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Changes in Coronal Lower-Limb Alignment and Knee Phenotypes After Total Hip Arthroplasty in Patients Who Have Crowe IV Developmental Dysplasia of the Hip

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Abstract

Background: Total hip arthroplasty (THA) can alter coronal lower-limb alignment in patients who have developmental dysplasia of the hip (DDH), but changes in hip–knee–ankle angle (HKA), femoral mechanical angle (FMA), and tibial mechanical angle (TMA) phenotypes and Coronal Plane Alignment of the Knee (CPAK) types after THA for Crowe IV DDH remain incompletely characterized. We evaluated these changes, residual alignment deviations, and associated factors.

Methods: We retrospectively reviewed 86 patients who underwent primary THA for unilateral Crowe IV DDH. Preoperative and final follow-up standing full-length lower-extremity radiographs were compared. We determined HKA, FMA, and TMA phenotypes and CPAK types and assessed alignment deviations using reference values from a Chinese population without knee osteoarthritis. Paired tests, Bowker tests of symmetry, and multivariable regression analyses were performed.

Results: After THA, FMA and HKA shifted toward varus by 2.68° and 2.44°, respectively (both $P < 0.001$), whereas TMA did not change significantly ($P = 0.436$). Phenotype changes occurred in 74 and 62 patients (86.0 and 72.1%) for FMA and HKA, respectively, with transitions predominantly toward varus (both Bowker $P < 0.001$); the TMA phenotype changed in only 11 patients (12.8%). A change in CPAK type occurred in 40 patients (46.5%), whereas the number of patients who had at least one deviant or aberrant angle decreased from 45 (52.3%) preoperatively to 21 (24.4%) postoperatively. Multivariable analysis showed that change in femoral offset was independently associated with change in HKA ($B = -0.083°/\text{mm}$; 95% confidence interval, -0.155 to -0.010; $P = 0.026$).

Conclusions: In patients who had Crowe IV DDH, changes in coronal alignment after THA occurred predominantly on the femoral side, whereas tibial alignment remained largely stable. Although marked alignment deviations decreased after THA, residual alignment deviations persisted in some patients. FMA and HKA functional

phenotypes shifted predominantly toward varus, and changes in CPAK type were common. Therefore, coronal lower-limb alignment and knee phenotypes should be reassessed after THA in patients who may subsequently undergo total knee arthroplasty to inform preoperative planning.

Keywords: developmental dysplasia of the hip; total hip arthroplasty; coronal alignment; functional knee phenotype; CPAK

1 Background

Crowe IV developmental dysplasia of the hip (DDH) is the most severe form of DDH and is associated with a hypoplastic acetabulum, proximal femoral deformity, soft-tissue contractures, and relative limb shortening [1–6]. Longstanding anatomical abnormalities and abnormal loading may also affect the knee and coronal lower-limb alignment [7, 8]. Total hip arthroplasty (THA) is the main treatment for these patients [2–4, 6, 9].

Previous studies have reported valgus lower-limb alignment in patients who have Crowe IV DDH and improvement in hip–knee–ankle angle (HKA) toward neutral after THA [10–13]. However, comparing radiographic angles such as HKA, lateral distal femoral angle (LDFA), and medial proximal tibial angle (MPTA) alone may oversimplify coronal alignment [14–16]. Functional knee phenotypes and the Coronal Plane Alignment of the Knee (CPAK) classification describe complementary aspects of coronal alignment and individual anatomical variability [15, 17–19]. Although CPAK has been applied to assess coronal alignment after primary THA [20–22], transitions in HKA, femoral mechanical angle (FMA), and tibial mechanical angle (TMA) phenotypes and CPAK type changes remain poorly characterized in patients who have Crowe IV DDH.

One of the key questions in coronal alignment assessment is what constitutes normal and abnormal alignment. Hirschmann et al proposed defining normal coronal alignment

from a reference population's mean, standard deviation (SD), and confidence intervals (CIs), and grading alignment by deviation from this distribution [23]. Applying this framework with Chinese reference data permits quantification of preoperative coronal malalignment and any reduction after THA.

This study aimed to (1) evaluate changes in HKA, FMA, and TMA and their functional phenotypes after THA in patients who had unilateral Crowe IV DDH; (2) characterize preoperative-to-postoperative changes in CPAK type; (3) compare preoperative and postoperative deviations from reference ranges; and (4) identify factors associated with changes in coronal alignment and CPAK type.

