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Definition of the knee phenotype in the ukrainian population based on the CPAK classification

M. D. Moroz [1], R. A. Kozak [1], O. A. Kostogryz [1], Y. O. Kostogryz [1], M. Yu. Kyrylenko [2]

[1] Diagnostic Center «M24», Kyiv. Ukraine
[2] SI «Institute of Traumatology and Orthopedics of the NAMS of Ukraine», Kyiv

Native coronal alignment of the knee joint demonstrates marked individual variability, which influences total knee arthroplasty planning and functional outcomes. The CPAK classification allows systematization of these anatomical variations based on the parameters aHKA and JLO. Although CPAK phenotypes have been described in several populations, data regarding the Ukrainian population have so far been lacking. Objective. To determine the characteristics of native lower-limb alignment and CPAK phenotypes of the knee joint in the Ukrainian population. Methods. A total of 500 full-length standing radiographs of the lower limbs were analyzed: 300 in the healthy group and 200 in the group with Kellgren-Lawrence grade III–IV osteoarthritis. LDFA and MPTA were measured, aHKA and JLO were calculated in accordance with CPAK principles, and knees were subsequently classified within the 3×3 CPAK matrix. Results. In the healthy group, the most common CPAK phenotypes were type II (24.7 %), type I (21.7 %), and type V (21.0 %). Neutral aHKA was observed in 47.3 %, varus in 39.3 %, and valgus in 13.3 %. The most frequent JLO orientation was apex distal (50.3 %). In sex-specific subgroups, type II predominated in males (28 %) and type V in females (25 %). In the osteoarthritis group, varus aHKA values predominated (58 %), with CPAK phenotypes I (35.5 %), IV (22 %), and II (19.5 %) being most common. Conclusions. This study describes for the first time the distribution of CPAK phenotypes of the knee joint in the Ukrainian population. Among healthy individuals, CPAK phenotypes I, II, and V were most prevalent, with neutral alignment observed in 47 %. In patients with grade III–IV osteoarthritis, a marked shift toward varus alignment was noted, with varus phenotypes accounting for 58 %, whereas neutral phenotypes were observed in only 34 %. These findings reflect population-specific patterns of native coronal knee alignment and may serve as a basis for further research into the clinical relevance of CPAK phenotypes and their impact on outcomes of total knee arthroplasty.

Нативне вирівнювання колінного суглоба має виражену індивідуальну варіабельність, що впливає на планування тотального ендопротезування та кінцевий функціональний результат. Класифікація «Coronal Plane Alignment of the Knee» (CPAK) дозволяє систематизувати ці анатомічні варіанти на основі параметрів aHKA та JLO. Мета. Визначити особливості нативного вирівнювання нижньої кінцівки та CPAK-фенотипів колінного суглоба в українській популяції. Методи. Проаналізовано 500 панорамних рентгенограм нижніх кінцівок, які розподілено на 2 групи: 300 — група 1 — умовно здорові, 200 — 2 (остеоартроз III–IV ст. за Kellgren-Lawrence). Вимірювали mLDFA та mMPTA, розраховували aHKA та JLO згідно з принципами CPAK-класифікації, після чого виконували розподіл фенотипів у матриці CPAK 3 × 3. Результати. У здоровій групі найпоширенішими CPAK-фенотипами були тип II (24,7 %), I (21,7 %) та тип V (21,0 %). Нейтральний тип aHKA визначався у 47,3, варусний — у 39,3, вальгусний — у 13,3 %. Найчастіший варіант JLO — apex distal (50,3 %). У статевих підгрупах домінував тип II у чоловіків (28 %) та V у жінок (25 %). У групі остеоартрозу відзначалося переважання варусних значень aHKA (58 %) із домінуванням фенотипів I (35,5 %) та IV (22 %). Висновок. На основі нашого дослідження описано розподіл CPAK-фенотипів колінного суглоба в українській популяції. У групі 1 найпоширенішими були I, II та V типи з переважанням нейтрального вирівнювання у 47 %, а у 2 — I, II та IV типи, проте спостерігалося виразне зміщення в бік варусних варіантів: їхня частка була до 58 %, тоді як частота нейтральних фенотипів склала лише 34 %. Отримані результати відображають особливості нативного фронтального вирівнювання нижньої кінцівки й можуть слугувати основою для подальших досліджень, спрямованих на вивчення клінічного значення CPAK-фенотипів та їхнього впливу на результати тотального ендопротезування колінного суглоба. Ключові слова. Колінний суглоб, вирівнювання, CPAK, aHKA, JLO, фенотипи колінного суглоба.

