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Knees with anteromedial osteoarthritis show a substantial phenotypic variation prior and following medial unicompartmental knee arthroplasty

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Abstract

Purpose The primary aim of this study was to evaluate the phenotypic variation using the Coronal Plane Alignment of the Knee (CPAK) classification among 1000 knees with anteromedial osteoarthritis (OA) both prior to and following medial unicompartmental knee arthroplasty (UKA). The secondary aim of this study was to investigate whether knees maintained their preoperative CPAK phenotype and to evaluate the phenotypic alterations following medial UKA.

Methods The CPAK classification was used to analyze 1000 knees that underwent medial UKA as treatment for anteromedial OA. Knees were categorized into nine distinct CPAK phenotypes based on their arithmetic hip–knee–ankle angle (aHKA), which estimates the pre-arthritic alignment, and joint line obliquity (JLO), both pre- and postoperatively. Phenotypic variation was analyzed by sex and age, and the phenotypic alterations following medial UKA were evaluated by phenotype.

Results Preoperatively, CPAK phenotype I had the highest prevalence (45.0%). Among males, the preoperative prevalence of CPAK phenotype I was significantly higher compared to females (53.2% vs. 35.0%, respectively; $p \leq .001$), whereas females exhibited a significantly higher occurrence of CPAK phenotype V compared to males (9.8% vs. 4.4%, respectively; $p \leq .015$). Following medial UKA, CPAK phenotype II had the highest prevalence (53.3%). Overall, 45.1% of knees maintained their preoperative CPAK phenotype following medial UKA, which was most frequently observed among CPAK phenotype II (67.7%) and III (65.8%).

Conclusion There is a substantial variation in CPAK phenotypes among knees with anteromedial OA, as well as following treatment with medial UKA. This variability challenges the assumption of uniform characteristics among knees with an identical wear pattern associated with anteromedial OA and emphasizes the complexity and variability of this specific form of OA.

Level of evidence III, Retrospective cohort study.

Keywords Unicompartmental knee arthroplasty · Osteoarthritis · Coronal Plane Alignment of the Knee (CPAK) · Knee phenotypes · Knee alignment · Robotic-assisted surgery

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Introduction

Medial unicompartmental knee arthroplasty (UKA) is an effective surgical procedure for patients with symptomatic anteromedial osteoarthritis (OA) of the knee [2, 20]. This specific form of OA manifests when the anterior cruciate ligament (ACL) is intact and the varus deformity is correctable [45]. Component positioning and lower limb alignment are significant factors affecting the survivorship and outcomes of UKA [1, 4, 7, 25, 26, 33, 41, 47]. Nevertheless, the optimal component positioning and lower limb alignment continue to be subjects of uncertainty and ongoing debate [25].

Traditionally, alignment strategies have solely focused on classifying knees into a neutral, varus, or valgus alignment and aimed to restore knees to neutral mechanical alignment [28, 48]. However, multiple recent studies have emphasized the substantial variability in coronal plane phenotypes, highlighting the necessity of re-evaluation of traditional alignment strategies for knee arthroplasty [8, 10, 12, 13, 15, 17, 18, 21, 31]. Recently, the Coronal Plane Alignment of the Knee (CPAK) classification was introduced [18]. This system utilizes both the pre-arthritic alignment, and knee joint line orientation (JLO) to classify the phenotypic variation in knees.

So far, the CPAK classification has primarily been used to describe healthy and osteoarthritic knees undergoing total knee arthroplasty (TKA), with a specific emphasis on examining the preoperative distribution [12, 18, 21, 22, 31, 36, 37, 40]. There is a common belief that patients with anteromedial OA consistently present with an identical intra-articular wear pattern. Nevertheless, the extent of phenotypic variation in knees affected by this specific form of OA remains unknown. Furthermore, to understand alignment adjustments that take place during medial UKA, it is essential to evaluate the phenotypic alterations in the coronal plane that occur during medial UKA.

Therefore, the primary aim of this study was to evaluate the phenotypic variation using the CPAK classification among 1000 knees with anteromedial OA both prior to and following medial UKA. The secondary aim of this study was to investigate whether knees maintained their preoperative CPAK phenotype and to evaluate the phenotypic alterations following medial UKA. It was hypothesized that a substantial phenotype variation would be present, challenging the assumption of uniform characteristics among knees affected by anteromedial OA.

Methods

Study design

Following approval from the Institutional Review Board of the Hospital for Special Surgery (New York, NY, United States) (#2022-1401), a retrospective review of a single surgeon's arthroplasty registry was conducted. The first consecutive 1000 knees of 835 patients with anteromedial OA who met the criteria for complete radiographic data collection were selected. All patients underwent robotic-arm assisted medial UKA between January 2012 and July 2022. Patients were included if they had anteromedial OA (Kellgren–Lawrence [KL] grade III–IV [16]) and had complete radiographic records consisting of pre- and postoperative long-leg radiographs. Patients were excluded if they had poor-quality or incomplete radiographic records, a history of ipsilateral tibial or femoral fractures, or prior ipsilateral knee-, ankle-, or hip arthroplasty.

The primary surgical indication for medial UKA was symptomatic, isolated anteromedial compartment OA with a varus deformity correctable to $< 10°$ and fixed flexion deformity of $< 10°$. Clinical or radiographical signs of advanced lateral compartment OA, signs of inflammatory arthritis, ACL deficiency, or a history of medial collateral ligament (MCL) surgery were considered contraindications for medial UKA.

Implant and surgical technique

All patients received a cemented medial UKA with a fixed-bearing tibial only implant (Restoris MCK system, Mako Surgical Corp. (Stryker), Fort Lauderdale, FL, USA). The surgeon used a robotic-arm assisted system (Mako Surgical Corp. (Stryker). Fort Lauderdale, FL, USA) for precise implant planning and bone preparation in all cases. The primary surgical objective was to resurface the medial compartment and to restore the knee to its pre-arthritic state, which is associated with improved survivorship and favorable outcomes [1]. This surgical objective was guided by a ligament-guided approach, rather than targeting a specific range of final coronal limb alignment. The specific aim was to restore the native MCL tension throughout the entire range of motion (ROM) to recreate the pre-arthritic alignment. The knee was considered well-balanced if a medial gap of 1–2 mm was achieved under valgus stress throughout the ROM and with the polyethylene insert in place. The surgical technique utilized in all cases has been described comprehensively [24, 29].