2 Methods

2.1 Study Design and Participants

We retrospectively reviewed 92 patients who underwent primary THA for osteoarthritis secondary to unilateral Crowe IV DDH at a tertiary teaching hospital between 2015 and 2025. Crowe IV DDH was defined according to the original Crowe classification [1]. Patients were excluded if they had contralateral DDH, had undergone previous surgery on the affected hip, had Kellgren–Lawrence grade III or IV osteoarthritis of the affected knee [24], underwent surgery of the affected knee or lumbar fusion before or during follow-up, had a neurologic or neuromuscular disorder, had less than 1 year of follow-up, or had incomplete clinical or radiographic data. The final cohort comprised 86 patients, including 78 women (90.7%), with a mean age of 44.9 ± 8.6 years and a mean BMI of 23.2 ± 2.7 kg/m^2.

The institutional review board approved the study (KYLL-2026-04-042), and all patients provided written informed consent.

2.2 Surgical Technique

All THAs were performed through a direct lateral approach using a cementless S-ROM modular femoral stem (Keyi Bang'en Medical, Beijing, China), with the acetabular component placed in the true acetabulum. Subtrochanteric shortening osteotomy (STO) was selected according to preoperative templating, intraoperative soft-tissue tension, and the feasibility of stable reduction without excessive limb lengthening. When required, a transverse STO was performed; the overlapped fragments were fixed with titanium cables, and autologous femoral-head bone was grafted at the osteotomy site. Stable reduction and satisfactory component position were confirmed intraoperatively.

2.3 Radiographic Assessment

Standing full-length anteroposterior radiographs of both lower extremities were obtained preoperatively and at final follow-up with the knees extended and patellae facing forward; a block was placed under the shorter limb when needed to level the pelvis. Measurements were performed using the hospital picture archiving and communication system (PACS; Medcare, Qingdao, China). Two surgeons independently measured all parameters, and their mean was analyzed. Discrepancies greater than 3° were resolved by consensus with a senior surgeon. Intraobserver and interobserver reliability were evaluated using intraclass correlation coefficients.

The HKA was the medial angle between the femoral and tibial mechanical axes; FMA, the medial angle between the femoral mechanical axis and distal femoral joint line; and TMA, the medial angle between the tibial mechanical axis and proximal tibial joint line [15, 25]. Height of the hip center (HHC) was the vertical distance from the femoral head center to the interteardrop line, and femoral offset (FO) was the perpendicular distance from the femoral head center to the femoral shaft axis. Leg-length discrepancy (LLD) was the difference between the anterior superior iliac

spine–to–ankle center distances of the affected and contralateral limbs. Lower HKA, FMA, and TMA values indicated a shift toward varus and higher values a shift toward valgus.

2.3.1 Functional Knee Phenotypes

According to Hirschmann et al [15], phenotypes were assigned separately for overall lower-limb alignment based on HKA, femoral alignment based on FMA, and tibial alignment based on TMA. Neutral phenotype centers were 180°, 93°, and 87°, respectively. Adjacent centers differed by 3°, and each phenotype covered ±1.5° around its center. Phenotype labels combined alignment direction (NEU, VAR, or VAL), the measured angle (HKA, FMA, or TMA), and deviation from the neutral center.

2.3.2 CPAK Classification

According to MacDessi et al [17], CPAK combines the arithmetic hip–knee–ankle angle (aHKA) and joint-line obliquity (JLO) to define 9 types. Because FMA and TMA were expressed as medial angles, aHKA was calculated as $\text{FMA} + \text{TMA} - 180°$ and categorized as varus ($< -2°$), neutral ($-2° \leq \text{aHKA} \leq 2°$), or valgus ($> 2°$). The JLO was calculated as $180° + \text{TMA} - \text{FMA}$ and categorized as apex-distal ($< 177°$), neutral ($177° \leq \text{JLO} \leq 183°$), or apex-proximal ($> 183°$).

2.4 Data Analyses

Analyses were performed using R version 4.4.1 (R Foundation for Statistical Computing, Vienna, Austria). Continuous variables were summarized as means with SDs or medians with interquartile ranges, as appropriate, and categorical variables as counts and percentages. Change (Δ) was defined as the postoperative minus the preoperative value. Paired continuous variables were compared using paired t tests or Wilcoxon signed-rank tests, as appropriate, and mean changes were reported with 95% CIs. Bowker tests of symmetry assessed the symmetry of preoperative-to-postoperative

