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RESEARCH

Does the preoperative CPAK classification influence clinical outcomes after medial and lateral unicompartmental knee arthroplasty? Short-term outcomes and phenotype distribution in a retrospective series of consecutive cases

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Abstract

Introduction Recent evidence suggest that mechanically aligned TKAs may yield heterogeneous outcomes across CPAK categories, but whether this applies to unicompartmental knee arthroplasty (UKA) remains unclear. This retrospective study evaluated the influence of preoperative CPAK category on postoperative clinical outcomes after UKA, with additional analyses assessing CPAK distribution, residual varus alignment, and their relationship with patient-reported outcomes.

Materials and methods A total of 312 consecutive UKAs (280 patients) with ≥1-year follow-up were analyzed. Preoperative HKA and JLO were measured on weight bearing long-leg radiographs, and patients were classified according to the CPAK system. Outcomes were compared across the six most represented CPAK groups (I – VI) in 253 patients with complete PROM data.

Results Mean postoperative OKS was 40.5 ± 5.3, with a mean ΔOKS of 21.3 ± 8.7 and 97% patients' satisfaction. No significant differences were observed among CPAK categories for OKS ($p = 0.80$), ΔOKS ($p = 0.90$), or satisfaction ($p = 0.70$), and alignment-based grouping (varus, neutral, valgus) showed similarly homogeneous outcomes. Residual varus ≥ 5° did not adversely affect results ($p > 0.10$), and no meaningful correlation was found between aHKA and postoperative OKS ($r = -0.003$, $p = 0.96$). CPAK distribution differed significantly by sex ($p < 0.001$). Five patients were revised (2 for persistent pain, 1 for PCL instability, 2 for infection).

Conclusions Preoperative CPAK phenotype did not influence short-term clinical outcomes after UKA, and no heterogeneity in PROMs was detected across phenotypes. These findings support UKA as a reliable and alignment-tolerant procedure across a wide range of coronal morphotypes. Prospective studies with postoperative long-leg radiographs and longer follow-up are warranted to determine whether CPAK preservation influences long-term survivorship.

Keywords Coronal plane alignment · Knee phenotype · Constitutional varus · Joint line obliquity · Patient-reported outcome measures · Oxford Knee Score · Alignment philosophy · Knee osteoarthritis

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Introduction

In the last decade, emerging alignment strategies have reshaped total knee arthroplasty, challenging mechanical alignment as the gold standard and drifting toward personalized alignment approaches tailored to each patient's native anatomy.

The "knee phenotype system" proposed by Hirschmann [1–3] and the "Coronal Plane Alignment of the Knee (CPAK) classification" by MacDessi [4] have introduced the concept of limb phenotype and defined a new way of assessing and describing patients' lower limb anatomy. In total knee arthroplasty (TKA), phenotypes and changes in coronal alignment have been associated with heterogeneous outcomes, and alignment modifications may negatively influence patient-reported results in selected CPAK categories [5]. In this scenario, procedures that better preserve native alignment and joint line orientation could be less sensitive to preoperative phenotype and may provide more homogeneous results across CPAK categories.

Unicompartmental knee arthroplasty (UKA) is a bone- and ligament-preserving resurfacing procedure for isolated medial or lateral compartment osteoarthritis. By preserving cruciate ligaments and minimizing changes to joint-line orientation, UKA may potentially reduce the impact of coronal phenotype on postoperative outcome.

To date, most CPAK-related studies [12–16] in UKA cohorts have focused on either medial or lateral procedures and on postoperative changes in phenotype, rather than on the prognostic value of the preoperative CPAK category itself. Moreover, little is known about how CPAK phenotypes are distributed among UKA candidates and whether relevant sex-based differences exist.

This study had two primary purposes: (1) to evaluate the effect of the preoperative CPAK category on the postoperative outcomes and patient satisfaction following UKA; (2) to analyze the distribution of UKA candidates among the various CPAK categories, with particular attention to potential sex-based differences in categories distribution between male and female patients.

Secondary objectives were to investigate if constitutional varus > 5° may affect the clinical results after medial UKA and potential correlations between calculated radiographic parameters and postoperative outcomes. We hypothesized that, due to its anatomy-preserving nature, UKA would provide homogeneous short-term outcomes across CPAK categories and that no single coronal phenotype would represent a contraindication to the procedure.

Materials and methods

Study design and participants

A retrospective analysis was conducted on a consecutive series of patients who underwent medial or lateral unicompartmental knee arthroplasty at the hospital "XXXXXXXXXXXXXXX", between September 2022 and December 2023. Data were retrieved from a prospectively maintained institutional database and cross-checked with the hospital's radiographic archive. The study was approved by the local institutional review board, and all patients provided informed consent for the use of their anonymized data for research purposes.

During the study period, 280 patients (120 males, 160 females) received UKA for isolated medial or lateral compartment osteoarthritis, accounting for a total of 312 knees. Bilateral procedures, whether performed in a staged or single-stage manner, were included and analyzed at the knee level.

All surgeries were performed by high-volume surgeons experienced in UKA, using a conventional non-robotic technique. A fixed bearing, cemented unicompartmental prostheses were used in the majority of cases, including Physica ZUK (LimaCorporate), Persona Partial Knee (Zimmer Biomet), Journey UK (Smith & Nephew), and MOTO Partial Knee (Medacta). A mobile-bearing medial unicompartmental prosthesis (Oxford Partial Knee, Zimmer Biomet) was used in 18 patients, exclusively by a surgeon (XX).

Patient selection followed the Oxford criteria [6, 7] for UKA eligibility: severe, symptomatic osteoarthritis limited to the medial or lateral compartment, flexion deformity < 15°, constitutional varus or valgus < 15°, correctable intra-articular deformity, no severe damage or bone loss in the lateral patellofemoral joint or avascular necrosis. Integrity of the contralateral tibiofemoral and patellofemoral compartments, as well as a functional anterior cruciate ligament (ACL), were confirmed intraoperatively. Exclusion criteria included the absence of full-length preoperative radiographs of the lower limbs or missing anteroposterior and lateral views in the hospital's radiographic archive system.

From patient records, demographic data (age, sex, height, weight, BMI), medical history (comorbidities potentially affecting postoperative outcomes, previous surgeries at the operative site), surgical data (ASA classification, operated side and compartment, type of implant [mobile or fixed bearing], and any postoperative complications requiring rehospitalization or revision surgery) were collected.

