

Association of CPAK Phenotypes With Valgus Overcorrection After Robotic-Assisted Total Knee Arthroplasty

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Abstract

Objective

To investigate the discrepancy between intraoperative coronal alignment (hip-knee-ankle angle, HKA) measured during MAKO robotic-assisted total knee arthroplasty (raTKA) and postoperative full-leg radiographs (FLR), analyze the influence of CPAK phenotypes (especially types II and V) on this alignment shift, and identify risk factors for valgus overcorrection.

Methods

A retrospective analysis was conducted on 264 knees with knee osteoarthritis that underwent primary raTKA using the MAKO RIO system (Stryker, Kalamazoo, MI, USA) at a single center from August 2023 to December 2025. All patients had preoperative CT (for MAKO planning), complete intraoperative navigation logs, and standard weight-bearing FLR at 3 months postoperatively. Preoperative CT three-dimensional reconstruction was used to measure the mechanical medial proximal tibial angle (mMPTA) and mechanical lateral distal femoral angle (mLDFA), from which joint line obliquity (JLO) and arithmetic HKA (aHKA) were derived for CPAK classification. The primary outcome was ΔHKA = intraoperative HKA – postoperative HKA (varus as positive; thus $\Delta\text{HKA} > 0$ indicated more valgus postoperatively). $|\Delta\text{HKA}| > 2^\circ$ was defined as clinically significant alignment drift, and valgus overcorrection was defined as postoperative weight-bearing FLR HKA $< -2^\circ$ in knees with (1) preoperative varus deformity (FLR HKA $> 0^\circ$ or CT aHKA $< -2^\circ$) and (2) a varus-alignment surgical plan (MAKO planned intraoperative HKA $> 0^\circ$). Multivariable logistic regression assessed factors independently associated with valgus overcorrection, and multivariable linear regression assessed factors associated with continuous ΔHKA .

Results

Among 264 knees, CPAK type II accounted for 17.8% (47/264), type V for 7.6% (20/264), totaling 25.4% (67/264). Mean intraoperative MAKO varus was $2.30^\circ \pm 1.73^\circ$, while postoperative FLR showed varus of $1.37^\circ \pm 2.01^\circ$, with a mean ΔHKA of $0.93^\circ \pm 2.23^\circ$, indicating that postoperative weight-bearing alignment was systematically more valgus than intraoperative measurements ($P < 0.001$). Bland-Altman analysis using postoperative minus intraoperative HKA showed a mean difference of -0.93° and 95% limits of agreement of -5.30° to $+3.43^\circ$. Overall incidence of $|\Delta\text{HKA}| > 2^\circ$ was 36.4% (96/264); 42.6% in type II and 45.0% in type V. Valgus overcorrection occurred in 28.4% (75/264) overall; the pre-specified merged II/V group had a rate of 35.8% (24/67) versus 25.9% (51/197) in non-II/V (Fisher's exact test, unadjusted $P = 0.161$). After adjusting for bone defect, mMPTA difference, MCL release, sex, and BMI, the II/V phenotype was independently associated with valgus overcorrection (OR = 2.68, 95% CI 1.27–5.63, $P = 0.010$).

Conclusion

The residual varus alignment measured intraoperatively by the MAKO system in the supine, non-weight-bearing, anesthetized state does not fully represent postoperative weight-bearing mechanical alignment; this difference is multifactorial. CPAK types II and V were associated with greater postoperative valgus drift and higher adjusted odds of valgus overcorrection. Intraoperative non-weight-bearing alignment measurements may not fully represent postoperative weight-bearing alignment. CPAK classification may be useful for individualized alignment planning in raTKA, although optimal phenotype-specific alignment targets require prospective validation.

1. Introduction

The alignment philosophy in total knee arthroplasty (TKA) has increasingly shifted from conventional mechanical alignment toward more individualized alignment strategies. Mechanical alignment (MA), historically used to standardize the hip-knee-ankle angle (HKA) near neutral ($0^\circ \pm 3^\circ$), has been widely adopted in TKA [1]. Robotic-assisted TKA (raTKA), particularly the MAKO system, has substantially improved the precision of bone resection and component positioning through preoperative three-dimensional planning and robotic arm control [2, 3]. However, high technical precision does not necessarily eliminate discrepancies between intraoperative and postoperative alignment measurements [4–5], and previous studies have reported HKA differences of approximately 1.5° – 2.0° between intraoperative and postoperative FLR measurements [6–8]. These findings indicate that intraoperative alignment under anesthesia and without weight bearing may not be identical to postoperative weight-bearing alignment. Previous studies have attributed such differences mainly to positional changes or radiographic projection errors, while Tarassoli demonstrated that postoperative FLR may underestimate constitutional varus and joint line obliquity, significantly altering CPAK type I/II distribution and suggesting that phenotypic characteristics may contribute to heterogeneity in alignment measurements [9, 10]. Nevertheless, existing research has not systematically evaluated alignment drift between non-weight-bearing and weight-bearing states at the CPAK phenotype level [11].

Concurrently, TKA alignment strategies are increasingly moving from a uniform alignment target toward phenotype-informed individualization [12]. MacDessi et al. proposed the coronal plane alignment of the knee (CPAK) classification, emphasizing that the same HKA of 0° may represent different native bone morphologies and joint-line orientations [11]. The most common CPAK phenotypes in healthy and osteoarthritic populations include types II, I, and V [13, 14]. Among these, CPAK types II and V account for a substantial proportion of East Asian varus-type OA populations [15–18]. Whether these phenotypes are associated with greater intraoperative-to-postoperative alignment discrepancies remains insufficiently studied [6, 19–20].