HKA, FMA, and TMA phenotype transitions. Sex-specific means and SDs for HKA, FMA, and TMA reported by Jiang et al [25] for a Chinese population without knee osteoarthritis served as reference values. Following Hirschmann et al [23], alignment measurements were categorized as neutral (within ±1 SD of the reference mean), normal (within ±1–2 SDs), deviant (within ±2–3 SDs), or aberrant (> ±3 SDs). Each patient was classified by the most severe category among HKA, FMA, and TMA. Multivariable linear regression identified factors associated with changes in HKA, FMA, TMA, aHKA, and JLO. Candidate variables were prespecified on the basis of previous literature and clinical relevance [12, 26, 27] and included age, body mass index (BMI), STO, change in FO, HHC decrease, and preoperative alignment parameters. The HKA, FMA, and TMA models included the corresponding preoperative angle, whereas the aHKA and JLO models included both preoperative aHKA and JLO. A Firth penalized logistic regression model for change in CPAK type included age, BMI, STO, change in FO, HHC decrease, preoperative aHKA, and preoperative JLO. Results were reported as unstandardized regression coefficients (B) for linear models and odds ratios (ORs) for logistic models, with 95% CIs. Statistical significance was set at $P < 0.05$.

3 Results

3.1 Changes in Radiographic Parameters

A total of 86 patients with unilateral Crowe IV DDH underwent primary THA. Of these, 49 patients (57.0%) underwent STO.

After THA, FO increased by a mean of 8.7 mm, whereas HHC and LLD decreased by means of 47.7 and 44.4 mm, respectively (all $P < 0.001$). Mean HKA and FMA decreased by 2.44° and 2.68°, respectively (both $P < 0.001$), whereas TMA did not change significantly (mean change, 0.09°; $P = 0.436$). Mean aHKA decreased by 2.59°, whereas JLO increased by a mean of 2.77° (both $P < 0.001$; Table 1). Changes in

Table 1 Changes in Radiographic Parameters After Total Hip Arthroplasty

Parameter	Preoperative	Postoperative	Mean Change (95% CI)	P Value
Hip parameters				
FO (mm)	25.8 ± 8.4	34.5 ± 7.1	8.7 (7.0 to 10.4)	< 0.001
HHC (mm)	73.6 ± 17.6	25.8 ± 7.1	-47.7 (-52.0 to -43.5)	< 0.001
LLD (mm)	51.7 ± 11.6	7.3 ± 3.8	-44.4 (-46.7 to -42.1)	< 0.001
Coronal alignment parameters				
HKA (°)	183.8 ± 3.6	181.4 ± 3.8	-2.4 (-3.0 to -1.9)	< 0.001
FMA (°)	96.1 ± 2.7	93.4 ± 2.9	-2.7 (-3.1 to -2.3)	< 0.001
TMA (°)	88.7 ± 2.0	88.8 ± 2.2	0.1 (-0.1 to 0.3)	0.436
aHKA (°)	4.8 ± 3.4	2.2 ± 3.5	-2.6 (-3.1 to -2.1)	< 0.001
JLO (°)	172.6 ± 3.4	175.4 ± 3.7	2.8 (2.3 to 3.2)	< 0.001

Values are mean ± SD. Mean change was calculated as postoperative minus preoperative. P values were calculated using paired t tests.
Abbreviations: aHKA, arithmetic hip–knee–ankle angle; CI, confidence interval; FMA, femoral mechanical angle; FO, femoral offset; HHC, height of the hip center; HKA, hip–knee–ankle angle; JLO, joint-line obliquity; LLD, leg-length discrepancy; SD, standard deviation; THA, total hip arthroplasty; TMA, tibial mechanical angle.

HKA, FMA, and TMA did not differ significantly between patients who underwent and did not undergo STO (all $P \geq 0.140$; Table S1).

3.2 Changes in Femoral, Tibial, and Lower-Limb Functional Phenotypes

The FMA phenotype changed in 74 patients (86.0%). These phenotype transitions were asymmetric (Bowker $P < 0.001$). The most common preoperative FMA phenotypes were $\text{VAL}_{\text{FMA3}^\circ}$ and $\text{VAL}_{\text{FMA6}^\circ}$ (31 and 29 patients [36.0 and 33.7%], respectively). The most common postoperative FMA phenotypes were $\text{NEU}_{\text{FMA0}^\circ}$ and $\text{VAL}_{\text{FMA3}^\circ}$ (30 and 29 patients [34.9 and 33.7%], respectively). The most common phenotype transitions were from $\text{VAL}_{\text{FMA6}^\circ}$ to $\text{VAL}_{\text{FMA3}^\circ}$ (24 patients) and from $\text{VAL}_{\text{FMA3}^\circ}$ to $\text{NEU}_{\text{FMA0}^\circ}$ (20 patients).

