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Lateral deviation of the prosthetic trochlear angle relative to the quadriceps vector in mechanically aligned total knee arthroplasty: a radiological and clinical analysis

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Abstract

Background Patellofemoral alignment, particularly the relationship between the prosthetic trochlear angle (PTA) and the quadriceps vector (QV), is emerging as a new determinant of postoperative outcomes in total knee arthroplasty (TKA).

Questions/Purposes To evaluate the deviation of the PTA relative to the QV in mechanically aligned (MA) TKAs and determine its association with patient-reported outcomes.

Methods A retrospective cohort study was conducted including patients who underwent primary posterior-stabilized MA TKA between February 2019 and February 2020, with a minimum follow-up of five years. Long-leg radiographs were used to assess coronal alignment parameters and measure PTA deviation relative to the QV. The deviation angle was calculated by comparing the PTA, defined as 6–7° valgus to the distal joint line, with the QV defined from the anterior inferior iliac spine to the trochlear groove center.

Results The final cohort included 222 patients (mean age at the time of surgery: 66.0 ± 7.5 years; 81.9% female). The mean lateral deviation of the PTA relative to the QV was $5.6 \pm 2.4^\circ$, with only one patient showing medial deviation. Correlation analysis revealed a significant association between PTA-QV deviation and final hip-knee-ankle (HKA) angle ($r=0.672$, 95% CI 0.417 – 0.559, $p<0.001$), but no correlation with functional scores or CPAK subtypes.

Conclusion Prosthetic trochlear angle exhibits a lateral deviation from the native quadriceps vector in total knee arthroplasty patients operated with a mechanical alignment strategy. This deviation is only associated with the final HKA angle, but not with poorer outcomes.

Keywords Total knee arthroplasty, Mechanical alignment, Patellofemoral joint, Quadriceps vector

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Introduction

Total knee arthroplasty (TKA) has evolved significantly with the advent of new alignment philosophies aimed at improving functional outcomes and patient satisfaction [11, 21]. Traditionally, mechanical alignment (MA) has been the gold standard, positioning the femoral component perpendicular to the mechanical axis with a fixed prosthetic trochlear angle (PTA) of approximately 6° valgus [7, 9, 13]. The native distal femur is not a symmetric structure and shows substantial inter-individual variability in mediolateral dimensions, distal femoral shape, condylar curvature radii, and trochlear morphology and orientation. Off-the-shelf femoral components, by contrast, necessarily simplify this anatomy and typically incorporate a fixed valgus prosthetic trochlear angle (commonly ~ 6°) with a standardized trochlear geometry. These implants cannot reproduce the full spectrum of native distal femoral asymmetry in every patient [3, 13].

The quadriceps line of force, or the quadriceps vector (QV), specifically characterizes the direction of quadriceps pull acting on the patella, a concept refined over the last decade by recognizing that this vector is directed by the quadriceps muscle from the anterior inferior iliac spine (AIIS) to the patella and further to the tibial tuberosity [20]. The interaction between the QV and the PTA significantly influences the distribution of forces within the knee joint, particularly during dynamic movements [7, 13]. While the concept of the QV has been extensively studied in native knees, its role in prosthetic knees, especially in the context of various alignment strategies, remains less understood.

The patellofemoral alignment, particularly the relationship between the PTA and the quadriceps vector, has been recently introduced as a new determinant of optimal outcomes, especially in kinematically aligned (KA) TKAs [7]. Lateral deviation of the prosthetic trochlear