Based on this, we hypothesized that: (1) a systematic difference exists between MAKO intraoperative HKA and postoperative FLR-HKA, with the direction of postoperative readings being more valgus ($\Delta\text{HKA} = \text{intraoperative} - \text{postoperative} > 0$); (2) CPAK types II and V are more sensitive to this difference under

MA-based correction and more prone to valgus overcorrection (defined as postoperative FLR-HKA < -2°). This study aimed to (i) quantify the systematic difference in HKA/mMPTA between MAKO intraoperative and postoperative FLR; (ii) identify phenotype-specific associations; and (iii) explore potential clinical implications for raTKA alignment targets.

2. Materials and Methods

2.1 Study Design and Ethical Approval

This was a single-center retrospective cohort study conducted at Tianjin Beichen Hospital. This study was approved by the Ethics Committee of Tianjin Beichen Hospital (Approval No. 2026010509). Due to its retrospective design, the requirement for informed consent was waived by the Ethics Committee. All procedures performed in this study were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki Declaration and its later amendments. The study followed the STROBE reporting guidelines.

2.2 Patient Inclusion and Exclusion Criteria

Consecutive patients who underwent primary raTKA (MAKO RIO system, Stryker, Kalamazoo, MI, USA) for knee osteoarthritis between August 2023 and December 2025 were screened, totaling 280 knees (255 patients, including 25 bilateral cases).

Inclusion criteria:

(1) primary raTKA (MAKO system); (2) preoperative imaging confirming knee osteoarthritis with coronal plane deformity; (3) complete intraoperative MAKO navigation data; (4) high-quality preoperative and postoperative standing FLR; (5) follow-up ≥ 3 months.

Exclusion criteria:

(1) revision surgery; (2) extra-articular deformity or previous high tibial osteotomy/femoral supracondylar osteotomy; (3) preoperative flexion contracture > 15°; (4) poor FLR image quality (rotation or flexion artifacts); (5) concomitant severe hip or ankle disease affecting lower limb full-length alignment measurement. Initial screening identified 280 knees (255 patients); 16 knees (involving 8 patients, all bilateral, counted as single knees) were excluded, leaving 264 knees (247 patients) for final analysis. No statistically significant differences were observed in baseline age, BMI, or preoperative HKA between included and excluded knees ($p > 0.05$). There were no missing data for the variables included in the primary analyses.

2.3 Surgical Procedure and Intraoperative Data Collection

All surgeries were performed by the same senior chief orthopedic surgeon using the MAKO RIO system via a standard medial parapatellar approach. Bone cuts were made according to preoperative CT 3D planning, with the alignment target set at neutral mechanical alignment (HKA $0^\circ \pm 3^\circ$). Adjusted

mechanical alignment was used based on intraoperative gap balancing. All surgeries used posterior-stabilized prostheses (Triathlon, Stryker, MI, USA). Tibial component posterior slope was dynamically adjusted according to intraoperative soft tissue tension (range 0–4°) and fixed with bone cement. MCL release criteria: medial gap > 2 mm wider than lateral gap at 0° extension under valgus stress; release was performed by peeling the superficial MCL from the tibial side, and the need for and extent of release were recorded. After final prosthesis trialing, intraoperative HKA, mMPTA, and mLDFA were recorded from the MAKO console.

Bone defect measurement [21]:

Based on preoperative CT 3D reconstruction (MAKO standard protocol) in coronal and sagittal planes, referencing radiographic assessment of osteoarthritic bone loss. On coronal CT images, at the most concave point of the medial tibial plateau, the vertical distance from the original tibial plateau articular surface line (referenced to the contralateral side or estimated from the lateral plateau height) to the deepest point of the defect (sclerotic bone surface) was measured. Modified grading: Grade 0 (none), intact articular surface or cartilage wear without bone loss; Grade 1 (< 5 mm), mild defect; Grade 2 (5–10 mm), moderate defect; Grade 3 (> 10 mm), severe defect. In this study, ≥ 5 mm (grade 2 or above) was defined as “significant bone defect.”

2.4 Radiological Assessment Protocol

CT measurement (MAKO standard protocol):

All patients underwent standard MAKO CT scans preoperatively, including scout views and three-dimensional segmentation reconstruction. Preoperative CPAK classification was based on mMPTA and mLDFA measured from the preoperative CT-based three-dimensional reconstruction. Postoperative mMPTA and mLDFA were measured on standing full-leg radiographs to assess postoperative coronal alignment.

Preoperative and postoperative standing FLR:

Standardized radiographs were obtained [22], ensuring consistent positioning of hip, knee, and ankle joints. All X-rays were independently measured by three attending physicians with 5 years of joint surgery experience using the angle measurement tool of the PACS system (blinded to CPAK classification and surgical plan), and the mean value was used for analysis. Reliability was assessed using intra-rater ICC (ICC = 0.94, 95% CI 0.91–0.96) and inter-rater ICC (ICC = 0.92, 95% CI 0.89–0.95). Postoperative FLR was obtained at 6 weeks and 3 months, respectively; the 3-month measurement was used for final analysis. All included knees had available 3-month postoperative FLR. Valgus overcorrection was pre-defined as postoperative 3-month weight-bearing FLR HKA < -2° in knees meeting both criteria: (i) preoperative varus deformity, defined as standing FLR HKA > 0° (varus positive per our sign convention) or CT-derived aHKA < -2° (constitutional varus); and (ii) a varus-alignment surgical plan, defined as MAKO planned HKA > 0° , reflecting that the surgeon planned to retain varus rather than target neutral or valgus. This

two-step definition distinguishes overcorrection from cases where valgus alignment was intended. Threshold determination was completed by an independent investigator blinded to CPAK classification.

Threshold determination was completed by an independent investigator who did not participate in the surgery grouping and was unaware of the patient's CPAK classification and clinical information (blinded adjudication) to avoid measurement bias.