Of the 312 knees, 253 (236 patients) had complete preoperative and 1-year postoperative clinical data and were included in the outcome analysis. The remaining 58 knees

(44 patients) were excluded from the PROMs analysis due to incomplete follow-up, and no imputation of missing values was performed (complete-case analysis). A dropout analysis was performed comparing baseline demographic and surgical characteristics (age, sex, BMI, ASA score, operated compartment, and side) between knees with complete 1-year PROMs and those lost to follow-up.

Medial and lateral UKA procedures were analyzed together to evaluate the influence of preoperative coronal alignment phenotype on overall UKA outcomes, rather than compartment-specific biomechanical effects.

Radiographic assessment

Preoperative coronal alignment was assessed on standardized long-leg weight-bearing radiographs; anteroposterior and lateral views of the knee in full extension were also acquired. Measurements were performed on a calibrated PACS (Carestream Imageview). The following parameters were recorded: hip–knee–ankle angle (HKA), medial proximal tibial angle (MPTA), lateral distal femoral angle (LDFA), joint line convergence angle (JLCA), and tibial slope. Based on arithmetic hip–knee–ankle angle (aHKA = MPTA − LDFA) and joint line obliquity (JLO = MPTA + LDFA), knees were classified according to the nine categories of the CPAK classification system[4]. An aHKA < 2°, 0 ± 2° and > 2° defined varus, neutral and valgus categories, respectively, while a JLO < 177°, 180 ± 3° and > 183° defined 'apex distal', 'apex neutral' and 'apex proximal' categories, respectively.

All measurements were performed by a single surgeon using the same workstation and software. To assess intraobserver reliability, measurements were repeated after 8 weeks, with all parameters showing a variation of less than 1° (intraclass correlation coefficient [ICC] = 0.92). Interobserver reliability was assessed by a second surgeon on a random sample of 20 patients, yielding an ICC of 0.90.

In our Institution, postoperative long-leg radiographs are not routinely performed at 1-year follow-up for UKA patients. In addition, rotational variability between pre- and postoperative acquisitions may introduce substantial error in coronal alignment measurements [8, 9]. For these reasons, no systematic comparison of pre- versus postoperative CPAK phenotype was conducted.

Clinical assessment

Clinical outcomes were assessed using validated patient-reported outcome measures (PROMs). The Oxford Knee Score (OKS) was collected both preoperatively and at one-year postoperative follow-up.

The change in OKS from pre- to postoperative assessment (ΔOKS) was calculated for each knee. The minimal clinically important difference (MCID) for the Oxford Knee Score was set at 5 points, in accordance with previously published literature [10].

Patient satisfaction at one year was assessed using four primary questions, targeting distinct domains: (1) resolution of pain, (2) improvement in the ability to perform housework or gardening; (3) improvement in the ability to engage in recreational activities; and (4) overall satisfaction with the surgical procedure. Each item was rated on a 5-point Likert scale with the following responses options: *very satisfied*, *somewhat satisfied*, *indifferent*, *somewhat dissatisfied*, *and very dissatisfied.* These responses were converted to numerical scores as follows: 100, 75, 50, 25, and 0, respectively. A composite satisfaction score (range: 0–100) was then calculated by averaging the scores from the four domains, with higher scores indicating greater satisfaction. In cases of bilateral surgery, patients were instructed to provide a general overall assessment.

To assess perceived change in quality of life (QOL) following surgery, patients answered the single question: "*How much did surgery improve your quality of life?*" Available response options were *it got worse*, *no change*, *a little bit better*, *better*, *much better*, *and improved more than I imagined*. This item was analyzed separately and was not included in the composite satisfaction score.

Only knees with complete pre- and postoperative OKS and satisfaction data were included in the outcome analysis. Missing PROMs were not imputed; rather, a complete-case analysis was adopted to avoid introducing assumptions on patient-reported data.

Statistical analysis

Statistical analysis was performed using STATA version 18 (StataCorp LLC, College Station, TX, USA). Continuous variables are reported as means and standard deviations, and categorical variables as counts and percentages. The primary endpoint was postoperative OKS at 1 year, and the primary hypothesis was that postoperative OKS would not differ significantly between CPAK categories. Secondary endpoints included ΔOKS, satisfaction scores, complication and revision rates, and correlations between radiographic parameters and postoperative outcomes. Due to the retrospective nature of the study, no a priori sample size calculation was conducted. Given the unbalanced distribution of cases across the nine CPAK categories, formal post hoc power estimates for individual subgroup comparisons were considered unreliable. Therefore, results were primarily interpreted based on effect sizes and confidence intervals rather than on post hoc power calculations.

Differences in continuous variables among CPAK categories or aHKA-based groups (varus, neutral, valgus) were analyzed using one-way analysis of variance (ANOVA). When significant, post hoc pairwise comparisons were performed using Tukey's Honestly Significant Difference (HSD) test to control for multiple comparisons. Categorical variables were compared using the chi-square test or Fisher's exact test when appropriate.

Assumptions of normality and homogeneity of variance were evaluated by visual inspection of histograms and Q–Q plots, as well as by Shapiro–Wilk and Levene tests. Where appropriate, effect sizes were calculated (eta-squared [η^2] for ANOVA and Cohen's d for pairwise comparisons) to complement p-values and to aid interpretation of clinical relevance.

The correlation between radiographic parameters and postoperative outcomes was examined using Spearman's rank correlation coefficient. Radiographic measurements were independently performed in a blinded manner by two observers, and intraclass correlation coefficients (ICCs) were calculated to assess interobserver agreement. A p-value < 0.05 was considered statistically significant.

Results

Patient demographics and surgical procedures

Between September 2022 and December 2023, a total of 312 UKAs were performed in 280 patients (120 males, 160 females): 218 medial UKAs, 28 bilateral medial UKAs, 30 lateral UKAs, and 4 bilateral lateral UKAs.

Mean age and BMI were comparable across CPAK categories (Age: 68–71 years; BMI: 27.3–29.6 kg/m²), with no statistically significant differences. The corresponding 95% confidence intervals of age and BMI across groups demonstrated a consistent overlap, supporting demographic comparability (Table 1).