Radiographic evaluation

This study used routine preoperative and 6-week postoperative long-leg radiographs to assess coronal alignment. These radiographs were obtained uniformly, with patients instructed to stand with their feet closely together, knees in full extension, and body weight equally distributed over both limbs, while keeping their patellae aligned with the X-ray beam.

Radiographic measurements were performed by one observer (GV) and independently repeated on a random sample of 100 knees by a second observer (LR). Radiographic measurements included the mechanical hip–knee–ankle angle (mHKA; i.e., the angle subtended by the mechanical axes of the femur and tibia), mechanical lateral distal femoral angle (mLDFA; i.e., the lateral angle subtended by the mechanical femoral axis and distal femoral joint line), and the medial proximal tibia angle (MPTA; i.e., the medial angle subtended by the mechanical tibial axis and proximal tibial joint line). Subsequently, the JLO and arithmetic hip–knee–ankle angle (aHKA), which estimates the pre-arthritic alignment, were derived by adding and subtracting the MPTA and mLDFA, respectively. Inter-observer reliability was assessed using interclass correlation coefficients with a two-way mixed model and absolute agreement. ICC between observers for mHKA, mLDFA, and MPTA, were 0.97 (95% confidence interval [CI] 0.96–0.98), 0.89 (95% CI 0.82–0.93), and 0.90 (95% CI 0.85–0.93), respectively.

CPAK classification

Knees were classified according to the CPAK classification [18]. The system combines the aHKA and JLO to categorize knees into nine distinct phenotypes (Fig. 1). The JLO describes the direction of the joint line and classifies knees into three categories (i.e., apex distal, apex neutral, and apex proximal). This clearly specifies the orientation of the knee joint line in relation to a hypothetical neutral horizontal joint line with a range of 3°, which determines whether the joint line of the knee is located below, at the same level as, or above the neutral joint line (i.e., MPTA + mLDFA = 180°). The pre-arthritic alignment of the operative knee is determined by the aHKA and represents the alignment before the onset of OA in the knee in relation to a neutral limb alignment (i.e., MPTA − mLDFA = 0°) with a range of 2°. This categorizes knees into three additional categories (i.e., varus, neutral, and valgus).

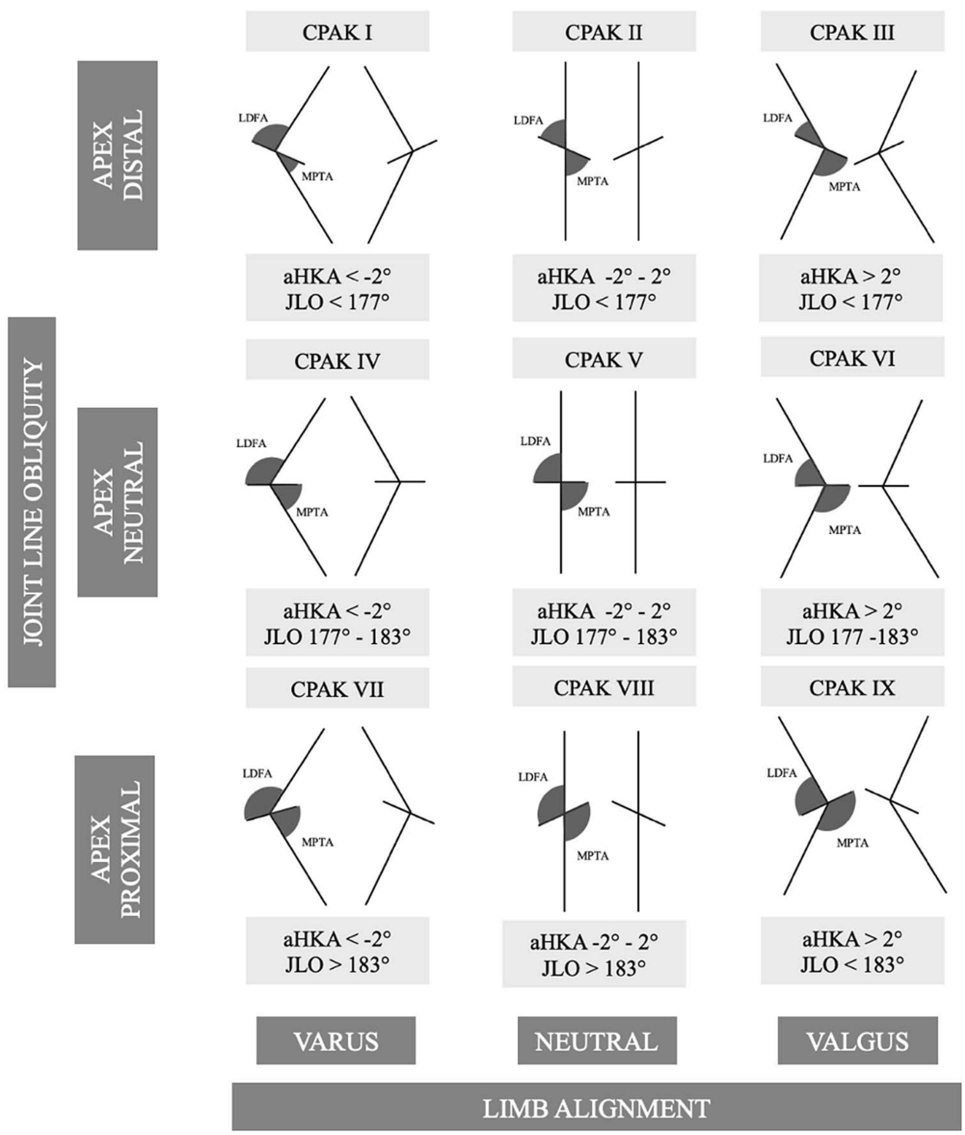

Fig. 1 Coronal Plane Alignment of the Knee (CPAK) classification with nine identified CPAK knee phenotypes. *aHKA*, arithmetic hip–knee–ankle angle (i.e., MPTA − LDFA); *JLO*, joint line obliquity (i.e., MPTA + LDFA)