Keywords. Knee joint, alignment, CPAK, aHKA, JLO, knee joint phenotypes

Introduction

A key principle in knee joint arthroplasty has long been to create a stable joint with a neutral lower limb axis. This approach was long considered universal for achieving predictable clinical outcomes. Despite the high effectiveness of this method, up to 20 % of patients remain dissatisfied with the treatment results. The most frequent complaints in the postoperative period include persistent pain, limited range of motion, and a lack of anticipated functional recovery [1, 2]. A potential reason for these symptoms is not considering the patient's unique anatomical characteristics.

Recent studies have shown that neutral alignment of the lower limb is not typical for all patients [3, 4], so attempting to bring the limb axis to a neutral position during surgery may require excessive bone resections or additional soft tissue releases. These conditions disrupt joint biomechanics, leading to a longer, more complex post-surgical recovery.

Over the past decade, a significant number of studies have been assessed native alignment of the KJ. Their results convincingly show that such alignment is highly variable, and a notable proportion of healthy individuals have a natural varus or valgus axis of the lower limb [3–7]. Some studies have also focused on examining population and gender differences in KJ phenotypes. M. T. Hirschmann et al., E. Sappey-Marinier, T. Kobayashi et al. have shown that the frequency of varus, valgus, and neutral phenotypes differs significantly based on ethnic group and gender, which may determine characteristic biomechanical features of the KJ [8–12].

The need to consider this anatomical variability has contributed to the development of personalized approaches to implant positioning, based on the consideration of morphological phenotypes of the lower limb as an important element of preoperative planning. The task is complicated by the fact that as osteoarthritis progresses, the native alignment of the lower limb changes, typically towards an increase in the existing deformity, making it extremely difficult to determine the initial anatomical axis.

One of the most promising modern methods for systematically assessing individual frontal alignment of the knee joint is the “Coronal Plane Alignment of the Knee” (CPAK) classification, which emphasizes the arithmetic angle “hip-knee-ankle” (aHKA) and the joint line orientation (JLO) [13]. In 2020, S. J. MacDessi et al. proposed the aHKA concept and demonstrated that this measure is a reliable marker of constitutional alignment of the knee joint, regardless of the presence of arthritic changes [14]. In 2021, the concept of JLO was introduced, categorizing it into three distinct types: “proximal peak”, “distal peak”, and “neutral”. This distinction helped clarify the difference between limb frontal alignment and the inclination of the joint surface.

The combination of aHKA and JLO made it possible to form the CPAK classification, which is presented in the form of a 3 × 3 matrix and encompasses 9 morphological phenotypes of the knee joint. This system allows for a more precise characterization of individual alignment variations and can serve as a guide for personalized strategies.

Despite the significant number of publications on the morphological phenotype of the knee joint in different populations, there is currently no information regarding the features of frontal alignment among the Ukrainian population. This limits the ability to correctly compare anatomical indicators and increases the potential impact of phenotype-specific features of the knee joint on surgical treatment outcomes.

In recent years, clinical interest in the individualization of surgical tactics in Ukraine has been growing, as evidenced by national studies related to the restoration of native kinematics, optimization of implant positioning, and comparison of different alignment concepts during total joint replacement [16–19].

In light of this, it is appropriate to study the distribution of CPAK phenotypes in the domestic population as an anatomical foundation for justified individualized surgical planning, with further comparison of the obtained results with data from European studies.

Purpose: To identify the features of native alignment of the lower limb and CPAK phenotypes of the knee joint in the Ukrainian population.