angle relative to the quadriceps vector is clinically relevant, as it influences patellar tracking, contact pressures, and extensor mechanism mechanics. Howell et al. have shown that deviations from the ideal alignment, especially medial deviation of the PTA relative to the QV, can result in patellar maltracking, altered patellofemoral kinematics, and inferior patient-reported outcomes [7, 9]. Simulated studies have stipulated that mechanically aligned (MA) TKAs would lead to a more lateral deviation of the PTA and this may promote better functional outcomes in these patients [7, 17]. The aim of this study therefore is to evaluate the range of deviation of the PTA from the quadriceps vector in mechanically aligned TKAs and to determine whether the relative alignment of the PTA influences patient-reported outcomes. Although mechanical alignment aims to restore neutral coronal limb alignment, it does not explicitly account for patellofemoral kinematics or the relationship between the trochlear orientation and the quadriceps line of action. It was therefore hypothesized that, even in mechanically aligned total knee arthroplasty, systematic deviations between the prosthetic trochlear axis and the quadriceps vector may occur and that such deviations may not be associated with inferior patient-reported outcomes despite residual patellofemoral malalignment.

Methods

Study design

This retrospective cohort study was carried out following approval from the Local Ethics Committee (approval number XXX). Patients treated with a primary total knee arthroplasty (TKA) at our institution between 1st of February 2019 and 1st of April 2020 were eligible for this study. Inclusion criteria were patients who had undergone a primary posterior stabilized TKA, had complete radiological and clinical data (including pre-operative and postoperative long-leg radiographs), and with a minimum follow up of 5 years. Patients with any prior ipsilateral hip or knee surgery, extra-articular deformity, inflammatory arthritis, or inadequate radiographic quality were excluded to minimize confounding factors affecting alignment and patellofemoral mechanics. Only patients with complete clinical and radiological follow-up at a minimum of five years were included in the final analysis.

The local institutional registry scan identified 294 patients operated between the mentioned timeframes. Of those, 21 were excluded for a history of previous surgery, 5 patients had deformities in the osseous structures surrounding the knee, 29 patients had been lost to follow up or had died and 17 patients had incomplete data. A cohort of 222 patients was included in the final analysis (Fig. 1).

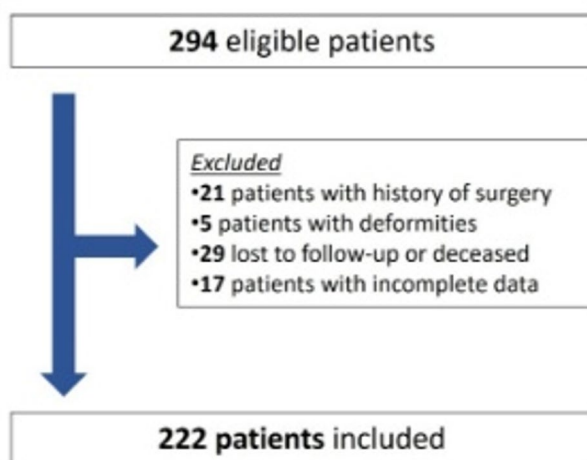


Fig. 1 Flowchart of the study cohort

Surgical procedure and rehabilitation

Patients were operated in supine position under spinal or general anesthesia. A team of 5 high volume (>200 arthroplasty cases/year) surgeons with more than 10 years of experience in joint reconstruction performed the procedures over the study period. A tourniquet was routinely used, and the surgery followed an ‘extension gap first’ approach. The knee joint was accessed with a medial parapatellar incision, and the patella was dislocated laterally. Osteophytes were removed and the anterior cruciate ligament was resected. The knee was then dislocated, and the tibial cutting guide was placed so that the cut would be perpendicular to the tibial mechanical axis. Upon completing the tibial cut the femoral canal was accessed with an intramedullary guide and the distal cut was performed according to preoperative planning. The extension gap was assessed. Anterior and posterior cuts followed with the implant positioned in a routine 3 degrees of external rotation.

After bone cuts were completed gap balance was checked and achieved through minimal ligamentous release, when needed. The joint was irrigated, and a posterior stabilized cemented implant was used in all cases. Three different implants were used throughout the years at our institution (*Vanguard TKA & NexGen PS* Zimmer-Biomet, Warsaw, Indiana, USA, *Superadius PS*, Trauson/Stryker, Changzhou, China) and the choice was generally dependent on availability. The tourniquet was released, and bleeding control was performed. The layers were closed in standard fashion, and the procedure was concluded with a compressive bandage.