The distribution of knees by CPAK category is reported in Table 1; Figs. 1, 2, 3 and 4. The most common phenotypes were Type 1 (varus, distal apex; 34.9%) and Type 2 (neutral, distal apex; 27.9%). Types 3–6 were less frequent, while no knees exhibited a proximal-apex joint line configuration (Types 7–9). Overall, 46.4% of knees showed varus alignment, 36.9% neutral alignment, and 16.6% valgus alignment based on aHKA.

A statistically significant difference was observed in sex distribution across CPAK groups ($p = 0.000009$; Figs. 2, 3 and 4), with males showing a higher prevalence of Type 1 (46.3%) and females showing a proportionally higher representation of Type 3 and Type 6. From a clinical standpoint, this reflects known sex-related anatomical differences in coronal alignment and joint line orientation, and it may help interpret phenotype prevalence in UKA candidates. However, these variations did not translate into different postoperative outcomes.

A total of 44 patients (58 knees) were lost to follow-up, leaving 236 patients (253 knees) with complete pre- and postoperative PROMs included in the final analysis. Dropout analysis (Supplementary Table S1) showed no significant differences between included and excluded knees in terms of age, sex, BMI, ASA score, operated compartment (medial vs. lateral), or side, suggesting a limited risk of attrition bias.

Complications and revisions

At 1-year follow-up, five patients required revision surgery (revision rate of 1.6 per 100 knees). Two of these revisions involved fixed-bearing UKAs and were performed for persistent, unexplained pain after an exhaustive work-up had excluded infection and obvious mechanical causes. One patient who received a mobile-bearing UKA underwent revision for posterior cruciate ligament rupture resulting in pain and instability.

Two suspected cases of periprosthetic joint infection were recorded within the first postoperative month (0.6 per 100 knees). One patient underwent surgical wound revision and insert exchange due to elevated inflammatory markers and clinical suspicion, but cultures were negative. The second patient underwent implant removal and placement of an antibiotic spacer for a confirmed periprosthetic infection

Table 1 number, age, BMI and sex distribution according CPAK categories

CPAK ($n=312$)	Number (%)	Age (mean ± SD, 95% CI)	p	BMI (mean ± SD, 95% CI)	p	Male n (%)	Female n (%)	p
1	109 (34.9)	71 ± 9.2 (69.0–73.0)	0.2	28.6 ± 4.4 (27.8–29.5)	0.5	62 (46.3)	47 (26.4)	0.000009
2	87 (27.9)	68 ± 9.2 (66.0–70.1)		28.5 ± 5.6 (27.3–29.6)		39 (28.4)	49 (27.5)	
3	31 (9.9)	68 ± 8.6 (65.0–71.6)		27.3 ± 4.4 (25.7–29.0)		4 (3)	27 (15.2)	
4	36 (11.5)	71 ± 8.2 (68.2–73.8)		29.6 ± 5.4 (27.7–31.6)		18 (13.4)	18 (10.1)	
5	28 (9)	70 ± 11.2 (65.7–74.3)		28.2 ± 4.4 (26.5–29.9)		10 (7.5)	18 (10.1)	
6	21 (6.7)	68 ± 7.9 (64.0–71.9)		27.7 ± 3.9 (26.1–29.3)		2 (1.5)	19 (10.7)	
7	0 (0,0)	–		–		0 (0,0)	0 (0,0)	
8	0 (0,0)	–		–		0 (0,0)	0 (0,0)	
9	0 (0,0)	–		–		0 (0,0)	0 (0,0)	