Materials and Methods

The study was conducted at the State Institution “National Institute of Traumatology and Orthopedics of the National Academy of Medical Sciences of Ukraine” and the diagnostic center “M24” from August 2024 to October 2025.

A total of 500 knee joint X-rays of patients from the Ukrainian population were selected, divided into two groups according to the radiological state of the joint. Group 1 (n = 300) included X-rays of individuals aged 18 years and older, who had no complaints regarding the knee joint, no signs of deformities, no history of trauma, and no previous surgeries on the lower limbs. A mandatory condition was the complete absence of radiological signs of knee impairment. The group consisted of 166 men and 134 women, with an average age of (44.95 ± 13.17) years (M ± SD).

Group 2 (n = 200) included X-rays of patients with osteoarthritis stages III–IV according to the Kellgren-Lawrence classification. This group excluded individuals with post-traumatic osteoarthritis, previous septic arthritis, or a history of any surgical intervention. Also excluded were those with significant bone defects in the femoral or tibial condyles, frontal deformities, and contractures greater than 20°, as such changes could influence the accuracy of radiological measurements. Demographically, the group consisted of 89 men and 111 women, with an average age of (58.98 ± 11.34) years (M ± SD). Given that after the completion of skeletal growth, the main anatomical parameters of the lower limb bones remain relatively stable, the age difference observed between the groups was not considered a decisive factor affecting the results of radiological analysis.

All participants in the study underwent axial X-rays in a standing position with even load on both lower limbs, with maximum knee extension and patellar orientation forward. The rotation of the lower limbs was controlled by assessing the symmetry of anatomical landmarks, including the contour of the femoral head and the position of the patella.

In all cases, standardized construction of anatomical and mechanical axes and measurement of main reference angles were performed according to the Paley protocol (Figure 1) [20].

Radiological parameters in the healthy group were evaluated by a radiologist using the QxLink (v3.3.12) software according to the standardized protocol. Radiological assessments in the osteoarthritis patient group were carried out as part of preoperative planning using the mediCAD (v7.0) software. Only panoramic radiographic images that were technically correct and suitable according to commonly accepted criteria for assessing the quality of axial X-rays [21] were included in the analysis.

For determining the mechanical and anatomical axes of the lower limb, the following reference points were used (Figure 2):

– The center of the femur was determined by the Mose method [20];

– The center of the knee joint was defined as the midpoint between the tibial eminences;

– The center of the ankle joint was defined as the midpoint of the talus bone.

After constructing these axes, the main reference angles characterizing the alignment of the knee joint in the frontal plane were calculated:

– Mechanical Lateral Distal Femoral Angle (mLDFA) — the mechanical lateral distal angle of the femur was determined as the angle between the mechanical axis of the femur and the line of the distal femoral joint surface, which was drawn through the most distal points of the medial and lateral femoral condyles;

– Mechanical Medial Proximal Tibial Angle (mMPTA) — the mechanical medial proximal angle of the tibia was defined as the angle between the mechanical axis of the tibia and the line of its proximal joint surface, which was drawn through the deepest points of the medial and lateral tibial plateaus.

In Group 1, the mean value of the mLDFA was 89.11° ± 2.05°. In Group 2, this value was 89.53° ± 1.96°. The average values of the mMPTA were 87.98° ± 2.28° in Group 1 and 86.93° ± 2.25° in Group 2.

According to the current recommendations for the use of the CPAK classification, two additional derived parameters, aHKA and JLO, were also calculated based on the obtained radiological measurements [13]. They were computed using the following formulas:

$$aHKA = MPTA - LDFA, \quad (1)$$

$$JLO = MPTA + LDFA. \quad (2)$$

Negative values of the arithmetic angle aHKA were interpreted as varus constitutional alignment (*varus*) of the lower limb, while positive values indicated valgus alignment (*valgus*); values close to zero corresponded to neutral alignment (*neutral*). The joint line orientation (JLO) parameter was determined as the angle between the joint surface line of the KJ and the horizontal line: JLO values < 180° indicated an *apex distal* orientation, JLO ≈ 180° indicated an *apex neutral* orientation, and JLO > 180° indicated an *apex proximal* orientation.