Statistical analysis

All analyses were performed in R, version 2023.03.1 + 446 (R Foundation for Statistical Computing, Vienna, Austria), with the significance level set at 0.05. The prevalence of different CPAK phenotypes was assessed, both pre- and postoperatively. Gender-specific differences and age-related variations in the prevalence of different CPAK phenotypes were assessed. Patients were divided into the following three age groups: patients aged under 50 years, those between 50 and 70 years, and those over 70 years. Normal distribution of continuous variables was assessed using the Shapiro–Wilk test. The Pearson's correlation coefficient was used to assess associations for normally distributed variables, while Spearman's rank correlation was utilized for variables without a normal distribution. The Mann–Whitney *U* test was used to compare the means of two independent samples for variables without a normal distribution. Comparison of discrete variables was performed using the Chi-squared test or Fisher's exact test. Post-hoc power analyses were performed using nQuery version 8.5.1 (Statistical Solutions Ltd, Cork, Ireland). Post-hoc power calculations of evaluated comparisons resulted in a high observed power ranging from 0.87 to 0.99.

Results

Among the 1000 patients included in the study, most patients were Caucasian (89.9%) and male (54.9%). The mean age was 63.4 ± 9.2 years. Radiographic outcomes of the included patients are presented in Table 1.

Preoperative CPAK distribution

Preoperatively, the majority of knees exhibited CPAK phenotype I (45.0%; Fig. 2). Among males, the prevalence of CPAK phenotype I was significantly higher compared to females (53.2% vs. 35.0%, respectively; $p \leq .001$; Table 2). Females exhibited a significantly higher occurrence of CPAK phenotype V compared to males (9.8% vs. 4.4%, respectively; $p \leq .015$). A detailed overview of the distribution of phenotypes within distinct age groups is presented in Fig. 3.

Postoperative CPAK distribution

Postoperatively, CPAK phenotype II was most frequently observed (53.3%; Fig. 4). Among males, the postoperative prevalence of CPAK phenotypes I significantly higher compared to females (22.4% vs 9.8%, respectively; $p \leq .001$;

Table 1 Radiographic outcomes of knees with anteromedial osteoarthritis and following medial unicompartmental knee arthroplasty

	Preoperatively				Postoperatively			
	Total $n = 1000$	Male $n = 549$	Female $n = 451$	p value§	Total $n = 1000$	Male $n = 549$	Female $n = 451$	p value§
HKA (°)								
Mean ± SD	7.1 ± 3.4	7.4 ± 3.4	6.6 ± 3.4	< .001*	2.6 ± 2.2	2.9 ± 2.3	2.3 ± 2.2	< .001*
Range	− 3.5 to 17.0	− 3.5 to 17.0	− 2.4 to 16.8		− 3.6 to 10.1	− 2.5 to 10.1	− 3.6 to 9.8	
aHKA (°)								
Mean ± SD	− 2.4 ± 2.8	− 2.9 ± 2.8	− 1.7	< .001*	− 0.3 ± 2.4	− 0.6 ± 2.4	0.08 ± 2.3	< .001*
Range	− 11.3 to 7.5	− 11.3 to 6.5	− 9.6 to 7.5		− 13.5 to 7.6	− 13.5 to 6.2	− 8.1 to 7.6	
LDFA (°)								
Mean ± SD	88.3 ± 2.1	88.3 ± 2.0	88.2 ± 2.1	n.s	87.1 ± 87.0	86.9 ± 2.1	87.2 ± 2.0	.04*
Range	81.0–98.9	81.0–98.9	81.6–95.9		80.5–97.3	81.3–97.3	80.5–94.4	
MPTA (°)								
Mean ± SD	85.9 ± 2.2	85.4 ± 2.1	86.5 ± 2.1	< .001*	86.8 ± 1.9	86.4 ± 1.9	87.3 ± 1.8	< .001*
Range	79.7–93.8	79.7–91.8	80.3–93.8		78.9–92.7	78.9–92.6	81.7–92.7	
JLO (°)								
Mean ± SD	174.2 ± 3.2	173.8 ± 3.1	174.7 ± 3.2	< .001*	173.8 ± 3.2	173.3 ± 3.2	174.5 ± 3.1	< .001*
Range	164.4–188.1	164.4–188.1	164.4–187.3		160.5–185.1	160.5–185.1	164.9–184.3	

Preoperative and postoperative radiographic outcomes are given in mean ± standard deviation (SD) and range and stratified by gender. *aHKA*, arithmetic hip–knee–ankle angle; *HKA*, hip–knee–ankle angle; *JLO*, joint line obliquity; *LDFA*, lateral distal femoral angle; *MPTA*, medial proximal tibial angle