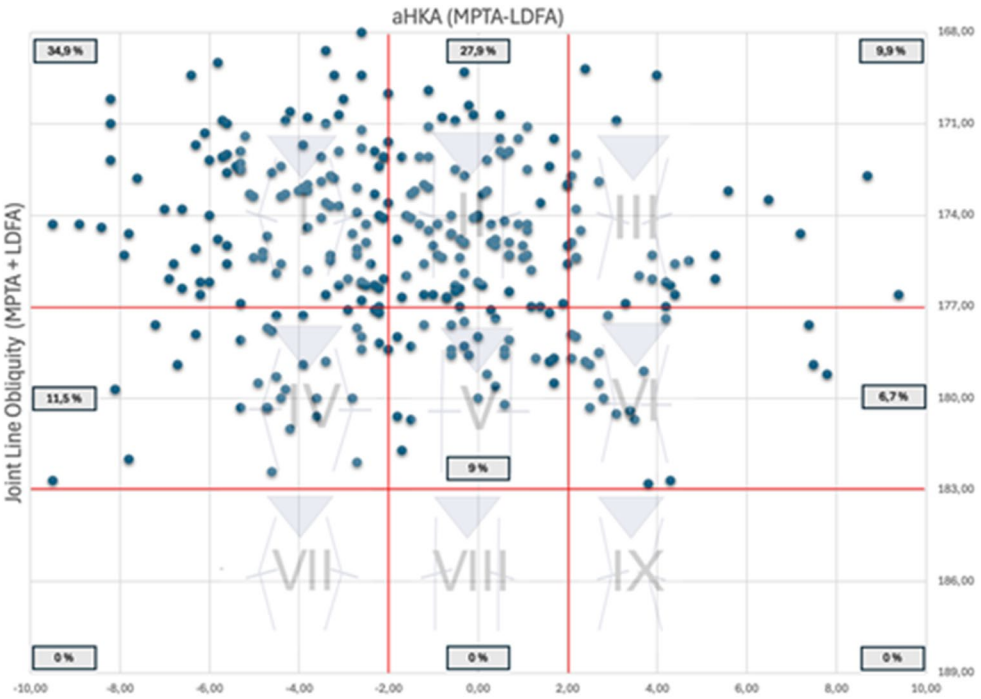


Fig. 1 CPAK categories distribution, according on aHKA and JLO

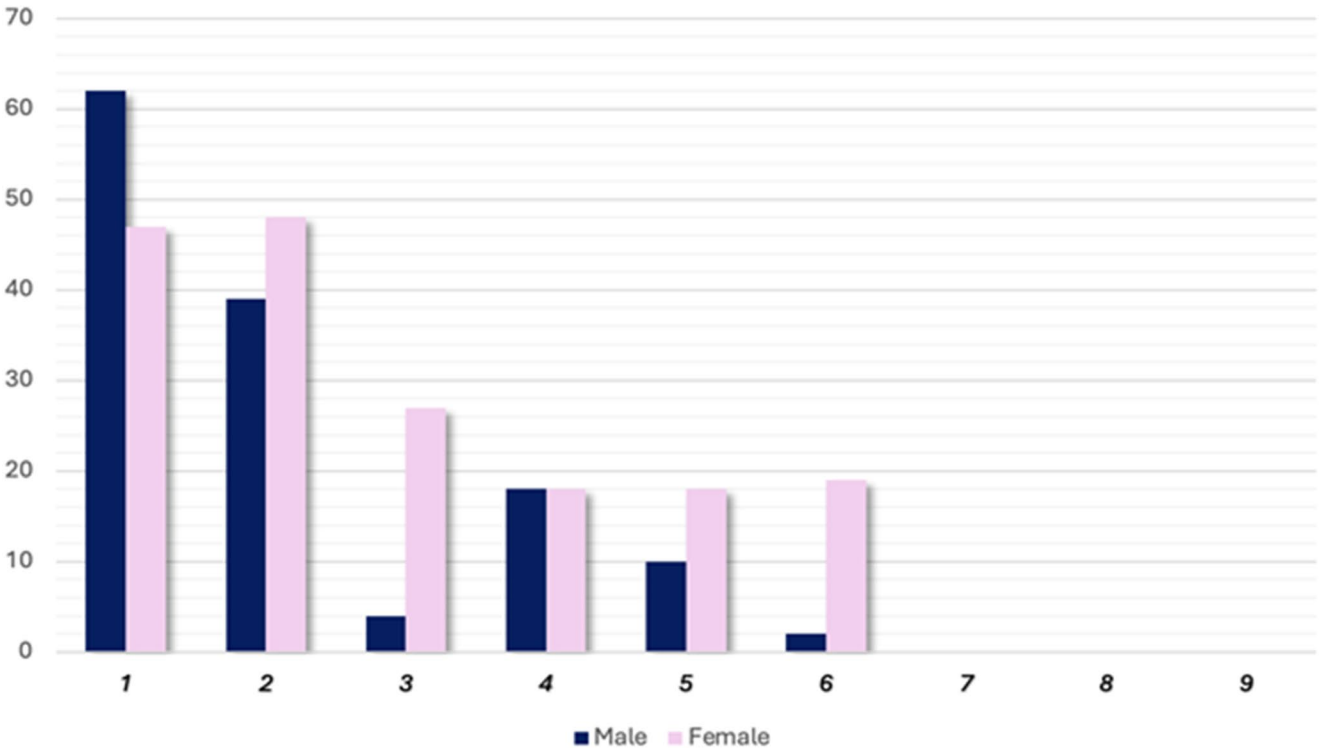


Fig. 2 sex distribution based on CPAK categories

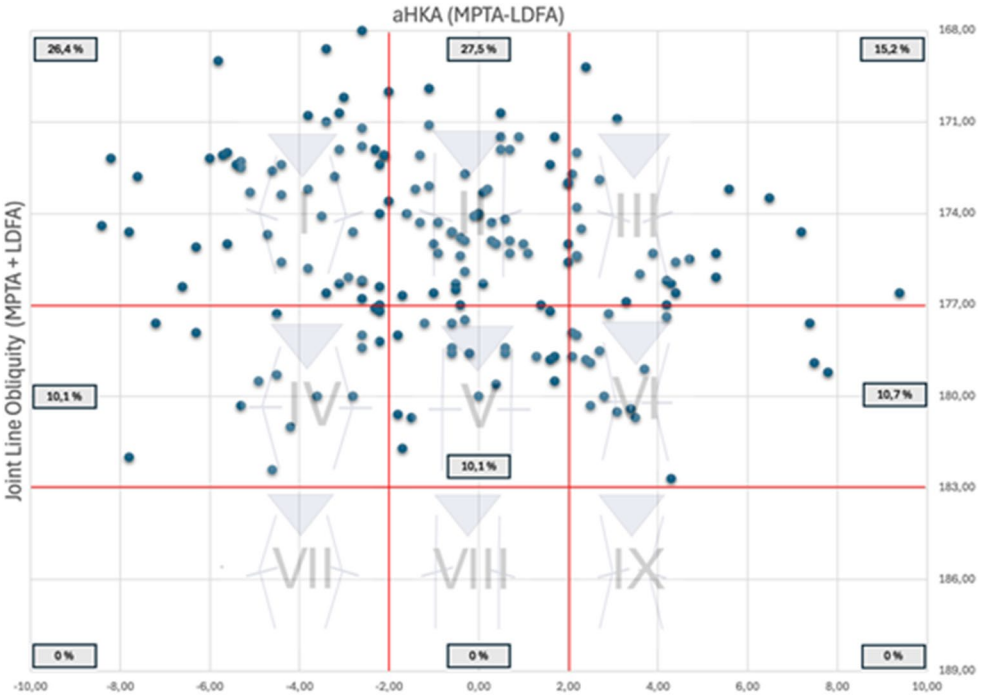


Fig. 3 distribution of the male population by CPAK categories

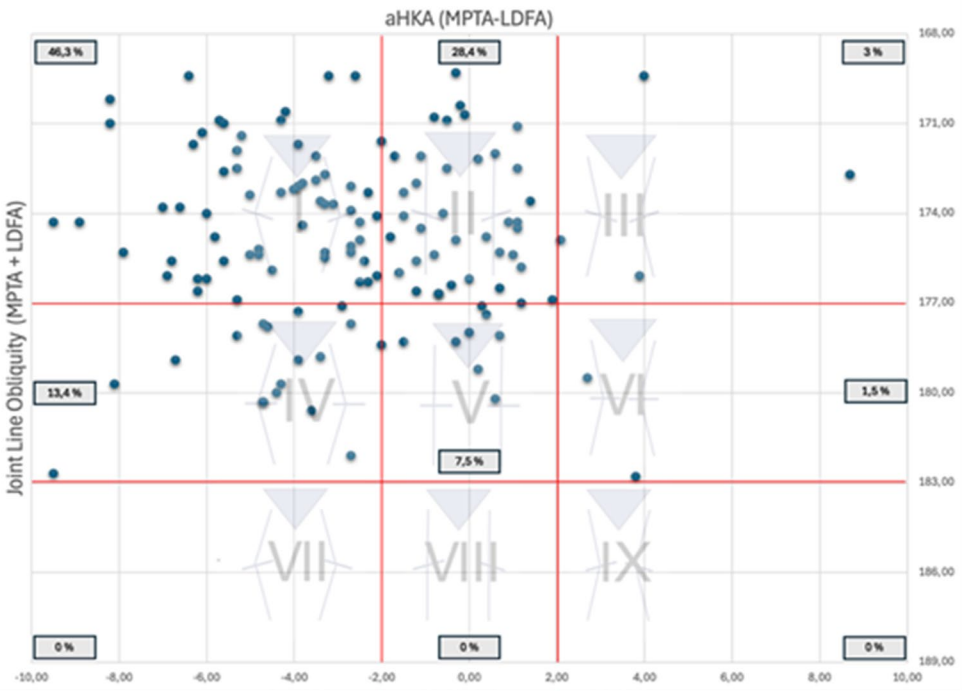


Fig. 4 distribution of the female population by CPAK categories

(sinus, positive cell counts and positive culture for Cutibacterium acnes).