The TMA phenotypes remained relatively stable, with changes observed in only 11 patients (12.8%) and no significant asymmetry in the transitions (Bowker $P = 0.187$). The predominant phenotypes before and after THA were $\text{NEU}_{\text{TMA0}^\circ}$ and $\text{VAL}_{\text{TMA3}^\circ}$. The most common transitions were from $\text{NEU}_{\text{TMA0}^\circ}$ to $\text{VAL}_{\text{TMA3}^\circ}$ (4 patients) and from $\text{VAL}_{\text{TMA3}^\circ}$ to $\text{VAL}_{\text{TMA6}^\circ}$ (3 patients).

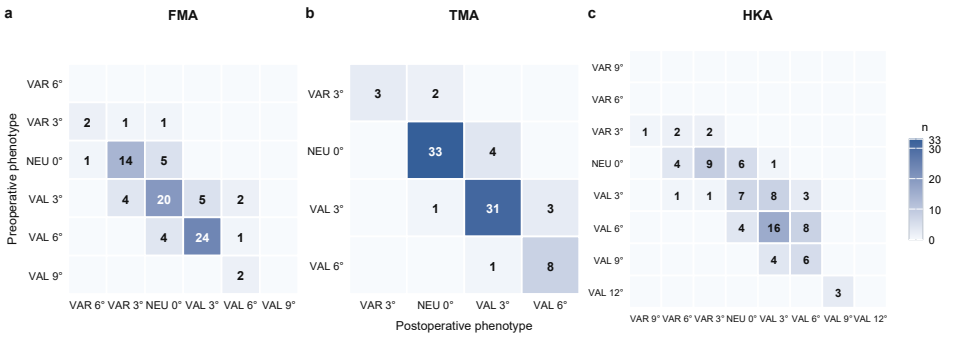


Fig. 1 Preoperative-to-postoperative transitions in (A) FMA, (B) TMA, and (C) HKA phenotypes. Cell labels and shading indicate patient counts. Abbreviations: FMA, femoral mechanical angle; HKA, hip–knee–ankle angle; NEU, neutral; TMA, tibial mechanical angle; VAL, valgus; VAR, varus.

The HKA phenotype changed in 62 patients (72.1%), and the transitions were significantly asymmetric (Bowker $P < 0.001$). The most common phenotype changed from $\text{VAL}_{\text{HKA6°}}$ preoperatively to $\text{VAL}_{\text{HKA3°}}$ postoperatively (28 and 29 patients [32.6 and 33.7%], respectively). The most common transitions were from $\text{VAL}_{\text{HKA6°}}$ to $\text{VAL}_{\text{HKA3°}}$ (16 patients) and from $\text{NEU}_{\text{HKA0°}}$ to $\text{VAR}_{\text{HKA3°}}$ (9 patients) (Figure 1; Tables S2 and S3).

3.3 Changes in CPAK Types

The most common preoperative CPAK type was type III (59 patients, 68.6%), followed by types II and VI (17 and 8 patients [19.8 and 9.3%], respectively). Type III remained the most common postoperative CPAK type (35 patients, 40.7%), followed by types II and VI (18 and 12 patients [20.9 and 14.0%], respectively) (Figure 2; Table S4).

When the two CPAK dimensions were considered, apex-distal JLO (types I to III) decreased from 76 to 56 patients (88.4 to 65.1%), whereas neutral JLO (types IV to VI) increased from 10 to 29 patients (11.6 to 33.7%). Valgus aHKA decreased from 67 to 47 patients (77.9 to 54.7%), whereas neutral and varus aHKA increased from 18 to 29 patients (20.9 to 33.7%) and from 1 to 10 patients (1.2 to 11.6%), respectively.

