Coronal Plane Alignment of the Knee (CPAK) classification

A NEW SYSTEM FOR DESCRIBING KNEE PHENOTYPES

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Aims
A comprehensive classification for coronal lower limb alignment with predictive capabilities for knee balance would be beneficial in total knee arthroplasty (TKA). This paper describes the Coronal Plane Alignment of the Knee (CPAK) classification and examines its utility in preoperative soft tissue balance prediction, comparing kinematic alignment (KA) to mechanical alignment (MA).

Methods
A radiological analysis of 500 healthy and 500 osteoarthritic (OA) knees was used to assess the applicability of the CPAK classification. CPAK comprises nine phenotypes based on the arithmetic HKA (aHKA) that estimates constitutional limb alignment and joint line obliquity (JLO). Intraoperative balance was compared within each phenotype in a cohort of 138 computer-assisted TKAs randomized to KA or MA. Primary outcomes included descriptive analyses of healthy and OA groups per CPAK type, and comparison of balance at 10° of flexion within each type. Secondary outcomes assessed balance at 45° and 90° and bone recuts required to achieve final knee balance within each CPAK type.

Results
There was similar frequency distribution between healthy and arthritic groups across all CPAK types. The most common categories were Type II (39.2% healthy vs 32.2% OA), Type I (26.4% healthy vs 19.4% OA) and Type V (15.4% healthy vs 14.6% OA). CPAK Types VII, VIII, and IX were rare in both populations. Across all CPAK types, a greater proportion of KA TKAs achieved optimal balance compared to MA. This effect was largest, and statistically significant, in CPAK Types I (100% KA vs 15% MA; p < 0.001), Type II (78% KA vs 46% MA; p = 0.018), and Type IV (89% KA vs 0% MA; p < 0.001).

Conclusion
CPAK is a pragmatic, comprehensive classification for coronal knee alignment, based on constitutional alignment and JLO, that can be used in healthy and arthritic knees. CPAK identifies which knee phenotypes may benefit most from KA when optimization of soft tissue balance is prioritized. Further, it will allow for consistency of reporting in future studies.

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Introduction
Determining the ideal coronal alignment for individuals undergoing total knee arthroplasty (TKA) is one of the great challenges in reconstructive knee surgery. The ‘mechanical alignment’ (MA) method has been the gold-standard technique since early in TKA development, with good historic long-term survivorship.2-4 MA results in a horizontal joint line and a neutral mechanical axis, which has long been believed to provide the best mechanical environment for prosthetic longevity.5 MA, however, disregards the significant inherent variability in coronal alignment that exists across individuals6-10 and the biomechanical sequelae that may result from this ‘one-size-fits-all’ approach.11-16

The pursuit of improvement in patient satisfaction has led some to suggest a shift in technique favouring recreation of a patient’s constitutional (prearthritic) alignment, possibly resulting in more natural knee movements11-13 and improved soft tissue balance.16-20 Commonly termed the ‘kinematic alignment’ (KA) method,21 this approach attempts to restore the constitutional knee joint by
The primary aim of this paper is to propose a new classification system for the Coronal Plane Alignment of the Knee (CPAK). We also aim to determine the CPAK types for which KA may provide a greater benefit than MA in optimizing soft tissue balance. The study’s first primary outcome was to examine the universal applicability of the CPAK classification using descriptive analyses of large, population-based, cross-sectional radiological datasets from healthy volunteers and osteoarthritic (OA) patients undergoing TKA. The second primary outcome was to assess the relative proportion of balanced knees at 10° of flexion for each CPAK type using KA versus MA techniques. Secondary outcomes included the quantitative mean intercompartmental pressure difference (ICPD) at 10°, 45°, and 90°, and the need for major knee balancing procedures comparing KA and MA for each CPAK type. Data from this study will provide a framework for classifying coronal plane alignment of the knee and, furthermore, will allow preoperative identification of the patients most likely to benefit from kinematic TKA according to CPAK-type.