2.5 CPAK Classification

According to the criteria proposed by MacDessi et al. [11], mMPTA and mL DFA were measured based on preoperative CT 3D reconstruction. The arithmetic hip-knee-ankle angle (aHKA = mMPTA - mL DFA) was calculated to assess constitutional limb alignment; joint line obliquity (JLO = mMPTA + mL DFA) was calculated to assess joint line orientation. aHKA groups: varus (aHKA $\leq -2^\circ$), neutral (-2° to $+2^\circ$), valgus (aHKA $\geq +2^\circ$). JLO groups: apex distal (JLO $< 177^\circ$), neutral (177° – 183°), apex proximal (JLO $> 183^\circ$). The combination yielded 9 CPAK phenotypes (Types I–IX).

Sign convention: In this paper, HKA was recorded with neutral 0° as the baseline, varus as positive (+) and valgus as negative (-). Conversely, aHKA negative values represent varus tendency, and positive values represent valgus tendency, consistent with the original MacDessi publication. Δ HKA = intraoperative HKA - postoperative HKA, so Δ HKA > 0 represents a lateral shift in postoperative alignment relative to intraoperative (more valgus).

2.6 Statistical Methods

Based on anatomical considerations, CPAK types II and V were pre-specified as a combined group because both represent neutral constitutional aHKA phenotypes, although their joint-line orientations differ. This “neutral HKA group” was compared with all other phenotypes (Others).

Normality of continuous variables was assessed using the Shapiro-Wilk test. Normally distributed data are expressed as mean $\pm$ standard deviation, non-normal data as median (interquartile range). Between-group comparisons used the independent-samples t-test for normally distributed data and the Mann-Whitney U test otherwise. Multiple-group comparisons used one-way ANOVA or the Kruskal-Wallis test as appropriate, with post-hoc pairwise comparisons using Tukey or Dunn tests. Categorical variables were compared using the chi-square or Fisher exact test. Paired comparisons of intraoperative MAKO and postoperative FLR measurements used the one-sample t-test or Wilcoxon signed-rank test as appropriate. Consistency was assessed using ICC and Bland-Altman analysis. For Bland-Altman analysis, the difference was defined as postoperative HKA minus intraoperative HKA; this convention was used only for the agreement analysis, whereas the primary Δ HKA definition remained intraoperative HKA minus postoperative HKA. Bilateral knees were treated as independent observations in the primary analysis.

Multivariable linear regression analyzed factors associated with continuous Δ HKA. Multivariable logistic regression was performed using prespecified clinically relevant covariates to analyze factors associated

with valgus overcorrection (FLR-HKA < - 2°). Covariates included CPAK phenotype (II/V vs. others), medial tibial bone defect (< 5 mm vs. ≥ 5 mm), intraoperative MCL release (yes/no), mMPTA difference (postoperative – preoperative, continuous), sex, and BMI. Variance inflation factor (VIF) was used to assess multicollinearity (VIF < 2.0 considered no collinearity).

A priori power analysis using G*Power (v3.1) with medium effect size ($f^2 = 0.15$), power 80% ($1 - \beta = 0.80$), and $\alpha = 0.05$ (two-sided) calculated a minimum required sample size of 210; 264 knees were included in the final analysis. All statistical tests were two-sided, and $p < 0.05$ was considered statistically significant. Statistical analyses were performed using SPSS 26.0 (IBM, Armonk, NY, USA) and R software (v4.2.1).

3. Results

3.1 Patient Baseline Characteristics and CPAK Phenotype Distribution

A total of 264 knees (247 patients, including 17 bilateral cases) were included. Mean age was 67.2 ± 6.3 years, mean BMI 27.3 ± 3.8 kg/m². Mean preoperative HKA (varus as positive) was $8.9^\circ \pm 6.7^\circ$, preoperative mMPTA $84.7^\circ \pm 3.2^\circ$, preoperative mL DFA $89.6^\circ \pm 3.3^\circ$. According to modified grading, medial tibial plateau bone defects of grade I (< 5 mm) accounted for 81.8% (216/264), grade II (5–10 mm) 16.7% (44/264), and grade III (> 10 mm) 1.5% (4/264). Baseline data across CPAK phenotypes are shown in Table 1.

Table 1
Comparison of baseline data across CPAK phenotypes

Parameter	Total (n = 264)	Type I (n = 139)	Type II (n = 47)	Type IV (n = 47)	Type V (n = 20)	Other CPAK phenotypes (n = 11)	p- value
BMI (kg/m ²)	27.3 ± 3.8	27.5 ± 4.0	27.5 ± 3.5	26.6 ± 3.5	27.1 ± 4.1	26.7 ± 3.8	0.689
Preop HKA (°, varus +)	8.9 ± 6.7	11.8 ± 5.4	5.6 ± 3.6	10.3 ± 4.3	3.7 ± 1.4	−9.4 ± 6.6	< 0.001
Preop mMPTA (°)	84.7 ± 3.2	82.7 ± 2.5	86.2 ± 1.5	86.2 ± 2.4	88.9 ± 0.7	89.7 ± 2.3	< 0.001
Preop mLDFA (°)	89.7 ± 3.3	90.2 ± 2.3	87.2 ± 1.5	92.6 ± 2.1	89.6 ± 1.0	80.5 ± 4.5	< 0.001
Preop JLO (°)	174.4 ± 3.8	172.9 ± 2.6	173.3 ± 3.3	178.9 ± 1.4	178.5 ± 1.3	171.1 ± 5.7	< 0.001
Preop aHKA (°)	−4.8 ± 5.4	−7.5 ± 3.8	−0.6 ± 1.2	−6.4 ± 3.9	−0.4 ± 1.2	9.2 ± 5.2	< 0.001
Medial bone defect ≥ 5 mm (%)	48 (18.2)	38 (27.3)	4 (8.5)	3 (6.4)	2 (10.0)	0 (0.0)	0.002*
Female (%)	166 (62.9)	88 (63.3)	25 (53.2)	30 (63.8)	13 (65.0)	10 (90.9)	0.231*

BMI = body mass index; HKA = hip-knee-ankle angle; mMPTA = mechanical medial proximal tibial angle; mLDFA = mechanical lateral distal femoral angle; JLO = joint line obliquity; aHKA = arithmetic hip-knee-ankle angle; CPAK = Coronal Plane Alignment of the Knee classification. Data expressed as mean ± standard deviation; categorical variables as n (%). “Others” includes CPAK types III and VI–IX. Bone defect grading based on modified criteria [21].

