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Coronal Plane Alignment of the Knee (CPAK) Type Shifts Toward Constitutional Varus with Increasing Kellgren and Lawrence Grade

A Radiographic Analysis of 17,365 Knees

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Background: Studies investigating constitutional alignment across various grades of osteoarthritis (OA) are limited. This study explored the distribution of Coronal Plane Alignment of the Knee (CPAK) types and associated radiographic parameters with increasing OA severity.

Methods: In this retrospective cross-sectional study, 17,365 knees were analyzed using deep learning software for radiographic measurements. Knees were categorized on the basis of the Kellgren and Lawrence (KL) grade and CPAK type. Radiographic measurements were the hip-knee-ankle angle (HKAA), lateral distal femoral angle (LDFA), medial proximal tibial angle (MPTA), arithmetic HKAA (aHKA), joint line obliquity (JLO), and joint line convergence angle (JLCA). Age-stratified analysis was performed to differentiate the impact of age on OA severity.

Results: A shift in the most common CPAK type from II to I was found with increasing KL grade ($p < 0.05$). Furthermore, there was a corresponding increase in LDFA and JLCA with increasing KL grade, while HKAA, MPTA, and aHKA decreased after KL grade 2. Age exhibited limited association with LDFA and MPTA, suggesting that OA severity is the dominant factor related to the CPAK distribution.

Conclusions: The study found a shift in CPAK type with worsening OA. It is possible that constitutional varus types are more susceptible to OA, or that their increased OA prevalence is related to anatomical changes. This analysis offers new insights into alterations in CPAK type that occur with OA and underscores the importance of understanding pre-arthritic anatomy when performing joint reconstruction.

Level of Evidence: Prognostic Level III. See Instructions for Authors for a complete description of levels of evidence.

The kinematic alignment (KA) concept and its derivatives have emerged with the purpose of individualizing the position of implants in total knee arthroplasty (TKA)[1]. These new concepts focus on restoring pre-arthritic anatomy, with the aim of preserving the physiological function of the knee[1-3]. However, personalized approaches in TKA become problematic when the native knee alignment is unclear, particularly when arthritic deformity has occurred.

The Coronal Plane Alignment of the Knee (CPAK) classification was introduced to address this issue[4]. Knees are categorized by the arithmetic hip-knee-ankle angle (aHKA) and the joint line obliquity (JLO), both of which are derived from the medial proximal tibial angle (MPTA) and the lateral distal femoral angle (LDFA). The CPAK classification has 9 phenotypes based on the pre-arthritic alignment (varus, neutral, and valgus) for the aHKA and on the constitutional JLO (apex distal,

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neutral, and apex proximal) (Fig. 1)[4,5]. The CPAK estimates constitutional lower limb alignment on the basis of the osseous articular surfaces of the femur and tibia, thereby excluding influences from cartilage loss-induced joint-space narrowing and adjacent soft-tissue alterations. As a result, it provides a reliable retrospective estimate of the pre-arthritic knee alignment[6].

Studies investigating how the CPAK distribution varies with osteoarthritis (OA) progression are limited[7]. Discerning possible shifts in CPAK type that occur with OA is critical in determining if certain phenotypes are more predisposed to this common disease process. Furthermore, understanding variations in CPAK type with OA progression is important in reconstructive knee surgery when restoring the native alignment is required. Although long-term radiographic follow-up of large cohorts over decades could address these questions, such observational studies may not be feasible, especially in terms of recruitment of younger, asymptomatic individuals. To address these limitations, a cross-sectional study involving a large population across various stages of OA may be an effective alternative, indirectly offering insights into changes in CPAK over a lifetime.

Therefore, the purpose of this study was to identify variations in the CPAK types relative to OA severity via a cross-sectional analysis, with the aim of elucidating the transition of the CPAK distribution from the pre-arthritic to the arthritic knee. We hypothesized that the most common CPAK types would shift with increasing OA severity, as represented by Kellgren and Lawrence (KL) grades[8], and that radiographic coronal knee parameters would exhibit changes corresponding to the progression of OA.