Methods

Study design. Part 1 of the study outlines a stepwise methodological description of the CPAK classification by undertaking a cross-sectional radiological descriptive analysis of healthy and arthritic cohorts. Part 2, CPAK Surgical Validation, was a retrospective analysis of soft tissue balance based on CPAK type. Data were obtained from a convenience sample of patients from a randomized controlled trial (RCT) that compared intraoperative soft tissue balance in TKAs positioned with KA versus MA, the methodology and findings of which were described previously.16

Ethical approval for the overarching RCT was provided by Bellberry Limited (approval #2017-12-911) and was prospectively registered with the Australian New Zealand Clinical Trials Registry (#ACTRN12617001627347p). Approval for the current study was provided by Hunter New England Local Health District (approvals #EX201905-03 and #EX201905-04).

Study groups. The study group used to validate the CPAK classification for Part 1 comprised two cohorts. The healthy population consisted of 250 young adults aged between 20 and 27 years from a previous cross-sectional study of knee alignment by one of the authors (JB).7 Both limbs were imaged, providing data from a total of 500 knees. Participants were recruited at high school and university campuses, cinemas, and job recruitment bureaux in Leuven, Belgium between October 2009 and March 2010. In all, 50% (n = 125) of the volunteers were female. Only asymptomatic volunteers with no history of orthopaedic injury or disease were included.

The arthritic population consisted of 500 consecutive patients scheduled for primary total or unicompartmental knee arthroplasty by two of the authors (SJM, DBC) at a private hospital in Sydney, Australia between October 2016 and March 2018. Only the limb undergoing surgery was included. The patients’ mean age was 66 years (44 to 88). Overall, 62% (n = 310) of patients were female. Patients were included regardless of underlying diagnosis and any history of lower limb surgery or trauma.
Arithmetic HKA = MPTA - LDFA

Joint Line Obliquity (JLO) = MPTA + LDFA

Fig. 2

Relationship between the lateral distal femoral angle (LDFA) and medial proximal tibial angle (MPTA) in varus, neutral, and valgus lower limb alignment with the arithmetic hip-knee-ankle angle (aHKA).

The study group for Part 2 consisted of a separate cohort of patients scheduled for primary unilateral or bilateral TKA. Two authors (SJM, DBC) performed all operations at a single institution in Sydney, Australia. There were 125 patients included in the study, with 13 bilateral procedures; 138 knees received the allocated intervention and were analyzed—68 in the MA group and 70 in the KA group. The mean age was 67.4 years (36 to 89) with a mean body mass index of 30.1 kg/m² (21.5 to 54.8). There were 74 females and 51 males.

**Radiological measurements.** All participants underwent digital long leg radiographs (LLRs) as per Paley and Pfiehl. Measurements were taken by a single observer in the healthy group and by two observers in the arthritic group (WGJ), using the same methodology (described below), which has been shown to have high inter- and intraobserver reliability. The mechanical hip-knee-ankle (mHKA) angle was the angle subtended by the mechanical axes of the femur and tibia. The mechanical lateral distal femoral angle (LDFA) was defined as the lateral angle formed between the femoral mechanical axis and the joint line of the distal femur. The mechanical medial proximal tibial angle (MPTA) was defined as the medial angle formed between the tibial mechanical axis and the joint line of the proximal tibia.

As an assessment of reproducibility of these measurements, the correlations were calculated using Pearson’s $r$ in a subgroup of 25 arthritic LLRs among three surgeons (SJM, DBC, WGJ) and one trainee for the mHKA. The interobserver $r$ was near-perfect (0.99; $p < 0.001$) for measures between all four observers, and the intraobserver $r$ was near-perfect (0.99; $p < 0.001$) for measures among observers at a one-week interval.

**Part 1: CPAK classification**

**The arithmetic HKA.** With the unicompartamental joint space narrowing that occurs as part of the arthritic process, the overall alignment of the limb (mHKA) can change significantly with time (Figure 1a and b). In the absence of arthritic bone loss at the central compartmental contact points, the constitutional alignment of the lower limb can be determined using “the arithmetic HKA”, by identifying bony landmarks and applying the algorithm: $aHKA = MPTA - LDFA$. This algorithm has been previously validated in a matched-pairs radiological study by our group to predict constitutional alignment. A negative $aHKA$ indicates varus, and a positive $aHKA$ indicates valgus constitutional limb alignment (Figure 2). The $aHKA$ is not affected by joint space narrowing or tibiofemoral subluxation. It disregards the joint line convergence angle, which has been shown in our prior study of normal knees to be approximately $0.5^\circ$, and its contribution to prediction of constitutional knee alignment has minimal clinical significance. The method makes the assumption that when the distal femoral and proximal tibial joint lines are parallel, the $aHKA$ equals the mHKA. Hence, the $aHKA$ can be used to estimate constitutional alignment.