No additional aseptic loosening, periprosthetic fractures, or thromboembolic events requiring surgical intervention were observed within the follow-up period.

Clinical outcomes by CPAK categories

At one year, 253 patients had full pre- and post-operative clinical data. Mean preoperative and postoperative OKS, ΔOKS, and satisfaction scores for each CPAK category are reported in Table 2.

Preoperative OKS values were comparable across CPAK categories ($p = 0.60$), confirming baseline homogeneity

Table 2 Mean values and standard deviations of OKS pre and post, ΔOKS and satisfaction rate by CPAK categories

CPAK	Number ($n=253$)	OKS pre (mean ± SD, 95% CI)	p	OKS post (mean ± SD, 95% CI)	p	OKS Δ (mean ± SD, 95% CI)	p	Satisfaction (mean ± SD, 95% CI)	p
1	83	19.1 ± 7.7 (17.42–20.78)	0.6	40.8 ± 7.1 (39.25–42.35)	0.8	21,7 ± 8,9 (19.76–23.64)	0.9	90,1 ± 18,9 (85.36–94.84)	0.7
2	76	20.5 ± 8.5 (18.56–22.44)		41.4 ± 5.3 (40.19–42.61)		20.9 ± 9.3 (18.77–23.03)		92.0 ± 15.57 (88.47–95.58)	
3	25	20.2 ± 6.5 (17.52–22.88)		40.2 ± 7.1 (37.27–43.13)		20.0 ± 8.5 (16.49–23.51)		92.0 ± 11.76 (86.57–97.43)	
4	29	17.9 ± 8.7 (14.59–21.21)		39.9 ± 6.0 (37.62–42.18)		22.0 ± 9.8 (18.27–25.73)		91.6 ± 15.69 (85.63–97.56)	
5	23	20.3 ± 5.9 (17.75–22.85)		40.9 ± 5.4 (38.56–43.24)		20.6 ± 6.6 (17.75–23.45)		92.7 ± 14.55 (86.37–98.96)	
6	17	19.6 ± 8.3 (15.33–23.87)		40.0 ± 8.4 (35.68–44.32)		20.4 ± 7.0 (16.80–24.00)		90.4 ± 18,8 (80.73–100.16)	

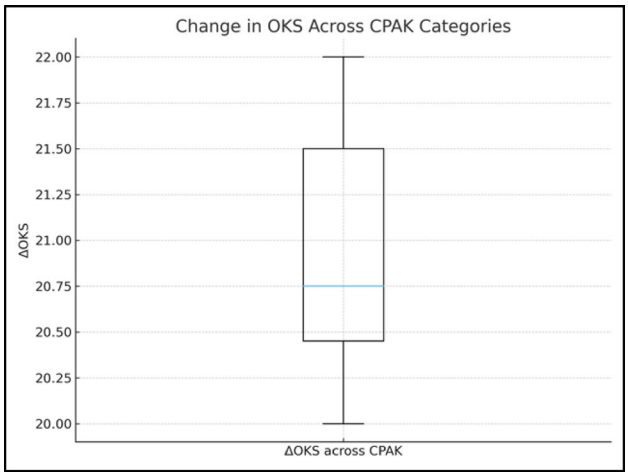


Fig. 5 Boxplot ΔOKS across CPAK

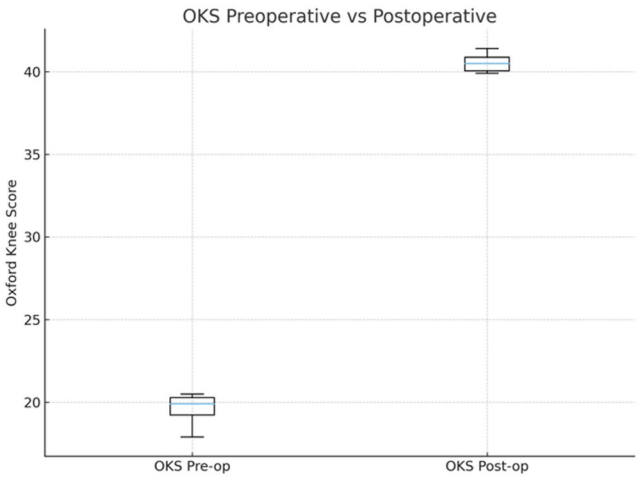


Fig. 6 Boxplot pre/post OKS

between groups. Mean preoperative OKS ranged from 17.9 ± 8.7 (CPAK 4) to 20.5 ± 8.5 (CPAK 2), with overlapping confidence intervals across categories.

At 1-year follow-up, postoperative OKS remained consistently high in all CPAK groups, with mean scores ranging from 39.9 to 41.4 points; representative confidence intervals such as CPAK 1 (39.25–42.35) and CPAK 2 (40.19–42.61) demonstrated substantial overlap, and no statistically significant differences were detected ($p=0.8$). Similarly, ΔOKS showed uniform improvements across CPAK types (mean 20.0–22.0 points), with confidence intervals overlapping for all categories. Satisfaction scores followed the same pattern, with high mean values (90–95 points) and no significant intergroup variation ($p=0.70$). Together, these results confirm the absence of phenotype-related differences in postoperative function or satisfaction when outcomes are analyzed according to the nine CPAK categories.

Visual inspection of OKS distributions using boxplots (Fig. 5: pre/post OKS; Fig. 6: ΔOKS by CPAK) confirmed the absence of outliers or subgroup clustering that might suggest phenotype-driven variability.