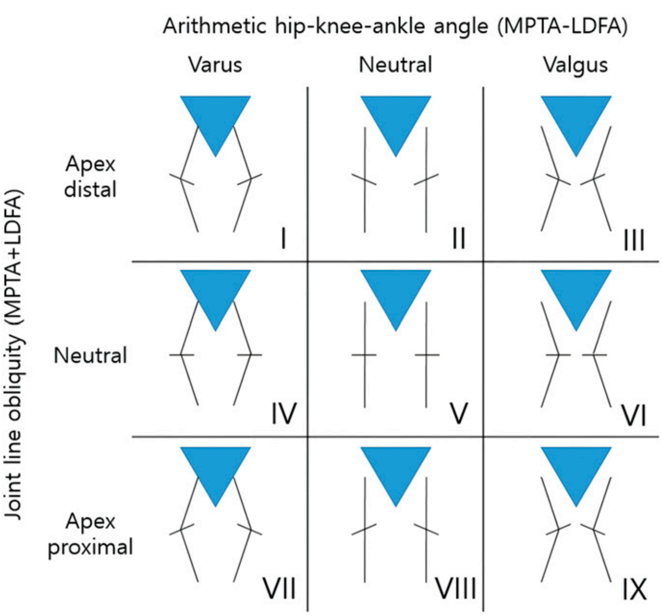

Fig. 1
CPAK (Coronal Alignment of the Knee) classification according to MacDessi et al.[4].

Materials and Methods

This retrospective cross-sectional study received approval from our institutional review board (2110-200-1269). The study was conducted in South Korea, and included all patients with long-leg standing radiographs, anteroposterior (AP) standing knee radiographs, and posteroanterior (PA) standing knee radiographs made at the authors' institute between January 2002 and June 2022. Radiographs of 22,808 knees made during the study period were reviewed. Patients <18 years of age were excluded from the study. Patients with a history of osseous knee surgery and patients displaying osseous attrition of >5 mm or knee subluxation (Ahlbäck grade 4 or 5)[9] were also excluded. This was done to minimize direct alterations in MPTA and LDFA due to osseous changes and potential measurement errors.

A total of 17,365 knees in eligible patients were analyzed. Radiographic parameters were measured using deep learning software previously validated to achieve an accuracy comparable to that of an orthopaedic specialist, with interobserver and intraobserver intraclass correlation coefficients of >0.98[10]. OA severity was assessed using the KL grading system, which is based on the degree of joint-space narrowing and the presence of osteophytes, on AP and PA knee radiographs[8]. The assessments were performed by an orthopaedic specialist with >7 years of experience in knee surgery. Radiographic coronal knee parameters, including the hip-knee-ankle angle (HKAA), LDFA, MPTA, and joint line convergence angle (JLCA), were measured on long-leg standing radiographs with both patellae facing forward. The HKAA was measured as the angle formed by the mechanical axes of the femur and tibia[11]. The LDFA was measured as the angle formed by the mechanical axis of the femur and the distal femoral joint line. The MPTA was measured as the angle formed by the mechanical axis of the tibia and the proximal tibial joint line. The JLCA was measured as the angle formed by lines drawn parallel to the distal femoral and proximal tibial joint lines[12]. Based on the classification of MacDessi et al., the CPAK phenotype was calculated from the aHKA (which equals MPTA − LDFA) and JLO (which equals MPTA + LDFA)[4].

Outcome Measures

The primary outcomes were (1) the changes in the radiographic coronal knee parameters according to the KL grade, and (2) the distribution of CPAK type proportions according to the KL grade. The secondary outcome was the influence of age on radiographic parameters, particularly MPTA and LDFA, in order to differentiate any confounding age-related effects on OA severity.