Based on the obtained values of aHKA and JLO for each KJ, a classification according to the CPAK system was performed, presented as a 3 × 3 matrix (Figure 3). This matrix combines 3 categories of constitutional alignment (varus, neutral, valgus) with 3 variants of joint line orientation, forming 9 possible morphological phenotypes. The obtained phenotypes were recorded for further comparison between groups and statistical analysis.

All obtained values were entered into a unified database, followed by analytical and statistical processing.

The study was conducted in strict accordance with the principles of bioethics, legislative requirements, and established norms for biomedical research, as outlined in the Declaration of Helsinki of the World Medical Association, the Constitution of Ukraine, the Civil Code of Ukraine, the basic laws of Ukraine on health protection, and the Law of Ukraine on Information. Radiological studies were carried out within the framework of standard clinical diagnostic and treatment processes with written informed consent obtained from patients for examination and processing of medical data. The retrospective analysis of clinical and radiological data was approved by the bioethics committee of the State Institution "Institute of Traumatology and Orthopedics of the National Academy of Medical Sciences of Ukraine" (protocol No. 8 dated 25 November 2025).

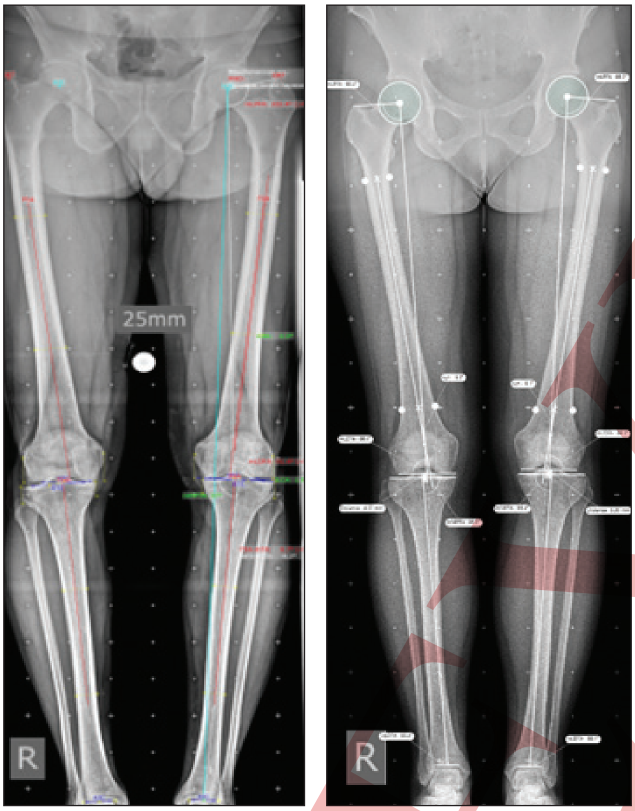

Fig. 1. Example of using software for radiometric analysis: QxLink for healthy knee joints and mediCAD for knee joints with signs of osteoarthritis

Statistical data processing was performed using Microsoft Excel and Statistica 8.0 software. The Mann-Whitney U test was used to compare independent samples, and the Wilcoxon signed-rank test was used for paired samples.

To evaluate the relationship between individual radiometric parameters of frontal alignment, a Spearman correlation analysis was used. The data were analyzed using standard descriptive statistics methods, which included calculation of sample size (n), arithmetic mean (M), and standard deviation (SD). The level of statistical significance was set at $p < 0.05$.

Results

To evaluate the internal consistency of the radiometric indicators, a Spearman correlation analysis was performed on the entire study cohort. A statistically significant correlation was found between mLDFA and aHKA ($\rho = -0.65$; $p < 0.001$), as well as between mMPTA and aHKA ($\rho = 0.74$; $p < 0.001$), confirming the anatomical relationship between the indicators of frontal alignment in the femoral and tibial segments and the internal consistency of the measured parameters.

To determine the typical phenotype of frontal alignment of the lower limb, the analysis was carried out based on data from the conditionally healthy population group, as this cohort reflects the native anatomical variability of the knee joint without secondary changes related to degenerative-dystrophic processes.