§ Comparison of radiographic outcomes by gender

*Indicates statistical significance

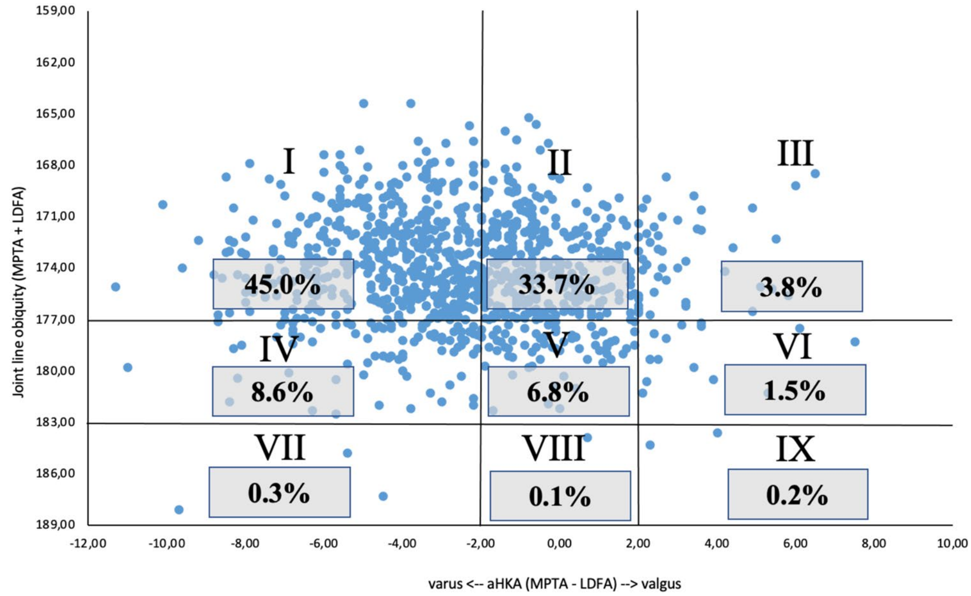

Fig. 2 Scatterplot of the preoperative phenotype distribution in knees with anteromedial osteoarthritis according to the Coronal Plane Alignment of the Knee (CPAK) classification. Percentages are given for each phenotype. *aHKA*, arithmetic hip–knee–ankle angle; *LDFA*, lateral distal femoral angle; *MPTA*, medial proximal tibial angle

Table 2 Preoperative and postoperative CPAK phenotype distribution

CPAK phenotype	Preoperatively				Postoperatively			
	Total $n = 1000$	Male $n = 549$	Female $n = 451$	p value[§]	Total $n = 1000$	Male $n = 549$	Female $n = 451$	p value[§]
I	450 (45.0%)	292 (53.2%)	158 (35.0%)	< .001*	167 (16.7%)	123 (22.4%)	44 (9.8%)	< .001*
II	337 (33.7%)	172 (31.3%)	165 (36.6%)	n.s	533 (53.3%)	300 (54.6%)	233 (51.7%)	n.s
III	38 (3.8%)	13 (2.4%)	25 (5.5%)	n.s	138 (13.8%)	64 (11.7%)	74 (16.4%)	n.s
IV	86 (8.6%)	42 (7.7%)	44 (9.8%)	n.s	41 (4.1%)	17 (3.1%)	24 (5.3%)	n.s
V	68 (6.8%)	24 (4.4%)	44 (9.8%)	.015*	92 (9.2%)	35 (6.4%)	57 (12.6%)	< .001*
VI	15 (1.5%)	4 (0.7%)	11 (2.4%)	n.s	26 (2.6%)	9 (1.6%)	17 (3.8%)	n.s
VII	3 (0.3%)	2 (0.4%)	1 (0.2%)	*n/a*	2 (0.2%)	1 (0.2%)	1 (0.2%)	*n/a*
VIII	1 (0.1%)	0 (0.0%)	1 (0.2%)	*n/a*	1 (0.1%)	0 (0.0%)	1 (0.2%)	*n/a*
IX	2 (0.2%)	0 (0.0%)	2 (0.4%)	*n/a*	0 (0.0%)	0 (0.0%)	0 (0.0%)	*n/a*

The preoperative and postoperative incidence of each CPAK phenotype is given in numbers and frequencies (%) and stratified by gender. *CPAK*, Coronal Plane Alignment of the Knee

[§]Comparison of distribution of CPAK phenotypes by gender

*Indicates statistical significance

Table 2), whereas CPAK phenotype V was significantly higher among females (12.6% vs 6.4%, respectively; $p \leq .001$).

Distribution of limb alignment and JLO

Preoperatively, 53.9% of knees exhibited pre-arthritic varus alignment (Fig. 5). Males exhibited a significantly higher prevalence of pre-arthritic varus alignment compared to females (61.2% vs. 45.0%, respectively; $p \leq .001$; Table 3). Conversely, the prevalence of pre-arthritic neutral and valgus alignment was significantly greater among females compared to males (neutral alignment: 46.6% vs. 35.7%, respectively; $p \leq .001$ and valgus alignment: 8.4% vs. 3.1%, respectively; $p \leq .001$). Additionally, males exhibited a significantly higher prevalence of apex distal JLO compared to females (86.9% vs 77.2%, respectively; $p \leq .001$), whereas the apex neutral JLO was significantly higher among females (21.9% vs 12.7%; $p = .02$). A detailed overview of radiographic outcomes by CPAK phenotype is available in Table 4.

CPAK phenotype alterations following medial UKA

Following medial UKA, a total of 45.1% of knees maintained their preoperative CPAK phenotype. Knees