3.2 Overall Comparison of Intraoperative MAKO and Postoperative FLR Alignment Parameters

Comparison of alignment parameters between intraoperative MAKO measurements and postoperative 3-month standing FLR is shown in Table 2. Mean intraoperative MAKO HKA (varus positive) was 2.30° ± 1.73°, while mean postoperative FLR HKA was 1.37° ± 2.01°, representing 0.93° more varus read intraoperatively, a statistically significant difference (p < 0.001). Mean ΔHKA was 0.93° ± 2.23°. The distribution range of ΔHKA was − 4.5° to 6.9°, with 172 cases (65.2%) showing positive ΔHKA (i.e., more valgus postoperatively). Bland-Altman analysis using postoperative minus intraoperative HKA showed a bias of − 0.93° and 95% LoA of − 5.30° to + 3.43°, Pearson r = 0.30.

Further analysis showed that weight-bearing measured mMPTA was on average 0.39° ± 1.31° higher than the MAKO planned target (one-sample t-test, P < 0.001), indicating a small systematic tibial-side

difference; ΔmLDFA ($-0.03^\circ \pm 1.70^\circ$) and ΔJLO ($0.59^\circ \pm 6.00^\circ$) showed no consistent direction. HKA and mMPTA comparisons across CPAK phenotypes are shown in Tables 2 and 3. To facilitate conventional Bland–Altman plotting, the difference was defined as postoperative minus intraoperative HKA.

Table 2
Comparison of intraoperative and postoperative HKA and mMPTA across CPAK phenotypes

Index	Total (n = 264)	Type I (n = 139)	Type II (n = 47)	Type III (n = 10)	Type IV (n = 47)	Type V (n = 20)	p-value
Weight-bearing postop HKA ($^\circ$)	1.37 ± 2.01	1.71 ± 1.82	0.74 ± 1.87	0.43 ± 2.93	1.72 ± 2.02	0.11 ± 2.26	0.005
Intraop – postop HKA diff ($^\circ$)	0.93 ± 2.23	0.92 ± 1.99	1.37 ± 2.17	0.32 ± 3.75	0.54 ± 2.24	1.35 ± 2.86	0.279
Preop mMPTA ($^\circ$)	84.71 ± 3.19	82.70 ± 2.47	86.24 ± 1.50	89.73 ± 2.46	86.17 ± 2.41	88.92 ± 0.66	< 0.001
Intraop mMPTA ($^\circ$)	88.82 ± 1.07	87.37 ± 1.85	87.89 ± 1.31	89.25 ± 1.14	87.74 ± 1.63	88.55 ± 1.47	0.001
Postop mMPTA ($^\circ$)	89.20 ± 3.15	89.00 ± 2.55	89.74 ± 1.84	89.85 ± 2.84	89.94 ± 2.69	89.61 ± 0.95	0.315
Intraop – postop mMPTA diff ($^\circ$)	-0.39 ± 1.31	-0.47 ± 1.46	-0.36 ± 1.09	0.27 ± 1.03	-0.43 ± 1.22	-0.09 ± 1.02	0.110
Postop – preop mMPTA diff ($^\circ$)	4.50 ± 3.15	6.30 ± 2.55	3.26 ± 1.84	0.15 ± 2.84	3.06 ± 2.69	0.61 ± 0.95	< 0.001

mMPTA = mechanical medial proximal tibial angle; HKA = hip-knee-ankle angle; MAKO intraop = robotic planned value; weight-bearing postop = final alignment on weight-bearing radiographs. CPAK classification based on preoperative typing. ΔmMPTA alignment deviation = postoperative weight-bearing measured value – MAKO planned target value; postop – preop mMPTA = tibial resection correction amount (Correction of mMPTA); intraop – postop HKA (ΔHKA) = MAKO intraop HKA – postoperative weight-bearing full-leg radiograph (FLR) HKA. Intergroup comparisons by Kruskal-Wallis H test or ANOVA.

Figure 1. (A) Scatter plot of intraoperative planned versus postoperative weight-bearing HKA; (B) Bland–Altman analysis using postoperative minus intraoperative HKA, showing a bias of -0.93° and 95% limits of agreement from -5.30° to $+3.43^\circ$; (C) Histogram of ΔHKA with vertical dashed lines marking the $\pm 2^\circ$ thresholds. Pearson correlation coefficient $r = 0.30$. HKA: varus as positive, valgus as negative; $\Delta\text{HKA} =$ intraoperative MAKO HKA – postoperative weight-bearing full-leg radiograph (FLR) HKA; $\Delta\text{HKA} > 0$ indicates more valgus postoperatively than intraoperatively. In panel A, the red solid line represents the line of perfect agreement ($y = x$) and the orange line the linear regression fit; in panel B, the solid line is the mean difference (-0.93°) and the dashed lines are the 95% limits of agreement.

3.3 Coronal Drift Component Decomposition by CPAK Phenotype

Mean Δ HKA was $1.37^\circ \pm 2.17^\circ$ for CPAK type II and $1.35^\circ \pm 2.86^\circ$ for type V, both greater than type I ($0.92^\circ \pm 2.00^\circ$) and type IV ($0.54^\circ \pm 2.24^\circ$). The merged II/V group had a mean continuous Δ HKA of $1.36^\circ \pm 2.36^\circ$, significantly higher than non-II/V ($0.79^\circ \pm 2.18^\circ$) (Mann-Whitney U test, $P = 0.038$). Overall incidence of $|\Delta$ HKA| $> 2^\circ$ was 36.4% (96/264); 43.3% (29/67) in the II/V merged group versus 34.0% (67/197) in non-II/V. Overall incidence of valgus overcorrection (FLR-HKA $< -2^\circ$) was 28.4% (75/264); 35.8% (24/67) in II/V merged versus 25.9% (51/197) in non-II/V. Stratified data are shown in Table 4.

