Title

Posterior tibial slope is independent of coronal plane knee alignment and needs to be assessed to determine knee phenotype

Abstract

Introduction

Personalized total knee arthroplasty (TKA) alignment has gained popularity due to its perceived advantages. Results are usually reported using the Coronal Plane Alignment of the Knee (CPAK) system. However, CPAK takes into account only the coronal plane alignment and ignores posterior tibial slope (PTS), a key determinant of sagittal plane alignment impacting knee biomechanics and clinical outcomes. It is not known if the distribution of PTS is similar across different CPAK types and if there is a variation across ethnicities. This study investigates the relationship between PTS and CPAK classifications.

Materials and Methods

A retrospective analysis was conducted on long-leg anteroposterior and lateral radiographs from 420 patients (747 legs) of Japanese, Chinese, and Indian origin. Coronal alignment was classified using CPAK, and sagittal alignment was assessed via PTS.

Results

Weak or no correlations between CPAK and PTS was identified across all groups, indicating that coronal and sagittal alignments are largely independent.Significant ethnic differences were observed in PTS with Indian patients showing the steepest PTS and

Japanese the flattest. Sex differences in PTS were significant only among Chinese patients.

Conclusion

PTS varies significantly amongst different ethnicities and has no correlation to individual CPAK types. The independence of sagittal and coronal alignments underscores the need for a biplanar approach in knee phenotype assessment and personalized TKA strategies.

Keywords:

Posterior tibial slope (PTS), *Osteoarthritis, Knee Joint, Arthroplasty, Replacement Coronal alignment, sagittal alignment*

Introduction

In the total knee arthroplasty (TKA), patient dissatisfaction following an uncomplicated primary procedure is well documented, with an average rate of 10 to 20%(1). To decrease this dissatisfaction, concepts of personalized alignment targets has been developed and implemented in practice(2-4). Indeed only up to 17% of native knees have a neutral mechanical alignment (MA) i.e. a straight leg where the line joining the centre of the femoral head to the centre of the ankle passes through the centre of the intercondylar notch (5, 6).

To reproduce the native knee's pre-arthritic alignment, various classification systems have been developed which label each knee's phenotype, thereby providing the surgeon targets to aim for to try and reproduce the native knee anatomy. In 2018, Lin proposed a classification system comprising 27 potential knee phenotypes, of which only five were considered clinically relevant(7). Variations on this framework have since been introduced, including the Functional Knee Phenotype classification(2), the Coronal Plane Alignment of the Knee (CPAK) classification(5), mCPAK classification(8) and the Coronal Extraarticular Deformity Phenotype (CEDP) classification(9). A key limitation of these classification systems is that they categorize knees based solely on their coronal plane alignment. In reality, a replaced knee rarely fails due to coronal malalignment alone, and several studies have shown equal or even better implant survival in patients with coronal plane malalignment to those with well-aligned TKA(10, 11).

To date, all classification systems have relied on plain radiographs, which are two-dimensional (2D) representations of three-dimensional (3D) anatomical structures. However, these 2D images can be misleading due to observer variability, technical limitations (radiographs are not always perfectly standardized), subtle anatomical differences between individuals, and rotational or projectional variations. Recent reviews have further highlighted the substantial variability in methods used for 3D leg alignment analysis, underscoring the lack of consensus on how to derive axes and joint orientations from 3D bone models(12). This variability prevents the establishment of universal reference values and makes it difficult to compare alignment parameters across studies(13-15). Importantly, to achieve a comprehensive, biplanar assessment of knee alignment, sagittal plane alignment must also be evaluated in addition to coronal plane alignment. However, it remains unclear whether there is any correlation between sagittal and coronal plane alignment in native knees.The primary aim of this research is to investigate whether a correlation exists between coronal and sagittal knee alignment. The secondary aim is to analyse and understand differences in posterior tibial slope (PTS) among various racial groups.