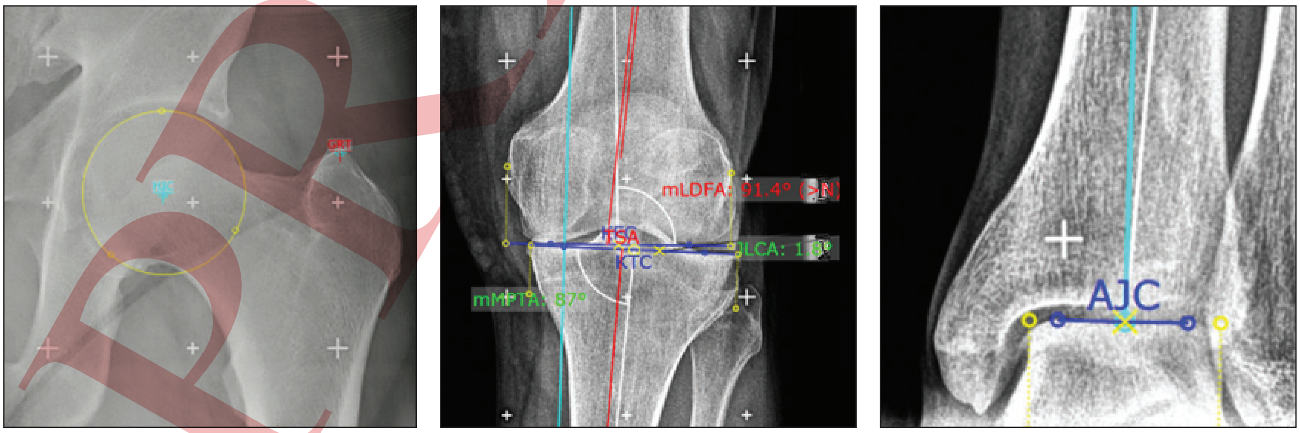

Fig. 2. Example of defining reference points according to the Paley method

A total of 9 possible combinations of the aHKA and JLO parameters were identified. Analysis of aHKA showed that in the conditionally healthy patients, neutral alignment was the most prevalent, found in 142 cases (≈ 47.3 %). Varus alignment was observed in 118 cases (≈ 39.3 %), while valgus alignment was present in 40 cases (≈ 13.3 %).

The JLO parameter highlighted that in 151 cases (≈ 50.3 %), the joint line had an *apex distal* orientation. Neutral JLO orientation was observed in 139 patients (≈ 46.3 %). The *apex proximal* orientation of the joint line was the rarest, occurring in only 10 cases (≈ 3.3 %).

Thus, the most common CPAK phenotypes in the conditionally healthy group were Type II — 74 cases (≈ 24.7 %), Type I — 65 cases (≈ 21.7%), and Type V — 63 cases (≈ 21.0 %).

The distribution of phenotypes according to the CPAK classification in the conditionally healthy group (n = 300) is shown in Table 1.

To identify potential characteristics of native frontal alignment, a separate analysis of the CPAK phenotypic distribution by gender was conducted.

In the male subgroup, the most frequent CPAK phenotype was Type II (28 %), followed by Types I (24 %) and IV (19 %). In the female subgroup, the distribution was slightly different: Type V was the leading phenotype (25 %), followed by Type II (20 %) and Type I (19 %).

In the group of patients with osteoarthritis of stage III–IV (Kellgren-Lawrence classification), during the analysis of aHKA, a significant predominance of varus alignment was noted, observed in 116 cases (58 %). Neutral values were observed in 68 patients (34 %), while valgus alignment was the least common — 16 cases (8 %).