Table 3
Component decomposition of coronal drift stratified by CPAK phenotype

CPAK Phenotype	n	Δ mLDFA ($^\circ$)	Δ mMPTA ($^\circ$)	Δ JLO ($^\circ$)	Descriptive Component Pattern
I	139	0.20 ± 1.66	0.47 ± 1.46	0.40 ± 2.06	Tibial
II*	47	-0.43 ± 1.70	0.36 ± 1.09	-0.03 ± 1.90	Tibial
III	10	-1.05 ± 1.71	-0.27 ± 1.03	7.63 ± 29.52	Mixed/outlier
IV	47	-0.13 ± 1.77	0.43 ± 1.22	0.29 ± 1.98	Tibial
V*	20	0.05 ± 1.62	0.09 ± 1.02	0.13 ± 1.90	Joint line
II/V merged	67	-0.29 ± 1.68	0.28 ± 1.07	0.02 ± 1.89	Tibial
Non-II/V	197	0.06 ± 1.71	0.42 ± 1.38	0.79 ± 6.85	Tibial + joint line
Total	264	-0.03 ± 1.70	0.39 ± 1.31	0.59 ± 6.00	—

* Types II and V were pre-specified as the merged neutral-nonparallel joint line group. Intraop (planned) = target values set by MAKO robot after bone cut planning; postop (weight-bearing) = measured values from postoperative weight-bearing radiographs. Δ = weight-bearing measured – planned target (anatomical angle, positive = more valgus than planned). Thus Δ mMPTA = $+0.39^\circ \pm 1.31^\circ$ indicates tibial plateau on average 0.4° more valgus on weight-bearing than planned, representing a “planned versus achieved” deviation rather than a resection error.

Table 4
 Δ HKA and valgus overcorrection rates stratified by CPAK phenotype

CPAK Phenotype	N	Δ HKA ($^{\circ}$, $\bar{x} \pm s$)	$ \Delta$ HKA > 2 $^{\circ}$ n (%)	Valgus overcorrection (FLR-HKA < - 2 $^{\circ}$) n (%)
I	139	0.92 $\pm$ 2.00	48 (34.5)	39 (28.1)
II*	47	1.37 $\pm$ 2.17	20 (42.6)	17 (36.2)
III	10	0.32 $\pm$ 3.75	5 (50.0)	2 (20.0)
IV	47	0.54 $\pm$ 2.24	14 (29.8)	10 (21.3)
V*	20	1.35 $\pm$ 2.86	9 (45.0)	7 (35.0)
Others (VI–IX)	1	—	0 (0)	0 (0)
Total	264	0.93 $\pm$ 2.23	96 (36.4)	75 (28.4)

Δ HKA = intraoperative HKA – postoperative HKA, positive indicates more valgus postoperatively; $|\Delta$ HKA| > 2 $^{\circ}$ indicates clinically significant alignment drift (direction-independent); valgus overcorrection defined as postoperative FLR-HKA < - 2 $^{\circ}$. *Compared with CPAK type I, $P < 0.05$; types II and V were pre-specified as the merged neutral-nonparallel joint line group. $|\Delta$ HKA| > 2 $^{\circ}$ and valgus overcorrection are two independently defined endpoints. II/V versus non-II/V continuous Δ HKA comparison: Mann-Whitney U test $P = 0.038$.

3.4 Multivariable Analysis of Factors Associated With Valgus Overcorrection

Multivariable logistic regression with valgus overcorrection (FLR-HKA < - 2 $^{\circ}$) as the dependent variable showed that the pre-specified CPAK neutral HKA group (types II/V) was independently associated with higher odds of valgus overcorrection (OR = 2.68, 95% CI 1.27–5.63, $P = 0.010$) compared with other phenotypes. Medial tibial bone defect ≥ 5 mm was likewise independently associated with valgus overcorrection (OR = 2.34, 95% CI 1.19–4.62, $P = 0.014$). The adjusted effects of mMPTA difference per 1 $^{\circ}$ (OR = 1.05, 95% CI 0.95–1.16, $P = 0.332$), MCL release (OR = 1.58, $P = 0.192$), sex ($P = 0.905$), and BMI ($P = 0.212$) did not reach statistical significance. The model yielded an AUC of 0.647 (95% CI 0.578–0.716) and a McFadden R^2 of 0.049. Details are shown in Table 5.

Table 5
Multivariable logistic regression for valgus overcorrection

Predictor	β coefficient	Wald χ^2	OR (95% CI)	p value
CPAK neutral HKA group (II/V vs Others)	0.984	6.71	2.68 (1.27–5.63)	0.010
Medial tibial bone defect ≥ 5 mm (ref < 5 mm)	0.850	6.01	2.34 (1.19–4.62)	0.014
mMPTA differential (post–pre, per 1°)	0.050	0.94	1.05 (0.95–1.16)	0.332
MCL release (yes vs no)	0.459	1.70	1.58 (0.79–3.15)	0.192
Sex (female vs male)	0.036	0.01	1.04 (0.57–1.87)	0.905
BMI (per 1 kg/m ²)	–0.048	1.56	0.95 (0.88–1.03)	0.212

Dependent variable was valgus overcorrection (FLR-HKA < – 2°). Model McFadden R^2 = 0.049; likelihood-ratio χ^2 = 15.37, P = 0.018; AUC = 0.647 (95% CI 0.578–0.716); Hosmer–Lemeshow goodness-of-fit P = 0.406. All variance inflation factors (VIF) were < 2.0. Bold indicates P < 0.05.