Materials and Methods

Patient enrollment

This study was retrospective analysis of prospectively collected data from three centers. The institutional review board of the ethics committee at the individual institution approved the study. The inclusion criteria included consecutive series of Japanese, Chinese and Indian patients who visited their respective outpatient hospital for knee-related complaints and underwent weight-bearing anterior to posterior long-leg radiograph (APLLR), either a full-length lateral x-ray or a full-length CT scan as part of their radiological assessment. Accurate assessment of PTS is only possible on a full-length radiographic image as demonstrated by Hees and Garra(16, 17). The accuracy and precision of PTS measurements improve as the length of the tibia used to define the anatomical axis increases. Because when anterior tibial bowing is pronounced, PTS measured on short knee radiographs tends to be underestimated compared to measurements taken using the full-length knee radiographs.

For the Chinese and Indian patients, weight-bearing APLLR and long-leg lateral views including hip, knee, and ankle joints were available. For the Japanese patients, weight-bearing APLLR and full lower limb CT were available.

We collected anonymized imaging data at a single centre and measurements were independently performed by two orthopaedic specialists. We excluded patients with incomplete datasets and those with evidence of previous bony trauma or surgery.

Radiograph measurements

Coronal alignment

For coronal alignment, the coronal plane alignment of the knee (CPAK) classification was selected and the angles required for this classification were measured accordingly(5).The mechanical hip-knee-ankle (mHKA) angle was defined as the angle formed by the intersection of the mechanical axes of the femur and tibia. The mechanical lateral distal femoral angle (mLDFA) was defined as the lateral angle between the femoral mechanical axis and the joint line of the distal femur. The mechanical medial proximal tibial angle (mMPTA) was defined as the medial angle between the tibial mechanical axis and the joint line of the proximal tibia(5). The arithmetic hip-knee-ankle angle (aHKA), as described by Macdessi(18)is calculated from the mLDFA and the mMPTA. Calculate aHKA and the knee joint line obliquity (JLO) based on formulas; aHKA = mMPTA - mLDFA, and JLO = mMPTA + mLDFA(5).

Sagittal alignment

The medial proximal tibial joint orientation line was defined as the tangent to the deepest point of the medial plateau concavity(19) for the measurement of medial PTS. The proximal circle was positioned just distal to the tibial tuberosity, and the distal circle was positioned just proximal to the distal tibial diaphysis (20). The anatomical posterior proximal tibial angle (aPPTA) was measured as the acute angle formed between the perpendicular to the lateral tibial central anatomical axis and the proximal tibial joint orientation line. PTS was defined as 90°- aPPTA. (Fig.1)

Patients were categorized into classifications based on their PTS which were divided into intervals of four degrees as follows: Group A: less than 4.0°, Group B: 4.1° to 8.0°, Group C: 8.1° to 12.0°, Group D: 12.1° to 16.0°, Group E: 16.1° to 20.0° and Group F: greater than 20.0°. These intervals were determined arbitrarily as part of the study design, as no established precedent for PTS grouping exists in the current literature.

Data Analyses

Data are presented as mean values with standard deviation (SD). Group differences were evaluated using one-way analysis of variance (ANOVA) and Fisher's exact test with Bonferroni post hoc analysis. All statistical analyses were performed using EZR software (http://www.jichi.ac.jp/saitama-sct/SaitamaHP.files/statmed.html) (21).

The necessary sample size for inter-observer and intra-observer reliability calculations was based on Zou's method, using an intraclass correlation coefficient (ICC) effect size of 0.8, a two-tailed significance level (α) of 0.05, and a power (β) of 0.8(19). Inter- and intra-observer reliability was assessed using a random two-way, single-measure ICC (ICC(2,1)) to evaluate agreement between observations (22). According to Koo and Li's guidelines(22). ICC values above 0.9 indicate excellent reproducibility, values between

0.75 and 0.9 indicate good reproducibility, and values between 0.5 and 0.75 indicate moderate reproducibility.(22). We confirmed the ICC for the Japanese and Chinese groups, which had a larger number of cases. The relationship between CPAK and PTS was evaluated for each ethnicity using Spearman's rank correlation coefficient and Pearson's product-moment correlation coefficient.