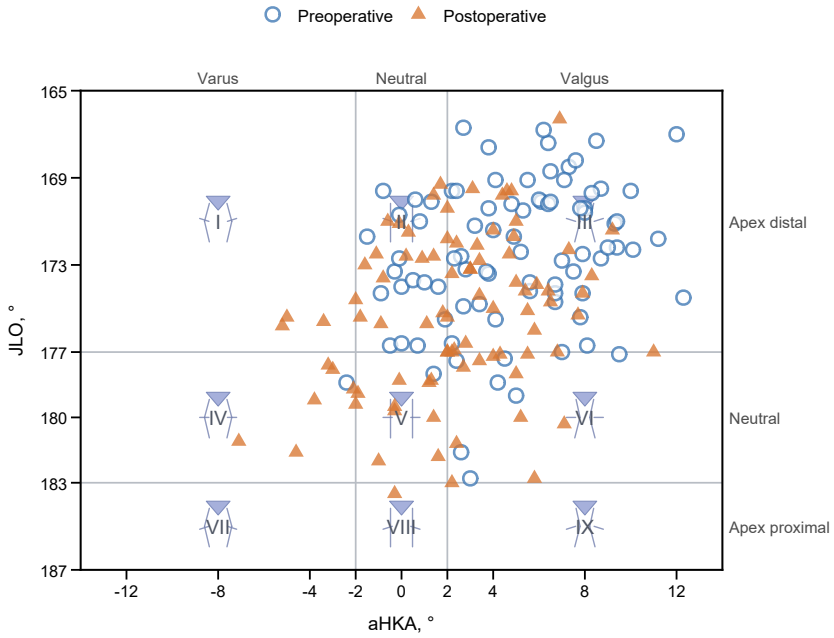


Fig. 2 Preoperative and postoperative distributions within CPAK. Blue open circles and orange triangles indicate preoperative and postoperative measurements, respectively. Gray lines indicate the aHKA (−2° and 2°) and JLO (177° and 183°) boundaries; Roman numerals indicate CPAK types. Abbreviations: aHKA, arithmetic hip–knee–ankle angle; CPAK, Coronal Plane Alignment of the Knee; JLO, joint-line obliquity.

A change in CPAK type occurred in 40 patients (46.5%). The most common transitions were from type III to II (12 patients), type III to VI (8 patients), type II to IV (5 patients), and type III to V (4 patients).

3.4 Preoperative and Postoperative Alignment Relative to Reference Values

The preoperative and postoperative distributions of FMA, TMA, and HKA across the neutral, normal, deviant, and aberrant categories are shown in Table 2. Preoperatively, 39, 28, and 4 patients (45.3, 32.6, and 4.7%) had a deviant or aberrant HKA, FMA, and TMA, respectively; all deviations were toward valgus. At least one of HKA, FMA, or TMA was deviant or aberrant in 45 patients (52.3%). Among these patients,

Table 2 Preoperative and Postoperative Coronal Alignment Categories Relative to Reference Ranges

Angle	Time	Neutral, n (%)	Normal, n (%)	Deviant, n (%)	Aberrant, n (%)
FMA	Preoperative	31 (36.0)	27 (31.4)	27 (31.4)	1 (1.2)
	Postoperative	46 (53.5)	36 (41.9)	4 (4.7)	0 (0.0)
TMA	Preoperative	58 (67.4)	24 (27.9)	4 (4.7)	0 (0.0)
	Postoperative	52 (60.5)	28 (32.6)	6 (7.0)	0 (0.0)
HKA	Preoperative	25 (29.1)	22 (25.6)	26 (30.2)	13 (15.1)
	Postoperative	33 (38.4)	40 (46.5)	11 (12.8)	2 (2.3)

Neutral, normal, deviant, and aberrant indicate absolute deviations of ≤ 1, > 1 to 2, > 2 to 3, and > 3 SDs from the sex-specific reference mean, respectively. Abbreviations: FMA, femoral mechanical angle; HKA, hip–knee–ankle angle; SD, standard deviation; TMA, tibial mechanical angle.

combined FMA and HKA deviation was the most common pattern (22 patients, 48.9%), followed by isolated HKA deviation (14 patients, 31.1%).

Postoperatively, 13, 6, and 4 patients (15.1, 7.0, and 4.7%) had a deviant or aberrant HKA, TMA, and FMA, respectively. At least one of HKA, FMA, or TMA was deviant or aberrant in 21 patients (24.4%), among whom isolated HKA deviation was the most common pattern (11 patients, 52.4%). Overall preoperative-to-postoperative category changes and the remaining combinations are shown in Figures 3A and 3B.