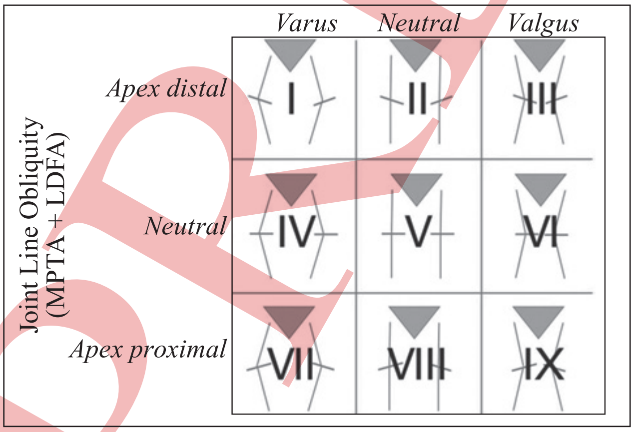

Fig. 3. Combinations of aHKA and JLO that form the CPAK phenotype matrix [13]

As for joint line orientation (JLO), the most common variant was *apex distal* — 118 cases (59 %). Neutral JLO was observed in 78 cases (39 %), while *apex proximal* was rare, occurring in 4 cases (2 %).

According to the CPAK classification, the most frequent phenotype was Type I — 71 cases (35.5 %). The next most common were Type IV — 44 cases (22 %) and Type II — 39 cases (19.5 %). The distribution of phenotypes in patients with osteoarthritis is shown in Table 2.

An analysis of the distribution of CPAK phenotypes in patients from Group 2, taking gender into account, revealed that in both subgroups, phenotypes associated with varus frontal alignment and *apex distal* joint line orientation predominated.

In the male subgroup, the most common were CPAK phenotypes I (≈ 48.3 %), IV, and II (≈ 21.3 %), reflecting a marked shift in the distribution towards varus variants of frontal alignment.

In the female subgroup, the leading phenotype was also CPAK Type I (≈ 25.2 %), followed by phenotypes II (≈ 22.5%) and V (≈ 18.9 %), indicating a more even distribution of CPAK phenotypes, with a relatively higher proportion of neutral variants compared to the males.

Among the valgus variants of frontal alignment, phenotype III was more common, with an overall frequency of about 6 % in the female population and about 3 % in the male population.

Study Limitations

This study has several limitations that should be considered when interpreting the results. It is a retrospective descriptive study, which does not allow establishing causal relationships between frontal alignment and the development of osteoarthritis.

Assessment of torsional deformities of the femur and tibia was not part of the objectives of this observation; the analysis of angular radiometric parameters was based solely on panoramic radiographs of the lower limbs, which is a widely accepted and sufficient method for evaluating frontal alignment and determining phenotypes according to the CPAK classification. Since the study had a descriptive nature and did not involve statistical comparison between cohorts, a formal assessment of measurement variability was not performed. Anthropometric and demographic factors that may significantly influence the clinical course of osteoarthritis were not analyzed in this work, as they are not decisive for determining the anatomical angular radiometric parameters of frontal alignment of the lower limb, which were the main subject of the study.

Table 1

Distribution of phenotypes according to the CPAK classification in Group 1

Parameter		aHKA			
		Varus	*Neutral*	*Valgus*	Усього
JLO	*Apex distal*	65	74	12	151
	Neutral	51	63	25	139
	Apex proximal	2	5	3	10
	Total	118	142	40	300

Table 2

Distribution of phenotypes according to the CPAK classification in Group 2

Parameter		aHKA			
		Varus	*Neutral*	*Valgus*	Усього
JLO	*Apex distal*	71	39	8	118
	Neutral	44	27	7	78
	Apex proximal	1	2	1	4
	Total	116	68	16	200

Although there are certain limitations, the findings from this study make it possible to identify the distinct characteristics of CPAK phenotype distribution within the sample examined, and establish a basis for future prospective investigations.

Discussion

This study analyzed the features of frontal alignment of the knee joint based on the CPAK classification, which uses two key radiological parameters, namely the arithmetic angle aHKA and JLO. These parameters are considered relatively stable in the absence of significant bone deformities and predominantly reflect native (constitutional) alignment, even in patients with existing osteoarthritis. Therefore, the analysis of CPAK phenotypes in the osteoarthritis group allows for interpreting frontal alignment not only as a result of degenerative changes but also as a possible reflection of the initial anatomy of the lower limb.