Results

We included in 147 Japanese patients (288 legs: 148 men and 140 women), with a mean age of 43.9 ± 19.6 years, 200 Chinese patients (324 legs: 71 men and 253 women), with a mean age of 63.8 ± 10.3 years and 73 Indian patients (135 legs: 60 men and 75 women), with a mean age of 29.2 ± 4.0 years. There were significant differences among the three ethnic groups in terms of PTS: Japanese: 7.9 ± 3.6°, Chinese: 10.3 ± 4.9°, Indian: 13.8 ± 4.1°. Post hoc analyses further revealed significant differences between each ethnicity (Table.1).

One-way ANOVA demonstrated significant differences among the three groups in age, mLDFA, mMPTA, aHKA, JLO and PTS. Post hoc analyses showed no significant differences between Chinese and Indian in mLDFA, mMPTA, aHKA and JLO.

Fisher's exact test identified significant differences among the three ethnicities in terms of sex, CPAK, and PTS classification. Post hoc analyses showed significant differences between each pair of countries in CPAK and PTS classification. However, regarding sex, there was no significant difference between Japanese and Indian groups.

Inter- and intra-observer reliability for PTS were 0.91(95% Confidence interval (CI): 0.85 – 0.93, $P<0.001$) in PTS of Japanese patients. Inter- and intra-observer reliability for PTS were 0.85(95% CI: 0.50 – 0.96, $P<0.001$) and 0.76(95% CI: 0.65 – 0.84, P<0.001), respectively in PTS of Chinese patients. Both ICC values indicated good reproducibility.

We analyzed the distribution of PTS across CPAK types in all three ethnic groups. (Table.2)

For all patients combined, the Spearman correlation coefficient between CPAK and PTS was 0.056 (p = 0.114), and the Pearson correlation coefficient was 0.038 (p = 0.283) indicating very low and non-significant correlations.

In Japanese patients, Spearman correlation coefficient was -0.153 (p = 0.076), and the Pearson correlation coefficient was -0.176 (p = 0.041). While both indicated a very weak negative correlation, only the Pearson correlation reached statistical significance.

In Chinese patients, Spearman correlation coefficient was -0.086 (p = 0.123), and the Pearson correlation coefficient was -0.092 (p = 0.100), both extremely low and not statistically significant.

In Indian patients, Spearman correlation coefficient was -0.153 (p = 0.076), and the Pearson correlation coefficient was -0.176 (p = 0.041). Again, the Spearman result suggested a weak, non-significant negative correlation, whereas the Pearson result showed a weak negative correlation with statistical significance.

Mean PTS values and PTS classification rates are presented in Table 3, and detailed PTS distributions across CPAK categories are shown in Table 4. (Table.3, 4)

Discussion

This study demonstrated significant differences in PTS across different ethnicities and found no meaningful correlation between coronal and sagittal plane alignment. These findings suggest that evaluating coronal plane alignment alone as a measure of knee phenotype is insufficient and, in some cases, potentially misleading.

Accurate and reproducible assessment of both coronal and sagittal alignment is essential in TKA, including during preoperative planning, surgical execution, and postoperative avaluation(23).

Historically, surgical strategies have focused predominantly on coronal alignment, guided by phenotyping classifications such as the CPAK system(5). While CPAK offers a structured framework, its two-dimensional nature limits its ability to capture the complexity of three-dimensional alignment and segmental deformities. Previous reports have highlighted CPAK's limited accuracy in identifying joint line apex(24) and inability to differentiate femoral from tibial deformities(25), raising concerns about its clinical applicability in surgical planning(26).