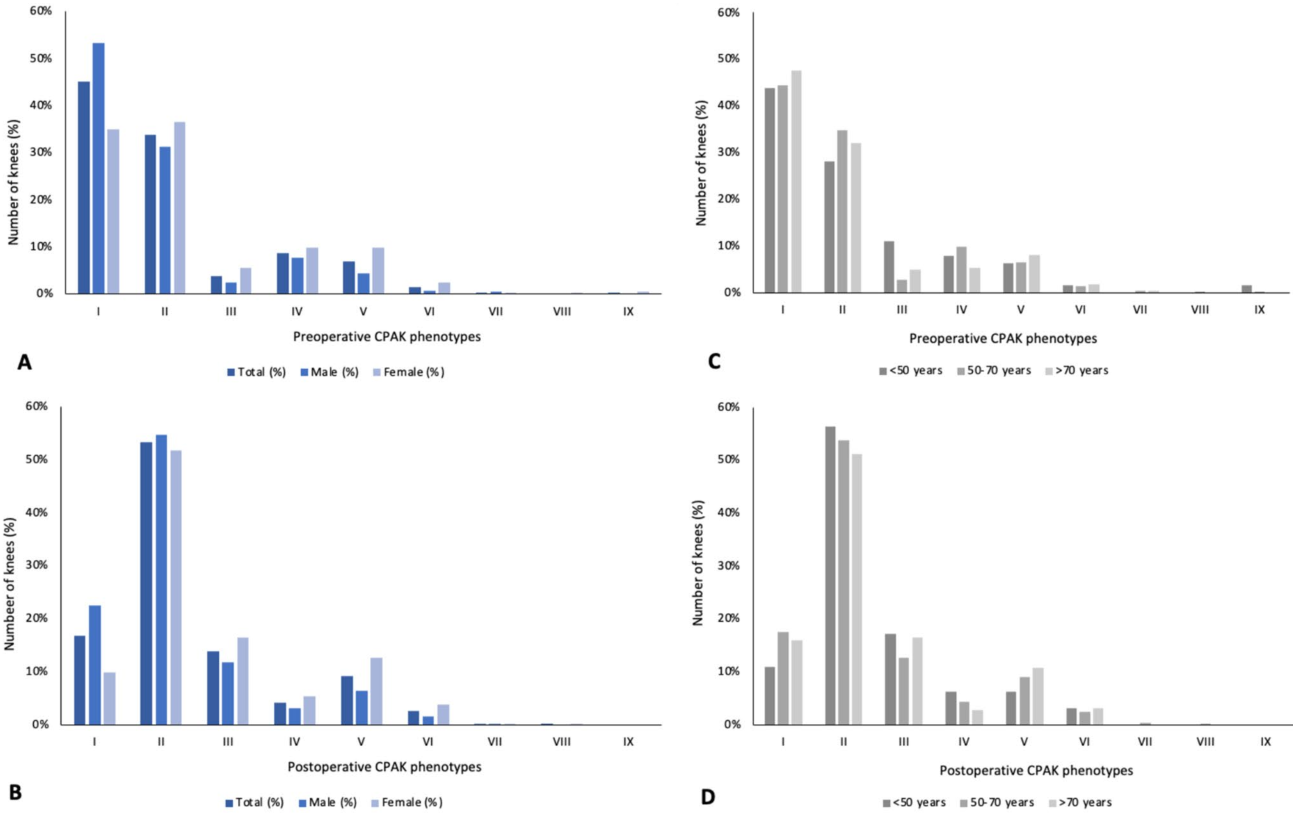

Fig. 3 Distribution of preoperative and postoperative Coronal Plane Alignment of the Knee (CPAK) phenotypes of knees with anteromedial osteoarthritis and following treatment with medial unicompartmental knee arthroplasty. **A** Preoperative CPAK phenotype distribution stratified by sex. **B** Postoperative CPAK phenotype distribution stratified by sex. **C** Preoperative CPAK phenotype distribution stratified by age. **D** Postoperative CPAK phenotype distribution stratified by age

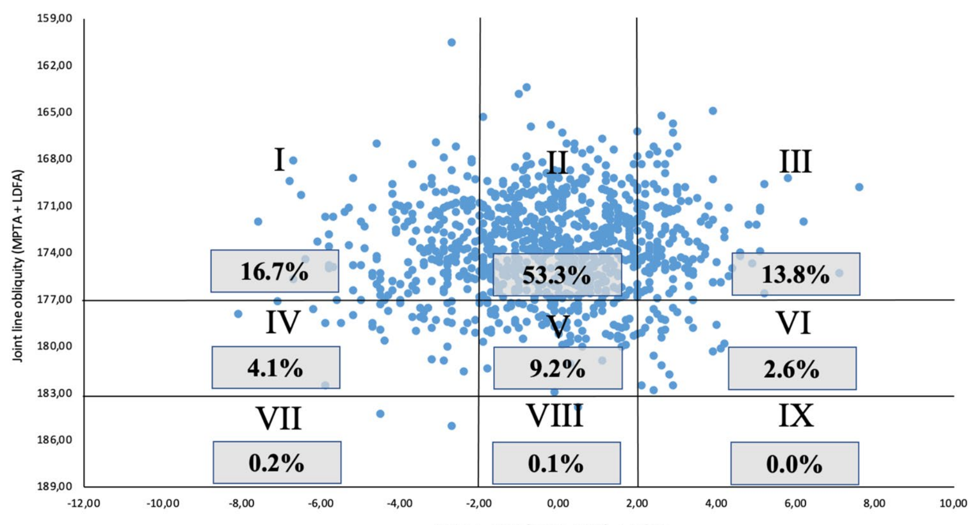

Fig. 4 Scatterplot of the postoperative phenotype distribution following medial unicompartmental knee arthroplasty according to the Coronal Plane Alignment of the Knee (CPAK) classification. The prevalence is given for each phenotype. *aHKA*, arithmetic hip–knee–ankle angle; *LDFA*, lateral distal femoral angle; *MPTA*, medial proximal tibial angle

with preoperative CPAK phenotype II and III were associated with the highest rate of maintaining their preoperative CPAK phenotype (67.7% and 65.8%, respectively; Table 5). Table 6 provides an overview of

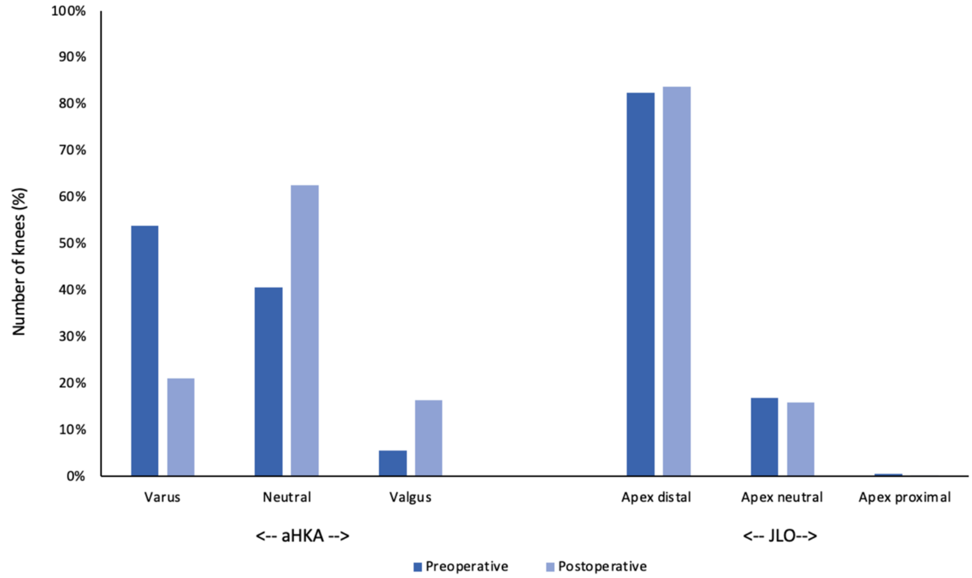

Fig. 5 Distribution of the preoperative and postoperative pre-arthritic alignment (i.e., aHKA) and joint line orientation. The incidence of the limb alignment and joint line orientation phenotypes are given in frequencies (%). *aHKA*, arithmetic hip–knee–ankle angle; *JLO*, joint line obliquity