Before performing ANOVA, assumptions of normality and homogeneity of variance were verified using Shapiro–Wilk and Levene tests, respectively. No violation of these assumptions was detected, confirming the appropriateness of ANOVA for between-group comparisons.

At the final follow-up, no patients reported a deterioration in quality of life, and only six patients (2.3%) indicated no perceived improvement. Trends in patient-reported quality of life improvements are shown in Fig. 7.

Grouped analysis by coronal alignment (aHKA)

Since several CPAK categories contained a limited number of knees, a complementary analysis was performed using the arithmetic hip–knee–ankle angle (aHKA), which represents the primary determinant of coronal limb phenotype

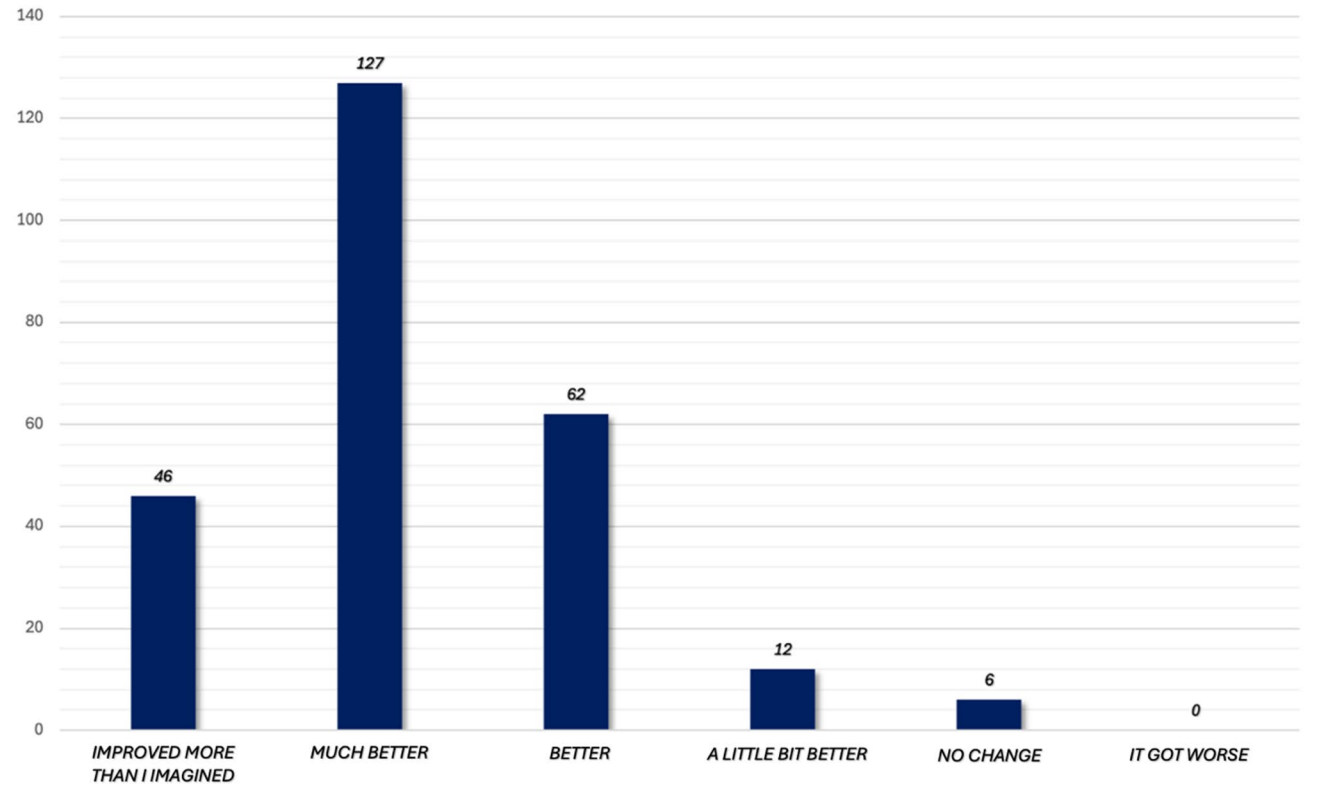


Fig. 7 Improvement in QoL (quality of life) after surgery

in the CPAK system. This grouping (varus = CPAK 1, 4, 7; neutral = CPAK 2, 5, 8; valgus = CPAK 3, 6, 9) was preplanned to allow clinically interpretable comparisons in the presence of unbalanced CPAK frequencies and is consistent with the biomechanical rationale of constitutional alignment as the dominant factor influencing knee loading patterns.

Postoperative outcomes were homogeneous across aHKA alignment groups. Postoperative OKS was 40.5 ± 6.9 (95% CI 39.21–41.79) in the varus group, 41.2 ± 5.2 (95% CI 40.16–42.24) in the neutral group, and 40.1 ± 7.8 (95% CI 37.67–42.53) in the valgus group ($p = 0.6$). Improvement in OKS (ΔOKS) was also comparable, with mean gains of 21.7 ± 9.1 (95% CI 20.00–23.40), 20.9 ± 8.9 (95% CI 19.12–22.68), and 20.2 ± 7.5 (95% CI 17.86–22.54), respectively ($p = 0.6$). Satisfaction scores were similarly high across all groups, with mean values of 89.0 ± 20.0 (95% CI 85.26–92.74), 92.3 ± 15.1 (95% CI 89.29–95.31), and 91.2 ± 15.2 (95% CI 86.46–95.94), respectively ($p = 0.4$).

Forest plots comparing varus vs. neutral, varus vs. valgus, and neutral vs. valgus demonstrated complete overlap of 95% confidence intervals, with all mean differences crossing zero, confirming the absence of statistically or clinically meaningful differences in postoperative OKS, ΔOKS, or satisfaction between alignment phenotypes (Supplementary Figures S1–S3). Together, these findings indicate that coronal alignment phenotype, whether described by CPAK or by aHKA grouping, does not influence short-term functional outcomes following UKA (Table 3).

Analysis by residual Varus, joint line obliquity (JLO) and other radiographic parameters

When knees were stratified according to joint-line obliquity (distal-apex vs. neutral-apex JLO, Table 4), no statistically significant differences were observed in postoperative OKS, ΔOKS, or satisfaction. Postoperative OKS ranged from 40.2 ± 6.4 (neutral-apex) to 40.9 ± 6.4 (distal-apex), with overlapping 95% confidence intervals (distal-apex: 39.97–41.83; neutral-apex: 38.66–41.74), confirming the absence of JLO-related variability in functional results. Improvements in OKS (ΔOKS ≈ 21.1 points in both groups) and satisfaction scores (90.3 ± 18.0 vs. 91.7 ± 16.0) showed a similar degree of overlap, further supporting equivalence between JLO phenotypes.