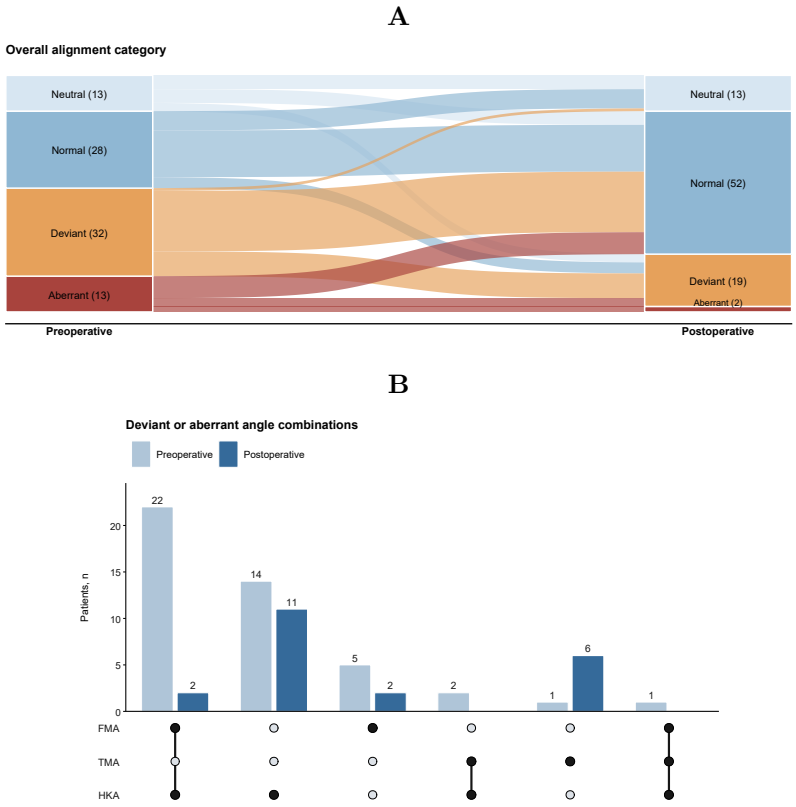


Fig. 3 Alignment relative to reference values before and after THA. (A) Highest category among FMA, TMA, and HKA for each patient. (B) Combinations of deviant or aberrant angles. Bars indicate patient counts; filled circles indicate included angles. Neutral, ≤ 1 SD; normal, $>$ 1–2 SDs; deviant, $>$ 2–3 SDs; aberrant, $>$ 3 SDs. Abbreviations: FMA, femoral mechanical angle; HKA, hip–knee–ankle angle; SD, standard deviation; THA, total hip arthroplasty; TMA, tibial mechanical angle.

3.5 Factors Associated With Changes in Coronal Alignment

Multivariable linear regression showed that change in FO (ΔFO) was independently associated with change in HKA (ΔHKA) ($B = -0.083°$/mm, 95% CI -0.155 to -0.010; $P = 0.026$). Each 1-mm increase in ΔFO was associated with a mean 0.083° decrease in HKA, corresponding to a shift toward varus. Preoperative HKA, FMA, and aHKA were independently associated with their respective changes (Table 3). No significant factors were identified in the ΔTMA or ΔJLO models, and Firth penalized logistic regression identified no factor independently associated with change in CPAK type (Table 3).

Table 3 Factors Associated With Changes in Coronal Alignment Parameters and CPAK Type: Multivariable Regression Analyses

Outcome	Predictor	Adjusted Estimate	95% CI	*P* Value
ΔHKA	Age, per year	−0.019	−0.086 to 0.047	0.566
	BMI, per kg/m^2	0.054	−0.158 to 0.266	0.613
	STO, yes vs no	0.182	−0.912 to 1.277	0.741
	ΔFO, per mm	−0.083	−0.155 to −0.010	0.026
	HHC decrease, per mm	0.010	−0.017 to 0.038	0.447
	Preoperative HKA, per degree	−0.162	−0.318 to −0.006	0.042
ΔFMA	Age, per year	0.013	−0.039 to 0.065	0.622
	BMI, per kg/m^2	0.083	−0.081 to 0.247	0.318
	STO, yes vs no	0.456	−0.387 to 1.298	0.285
	ΔFO, per mm	−0.036	−0.091 to 0.020	0.208
	HHC decrease, per mm	0.011	−0.010 to 0.031	0.319
	Preoperative FMA, per degree	−0.189	−0.349 to −0.029	0.021
ΔTMA	Age, per year	0.001	−0.027 to 0.029	0.939
	BMI, per kg/m^2	−0.048	−0.138 to 0.042	0.290
	STO, yes vs no	0.319	−0.149 to 0.786	0.179
	ΔFO, per mm	0.000	−0.031 to 0.031	0.998
	HHC decrease, per mm	0.001	−0.010 to 0.013	0.814
	Preoperative TMA, per degree	−0.068	−0.182 to 0.045	0.236
ΔaHKA	Age, per year	0.014	−0.048 to 0.076	0.664
	BMI, per kg/m^2	0.038	−0.159 to 0.234	0.703
	STO, yes vs no	0.789	−0.222 to 1.799	0.124
	ΔFO, per mm	−0.032	−0.100 to 0.035	0.339
	HHC decrease, per mm	0.011	−0.014 to 0.036	0.381
	Preoperative aHKA, per degree	−0.186	−0.342 to −0.031	0.019
	Preoperative JLO, per degree	0.012	−0.145 to 0.168	0.881
ΔJLO	Age, per year	−0.010	−0.067 to 0.046	0.715
	BMI, per kg/m^2	−0.131	−0.310 to 0.047	0.148
	STO, yes vs no	−0.157	−1.075 to 0.762	0.735
	ΔFO, per mm	0.033	−0.028 to 0.094	0.280
	HHC decrease, per mm	−0.008	−0.031 to 0.015	0.473
	Preoperative aHKA, per degree	0.109	−0.033 to 0.250	0.130
	Preoperative JLO, per degree	−0.070	−0.212 to 0.072	0.327
Change in CPAK type	Age, per year	0.990	0.939 to 1.042	0.688
	BMI, per kg/m^2	0.976	0.827 to 1.148	0.768
	STO, yes vs no	0.970	0.416 to 2.253	0.943
	ΔFO, per mm	1.028	0.973 to 1.089	0.325
	HHC decrease, per mm	0.990	0.969 to 1.011	0.367
	Preoperative aHKA, per degree	0.991	0.870 to 1.129	0.896
	Preoperative JLO, per degree	1.053	0.926 to 1.201	0.430