Table 3 Distribution of limb alignment and joint line orientation

	Preoperatively				**Postoperatively**			
	Total $n=1000$	Male $n=549$	Female $n=451$	p value§	Total $n=1000$	Male $n=549$	Female $n=451$	p value§
aHKA								
Varus	539 (53.9%)	336 (61.2%)	203 (45.0%)	<.001*	210 (21.0%)	141 (25.7%)	69 (15.3%)	<.001*
Neutral	406 (40.6%)	196 (35.7%)	210 (46.6%)	<.001*	626 (62.6%)	335 (61.0%)	291 (64.5%)	n.s
Valgus	55 (5.5%)	17 (3.1%)	38 (8.4%)	<.001*	164 (16.4%)	73 (13.3%)	91 (20.2%)	n.s
JLO								
Apex distal	825 (82.5%)	477 (86.9%)	348 (77.2%)	<.001*	838 (83.8%)	487 (88.7%)	351 (77.8%)	<.001*
Apex neutral	169 (16.9%)	70 (12.7%)	99 (21.9%)	.02*	159 (15.9%)	61 (11.1%)	98 (21.8%)	.003*
Apex proximal	6 (0.6%)	2 (0.4%)	4 (0.9%)	n.s	3 (0.3%)	1 (0.2%)	2 (0.4%)	n.s

Preoperative and postoperative incidence of neutral-, varus-, or valgus alignment and apex-neutral-, distal-, or proximal joint line orientation are given in numbers and frequencies (%) and stratified by gender. *aHKA,* arithmetic hip–knee–ankle angle; *JLO*, joint line obliquity

§ Comparison of limb alignment and joint line obliquity by gender

*Indicates statistical significance

the preoperative CPAK phenotype alterations following medial UKA.

Discussion

The most important findings were that knees with anteromedial OA express a substantial variability in CPAK phenotypes, both prior to and following medial UKA. Preoperatively, CPAK phenotype I and II exhibited the highest prevalence (45.0% and 33.7%, respectively). Postoperatively, there was a noticeable shift towards a more neutral alignment, with CPAK phenotype II exhibiting the highest prevalence (53.3%). Overall, 45.1% of knees maintained their preoperative CPAK phenotype following medial UKA. The term "anteromedial OA" refers to a unique clinicopathological pattern of osteoarthritis affecting the anteromedial compartment of the knee. This specific type of OA, including an intact ACL and a correctable varus deformity, is considered to be the primary suitable indication for medial UKA [39, 45]. However, the findings of the present study reveal that despite the well-defined identical intra-articular anteromedial wear pattern, knees with this type of OA exhibit a significant variability in their phenotypic expression (Fig. 6). These findings challenge the assumption that all anteromedial osteoarthritic knees share uniform features and highlight the complexity and heterogeneity of this specific form of OA.

The present findings are in accordance with previous studies demonstrating that either CPAK phenotypes I or

Table 4 Preoperative radiographic outcomes by CPAK phenotype in knees with anteromedial osteoarthritis

	CPAK I *n* = 450	CPAK II *n* = 337	CPAK III *n* = 38	CPAK IV *n* = 86	CPAK V *n* = 68	CPAK VI *n* = 15	CPAK VII *n* = 3	CPAK VIII *n* = 1	CPAK IX *n* = 2
HKA (°)									
Mean ± SD	9.1 ± 2.6	5.1 ± 2.2	1.7 ± 2.3	8.9 ± 2.7	4.7 ± 2.7	2.4 ± 2.9	11.2 ± 2.5	2.3 ± *n/a*	3.4 ± 6.9
Range	2.2–17.0	− 2.0 to 11.8	− 3.5 to 7.5	2.8–16.4	− 2.0 to 11.6	− 2.4 to 6.2	8.4–13.3	*n/a*	− 1.5 to 8.2
aHKA (°)									
Mean ± SD	− 4.5 ± 1.7	− 0.4 ± 1.1	3.4 ± 1.3	− 4.4 ± 1.9	− 0.2 ± 1.1	3.5 ± 1.6	− 6.5 ± 2.8	0.7 ± *n/a*	3.2 ± 1.2
Range	− 11.3 to − 2.1	− 2 to 2	2.1–6.5	− 11.0 to − 2.1	− 2.0 to 1.9	2.1–7.5	− 9.7 to − 4.5	*n/a*	2.3–4.0
LDFA (°)									
Mean ± SD	88.7 ± 1.5	86.9 ± 1.2	84.8 ± 1.3	91.5 ± 1.2	89.4 ± 0.8	87.7 ± 1.2	96.6 ± 2.0	91.6 ± *n/a*	90.4 ± 0.8
Range	84–93.2	83–89.4	81.0–87.2	89.7–95.4	87.6–92.0	85.4–89.6	95.1–98.9	*n/a*	89.8–91.0
MPTA (°)									
Mean ± SD	84.3 ± 1.5	86.5 ± 1.4	88.1 ± 1.2	87.1 ± 1.2	89.2 ± 0.8	91.3 ± 1.0	90.1 ± 1.2	92.3 ± *n/a*	93.6 ± 0.4
Range	79.7–87.1	82.2–89.3	85.7–90.7	84.2–89.9	87.6–91.1	90.1–93.3	89.2–91.4	*n/a*	93.3–93.8
JLO (°)									
Mean ± SD	173.0 ± 2.5	173.5 ± 2.4	172.9 ± 2.2	178.6 ± 1.5	178.6 ± 1.2	179.0 ± 1.5	186.7 ± 1.7	183.9 ± *n/a*	183.9 ± 0.5
Range	164.4–176.9	165.2–176.9	168.5–176.7	177.0–182.5	177.0–182.3	177.2–181.3	184.8–188.1	*n/a*	183.6–184.3