To address these limitations, never systems such as the Functional Knee Phenotype Classification(27) have been developed, incorporating coronal variables like HKA, femoral mechanical angle (FMA), and tibial mechanical angle (TMA). This system allows for up to 125 possible phenotypes(2) and has shown better correlation with anatomical variability across diverse populations, offering greater reproducibility and clinical relevance(28-30). Similarly, the CEDP classification(9) builds upon CPAK by accounting for segmental coronal derformities, emphasizing the importance of individual femoral and tibial alignment in surgical decision making.

Despite these advances, sagittal alignment has received comparatively little attention, and currently, no well-established measurement methods or classification systems exist for sagittal plane assessment. To help address this gap, we employed a standardized measurement method for PTS, ensuring inter- and intra-observer reliability by using full-length radiographs and normalizing tibial length. Prior work by Garra(17) demostrated that PTS measurements can vary with tibial length, with the most consistent results achieved using half-tibial images.

Ethnic Differences

This study revealed significant differences among the three ethnic groups—Japanese, Chinese, and Indian—in both CPAK and PTS classifications. Post hoc analyses showed that these differences were significant between each ethnic pair. Our findings are consistent with a previous systematic review, which reported notable variation in CPAK classification prevalence across geographic regions, including Europe, North America, Asia, and Australia(31). Furthermore, a separate study examining PTS in 250 cadaveric specimens reported that African Americans/Blacks and Asian Americans generally have steeper PTS compared to Whites, with nearly 25% of individuals demonstrating clinically significant slopes outside the commonly referenced 6°–12° range, regardless of sex or age(32). imilarly, our research confirmed marked differences in PTS angles and classifications among Asian countries, with one-way ANOVA showing significant differences in mLDFA, mMPTA, aHKA, JLO, and PTS among the three countries. Notably, however, no significant differences were found between Chinese and Indian patients in mLDFA, mMPTA, aHKA, and JLO.

Relationship Between PTS and CPAK

Although a weak negative Pearson correlation between PTS and CPAK was observed in Indian patients, the practical impact appears minimal, and overall, no clinically meaningful correlation between PTS and CPAK was identified in any group. These findings suggest that PTS and CPAK represent independent variables influenced by ethnicity but unrelated to each other in terms of alignment behavior. Importantly, this independence highlights the need to evaluate sagittal plane alignment separately from coronal plane classifications when characterizing knee phenotypes or planning surgical interventions.

Clinical Implications, Limitations, and Future Directions

Taken together, these results underscore the importance of incorporating sagittal plane parameters, particularly posterior tibial slope (PTS), into knee phenotyping systems to improve surgical planning and optimise clinical outcomes. As personalised alignment strategies in total knee arthroplasty (TKA) continue to evolve, future research should aim to develop comprehensive classification systems that integrate both coronal and sagittal alignment to more accurately reflect the three-dimensional complexity of the knee. Such integrated systems may ultimately allow for more precise preoperative planning, better restoration of native knee kinematics, and improved patient satisfaction.

However, several limitations of this study should be acknowledged. First, this was a retrospective study, which may carry inherent selection bias and limit the ability to establish causal relationships. Second, the study population was restricted to three Asian ethnic groups (Japanese, Chinese, and Indian), which may limit the generalisability of the findings to other racial or geographic populations. Third, although inter- and intra-observer reliability was assessed and found to be good, radiographic measurement of PTS can still be influenced by subtle variations in imaging technique, positioning, or anatomical landmarks, which may introduce measurement error. Fourth, the study did not assess the clinical outcomes or functional impact of the observed anatomical variations; thus, the clinical relevance of the differences in PTS and their interaction with CPAK remains speculative. Finally, the cross-sectional design precludes evaluation of temporal changes or longitudinal effects, such as how these alignment patterns might evolve over time or influence the risk of osteoarthritis or implant survival.

Addressing these limitations in future research, including prospective, multi-ethnic, and longitudinal studies with functional outcome measures, will be crucial to refining knee phenotyping systems and advancing personalised approaches in TKA.