**Joint line obliquity.** JLO of the knee is independent of the mechanical axis of the lower limb. Several studies have previously described the native JLO, but no consistent methodology has been universally adopted. For example, the JLO commonly referred to as ‘varus’ is the product of tibial varus and femoral valgus in the neutrally aligned lower limb. Similarly, distal femoral valgus and a neutral proximal tibia can combine to create
approximately neutral. A sum of greater than 180° indicates an apex distal. If the sum of these two angles is 180°, the joint line is approximately neutral. A sum of less than 180° indicates that the joint line is apex proximal.

This terminology clearly specifies whether the joint lines of both knees when extended to the midline is either below, level with, or above the level of a horizontal joint line (figure 3).

Calculation of the JLO is derived from the same two variables used to calculate the aHKA (JLO = MPTA + LDFA) and defines its obliquity relative to the floor in double leg stance. If the sum of these two angles is 180°, the joint line is approximately neutral. A sum of greater than 180° indicates an apex proximal joint line, while a sum of less than 180° indicates that the joint line is apex distal.

CPAK classification matrix. The CPAK classification incorporates the two independent variables of aHKA (with varus, neutral, and valgus subgroups) and JLO (with apex distal, neutral, and apex proximal subgroups). The three subgroups of aHKA are set against the three subgroups of JLO in a matrix to create nine different phenotypes of knees (Figure 4).

CPAK type boundaries were determined to be one standard deviation (SD) (rounded to the nearest whole number) for the mean aHKA and JLO of the combined dataset of all 1,000 knees. CPAK boundaries for neutral aHKA are 0° ± 2°, inclusive (SD 1.80°). A varus aHKA is less than -2°, while a valgus aHKA is greater than +2°. CPAK boundaries for a neutral JLO are 180° ± 3°, inclusive (SD 2.90°). An apex distal JLO is less than 177°, while an apex proximal JLO is greater than 183°.

Part 2: CPAK surgical validation

Surgical planning. The mHKA, LDFA, and MPTA were measured in the surgical validation group of 138 knees. This allowed calculation of the aHKA, JLO, CPAK type, and distal femoral and proximal tibial resection angles.

In the MA group, bone resections were made perpendicular to the mechanical axis of the femur and tibia, with the aim of restoring a neutral (0°) mHKA. Femoral rotation was set parallel to the surgical transepicondylar axis, with secondary referencing perpendicular to the AP femoral axis and 3° externally rotated from the posterior condylar axis.

In the KA group, coronal bone resections were undertaken within a restricted alignment safe zone, with the aim of restoring constitutional LDFA, MPTA, and aHKA for each patient. The restricted safe zone was defined as 86° to 93° for recreation of both the LDFA and the MPTA, and -5° varus to +4° valgus for the final mHKA. If the aHKA was outside the final mHKA safe zone, the femoral and tibial resections were incrementally reduced to be within the safe zone. For patients who were older than 80 years or who had a history of osteoporosis, the safe zones for LDFA and MPTA were narrowed to 87° to 93°, and the final HKA was narrowed to -4° to +3° due to concern about greater risk of implant subsidence in those patients with alignment deviations further from neutral. Femoral rotation was initially planned parallel to the posterior condylar bone but adjusted if the tibial resection had to be reduced to fall within the safe zone.