Adjusted estimates are unstandardized regression coefficients for continuous outcomes and ORs for change in CPAK type. Δ, postoperative minus preoperative; HHC decrease, preoperative HHC minus postoperative HHC.

Abbreviations: aHKA, arithmetic hip–knee–ankle angle; BMI, body mass index; CI, confidence interval; CPAK, Coronal Plane Alignment of the Knee; FMA, femoral mechanical angle; FO, femoral offset; HHC, height of the hip center; HKA, hip–knee–ankle angle; JLO, joint-line obliquity; OR, odds ratio; STO, subtrochanteric shortening osteotomy; TMA, tibial mechanical angle.

4 Discussion

This study evaluated changes in coronal lower-limb alignment and functional phenotypes after THA in patients who had Crowe IV DDH. The principal finding was that FMA and HKA shifted toward varus after THA, whereas TMA remained largely unchanged, indicating that the realignment occurred predominantly on the femoral side. Nevertheless, approximately one-quarter of patients retained marked alignment deviations. Nearly half of patients (46.5%) changed CPAK type. Thus, THA produced a directional reorganization of coronal lower-limb alignment, while marked alignment deviations persisted in some patients.

Patients who have Crowe IV DDH often present with a high-riding dislocated femoral head, proximal femoral deformity, and valgus alignment of the ipsilateral lower limb [5, 7, 8]. Reconstruction in the true acetabulum repositions the hip center, thereby improving lower-limb alignment [11]. Kocabiyik et al and Zhao et al reported reduced overall valgus alignment after THA in patients who had Crowe IV DDH [10, 11]. Sun et al further showed that valgus alignment was predominantly femoral-sided both before and after surgery [12]. However, changes in mean alignment angles may not fully capture patient-level transition patterns. We therefore used functional phenotypes and CPAK to characterize interindividual variation and transition patterns in overall, femoral, and tibial alignment [15, 17, 19].

The FMA phenotypes shifted predominantly toward varus, and their transitions differed according to the preoperative phenotype: marked valgus most commonly transitioned to milder valgus, mild valgus to neutral, and neutral alignment to mild varus. The HKA phenotypes likewise shifted toward varus, whereas TMA phenotypes remained relatively stable, indicating that postoperative realignment occurred predominantly on the femoral side.

After THA, the proportion of type III decreased from 68.6% to 40.7%, while the proportions of types II, VI, and V increased, indicating that CPAK reclassification

involved both overall varus–valgus alignment and joint-line orientation. The preoperative predominance of type III was consistent with reports that valgus alignment in Crowe IV DDH originated mainly from the femoral side [11, 12]. With MPTA largely unchanged, the increase in LDFA shifted aHKA from valgus toward neutral or varus and JLO from apex distal toward neutral, thereby altering both CPAK dimensions. Despite differences in the underlying hip disorders, the proportion of patients who had a CPAK type change in our cohort was comparable to the 45.1 and 56.6% reported by Negayama et al and Aibara et al, respectively, with transitions likewise occurring predominantly toward varus [21, 22]. Bayram et al reported better early function with JLO neutralization in valgus CPAK types III and VI after total knee arthroplasty, but whether a similar association exists after THA remains to be determined [28].