3.5 Multivariable Linear Regression for Continuous Δ HKA and Sensitivity Analysis

Multivariable linear regression with continuous Δ HKA as the dependent variable showed that the CPAK neutral HKA group (types II/V) was independently associated with a greater magnitude of valgus drift (β = 1.071, 95% CI 0.339–1.803, standardized β = 0.210, P = 0.004); each 1° increase in mMPTA difference was associated with a 0.108° increase in Δ HKA (standardized β = 0.153, P = 0.031). The model adjusted R^2 was 0.024 (R^2 = 0.046), with F = 1.94 (df = 6, 257), P = 0.075. Sensitivity analysis: (1) using $|\Delta$ HKA| > 2° as an alternative endpoint, the drift rate was 43.3% in II/V versus 34.0% in non-II/V, and the corresponding II/V OR was 1.80 (95% CI 0.91–3.57), P = 0.091; (2) after excluding bilateral cases (one knee per patient, n = 230), reanalysis showed an II/V OR of 2.54 (P = 0.019) and a continuous Δ HKA β of 0.974 (P = 0.018), with no change in direction or significance. Details are shown in Table 6.

Table 6
Multivariable linear regression for continuous Δ HKA

Predictor	Unstandardized β	SE	95% CI	Standardized β	t	p value
CPAK neutral HKA group (II/V)	1.071	0.374	0.339–1.803	0.210	2.866	0.004
mMPTA difference (postop – preop, per 1°)	0.108	0.050	0.010–0.206	0.153	2.157	0.031
Medial tibial bone defect ≥ 5 mm (ref < 5 mm)	0.203	0.398	–0.577–0.983	0.035	0.511	0.609
MCL release (yes vs no)	0.353	0.324	–0.281–0.988	0.077	1.092	0.275
Sex (female vs male)	–0.151	0.297	–0.733–0.431	–0.032	–0.508	0.611
BMI (per 1 kg/m ²)	–0.014	0.033	–0.079–0.052	–0.023	–0.410	0.681
Note: The dependent variable was continuous Δ HKA (°). Model $R^2 = 0.046$; adjusted $R^2 = 0.024$; $F = 1.94$, $P = 0.075$ (df = 6, 257). Robust standard errors (HC3) were used. Standardized $\beta = t \times \sqrt{(1 - R^2)/df}$. Bold indicates $P < 0.05$.						

3.6 Interaction Analysis of II/V Phenotype

Interaction analysis showed that the interaction terms for MCL release (Wald $P = 0.332$) and bone defect severity (Wald $P = 0.597$) were not statistically significant. Likelihood-ratio tests for the incremental contribution of each interaction term likewise yielded $P = 0.121$ for II/V $\times$ MCL release and $P = 0.276$ for II/V $\times$ bone defect, indicating no evidence of effect modification by these surgical or anatomical factors. In all strata, the II/V group showed a higher crude rate of valgus overcorrection than the reference, with crude ORs of 3.11 in the MCL release–no stratum, 1.52 in the MCL release–yes stratum, 1.74 with bone defect < 5 mm, and 2.94 with bone defect ≥ 5 mm. However, these subgroup estimates should be interpreted cautiously because of the small sample sizes, particularly the bone-defect ≥ 5 mm subgroup ($n = 6$). Details are shown in Table 7.

Table 7
Interaction analysis in II/V subgroups

Stratified Variable	Subgroup (II/V n)	II/V OR (95% CI)	p-value	Interaction P (Wald)	Interaction P (LRT)
MCL release – Yes	18	1.94 (0.56–6.73)	0.296	0.332	0.121
MCL release – No	49	1.52 (0.61–3.80)	0.357		
Bone defect (mm) – ≥ 5	6	2.94 (0.35–24.6)	0.316	0.597	0.276
Bone defect (mm) – < 5	61	1.74 (0.76–3.99)	0.188		

Interaction P values were derived from product terms in the full model (II/V $\times$ stratified variable). ORs are unadjusted (crude) within each subgroup; “–” indicates not applicable. mMPTA difference = postoperative measured – preoperative (anatomical angle, valgus positive); cohort mean $+ 4.50^\circ \pm 3.15^\circ$.

4. Discussion

4.1 Systematic Difference Between Intraoperative and Postoperative Coronal Alignment

The core finding of this study is that the residual varus measured intraoperatively by MAKO (supine, non-weight-bearing, anesthetized-relaxed state) averaged 0.93° more than that measured on postoperative 3-month standing weight-bearing FLR, indicating that the two measurement states are not equivalent in representing the mechanical axis [4]. This mean difference is in the same order of magnitude as the 1.8° difference reported by Glowalla et al. in a MAKO series [6], but with wider limits of agreement, reflecting greater individual variation in weight-bearing adaptation within our cohort of varus OA patients.

In terms of component measurements, weight-bearing mMPTA was on average 0.39° higher than the MAKO planned target. Although this deviation was small and consistent in direction across CPAK phenotypes, Δ mMPTA showed no significant linear correlation with postoperative valgus degree (Pearson $r = -0.106$, $P = 0.091$), indicating that the systematic tibial-side difference may contribute to the direction of alignment shift but does not explain the magnitude of individual variation. Femoral Δ mLDFA ($-0.03^\circ \pm 1.70^\circ$) and Δ JLO also showed no consistent independent pattern. These findings suggest that the observed alignment drift is multifactorial and may reflect the combined effects of component positioning, weight-bearing conditions, and individual soft-tissue behavior [3, 19].