Residual limb alignment after UKA was also analyzed by comparing knees with residual varus ≥ 5° and < 5° (Table 5). Patients with residual varus ≥ 5° achieved postoperative OKS of 41.9 ± 5.6 (95% CI 40.20–43.60), ΔOKS of 23.1 ± 7.9 (95% CI 20.72–25.48), and satisfaction of 93.8 ± 9.9 (95% CI 90.78–96.82). These values were comparable to those observed in patients with residual varus < 5° (OKS 40.4 ± 6.6, 95% CI 39.20–41.60; ΔOKS 20.9 ± 9.3, 95% CI

Table 3 comparison between varus vs. valgus vs. neutral, varus vs. others (neutral + valgus), neutral vs. others (varus + valgus), valgus vs. others (neutral + varus), varus vs. neutral

aHKA	Number (n = 253)	OKS post (mean ± SD, 95% CI)	p	OKS Δ (mean ± SD, 95% CI)	p	Satisfaction (mean ± SD, 95% CI)	p
Varus	112	40.5 ± 6.9 (39.21–41.79)	0.6	21.7 ± 9.1 (20.00–23.40)	0.6	89.0 ± 20.0 (85.26–92.74)	0.4
Neutral	99	41.2 ± 5.2 (40.16–42.24)		20.9 ± 8.9 (19.12–22.68)		92.3 ± 15.1 (89.29–95.31)	
Valgus	42	40.1 ± 7.8 (37.67–42.53)		20.2 ± 7.5 (17.86–22.54)		91.2 ± 15.2 (86.46–95.94)	
VARUS	112	40.5 ± 6.9	0.7	21.7 ± 9.1	0.4	89.0 ± 20.0	0.2
Other	141	40.9 ± 6.0		20.7 ± 8.5		92.0 ± 15.1	
NEUTRAL	99	41.2 ± 5.2	0.3	20.9 ± 8.9	0.7	92.3 ± 15.1	0.2
Other	154	40.4 ± 7.1		21.3 ± 8.7		89.5 ± 18.9	
VALGUS	42	40.1 ± 7.8	0.5	20.2 ± 7.5	0.5	91.2 ± 15.2	0.8
Other	211	40.9 ± 6.1		21.3 ± 9.0		90.6 ± 17.8	
Varus	112	40.5 ± 6.9	0,4	21.7 ± 9.1	0.5	89.0 ± 20.0	0.2
Neutral	99	41.2 ± 5.2		20.9 ± 8.9		92.3 ± 15.1	

Table 4 Mean values and standard deviations of pre and post OKS, ΔOKS and satisfaction rate based on JLO

JLO apex	Number (n = 253)	OKS post ± DS	p	OKS Δ ± DS	p	Satisfaction ± DS	p
Distal	184	40.9 ± 6.4	0.4	21.1 ± 9.0	1	90.3 ± 18.0	0.6
Neutral	70	40.2 ± 6.4		21.1 ± 8.1		91.7 ± 16.0	

Table 5 Mean values and standard deviations of pre and post OKS, ΔOKS and satisfaction rate based on residual varus

Residual Varus	NcNumberc(n = 253)	OKS postc± DS	p	OKS Δχ± DS	p	Satisfaction ± DS	p
>/= 5	43	41.9 ± 5.6	0.2	23.1 ± 7.9	0.2	93.8 ± 9.9	0.1
< 5 − 0,1	118	40.4 ± 6.6		20.9 ± 9.3		88.1 ± 21.3	

Table 6 Correlation between preoperative radiographic parameters and post OKS, ΔOKS and satisfaction rate

	OKS post	p	OKS Δ	p	Satisfaction	p
HKA	− 0.00332	0.96	-0.09539	0.16	0.08604	0.2
JLCA	− 0.02799	0.68	0.04999	0.46	− 0.08259	0.2
SLOPE	− 0.03867	0.57	-0.03399	0.6	− 0.01918	0.78

18.85–22.95; satisfaction 88.1 ± 21.3, 95% CI 84.04–92.16). None of the between-group differences reached statistical significance, indicating that residual varus ≥ 5° did not negatively influence short-term functional outcomes.

Spearman correlation analysis further demonstrated no meaningful associations between radiographic parameters (HKA, aHKA, JLCA, JLO, tibial slope) and postoperative OKS, ΔOKS, or satisfaction (all $p > 0.16$). Correlation coefficients were close to zero (e.g., HKA vs. OKS: $r = -0.003$, $p = 0.96$), indicating the absence of linear or monotonic relationships between limb alignment parameters and clinical outcomes. No single coronal parameter emerged as a radiographic contraindication to UKA within the alignment ranges represented in this cohort (Table 6).

Although subgroup sample sizes for certain radiographic patterns were modest, the narrow and overlapping confidence intervals indicate that the study was sufficiently powered to detect moderate or clinically meaningful differences. Since none were observed, it is unlikely that important phenotype-related effects were missed.

Discussion

The main finding of the present study is that short-term functional outcomes and patient satisfaction after unicompartmental knee arthroplasty (UKA) were consistently high across all preoperative CPAK categories. Nearly all patients (97.4%) experienced a clinically meaningful improvement in OKS, and no statistically or clinically relevant differences in postoperative OKS, ΔOKS, or satisfaction were observed between phenotypes. These data suggest that, when appropriately indicated and performed, UKA appears to be less sensitive to preoperative coronal alignment phenotype than total knee arthroplasty (TKA). This observation is biologically plausible when considering the intrinsic biomechanical characteristics of UKA. Unlike TKA, UKA preserves both cruciate ligaments, requires limited bone resection, and aims to maintain native joint line orientation and ligament balance, which may mitigate phenotype-related variability observed in TKA cohorts [11].

Previous CPAK-related studies [12–16] in UKA cohorts have predominantly focused on either medial or lateral

procedures and often on postoperative phenotype changes rather than on the prognostic role of preoperative CPAK categories. In this context, the present study extends existing evidence by evaluating short-term outcomes of both medial and lateral UKA across the full spectrum of preoperative CPAK phenotypes, thereby providing a comprehensive representation of the UKA candidate population.