Surgical technique. All procedures were performed using optical navigation (OrthoMap Precision Navigation, Stryker, Mahwah, New Jersey, USA) to ensure accurate restoration of target alignments. A posterior-stabilized, fully cemented total knee prosthesis was used with patellar resurfacing in all cases (Legion, Smith & Nephew, Memphis, Tennessee, USA). After trial implant insertion, but prior to any soft tissue releases, a wireless pressure sensor (VERASENSE, OrthoSensor, Dania Beach, Florida, USA) was inserted, and medial and lateral compartmental pressures were recorded at 10°, 45°, and 90° of knee flexion with the arthrotomy closed. Pressures were recorded by both the operating surgeon and an assistant, with the mean of the two readings used. The
intercompartmental pressure difference (ICPD) was calculated as the absolute pressure difference between medial and lateral compartments at each flexion angle. An ICPD of 15 psi or less at each flexion angle was considered to be balanced based on prior studies showing improved patient-reported outcomes using this definition.34,35 If the ICPD was between 16 and 40 psi, a soft tissue release was performed.36 Bone recuts were performed if an ICPD was greater than 40 psi or if the absolute pressure in one compartment was greater than 60 psi.

Outcome measures. The primary outcome for Part 1 of the study was frequencies for each CPAK type in the healthy and arthritic populations. The primary outcome for Part 2 was a comparison of knee balance of KA versus MA as an estimate of severe imbalance requiring major balancing procedures.

Statistical analysis. Scatterplots for each population were created to demonstrate alignment distributions for healthy and arthritic groups. Normality of data distribution was assessed for non-parametric data. The chi-squared test and Fisher’s exact test were used for categorical data analysis. Statistical significance was set at a p-value ≤ 0.05. Statistical analyses were performed using XLSTAT v22.3.1 (Addinsoft, New York, New York, USA) and SPSS Statistics Package v.25 (IBM, Armonk, New York, USA).

Results
The mean MPTAs of the healthy and arthritic groups were 87.0° (SD 2.1°) and 87.3° (SD 2.1°) respectively. The mean LDFAs of the healthy and arthritic groups were 87.9° (SD 1.7°) and 88.1° (SD 2.1°) respectively. The mean and variance for mHKA were different between the healthy and arthritic groups (-1.3° (SD 2.3°) vs -2.9° (SD 7.4°)), but the mean and variance for aHKA were similar (-0.9° (SD 2.5°) vs -0.8° (SD 2.8°)).

CPAK classification. The frequencies of individuals representing all CPAK types were similar when comparing the two populations (Figures 5 and 6). The commonest CPAK types in order were Type II (neutral aHKA, apex distal JLO; 39.2% (n = 196) healthy vs 32.2% (n = 161) OA), Type I (varus aHKA, apex distal JLO; 26.4% (n = 132) healthy vs 19.4% (n = 97) OA), and Type V (neutral aHKA, neutral JLO; 15.4% (n

| Table I. Coronal Plane Alignment Knee type and balance at 10° knee flexion with kinematic alignment and mechanical alignment. |
|---------------------------------------------------------------|
| CPAK type | Knees, n | KA balanced, % (balanced/total) | MA balanced, % (balanced/total) | p-value |
|-----------|----------|---------------------------------|---------------------------------|---------|
| I         | 23       | 100 (10/10)                     | 15 (2/13)                       | <0.001*‡ |
| II        | 53       | 78 (21/27)                      | 46 (12/26)                      | 0.018*†  |
| III       | 28       | 62 (8/13)                       | 40 (6/15)                       | 0.290†   |
| IV        | 15       | 89 (8/9)                        | 0 (0/6)                         | <0.001**‡|
| V         | 12       | 100 (7/7)                       | 60 (3/5)                        | 0.152‡   |
| VI        | 7        | 50 (2/4)                        | 33 (1/3)                        | 1.000‡   |

*Statistically significant. †Mann-Whitney U test. ‡Fisher’s exact test.