Conclusions

PTS and CPAK exhibit variations across different races in Asia; however, no significant correlation was identified between these two parameters. To validate these findings and further explore potential racial differences, a larger study involving data from additional racial groups is necessary.

Table.1 demographic data in three ethnicities

	Japanese	Chinese	Indian	p
Man / Woman	148 (51.4%) 140 (48.6%)	72 (22.4%) 249 (77.6%)	60 (44.4%) 75 (55.6%)	< 0.01**
Age	43.9 ± 19.6	63.8 ± 10.3	29.2 ± 4.0	< 0.001*
mLDFA (°)	86.1 ± 2.8	87.7 ± 3.7	87.5 ± 2.2	< 0.001*
mMPTA (°)	84.2 ± 3.0	86.9 ± 2.9	87.2 ± 2.6	< 0.001*
aHKA (°)	-1.8 ± 4.5	-0.8 ± 5.6	-0.3 ± 3.2	0.003*
JLO (°)	170.3 ± 3.7	174.6 ± 3.7	174.7 ± 3.6	< 0.001*
CPAK				
I	136 (47.2%)	74 (23.1%)	26 (19.3%)	
II	112 (38.9%)	77 (24.0%)	51 (37.8%)	
III	34 (11.8%)	94 (29.3%)	21 (15.6%)	
IV	1 (0.3%)	40 (12.5%)	14 (10.4%)	< 0.001**
V	1 (0.3%)	20 (6.2%)	17 (12.6%)	
VI	4 (1.4%)	15 (4.7%)	6 (4.4%)	
VII	0	1 (0.3%)	0	
PTS (°)	7.9 ± 3.6	10.3 ± 4.9	13.8 ± 4.1	< 0.001*
A	36 (12.5)	31 (9.7)	1 (0.7)	
B	119 (41.3)	71 (22.1)	9 (6.7)	
C	96 (33.3)	118 (36.8)	36 (26.7)	< 0.001**
D	32 (11.1)	67 (20.9)	45 (33.3)	
E	2 (0.7)	24 (7.5)	40 (29.6)	
F	3 (1.0)	10 (3.1)	4 (3.0)	

mLDFA: mechanical lateral distal femoral angle

mMPTA: mechanical medial proximal tibial angle

aHKA: arithmetic hip-knee-ankle angle

JLO: joint line obliquity

CPAK: coronal plane alignment of the knee

PTS: posterior tibial slope

* One-way ANOVA

** Fisher's exact test

Table.2 The distribution of PTS across CPAK types

A)

The distribution of PTS across CPAK types was analyzed in patients from three ethnicities

		CPAK							
		1	2	3	4	5	6	7	total
PTS	A (~ 4.0°)	3.15	2.90	1.77	0.50	0.50	0.50	0.00	9.40
	B (4.1~8.0°)	10.21	8.70	4.41	1.64	1.39	0.76	0.25	27.36
	C (8.1~12.0°)	10.84	11.73	6.43	2.52	1.09	0.88	0.13	33.62
	D (12.1~16.0°)	5.42	5.80	4.54	1.00	1.51	0.76	0.00	19.03
	E (16.1~20.0°)	2.90	1.64	1.64	1.39	0.50	0.25	0.00	8.32
	F (20.1° ~)	1.01	0.63	0.13	0.50	0.00	0.00	0.00	2.27
	Total (%)	33.53	31.40	18.92	7.55	4.99	3.15	0.38	100.00

CPAK: coronal plane alignment of the knee

PTS: posterior tibial slope

B)