4.2 Association of CPAK II/V Phenotypes With Continuous Alignment Drift

The most important contribution of this study lies in distinguishing between two statistical frameworks: “continuous Δ HKA” and “valgus overcorrection”, support a phenotype-related association with postoperative alignment drift [11, 23]. In unadjusted group comparisons, the difference in valgus overcorrection rates between II/V and non-II/V did not reach significance. After adjusting for confounders including bone defect and mMPTA difference, the continuous Δ HKA model remained significant for II/V, whereas the categorical endpoint yielded an adjusted II/V OR of 2.68 with a relatively wide confidence interval. This discrepancy between the continuous and dichotomous models reflects the loss of information inherent in categorizing a continuously distributed alignment drift at a fixed threshold, coupled with the modest sample size of the II/V group. Together, the analyses support a phenotype-related association with postoperative alignment drift.

Interaction analysis did not provide evidence that the association between the II/V phenotype and valgus overcorrection was significantly modified by MCL release or bone defect severity. Anatomically, type II features bony tibial varus with a downward-inward sloping joint line; when pursuing MA 0°, greater lateral tibial resection may be required, potentially altering native JLO [12–13, 20, 23]. If MCL laxity is simultaneously addressed to achieve extension-gap balance, postoperative weight-bearing changes in soft-tissue tension may contribute to lateral alignment shift. Type V (neutral aHKA + neutral JLO) has less pronounced bony deformity, but extensive MCL release to achieve neutral alignment could likewise contribute to postoperative valgus drift [12, 23, 27]. The high proportion of varus apex-distal phenotypes, particularly type II, in East Asian populations [15–17]—with type V prevalence varying substantially across cohorts—makes this phenotype-related association clinically relevant. These findings are compatible with the concept proposed by MacDessi et al. [13] that CPAK phenotypes represent constitutional variation and may require consideration when selecting alignment targets [20, 29]. However, the present retrospective data do not establish a specific biomechanical mechanism.

Furthermore, the findings from the continuous Δ HKA model ($\beta = 1.071$, $P = 0.004$) and categorical overcorrection model (OR = 2.68, $P = 0.010$) provide complementary evidence for an association between the II/V phenotype and postoperative alignment drift. Because the continuous outcome retains more information than a binary threshold, the two models may yield different levels of statistical precision. These results support further investigation of phenotype-specific alignment behavior without establishing a specific biomechanical mechanism or dose-response relationship [23, 27, 29].

4.3 Association of Bone Defect and mMPTA Difference With Alignment Drift

In the multivariable logistic model, medial tibial bone defect ≥ 5 mm (OR = 2.34, 95% CI 1.19–4.62, $P = 0.014$) and each 1° increase in mMPTA difference (OR = 1.05, 95% CI 0.95–1.16) were associated with valgus overcorrection. Medial tibial bone defects may influence the amount of correction achievable by tibial resection and the resulting postoperative alignment. At the same time, bone defects may reflect more complex joint deformity, and the surgical strategy adopted (whether to retain residual varus or use augmentation) may act as a confounder. In this cohort, medial tibial bone defects ≥ 5 mm were more

frequent in type I knees (27.3%) than in the merged II/V group (9.0%). Despite this difference in distribution, II/V remained independently associated with valgus overcorrection after adjustment for defect severity. The present data do not establish whether bone defect mediates the phenotype association; future path analyses incorporating resection amount and gap tension may help clarify these relationships [2, 23]. The interaction analysis did not provide evidence that the association between the II/V phenotype and valgus overcorrection was significantly modified by MCL release or bone defect severity. However, the small subgroup sizes, particularly for knees with bone defects ≥ 5 mm, limit the reliability of these interaction estimates.

4.4 BMI as a Covariate

Although univariate analysis suggested an association between lower BMI and valgus overcorrection, BMI was not independently associated with valgus overcorrection in the multivariable model ($P = 0.212$). This finding does not support BMI as an independent explanatory factor in the present dataset, although it does not exclude a potential relationship between body composition, soft-tissue tension, and postoperative alignment that was not directly measured.

4.5 Potential Clinical Implications

The findings may support consideration of CPAK phenotype when interpreting intraoperative alignment in raTKA [23]. In the adjusted linear model, CPAK II/V phenotypes were associated with an approximately 1.07° greater Δ HKA than the reference phenotypes, independent of the other covariates. This coefficient represents an adjusted group difference rather than an alert threshold or dose-response slope. These data support prospective evaluation of phenotype-specific alignment targets and intraoperative-to-postoperative alignment monitoring [6, 19]. However, the optimal residual alignment target for each CPAK phenotype cannot be determined from the present retrospective study and requires prospective validation, particularly with stratification by bone defect and ligament tension.

4.5 Limitations

This study has several limitations. First, the single-center, retrospective design may limit generalizability. No statistically significant differences were observed in age, BMI, or preoperative HKA between included and excluded knees, but residual selection bias cannot be excluded. Second, the unit of analysis was knee rather than patient, and bilateral cases may introduce within-subject correlation. Third, postoperative weight-bearing CT was lacking, precluding separation of bony alignment from soft-tissue tension contributions [23], limb rotation on long-leg films may have caused additional measurement error [25, 26]. Fourth, FLR was only obtained at 3 months postoperatively, without evaluating dynamic changes in alignment over time. Fifth, the merged II/V sample ($n = 67$) limited the power for categorical endpoints. Sixth, MCL release was recorded as a binary variable without dose information such as release extent. Seventh, independent ankle valgus angle was not measured, so the role of the distal compensation chain could not be quantified [14, 22]. Eighth, only radiographic alignment was used as an endpoint, without incorporating patient-reported outcome measures (PROMs) or functional scores [28]. Ninth, interaction analyses were limited by sample size and should be interpreted cautiously (e.g., bone

defect ≥ 5 mm subgroup $n = 6$); negative interaction results do not equate to “no interaction.” Future studies should conduct prospective, multicenter studies with CPAK-stratified comparison of alignment strategies, combined with intraoperative pressure sensing [23, 17] and weight-bearing CT [27], and dynamic HKA assessment [24], to further elucidate the mechanisms of alignment drift. Finally, the overall linear model was not statistically significant ($F = 1.94$, $P = 0.075$), despite the II/V coefficient reaching statistical significance ($\beta = 1.071$, $P = 0.004$). This distinction should be considered when interpreting the adjusted association, and larger multicenter cohorts are needed to assess the incremental value of mMPTA difference and MCL release as predictors and to determine whether the observed alignment drift is associated with patient-reported outcomes [28, 30].