Preoperative radiographic outcomes are given in mean ± standard deviation (SD) and range. aHKA, arithmetic hip–knee–ankle angle; CPAK, Coronal Plane Alignment of the Knee classification; HKA, hip–knee–ankle angle; JLO, joint line obliquity; LDFA, lateral distal femoral angle; MPTA, medial proximal tibial angle

Table 5 Distribution of CPAK phenotype restoration

Preoperative CPAK phenotype	Number of knees	**Postoperative**	
		Maintained their preoperative CPAK phenotype	Not maintained their preoperative CPAK phenotype
I	450 (45.0%)	143 (31.8%)	307 (68.2)
II	337 (33.7%)	228 (67.7%)	109 (32.3%)
III	38 (3.8%)	25 (65.8%)	13 (34.2%)
IV	86 (8.6%)	21 (24.4%)	65 (75.6%)
V	68 (6.8%)	27 (39.7%)	41 (60.3%)
VI	15 (1.5%)	5 (33.3%)	10 (66.7%)
VII	3 (0.3%)	2 (66.7%)	1 (33.3%)
VIII	1 (0.1%)	0 (0.0%)	1 (100.0%)
IX	2 (0.2%)	0 (0.0%)	2 (100.0%)
Total	**1000 (100.0%)**	**451 (45.1%)**	**549 (54.9%)**

The preoperative and postoperative incidence is given in numbers and frequencies (%). CPAK, Coronal Plane Alignment of the Knee classification

II were the most commonly observed knee phenotypes in both healthy knees [12, 18, 21] and arthritic patients undergoing TKA [14, 18, 21, 31, 37, 40]. A recent study evaluating the CPAK phenotype distribution among 8739 osteoarthritic knees, identified CPAK phenotype I and II as the predominant phenotypes, with incidences of 28.1% and 27.3% respectively [14]. Nonetheless, the aforementioned studies primarily focused on healthy individuals and arthritic patients undergoing TKA. Therefore, it is noteworthy that the prevalence of CPAK phenotype I, characterized by varus alignment and an apex distal JLO, was higher in the present study as compared to the previously mentioned studies [12, 14, 18, 19, 31, 36, 37]. This may potentially be attributed to the association between pre-arthritic varus alignment, increased loading of the medial compartment of the knee, and consequently the higher risk of OA progression primarily affecting the anteromedial compartment of the knee [34, 35, 38].

Previous reports have demonstrated a higher prevalence of varus alignment among males compared to females [5,

Table 6 Preoperative CPAK phenotype alterations following medial unicompartmental knee arthroplasty

Preoperative CPAK phenotype	Number of knees	Postoperative CPAK phenotype								
		I	II	III	IV	V	VI	VII	VIII	IX
I	450 (45.0%)	143 (31.8%)	249 (55.3%)	18 (4.0%)	16 (3.6%)	22 (4.9%)	2 (0.4%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
II	337 (33.7%)	11 (3.3%)	228 (67.6%)	82 (24.3%)	0 (0.0%)	12 (3.6%)	4 (1.2%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
III	38 (3.8%)	0 (0.0%)	12 (31.6%)	25 (65.8%)	1 (2.6%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
IV	86 (8.6%)	10 (11.6%)	24 (27.9%)	1 (1.2%)	21 (24.4%)	26 (30.2%)	4 (4.7%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
V	68 (6.8%)	2 (2.9%)	18 (26.5%)	8 (11.8%)	2 (2.9%)	27 (39.7%)	10 (14.7%)	0 (0.0%)	1 (1.5%)	0 (0.0%)
VI	15 (1.5%)	1 (6.7%)	2 (13.3%)	4 (26.7%)	0 (0.0%)	3 (20.0%)	5 (33.3%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
VII	3 (0.3%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	1 (33.3%)	0 (0.0%)	0 (0.0%)	2 (66.7%)	0 (0.0%)	0 (0.0%)
VIII	1 (0.1%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	1 (100.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
IX	2 (0.2%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	1 (50.0%)	1 (50.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
Total	**1000 (100.0%)**	**167 (16.7%)**	**533 (53.3%)**	**138 (13.8%)**	**41 (4.1%)**	**92 (9.2%)**	**26 (2.6%)**	**2 (0.2%)**	**1 (0.1%)**	**0 (0.0%)**

The preoperative and postoperative incidence of CPAK phenotypes is given in numbers and frequencies (%). CPAK, Coronal Plane Alignment of the Knee classification