Statistical Analysis

Statistical analysis was performed using Python (version 3.10.12; Python Software Foundation) and SPSS (version 25; IBM). Differences in categorical variables were assessed using the chi-square test, and differences in continuous variables were assessed using 1-way analysis of variance (ANOVA). Changes in the proportions of the most common CPAK types (I, II, and III) across KL grades were illustrated using histograms. Scatterplots featuring 1-standard deviation (SD) contours for the aHKA and JLO were generated for each KL group, to estimate the percentage of knees within each CPAK type. Age was stratified into categories of <20 years, each subsequent decade up to the 70s, and ≥80 years. Post hoc analyses for the age groups included the Tukey Honestly Significant Difference (HSD) and Dunnett T3 tests. A p value of <0.05 was considered significant.

Results

Patient demographics and the distribution of radiographic coronal knee parameters are presented in Table I. Race and ethnicity information was not included in the dataset. With increasing KL grade, there was a corresponding increase in age, LDFA, and JLCA, while HKAA, MPTA, and aHKA decreased after KL grade 2 (Table II). No discernible trend was observed for JLO.

Radiographic Parameters According to KL Grade

Figure 2 illustrates the changes in radiographic parameters with increasing KL grade. The changes in HKAA and JLCA were the most pronounced as the KL grade progressed from 2 to 4. The significance of the changes in the radiographic parameters are presented in Appendix Supplementary Figure 1.

TABLE I Patient Demographics and Distribution of Radiographic Coronal Knee Parameters (N = 17,365)*

Age *(yr)*	61.7 ± 14.7 (18 to 91)
Male sex	24.6%
Height *(cm)*	158.3 ± 9.1 (133.8 to 197.0)
Weight *(kg)*	64.4 ± 11.3 (37.3 to 117.0)
Body mass index *(kg/m²)*	25.6 ± 3.6 (13.7 to 47.4)
KL grade	
0	2,849 (16.4%)
1	2,091 (12.0%)
2	6,116 (35.2%)
3	4,900 (28.2%)
4	1,409 (8.1%)
HKAA *(°)*	175.9 ± 4.8 (148.6 to 205.3)
LDFA *(°)*	87.6 ± 2.7 (71.4 to 105.1)
MPTA *(°)*	87.0 ± 2.6 (70.8 to 103.0)
JLCA *(°)*	3.4 ± 2.9 (−13.9 to 21.2)
aHKA, defined as MPTA − LDFA *(°)*	−0.7 ± 3.7 (−23.4 to 17.9)
JLO, defined as MPTA + LDFA *(°)*	174.6 ± 3.8 (152.8 to 197.5)

*The values are given as the mean ± standard deviation (range) or number and percent. KL = Kellgren and Lawrence, HKAA = hip-knee-ankle angle, LDFA = lateral distal femoral angle, MPTA = medial proximal tibial angle, JLCA = joint line convergence angle, aHKA = arithmetic HKAA, JLO = joint line obliquity.

CPAK Type According to KL Grade

The most common CPAK type in the cohort as a whole was II, accounting for 32.8% of knees, followed by type I (25.2%), type III (16.3%), type V (10.3%), type IV (8.5%), and type VI (5.2%). As in prior studies, CPAK types VII, VIII, and IX were rare[4,13-15]. The distribution of CPAK type proportions by KL grade is shown in Figure 3. CPAK type II was the most common type in KL grades 0, 1, and 2, while CPAK type I was the most common in KL grades 3 and 4. As CPAK types I to V represented the majority of the study population, we conducted a statistical analysis to evaluate the association between these CPAK types and KL grades. CPAK types I to V demonstrated significantly different distributions across the KL grades ($p < 0.05$ overall and in all post hoc pairwise comparisons between KL grades). The distribution of the most common CPAK types (I, II, and III) in each KL grade is shown in Figure 4.

The simplified scatterplots in Figure 5 display 1-SD contours of aHKA and JLO for each KL grade. Interestingly, CPAK types I and IV demonstrated expanding 1-SD contours with increasing KL grades, especially due to a decrease in aHKA, a trend absent in other CPAK types.

Relationship Between Age and Radiographic Parameters

As seen in Table II, an association was observed between increasing age and increasing OA severity. Figure 6 presents the MPTA and LDFA values by age group. Although no significant difference in MPTA was observed across age groups (all $p > 0.05$), LDFA exhibited a slight increase with age. However, differences in LDFA reached significance only when comparing individuals who were in their 50s to those who were in their 70s and to those who were ≥80 years old, with minimal mean differences of 0.3° and 0.5°, respectively.