Although our findings suggest that preoperative CPAK category was not associated with short-term outcomes after UKA, the prognostic significance of the postoperative CPAK change (or preservation) remains unclear [12–16]. Available literature reports considerable variability in postoperative CPAK pattern after UKA. *Kim et al.* [12] found that preservation of native CPAK alignment was associated with superior 1 year outcomes, although the magnitude of CPAK change did not influence PROMs. *Ten Noever de Brauw et al.* [14]. observed that only 45.1% of knees maintained their preoperative CPAK category after medial UKA, while *Vossen et al.* [13] reported wide variability in coronal alignment and joint line orientation following lateral UKA cohort without corresponding differences in PROMs. Similarly, *Sahbat Y et al.* [16]. demonstrated that although UKA altered preoperative phenotypes in more than half of patients, maintenance of coronal alignment and joint line obliquity did not affect PROMs or implant survival. Finally, *Zhao Y et al.* [15] further reported a general shift towards neutral alignment after both medial and lateral UKA, with preservation of the native phenotype observed in only one-third of cases. Taken together, these studies suggest that postoperative CPAK variability is common, yet its short-term clinical relevance appears limited.

Analysis of CPAK categories distribution in our cohort revealed a predominance of "distal apex" JLO phenotypes, with types 1 (34.9%), 2 (27.9%), and 4 (11.5%) being most common, and no "proximal-apex" JLO configuration (types 7–9) identified. These findings partially mirror those reported by MacDessi et al. [4], who found higher prevalence of phenotypes 1, 2, and 3 (19.4%, 32.2%, and 15.4%, respectively) in an osteoarthritic population. When stratified by sex, notable differences emerged: male patients predominantly exhibited types 1 (46.3%), 2 (28.4%), and 4 (13.4%), whereas female patients showed a relatively higher prevalence of types 2 (27.5%) and 3 (9.9%). Similar sex-based differences have been described in other UKA cohorts [12–14], although no previous study has specifically addressed sex-stratified CPAK distributions in a mixed medial and lateral UKA population. Importantly, despite these anatomical differences, postoperative outcomes remained homogeneous, suggesting that sex-based variations in coronal phenotype do not necessitate modification of current UKA indications.

The absence of meaningful associations between preoperative radiographic parameters (HKA, aHKA, JLCA, JLO, tibial slope) and postoperative outcomes further supports the concept that UKA may tolerate a relatively broad range of coronal alignments. In our cohort, residual varus $\geq 5°$ was not associated with inferior OKS (41.9 ± 5.6 vs. 40.4 ± 6.6), ΔOKS (23.1 ± 7.9 vs. 20.9 ± 9.3), or satisfaction rates (93.8 ± 9.9 vs. 88.1 ± 21.3) at one year. These findings align with previous reports indicating acceptable short-term outcomes across varying alignment ranges,. *Sekiguchi et al.* [17]. reported that coronal alignment between 2° of varus and neutral is preferable to > 4° of varus or valgus alignment, while *Zhao et al.* [15] found no significant differences in multiple PROMSs across neutral (varus ≤ 3°), mild varus (3° < varus ≤ 7°), or marked varus (varus > 7°) alignment groups at short-term follow-up. Collectively, available evidence indicates that, within appropriate indications, UKA appears to be relatively tolerant to coronal alignment variability in the short term.

Our study has several limitations that warrant cautious interpretation. First, the short follow-up period precluded the assessment of long-term implant survival, complications, and revision rates among CPAK categories. Second, postoperative long-leg radiographs were not routinely available, preventing direct evaluation of postoperative CPAK changes. Third, interobserver reliability (ICC) was based on a random sample of 20 cases and should be considered exploratory. Fourth, satisfaction was assessed with a non-validated Likert-derived composite score, which may be affected by ceiling effects and subjective bias. Finally, the cohort included different implant designs (fixed- and mobile-bearing) and procedures performed by multiple surgeons; these factors may act as confounders and were not modeled separately. In addition, pooling medial and lateral UKA provides a pragmatic representation of the overall UKA candidate population, but compartment-specific biomechanics may still influence outcomes and should be evaluated in future studies.

Despite these limitations, the present study has several strengths. Data were derived from a prospectively maintained institutional database and included a large consecutive cohort of patients undergoing unicompartmental knee arthroplasty. Both medial and lateral UKA procedures were analyzed, providing a comprehensive representation of the overall UKA candidate population. Clinical outcomes were assessed using a validated PROM and complemented by detailed radiographic analyses, effect size estimation, confidence intervals, and forest plot visualization.

The observed overlap of confidence intervals and the consistency of results across CPAK categories and aHKA-based groupings suggest that any phenotype-related differences in short-term PROMs are unlikely to be clinically meaningful within the alignment ranges represented in this cohort.

These findings have important implications for patient selection. Historically, UKA has been reserved for patients with a narrow set of alignment characteristics ("classic" indications). Our data add to the growing body of evidence indicating that UKA can be safely and effectively performed across a wider range of coronal phenotypes without compromising short-term outcomes. When compartmental indications are respected and the remaining joint structures are preserved, UKA appears to be toleranr of coronal alignment variability. Future prospective studies with standardized postoperative long-leg imaging, compartment-specific analyses, and longer follow-up are needed to clarify whether CPAK phenotype influences long-term survivorship or revision risk.

Conclusion

Unicompartmental knee arthroplasty appears to provide consistently high patient satisfaction and substantial functional improvement across all CPAK phenotypes, with no detectable heterogeneity in short-term outcomes. Preoperative coronal alignment and sex-related differences in CPAK distribution did not influence postoperative OKS, ΔOKS, or satisfaction, and residual varus ≥ 5° was not associated with inferior clinical results.

Prospective studies with standardized postoperative long-leg radiographs and longer follow-up are needed to clarify the extent of CPAK preservation after UKA and to determine whether long-term survivorship varies among phenotypes.

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Author contributions S.C. and C.E. conceived the study and wrote the manuscript. All other authors contributed to the interpretation of data, participated in patient follow-up, critically revised the manuscript, and approved the final version to be published.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest S.C. has received speaker and consultant honoraria from Smith and Nephew, Medacta, Stryker, Enovis, Zimmer Biomet. E.F. has received speaker and consultant honoraria from Medacta and Stryker.

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