88.7 ± 6.8	78.2
Type IV	61	91.2 ± 5.4	85.2
Type V	49	90.4 ± 5.8	83.7
Type VI	37	87.9 ± 6.7	75.7
Type VII	29	86.5 ± 7.5	72.4
Type VIII	23	84.8 ± 8.1	69.6
Type IX	16	83.9 ± 8.3	68.8
Total	350	88.5 ± 7.4	77.4

Patients with acceptable postoperative JLO achieved superior results, with 78% classified as excellent or good compared with 61% among patients with excessive obliquity ($p = 0.002$). Analysis of CPAK phenotypes demonstrated that restoration of constitutional alignment was associated with improved postoperative function. Patients classified within CPAK Types III–V achieved significantly higher HSS scores and a greater proportion of excellent or good outcomes than other phenotypes. Multivariate regression identified postoperative WBL position, JLO, and CPAK phenotype restoration as independent predictors of postoperative HSS score.

Table 2. Improvement in HSS scores from preoperative assessment to final follow-up.

Outcome	Preoperative	Final Follow-up	p-value
HSS Score	61.3 ± 8.7	88.5 ± 7.4	<0.001

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Table 3. Multivariate regression analysis of predictors of postoperative HSS score, including WBL position, JLO, age, BMI, and CPAK phenotype restoration.

Variable	Beta Coefficient	95% CI	p-value
Postoperative WBL Position	0.41	0.28 to 0.54	<0.001
Joint-Line Obliquity (JLO)	-0.29	-0.45 to -0.13	0.002
Age	-0.08	-0.19 to 0.03	0.150
BMI	-0.11	-0.24 to 0.02	0.080
CPAK Phenotype Restoration	0.22		

Table 5. Patient Demographics

Variable	Value
Patients	220
Knees	350
Mean age (years)	54.8 Â± 7.2
Male/Female	128/92
BMI (kg/mÂ²)	29.4 Â± 3.8
Mean follow-up (years)	3.2 Â± 0.6

Table 6. Clinical Outcomes

Outcome	Preoperative	Final Follow-up	p-value
HSS Score	61.3 Â± 8.7	88.5 Â± 7.4	<0.001

Table 7. WBL Position and Outcomes

WBL Position	Knees	Mean HSS Score
<60%	96	82.1 Â± 8.2
60â€“70%	178	92.4 Â± 5.6
>70%	76	84.5 Â± 7.8

p < 0.001

Table 8. Joint Line Obliquity and Outcome

Group	Knees	Excellent/Good Outcome
Acceptable JLO	273	78%
Increased JLO	77	61%

Discussion

The principal finding of this study is that successful LCWHTO depends not only on mechanical-axis correction but also on preservation of physiological joint-line orientation and restoration of constitutional alignment. Patients corrected to a postoperative WBL between 60% and 70% of the tibial plateau achieved the most favorable clinical outcomes, supporting the continued validity of the Fujisawa principle. However, our results suggest that mechanical-axis correction alone does not fully explain postoperative function. The growing emphasis on constitutional alignment recognizes substantial inter-individual variation in native coronal alignment. CPAK-based assessment provides a useful framework for understanding these variations and may facilitate more individualized correction strategies. Joint-line obliquity was independently associated with postoperative outcome. Excessive JLO may increase shear forces and alter ligament balance, thereby negatively affecting knee biomechanics. Preservation of physiological joint-line orientation should therefore be considered an important goal during osteotomy planning. These findings support recent literature highlighting the importance of phenotype-based alignment strategies. Patients with femoral-based or combined deformities may require alternative approaches, including double-level osteotomy, to avoid excessive postoperative obliquity while achieving appropriate correction.

Limitation

1- As a retrospective design introduces potential selection bias.
2- Follow-up was limited to a mean of 3.2 years, regarding long-term survivorship.
3- Patient-reported outcome measures, in addition to the HSS score, were not routinely available.

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Conclusion

Lateral closing-wedge high tibial osteotomy provides reliable improvement in pain and function for patients with medial compartment osteoarthritis and varus malalignment. The most favorable outcomes were observed when the postoperative weight-bearing line was corrected to 60–70% of the tibial plateau width while maintaining physiological joint-line obliquity. Incorporating CPAK-based alignment analysis into preoperative planning may improve individualized correction strategies and optimize functional outcomes.

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