Discussion

The primary finding of this study was that alterations in the CPAK type distribution occur as OA progresses. Specifically, CPAK type II was the most common type in knees with low KL grades (0, 1, and 2), but as OA severity increased (KL grades 3 and 4), a shift toward CPAK type I was found. CPAK types with an apex-distal JLO (I, II, and III) remained the most common types irrespective of OA, with CPAK type IV increasing in proportion with KL grades 3 and 4.

The increasing proportion of CPAK type I (and to a lesser extent type IV) with worsening OA may have 2 possible explanations. First, it is plausible that knees with constitutional varus may be more susceptible to OA, explaining the increasing proportion of these CPAK types with worsening grades of OA. In other words, individuals with constitutional varus may have a higher risk of OA. Alternatively, the observed decrease in aHKA and the population's shift toward types I and IV may have resulted from osseous attrition or bone remodeling as OA advances—that is, in advanced OA, these defined CPAK types no longer represent the original constitutional or pre-arthritic knee state. Both of these explanations align with previous studies involving Indian and Japanese populations, in which type II was common in healthy knees and type I was common in knees with advanced OA[13,15].

TABLE II Distribution of Age and Radiographic Coronal Knee Parameters According to Kellgren and Lawrence Grade*

KL Grade	Percentage	Age *(yr)*	HKAA *(°)*	LDFA *(°)*	MPTA *(°)*	JLCA *(°)*	aHKA *(°)*	JLO *(°)*
0	16.4%	48.5 ± 16.9	178.1 ± 2.8	86.8 ± 2.5	87.1 ± 2.3	2.2 ± 1.7	0.3 ± 3.1	173.9 ± 3.7
1	12.0%	55.0 ± 15.6	177.9 ± 3.0	87.2 ± 2.6	87.2 ± 2.4	2.1 ± 1.9	−0.0 ± 3.3	174.5 ± 3.7
2	35.2%	63.1 ± 11.6	177.5 ± 3.5	87.6 ± 2.7	87.5 ± 2.5	2.4 ± 2.1	−0.1 ± 3.5	175.1 ± 3.9
3	28.2%	68.1 ± 8.0	173.5 ± 4.4	88.1 ± 2.6	86.5 ± 2.6	4.9 ± 2.7	−1.6 ± 3.6	174.6 ± 3.7
4	8.1%	69.9 ± 8.0	169.6 ± 6.2	88.2 ± 2.8	85.3 ± 3.2	7.5 ± 3.9	−2.9 ± 4.5	173.5 ± 3.9

*The values are given as the mean ± standard deviation, except as noted. KL = Kellgren and Lawrence, HKAA = hip-knee-ankle angle, LDFA = lateral distal femoral angle, MPTA = medial proximal tibial angle, JLCA = joint line convergence angle, aHKA = arithmetic HKAA, JLO = joint line obliquity.

Whether one or both of these factors are at play cannot be extrapolated from these findings.

Our study found a slight linear increase in LDFA as KL grade incrementally increased, whereas a marked decrease in MPTA was observed only after KL grade 2. This reduction in MPTA is the likely underlying cause for the aHKA decrease (increase in constitutional varus) noted from KL grade 2 onward. Similar correlations between MPTA and HKAA have been reported in previous studies[16,17]. JLCA showed a pronounced increase from KL grade 2 onwards.

These findings paint a picture of what happens in patients with medial compartment OA as disease severity worsens. The initial stage is erosion of the articular cartilage on the distal medial femoral condyle, followed by a more rapid erosion of the cartilage on the medial tibial plateau that drives more consequential changes in knee alignment[7]. It is noteworthy that these findings align with those of the study by Colyn et al., in which changes in varus knee alignment were primarily influenced by a decrease in MPTA and an increase in JLCA[7]. That was a smaller study of 100 patients and only included patients over the age of 50. However, this pattern was also shown in our study (see Appendix Supplementary Figure 1): LDFA increased slowly in the early OA stages, whereas MPTA remained relatively stable until KL grade 2 and subsequently exhibited a sharp decline. Furthermore, JLCA displayed a prominent increase as the KL grade progressed, consistent with findings from earlier studies[18,19].