5. Conclusion

MAKO intraoperative HKA averaged 0.93° more varus than postoperative weight-bearing FLR, with individual Δ HKA values ranging from -4.5° to $+6.9^\circ$, indicating a systematic difference with substantial interindividual variability. CPAK II/V phenotypes were associated with greater continuous Δ HKA ($\beta = 1.071$, $P = 0.004$), and the adjusted odds of valgus overcorrection were higher for II/V than for other phenotypes (OR = 2.68, 95% CI 1.27–5.63, $P = 0.010$). CPAK types II and V were associated with greater postoperative valgus drift and higher adjusted odds of valgus overcorrection. Intraoperative non-weight-bearing alignment measurements may not fully represent postoperative weight-bearing alignment. CPAK classification may be useful for individualized alignment planning in raTKA [11, 23, 29], although optimal phenotype-specific alignment targets require prospective validation [30].

Abbreviations

raTKA Robotic arm-assisted total knee arthroplasty

CT Computed tomography

FLR Full leg radiograph

TKA Total knee arthroplasty

HKA Hip–knee–ankle angle

mLDFA Mechanical lateral distal femur angle

mMPTA Mechanical medial proximal tibia angle

JLCA Joint line convergence angle

CPAK Coronal Plane Alignment of the knee (classification)

Declarations

Ethics approval and consent to participate:

This study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of Tianjin Beichen Hospital (Approval No.: 2026010509; Date of approval: January 5, 2026). Due to the retrospective nature of the study and the use of anonymized patient data, the requirement for written informed consent was waived by the Ethics Committee. Consent to publish anonymized data was covered by the ethical approval.

Consent to publish:

Consent to publish anonymized data was obtained as part of the ethical approval process.

Data availability:

The datasets generated and/or analyzed during the current study are not publicly available due to patient confidentiality but are available from the corresponding author on reasonable request.

Competing interests:

The authors declare that they have no competing interests.

Clinical trial number:

not applicable.

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Author Contributions Statement

Hang Zhang: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. Sen He: Investigation, Validation. Qiang He: Investigation, Validation. Yunli He: Resources, Data Curation. Yujun Wang: Resources, Data Curation. Zhe Feng: Formal analysis, Software. Qian Zhang: Supervision, Project administration. Qingliang Sun: Funding acquisition, Supervision, Writing – review & editing.

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Figures

Figure 1. Agreement between intraoperative and postoperative hip-knee-ankle angle in MAKO robotic total knee arthroplasty (n = 264)

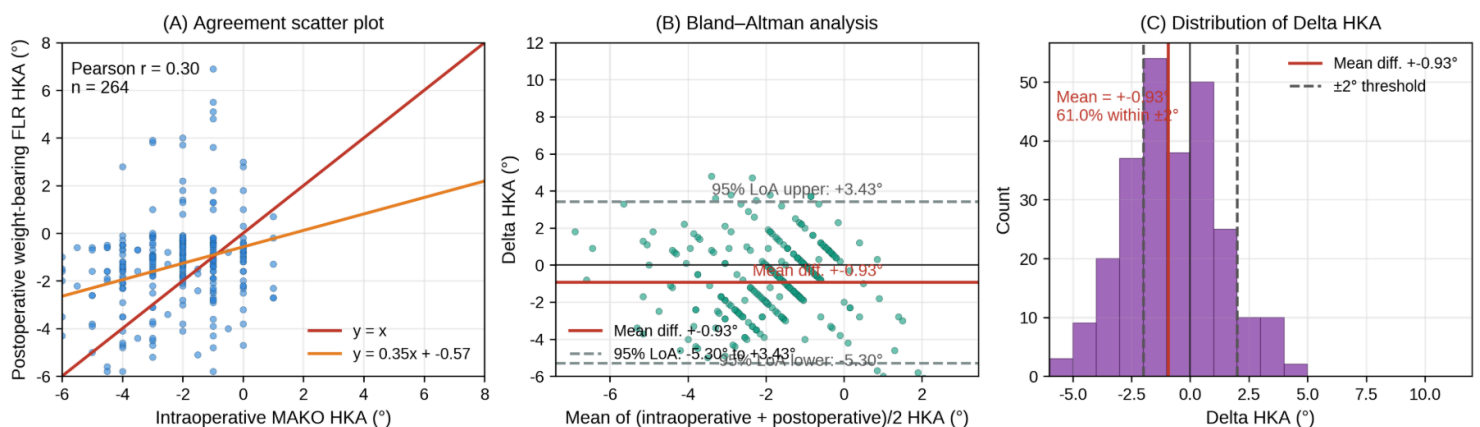


Figure 1

(A) Scatter plot of intraoperative planned versus postoperative weight-bearing HKA; (B) Bland-Altman analysis using postoperative minus intraoperative HKA, showing a bias of -0.93° and 95% limits of agreement from -5.30° to $+3.43^\circ$; (C) Histogram of ΔHKA with vertical dashed lines marking the $\pm 2^\circ$ thresholds. Pearson correlation coefficient $r = 0.30$. HKA: varus as positive, valgus as negative; $\Delta\text{HKA} = \text{intraoperative MAKO HKA} - \text{postoperative weight-bearing full-leg radiograph (FLR) HKA}$; $\Delta\text{HKA} > 0$ indicates more valgus postoperatively than intraoperatively. In panel A, the red solid line represents the line of perfect agreement ($y = x$) and the orange line the linear regression fit; in panel B, the solid line is the mean difference (-0.93°) and the dashed lines are the 95% limits of agreement.