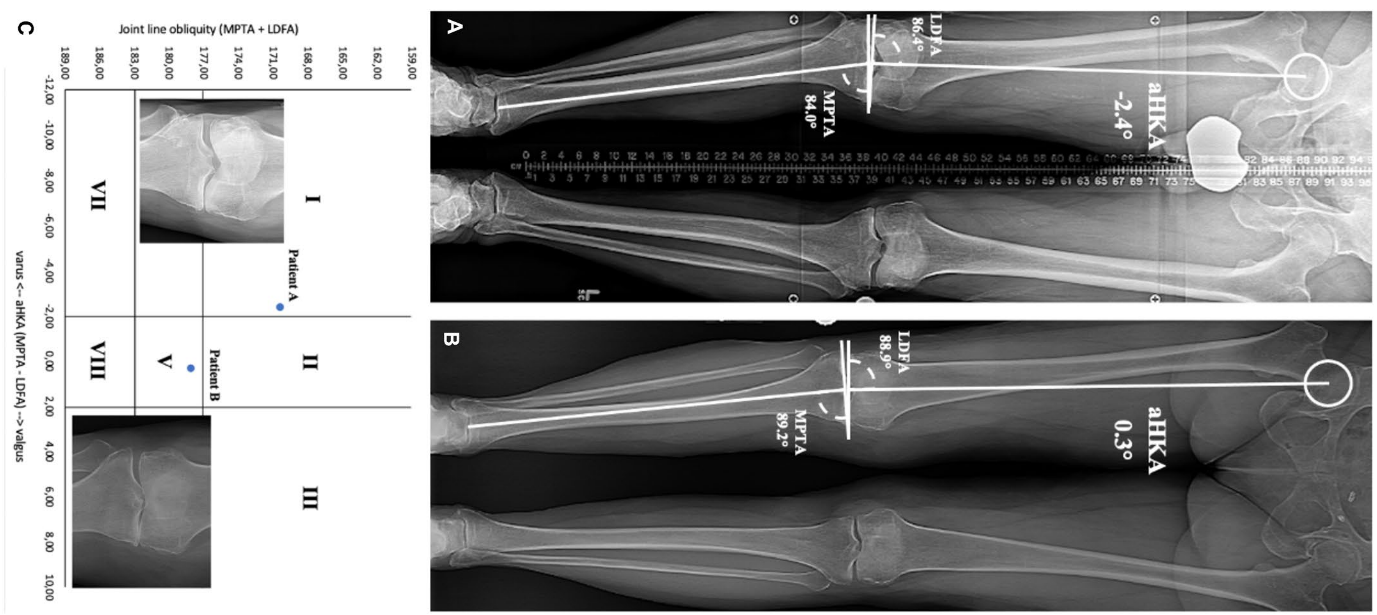

Fig. 6 Two patients with anteromedial osteoarthritis. This illustration demonstrates the phenotypic variability among patients with identical intra-articular wear patterns. Both patients exhibit an advanced Kellgren and Lawrence grade IV anteromedial osteoarthritis while displaying differing Coronal Plane Alignment of the Knee (CPAK) phenotypes. **A** Preoperative long-leg radiograph of patient A. **B** Preoperative long-leg radiograph of patient B. **C** Scatterplot of the preoperative phenotype distribution of patient A and B according to the CPAK classification. *aHKA*, arithmetic hip–knee–ankle angle; *LDFA*, lateral distal femoral angle; *MPTA*, medial proximal tibial angle

30, 32]. Moreover, a prior study, specifically evaluating the gender-specific distribution of CPAK knee phenotypes in osteoarthritic knees, reported that CPAK phenotypes characterized by a varus alignment were more common in males, whereas phenotypes characterized by a neutral or valgus alignment were more frequently observed in females [14]. These findings are supported by the current study evaluating patients with identical anteromedial OA, demonstrating a statistically significant predominance of pre-arthritic varus alignment among males, both prior to and following medial UKA. Additionally, a higher prevalence of pre-arthritic valgus alignment was observed among females prior to medial UKA.

Traditionally, the surgical objective in medial UKA has been to achieve a neutral mechanical alignment [46]. However, contrary to previously held beliefs, the majority of knees are not mechanically aligned, with only 15.4% and 14.6% of healthy and arthritic patients undergoing TKA exhibiting a neutral alignment, respectively [18]. Findings of the present study demonstrate an even lower prevalence, with only 6.8% of patients with anteromedial OA exhibited a neutral mechanical alignment. The present study demonstrated that 53.9% of patients with isolated medial compartment OA had a pre-arthritic alignment of 2° of varus or more. Consequently, restoring their knee to neutral mechanical alignment would be considered abnormal, and thus, may require a certain degree of medial soft tissue release, which should be avoided during UKA [3, 44]. More interestingly, 5.5% of patients with isolated medial OA had a pre-arthritic alignment in valgus (CPAK III, VI, and IX). Since the development of progressive lateral compartment OA is one of the most common causes of failure following medial UKA, caution should be exercised to avoid excessive overcorrection into valgus alignment when aiming to restore pre-arthritic alignment in these knees [42].

Utilizing individualized alignment strategies by restoring a knee to its pre-arthritic alignment during knee arthroplasty has been associated with improved survivorship and favorable functional outcomes [1, 6, 23, 26, 32, 43]. Moreover, recent TKA studies have demonstrated that altering limb and femoral phenotypes is associated with lower clinical outcome scores, whereas restoring a distal JLO is associated with less postoperative pain [27, 31]. This study demonstrated that 45.1% of knees maintained their preoperative CPAK phenotype following medial UKA. These findings suggest that relying solely on MCL re-tensioning might not be sufficient to restore both the pre-arthritic alignment and knee phenotype. Considering the preoperative CPAK phenotype during preoperative surgical planning may offer several advantages, as it enables surgeons to aim for the restoration of the knee to its pre-arthritic alignment and phenotype using a relatively straightforward and pragmatic classification system.

This study has several limitations. First, all procedures were performed by a single surgeon, which may affect the generalizability of the results. Second, the study cohort predominantly consisted of Caucasian patients. A recent systematic review demonstrated significant variation in the distribution of CPAK phenotypes across intercontinental populations, thereby limiting the generalizability of the current findings to individuals from other ethnic groups [22]. Third, the CPAK classification system neglects knee morphology in the sagittal plane, which may lead to an incomplete assessment of the entirety of the knee joint. Additionally, while the CPAK classification simplifies classification by relying on just two variables, Hirschmann et al. [11] introduced an alternative and more comprehensive system that integrates three variables (i.e., the mHKA, femoral mechanical angle, and tibial mechanical angle) enabling separate classification of the femur and tibia [9–11, 15]. Future studies should consider incorporating this classification system and explore its relation to clinical outcomes. Fourth, the present study lacks an analysis of functional outcomes. Therefore, it remains uncertain which pre- to postoperative alterations in CPAK phenotypes yield the most favorable functional outcomes following medial UKA. Future studies should investigate the specific advantages of maintaining the preoperative CPAK phenotype and identify the acceptable limits for pre- to postoperative alterations in CPAK phenotypes during medial UKA in relation to functional outcomes.

Conclusion

There is a substantial variation in CPAK phenotypes among knees with anteromedial OA, as well as following treatment with medial UKA. This variability challenges the assumption of uniform characteristics among knees with an identical wear pattern associated with anteromedial OA and emphasizes the complexity and variability of this specific form of OA.

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Declarations

Conflict of interest Dr. Andrew D. Pearle is a consultant of Smith & Nephew and DePuy Synthes. Dr. Hendrik A. Zuiderbaan is a consultant for Smith & Nephew. The other authors declare to have no potential conflict of interest.

Ethical approval Internal Review Board approval of Hospital for Special Surgery was obtained prior to the start of the study (IRB #2022-1401).

Informed consent Informed consent was not applicable for this study.

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