The relationship between aging and OA progression is well established in the existing literature[20,21]. Therefore, the potential for age to confound the relationship between the CPAK distribution and KL grade was considered. To investigate this, we examined the relationship of age with MPTA and LDFA, the key components determining the CPAK type. Interestingly, no significant change in MPTA across different age groups was observed. Slight differences in LDFA were identified when those in their 50s were compared with those in their 70s and those ≥80 years old; however, the mean differences were ≤0.5°. These findings

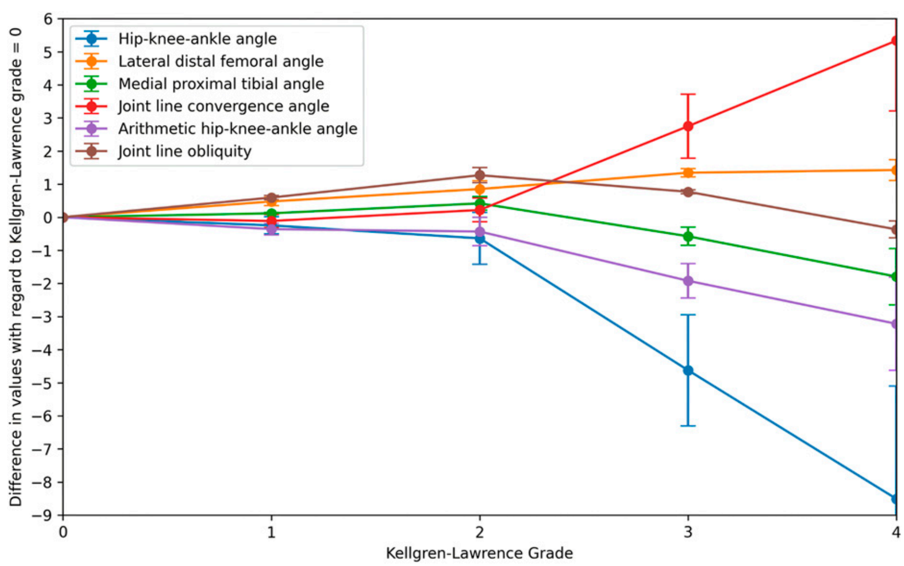

Fig. 2

Changes in radiographic coronal knee parameters (in degrees), relative to those in KL (Kellgren and Lawrence) grade 0, across the KL grades. The values are shown as the mean and standard deviation.

	KL 0	KL 1	KL 2	KL 3	KL 4
Type I	17.4% (496)	18.9% (395)	19.0% (1164)	33.4% (1636)	48.8% (688)
Type II	40.0% (1141)	36.7% (768)	31.9% (1950)	30.4% (1491)	24.3% (342)
Type III	23.2% (661)	19.6% (410)	18.3% (1122)	10.6% (518)	9.0% (127)
Type IV	5.0% (142)	8.0% (167)	8.6% (523)	10.7% (522)	8.2% (116)
Type V	8.1% (231)	10.3% (216)	12.9% (790)	9.7% (473)	6.1% (86)
Type VI	5.1% (145)	5.4% (113)	7.0% (426)	3.9% (190)	2.5% (35)
Type VII	0.5% (14)	0.3% (6)	0.8% (51)	0.7% (32)	0.5% (7)
Type VIII	0.4% (12)	0.5% (11)	0.9% (53)	0.5% (24)	0.4% (6)
Type IX	0.2% (7)	0.2% (5)	0.6% (37)	0.3% (14)	0.1% (2)

Fig. 3
Distribution of CPAK (Coronal Alignment of the Knee) types for each KL (Kellgren and Lawrence) grade. Values within parentheses indicate the number of knees within that category. The color gradient ranges from red, representing a higher proportion, to green, indicating a lower proportion.

suggest that the influence of age on MPTA and LDFA is limited, whereas the severity of OA (KL grade) appears to be the dominant factor.