The results confirm the presence of significant native variability in the frontal alignment of the knee joint. The most common CPAK phenotypes were II, I, and V, which generally align with data published by other European researchers, who also note the predominance of variants with neutral or mildly varus frontal alignment and joint line orientation of the *apex distal* type [3–5].

In the group of patients with osteoarthritis stage III–IV, the distribution of CPAK phenotypes was characterized by a pronounced shift toward varus variants of frontal alignment, with the most common being I, IV, and II. The predominance of varus phenotypes may be associated with the biomechanical characteristics of load distribution on the medial compartment of the knee joint and the role of initial frontal alignment in the formation of degenerative changes. However, it is impossible to establish a causal relationship within the scope of this study, as its design did not involve prospective observation or evaluation of native alignment prior to the development of the degenerative process.

According to the meta-analysis by G. Giurazza et al. [22], for the European population, the predominance of CPAK phenotypes I and II in healthy individuals and the increase in the proportion of varus phenotypes in patients with osteoarthritis have been described. Meanwhile, a significant feature of the distribution of CPAK phenotypes in our national cohort is the significantly lower frequency of phenotype III, particularly among the female population, compared to the aggregated European data. This difference may reflect population-specific anatomical features and underscores the need for further multicenter studies on CPAK phenotypes with a larger sample of patients.

The data obtained may have practical significance in the context of individualized planning for total knee arthroplasty. Knowledge of the distribution of CPAK phenotypes in a specific population allows for a better interpretation of native frontal alignment and helps avoid a universal approach to restoring the mechanical axis, which is particularly relevant in light of the development of personalized alignment strategies.

Conclusions

The predominance of CPAK phenotypes I, II, and V in the conditionally healthy group indicates a higher prevalence of neutral and moderately varus frontal alignment variants in the lower limbs. The observed distribution of CPAK phenotypes in patients with osteoarthritis, particularly the shift toward varus alignment, underscores the potential role of initial anatomy in the formation of degenerative changes. The results support the importance of considering the CPAK phenotype and native frontal alignment when planning personalized total knee arthroplasty.

Conflict of Interest. The authors declare no conflict of interest.

Perspectives for Future Research. Further studies, particularly prospective cohort observations, are needed to determine whether the initial phenotype is a risk factor for degeneration, or if the observed distribution merely reflects the inherent anatomical features of the population.

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Author Contributions. Moroz M. D. — Conceptualization of the study, collection of clinical material, statistical analysis and interpretation of findings, drafting the main text of the article; Kozak R. A. — Participation in manuscript preparation, analysis and generalization of research findings, editing the text; Kostohryz O. A. — Scientific supervision of the study, methodological consultation, critical review of the manuscript, and approval of the final version of the article; Kostohryz Yu. O. — Collection of clinical material, systematization, and primary processing of data; Kyrylenko M. Yu. — Performing radiometric measurements, analyzing and comparing clinical and radiological parameters.

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DEFINITION OF THE KNEE PHENOTYPE IN THE UKRAINIAN POPULATION BASED ON THE CPAK CLASSIFICATION

M. D. Moroz [1], R. A. Kozak [1], O. A. Kostogryz [1], Y. O. Kostogryz [1], M. Yu. Kyrylenko [2]

[1] Diagnostic Center «M24», Kyiv. Ukraine
[2] SI «Institute of Traumatology and Orthopedics of the NAMS of Ukraine», Kyiv

✉ Mykola Moroz: moroznd@ukr.net; https://orcid.org/0000-0003-4134-1322
✉ Roman Kozak: ra.kozak@gmail.com; https://orcid.org/0000-0002-5132-027X
✉ Oleg Kostogryz, MD, DMedSci: arztkostogryz@ukr.net; https://orcid.org/0000-0002-9533-9247
✉ Yurij Kostogryz, MD, PhD: Arzt@i.ua; https://orcid.org/0000-0001-7187-298X
✉ Mykola Kyrylenko: nikolakyrylenko@gmail.com; https://orcid.org/0009-0008-0872-6638