Using the distribution-based definitions proposed by Hirschmann et al [23], we also assessed the extent of coronal alignment deviation. More than half of the patients had at least one deviant or aberrant angle preoperatively, mainly involving HKA and FMA. This proportion decreased substantially after THA, although approximately one-quarter still had at least one deviant or aberrant angle postoperatively. This was consistent with the findings of Zhao et al, who reported that valgus alignment was reduced or neutralized after THA but not fully normalized [11]. Chen et al also reported incomplete correction of ipsilateral knee valgus at a mean follow-up of 10.2 years [13]. Isolated HKA deviation was the most common residual pattern. Small concordant deviations in FMA and TMA may have contributed to abnormal HKA. The HKA may also have been affected by joint-line convergence and soft-tissue balance.

Change in FO was the only hip-reconstruction parameter independently associated with change in HKA. Greater FO increases were associated with varus shifts, consistent with Tanaka et al [26]. The small effect indicated that FO explained only a limited proportion of the change in overall lower-limb alignment. Baseline alignment was also associated with subsequent changes, whereas most other measured factors were not

independently associated with alignment change. Postoperative coronal realignment therefore could not be explained by a single factor and may have reflected baseline alignment, hip reconstruction, and unmeasured factors.

Clinically, THA can be expected to reduce overall valgus alignment and marked alignment deviations in patients who have Crowe IV DDH. However, patients should be counseled before THA that postoperative coronal alignment, particularly HKA, may not completely normalize. Postoperative standing full-length lower-extremity radiographs should therefore be evaluated using FMA and TMA in addition to HKA. Because preoperative CPAK may not represent alignment after THA, aHKA, JLO, and CPAK should be reassessed in patients who may subsequently undergo knee arthroplasty [21, 22].

This study had several limitations. The single-center retrospective design may have introduced selection bias and precluded causal inference, while the limited sample size may have reduced the precision of the multivariable estimates. Only the preoperative and final follow-up time points were assessed, with varying follow-up durations, precluding evaluation of temporal changes in coronal alignment after THA. Despite standardized positioning and duplicate measurements, two-dimensional standing radiographs were susceptible to limb rotation and flexion. Only the affected limb was analyzed, preventing assessment of contralateral compensation. Moreover, functional phenotypes, CPAK, and alignment-deviation grades were defined using discrete cutoffs of continuous variables and may therefore have been sensitive to small measurement changes. Finally, the absence of knee pain, functional scores, and patient-reported outcomes prevented assessment of whether phenotype transitions, CPAK reclassification, or residual alignment deviations were associated with knee symptoms or function.

5 Conclusions

Coronal realignment after THA for Crowe IV DDH occurred predominantly on the femoral side, as FMA and HKA phenotypes shifted toward varus whereas TMA phenotypes remained relatively stable. Nevertheless, residual alignment deviations persisted in approximately one-quarter of patients. Nearly half of the patients changed CPAK type. Postoperative reassessment of coronal alignment may therefore be clinically relevant in patients who may subsequently undergo knee arthroplasty.

List of abbreviations

aHKA, arithmetic hip–knee–ankle angle; BMI, body mass index; CI, confidence interval; CPAK, Coronal Plane Alignment of the Knee; DDH, developmental dysplasia of the hip; FMA, femoral mechanical angle; FO, femoral offset; HHC, height of the hip center; HKA, hip–knee–ankle angle; ICC, intraclass correlation coefficient; JLO, joint-line obliquity; LLD, leg-length discrepancy; OR, odds ratio; PACS, picture archiving and communication system; SD, standard deviation; STO, subtrochanteric shortening osteotomy; THA, total hip arthroplasty; TMA, tibial mechanical angle.

Supplementary information

Additional file 1 (.pdf): Supplementary Tables S1–S4. Table S1 compares changes in coronal alignment parameters between patients who underwent and did not undergo STO. Table S2 presents the preoperative and postoperative distributions of FMA, TMA, and HKA phenotypes. Table S3 lists the observed phenotype transition patterns. Table S4 presents the preoperative and postoperative CPAK type distributions.

Declarations

Ethics approval and consent to participate

This study was approved by the Institutional Review Board of Qilu Hospital of Shandong University (KYLL-2026-04-042). All participants provided written informed consent to participate.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

Z.C.: Formal analysis, Data curation, Methodology, Software, Visualization, Writing–original draft. Z.W.: Investigation, Project administration, Writing–original draft. Y.T.: Project administration, Resources. D.L.: Validation, Resources. Y.W.: Software, Visualization. Y.M.: Investigation, Project administration. L.M.: Formal analysis, Writing–review and editing. Y.Z.: Conceptualization, Project administration, Supervision, Writing–review and editing. All authors read and approved the final manuscript.

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