There are several limitations to this study. First, the cross-sectional design precludes the establishment of causal relationships between the CPAK distribution and the KL grade, limiting the findings to associations only. However, the large and age-diverse patient sample could offer valuable insights, given that a longitudinal study on a comparable scale might be impractical. Second, selection bias may have influenced the study population, as individuals without knee symptoms are unlikely to seek radiographic evaluation. Third, although the radiographic outcomes assessed were standardized, they were susceptible to measurement errors arising from imaging angles and patient positioning. These errors are likely to be more pronounced as OA worsens, which must be considered in interpreting constitutional changes in CPAK type with advancing disease. Fourth, all patients analyzed were from South Korea. Although the dataset did not include race or ethnicity information, South Korea is predominantly ethnically homogeneous. Racial differences in other populations may affect the generalizability of our findings. Lastly, while age was considered as a potential confounding variable, the study did not account for other variables (e.g., sex, height, weight, and body mass index) that may influence the relationship between CPAK types and OA severity.

Conclusions

This large, cross-sectional analysis offers new insights into differences in constitutional knee phenotypes that occur with advancing OA. An increase in CPAK type I with a decrease in

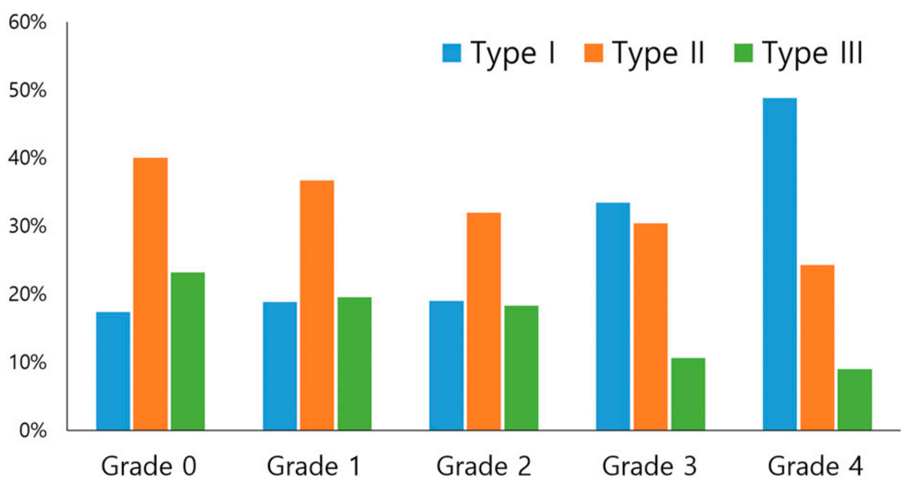

Fig. 4
Distribution of the most common CPAK (Coronal Alignment of the Knee) types according to the Kellgren and Lawrence grade.