CPAK, Coronal Plane Alignment Knee; KA, kinematic alignment; MA, mechanical alignment.

| Table II. Descriptive statistics for intercompartmental pressure differences at 10°, 45°, and 90° of knee flexion for kinematic alignment and mechanical alignment. |
|---------------------------------------------------------------|
| CPAK type | Knee angle, ° | Mean KA ICPD (SD; range) | Mean MA ICPD (SD; range) | p-value |
|-----------|---------------|--------------------------|--------------------------|---------|
| I         | 10            | 6.5 (3.2; 1 to 10)       | 55.9 (39.0; 7 to 138)    | 0.001*‡ |
|           | 45            | 8.7 (7.0; 2 to 26)       | 39.7 (28.4; 2 to 91)     | 0.004*†  |
|           | 90            | 7.3 (6.0; 0 to 21)       | 28.2 (21.3; 1 to 66)     | 0.008*‡ |
| II        | 10            | 13.7 (16.5; 1 to 63)     | 24.0 (24.1; 1 to 92)     | 0.065†   |
|           | 45            | 16.9 (14.6; 2 to 51)     | 26.0 (28.1; 3 to 141)    | 0.157†   |
|           | 90            | 12.4 (13.3; 2 to 50)     | 18.5 (13.3; 3 to 61)     | 0.039†   |
| III       | 10            | 22.5 (16.2; 1 to 54)     | 25.8 (17.3; 1 to 55)     | 0.612‡   |
|           | 45            | 25.1 (18.3; 7 to 72)     | 26.4 (25.3; 1 to 104)    | 0.990†   |
|           | 90            | 22.3 (18.6; 0 to 75)     | 26.8 (23.9; 1 to 89)     | 0.316†   |
| IV        | 10            | 11.6 (14.9; 3 to 50)     | 45.6 (28.6; 16 to 99)    | 0.006†   |
|           | 45            | 15.2 (9.8; 3 to 32)      | 33.6 (21.5; 4 to 69)     | 0.041*‡  |
|           | 90            | 15.3 (8.2; 4 to 28)      | 16.1 (11.9; 3 to 32)     | 0.887†   |
| V         | 10            | 10.3 (8.4; 4 to 28)      | 19.0 (16.2; 4 to 38)     | 0.606†   |
|           | 45            | 16.1 (12.4; 5 to 40)     | 22.0 (25.6; 5 to 65)     | 0.606†   |
|           | 90            | 11.4 (9.9)               | 14.5 (14.7)              | 0.965†   |
| VI        | 10            | 18.3 (15.7)              | 19.8 (20.2)              | 0.901†   |
|           | 45            | 32.6 (26.5)              | 12.2 (8.8)               | 0.251†   |
|           | 90            | 16.5 (14.3)              | 19.8 (20.2)              | 0.807†   |

*Statistically significant. †Mann-Whitney U test. ‡Independent-samples t-test.
Fig. 8

Box plot comparison of mean intercompartmental pressure differences at 10°, 45°, and 90° of knee flexion for kinematic alignment (KA) and mechanical alignment (MA). CPAK, Coronal Plane Alignment of the Knee; ICPD, intercompartmental pressure difference.

### Table III. Requirements for bone recuts for each Coronal Plane Alignment Knee type.

| CPAK type | KA group, n (total) | MA group, n (total) | MA recuts, % | p-value |
|-----------|---------------------|---------------------|--------------|---------|
| I         | 0 (10)              | 9 (13)              | 69           | 0.001** |
| II        | 4 (27)              | 11 (26)             | 42           | 0.026*  |
| III       | 0 (13)              | 7 (15)              | 47           | 0.004** |
| IV        | 1 (9)               | 3 (6)               | 50           | 0.235†  |
| V         | 0 (7)               | 2 (5)               | 40           | 0.152‡  |
| VI        | 1 (3)               | 1 (3)               | 33           | 1.000‡  |

Bone recuts performed when absolute pressure in either compartment was greater than 60 psi, or an intercompartmental pressure difference was greater than 40 psi.

*Statistically significant.
†Chi-squared test.
‡Fisher’s exact test.
CPAK, Coronal Plane Alignment Knee; KA, kinematic alignment; MA, mechanical alignment.

### Secondary outcome measures.

There was a significant ICPD at all three flexion angles for CPAK Type I, at 90° for CPAK Type II, and at 10° and 45° for CPAK Type IV, with MA having a greater difference (worse) than KA (Table II and Figure 8). There was a higher proportion of TKAs requiring bone recuts to achieve knee balance in CPAK Types I, II and III when MA was performed compared to KA (Table III).