Japanese

		CPAK							
		1	2	3	4	5	6	7	total
PTS	A (~ 4.0°)	5.56	4.17	1.74	0.00	0.35	0.69	0.00	12.51
	B (4.1~8.0°)	19.79	16.67	4.86	0.00	0.00	0.00	0.00	41.32
	C (8.1~12.0°)	15.97	12.85	3.47	0.35	0.00	0.69	0.00	33.33
	D (12.1~16.0°)	4.51	5.21	1.39	0.00	0.00	0.00	0.00	11.11
	E (16.1~20.0°)	0.35	0.00	0.35	0.00	0.00	0.00	0.00	0.70
	F (20.1° ~)	1.03	0.00	0.00	0.00	0.00	0.00	0.00	1.03
	Total (%)	47.21	38.90	11.81	0.35	0.35	1.38	0.00	100.00

CPAK: coronal plane alignment of the knee

PTS: posterior tibial slope

C)

Chinese

		CPAK							
		1	2	3	4	5	6	7	total
PTS	A (~ 4.0°)	1.88	2.50	2.81	1.25	0.62	0.62	0.00	9.68
	B (4.1~8.0°)	3.75	5.31	5.62	3.75	1.88	1.56	0.31	22.18
	C (8.1~12.0°)	7.50	11.88	11.56	3.12	1.25	1.25	0.00	36.56
	D (12.1~16.0°)	5.94	3.12	6.25	1.88	2.50	1.25	0.00	20.94
	E (16.1~20.0°)	3.12	0.62	2.50	1.25	0.00	0.00	0.00	7.49
	F (20.1° ~)	0.97	0.62	0.31	1.25	0.00	0.00	0.00	3.15
	Total (%)	23.16	24.05	29.05	12.50	6.25	4.68	0.31	100.00

CPAK: coronal plane alignment of the knee

PTS: posterior tibial slope

D)

Indian

		CPAK							
		1	2	3	4	5	6	7	total
PTS	A (~ 4.0°)	0.00	0.00	0.00	0.00	0.74	0.00	0.00	0.74
	B (4.1~8.0°)	0.00	1.48	2.22	0.00	2.22	0.74	0.00	6.66
	C (8.1~12.0°)	5.19	11.85	1.48	3.70	3.70	0.74	0.00	26.66
	D (12.1~16.0°)	4.47	14.07	8.89	1.48	2.96	1.48	0.00	33.35
	E (16.1~20.0°)	8.89	8.15	2.96	5.19	2.96	1.48	0.00	29.63
	F (20.1° ~)	0.74	2.22	0.00	0.00	0.00	0.00	0.00	2.96
	Total (%)	19.29	37.77	15.55	10.37	12.58	4.44	0.00	100.00

CPAK: coronal plane alignment of the knee

PTS: posterior tibial slope

Table.3 CPAK classification rate in three ethnicities (%)

	I	II	III	IV	V	VI	VII	VIII	IX
Japanese	47.2	38.9	11.8	0.3	0.3	1.4	0	0	0
Chinese	23.1	24.1	29.1	12.5	6.3	4.7	0.3	0	0
Indian	19.3	37.8	15.6	10.4	12.6	4.4	0	0	0

CPAK: coronal plane alignment of the knee

Table.4 PTS classification rate in three ethnicities (%)

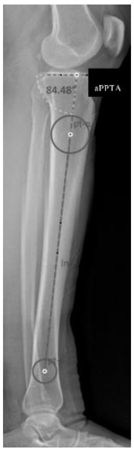
	A (~ 4.0°)	B (4.1~8.0°)	C (8.1~12.0°)	D (12.1~16.0°)	E (16.1~20.0°)	F (20.1° ~)
Japanese	12.5	41.3	33.3	11.1	0.7	1.0
Chinese	9.7	22.1	36.8	20.9	7.5	3.1
Indian	0.7	6.7	26.7	33.3	29.6	3.0

PTS: posterior tibial slope

Figures

Fig.1 posterior tibial slope measurement in long limb radiographs

Proximal tibial joint orientation line. The cross marks the deepest point of the medial plateau concavity. The line is tangent to the curve at the deepest point. Measurements of anatomical posterior tibial slope.



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