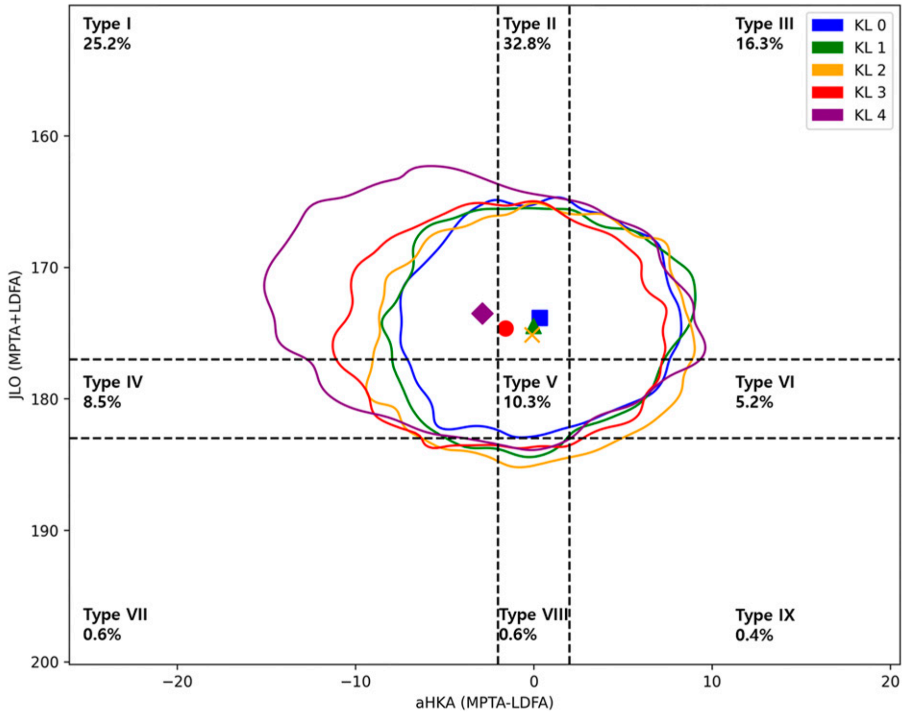

Fig. 5

Plot of aHKA (arithmetic hip-knee-ankle angle) versus JLO (joint line obliquity) according to KL (Kellgren and Lawrence) grade, simplified from a traditional scatterplot into 1-standard-deviation contours surrounding the means. The percentage of each CPAK (Coronal Alignment of the Knee) type is also shown. The aHKA distribution becomes broader toward varus as the KL grade increases.

CPAK type II was found with worsening OA. Constitutional varus CPAK types may be inherently more susceptible to OA progression, or this apparent shift toward varus CPAK types may result from attritional bone loss, independent of age. The strength of these findings is supported by the large sample size and inclusion of all adult age groups.

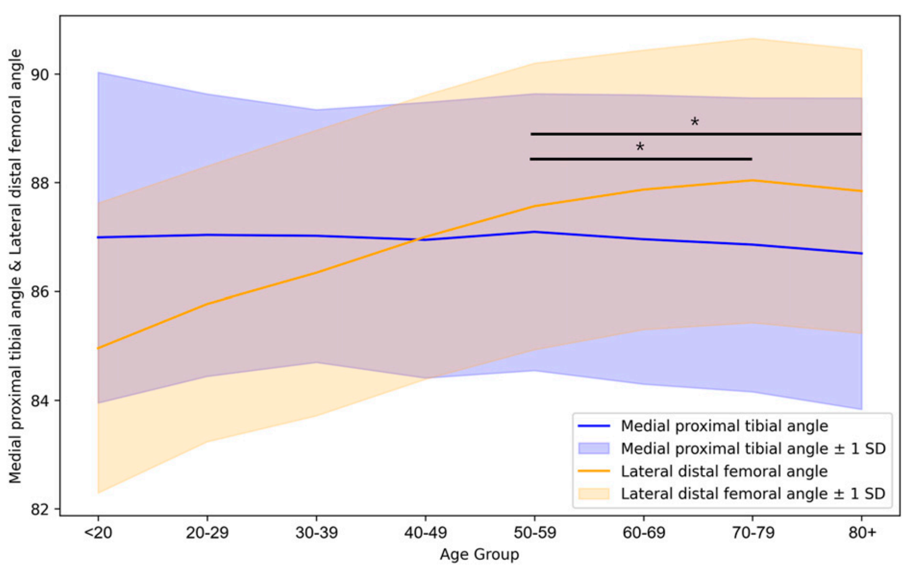

Fig. 6

Plot of the medial proximal tibial angle and lateral distal femoral angle across age groups. The lines represent the mean values, and the shading represents values within 1 standard deviation (SD) of the mean. *Significant differences ($p < 0.05$) in the lateral distal femoral angle were found between individuals in their 50s and those in their 70s and those ≥80 years old.

Furthermore, the results underscore the importance of considering the CPAK type as an estimate of the pre-arthritic alignment in reconstructive knee surgery.

Appendix

eA Supporting material provided by the authors is posted with the online version of this article as a data supplement at jbjs.org (http://links.lww.com/JBJS/I342). ■

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