### Discussion

We describe a straightforward, pragmatic, and comprehensive classification system incorporating algorithms for constitutional lower limb alignment and JLO. When comparing healthy and arthritic populations, there were similar frequencies among all CPAK types, suggesting that this classification can be used in healthy and arthritic knees. Although there are nine knee types, CPAK Types VII, VIII, and IX are rare. We believe their inclusion for completeness is important as they significantly higher likelihood of having optimal balance and the largest effect sizes compared to MA (Type I, 100% KA vs 15% MA; p < 0.001, chi-squared test; Type II, 78% KA vs 46% MA; p = 0.018, chi-squared test; Type IV, 89% KA versus 0% MA; p < 0.001, Fisher’s exact test).
provide a visual aid to understanding the CPAK matrix and can also be used in postoperative TKA assessment where the JLO has been inadvertently altered. The study also demonstrates that for each CPAK type, a greater proportion of knees implanted in KA achieved balance compared to those implanted in MA.

Despite CPAK Type V (neutral aHKa, neutral JLO) being the target for MA, only 15% of both populations fell within the classification boundaries. A greater proportion of Type V knees were objectively balanced when undertaking KA versus MA (100% versus 60% respectively). Although not statistically significant, it is likely that subtle knee alignment changes with KA to both the aHKa and JLO within 2° of its boundaries may increase the likelihood of achieving knee balance. This technique of altering alignment around the neutral resections is referred to as ‘adjusted MA’ or ‘modified MA.’

CPAK Type II knees (neutral aHKa and apex distal JLO) are the commonest knee type, comprising nearly 40% of knees in the normal population. This CPAK type is the foundation for which Hungerford et al described the anatomical alignment (AA) method. Despite this technique aligning the joint line based on mean population values of 3° femoral valgus and 3° tibial varus, precisely replicating these resection targets with conventional instrumentation was difficult and largely abandoned. In this CPAK type, where mechanical axis (aHKa) is neutral, the current study found a significant difference in the proportion of knees balanced at 10° and a trend for lower ICPD differences in favour of KA. At 90°, there was significantly improved balance in favour of KA (Table II). This suggests that JLO, as a separate variable to coronal limb alignment (aHKa), independently improves knee balance in flexion.

The distributions by CPAK type (Figures 5 and 6) show that 32% of normal and 30% of arthritic patients have constitutional varus and 76% of normal and 67% of arthritic patients have an apex distal JLO. This challenges the common philosophy of aligning the knee into a neutral mechanical alignment with neutral JLO, as this combination only represents normal for a small proportion of the population. The effect size for achieving a balanced knee for KA when compared to MA with constitutional varus was large for CPAK Type I (varus aHKa, apex distal JLO) and CPAK Type IV knees (varus aHKa, neutral JLO). Approximately 90% or more of CPAK Types I and IV were balanced at 10° if randomized to KA, compared to 15% or fewer when MA was used. When analyzing ICPDs, Type I knees had better balance at 10°, 45°, and 90°, supporting the proposition that restoring the apex distal JLO with KA has an impact on flexion balance as well, while creating a non-physiological neutral JLO with MA is unfavourable in this group. Type IV knees in the KA cohort had better balance at 10° and 45°, but both were equivalent, with normal balance, at 90°. Conceptually, this illustrates that while MA does not restore the varus aHKa and extension balance in the Type IV knee, it does restore the neutral JLO of this group; this is the reason KA and MA are both balanced in flexion. It is our opinion that CPAK Types I and IV are better aligned with a kinematic approach from the commencement of surgery. Otherwise, if MA is undertaken, significant interventions to restore balance will most likely be required, with either recuts into varus or extensive releasing of the medial collateral ligament.

CPAK Types III and VI are constitutional valgus knees, with an apex distal and neutral JLO respectively. In these types, complex morphological factors beyond coronal plane alignment may drive alterations in soft tissue balance. These include lateral femoral and tibial bone deficiencies, external rotation deformities of the femur and tibia, and secondary femoral metaphyseal remodelling. Soft tissue alterations may occur, particularly contractures of the lateral soft tissues, and as arthritic deformity increases, so may secondary attenuation of the medial collateral ligament. CPAK Types III and VI represent a more complex reconstructive solution beyond restoring constitutional alignment. A proportion of patients in these CPAK types had constitutional alignment and lateral distal femoral angles outside the restricted safe zones defined in this study. Further, there were fewer patients in these groups, which may have had an impact on whether a true difference existed when undertaking KA in these knees. Despite having a similar mean ICPD at 10° for MA and KA, significantly more Type III knees required bone recuts into valgus when MA was applied (47% MA vs 0% KA), suggesting that in this group, normalization of JLO is an important component for restoration of complex 3D kinematics.

In 2018, Lin et al described a classification system using LLRs of 214 healthy Taiwanese individuals aged 20 to 70 years. This classification had 27 possible combinations, although only five were described as clinically relevant. The following year, Hirschmann et al proposed a classification based on CT imaging from 160 nonarthritic individuals aged 16 to 44 years (308 knees), with 125 theoretical ‘functional phenotypes’ and 43 described as clinically relevant. Both classifications utilized three variables: mechanical limb alignment, distal femoral angle, and proximal tibial angle. In contrast, CPAK combines the anatomical joint line measures of the LDFa and MPTa, resulting in only two critical variables: aHKa (constitutional limb alignment) and JLO. In this way, CPAK classification simplifies categorization into nine knee phenotypes. Also, because CPAK also incorporates aHKa, it can be used in both healthy subjects and arthritic patients.

The CPAK classification allows for customization of preoperative alignment planning based on individualized, surgeon-defined restricted boundaries for aHKa and JLO. Secondly, CPAK determines whether a patient should be considered for a MA TKA (CPAK Type V), AA TKA (CPAK Type II), or KA TKA (including but not restricted to other CPAK Types I, III, IV, VI). Further, it allows for consideration of a ‘functional alignment’ strategy, where bone resections are performed within traditionally accepted boundaries, with the aim to limit alteration to the native soft tissue envelope.

This research has several limitations. First, the arthritic cohort included all patients on whom knee arthroplasty was conducted irrespective of significant arthritic bone loss, extra-articular bone deformity, or prior osteotomy. Second, the two populations studied were from different continents, and racial background was not analyzed. Racial differences have been shown in prior studies to influence alignment. Third, the groups studied did not have an equal sex distribution: the OA
group had a predominance of females, which is typical of a TKA population. Fourth, in the second part of the study, small sample sizes (particularly in CPAK Types V and VI) make comprehensive comparison of balance among groups less reliable, as this study was not powered to detect differences among all CPAK types. Fifth, radiological measurement errors related to rotational malpositioning and fixed flexion contractures could not be excluded, and as such, other advanced imaging methods may provide greater accuracy. Bone loss related to advanced OA will also contribute to measurement errors for determination of alignment parameters and resection angle calculations. Further research into methods that can account for bone loss is warranted. Sixth, because we used a restricted safe zone for KA surgery, it is possible that widening of alignment boundaries may have resulted in an even higher proportion of knees being balanced in the KA group. Seventh, although this classification has demonstrated utility in prediction of soft tissue balance, future research is required to correlate knee phenotype and patient outcomes. We believe that CPAK phenotype should be considered when assessing outcomes in kinematically aligned surgery. And finally, CPAK does not address axial or sagittal alignment, which also contribute to knee balance. Future research that addresses our understanding of 3D alignment and balance is warranted.

In summary, the new CPAK classification provides a simple and comprehensive system for describing knee alignment in the arthritic and healthy knee. In addition, CPAK allows determination of which patients are most likely to benefit from kinematic alignment when optimization of soft tissue balance is prioritized. With a greater understanding of the knee phenotypes, surgeons now have a preoperative method to determine which alignment strategy is best suited for each patient.

**Take home message**

The new coronal plane alignment of the knee (CPAK) classification provides a simple and comprehensive system for describing knee alignment in the arthritic and healthy knee and provides categorial data that will aid communication and stimulate further research.

- CPAK allows determination of which patients are most likely to benefit from kinematic alignment when optimization of soft tissue balance is prioritized.
- With a greater understanding of knee phenotypes, surgeons now have a preoperative method to determine which alignment strategy is best suited for each patient.

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