All patients were allowed full weight-bearing the following morning with additional range of motion and strengthening exercises. They were discharged on the 2nd postoperative day with a list of home exercises and recommendations, and they were referred to the physiotherapy department for routine rehab.

Radiological and clinical evaluation

A detailed radiological evaluation is performed for each patient during the preoperative workup consisting of weight-bearing long leg radiographs as well as antero-posterior and lateral knee views. The radiological analysis was repeated on the first postoperative day with long leg radiographs taken routinely between the first and second postoperative month.

On long leg radiographs the following measurements were performed on preoperative and postoperative views: the medial proximal tibial angle (MPTA), the mechanical lateral distal femoral angle (mLDFA) and hip-knee-ankle angle (HKA). The knees were classified according to the coronal plane alignment of the knee (CPAK) for further additional analyses (Fig. 2).

On postoperative views only, the deviation to the quadriceps vector (QV) was measured. To define the QV, a line was drawn connecting the anterior inferior iliac spine (AIIS) to the distal end of the trochlear groove at the center of the femoral component. Additionally, a line was positioned for the prosthetic trochlear angle (PTA) at various degrees of valgus relative to a vertical line drawn perpendicular to the distal joint line of the femoral component, following the manufacturer’s specified PTA orientation (valgus varying between 6 and 7 degrees, according to manufacturer’s information). A negative PTA-QV angle indicated medial deviation of the PTA relative to the QV, thereby reducing the patient’s Q-angle, while a positive PTA-QV angle indicated lateral deviation, increasing the patient’s Q-angle (Fig. 3). All measurements were performed by two different examiners independent of each other and only the mean values were used in the final analysis.

Clinical evaluation was conducted using the Knee Society Total Score (KSS) and Functional Score (KSS-F) [11], the Forgotten Joint Score (FJS) [4], a Visual Analog Scale (VAS) and degrees of flexion and extension measured with manual goniometer. All clinical scores were

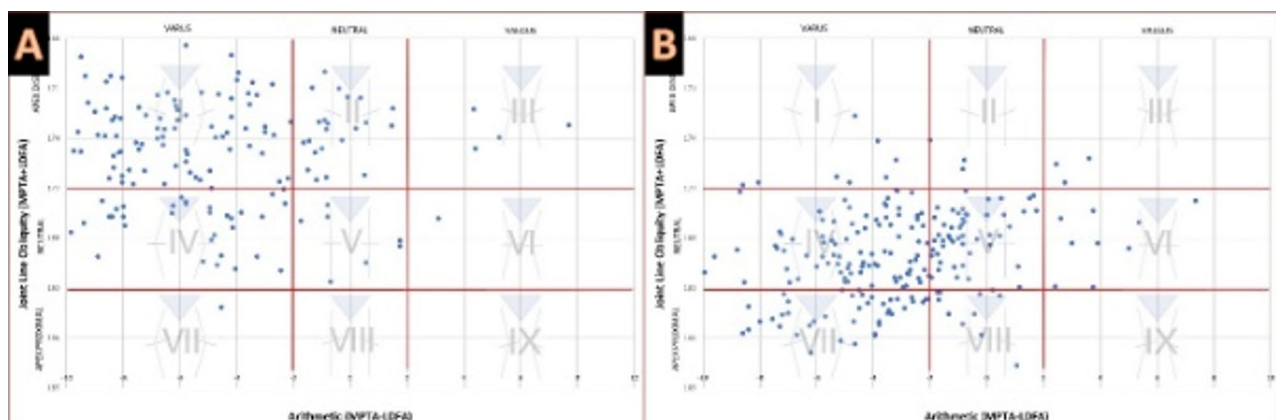


Fig. 2 Preoperative **A** and postoperative **B** alignment distribution for the mechanically aligned TKAs according to the CPAK classification

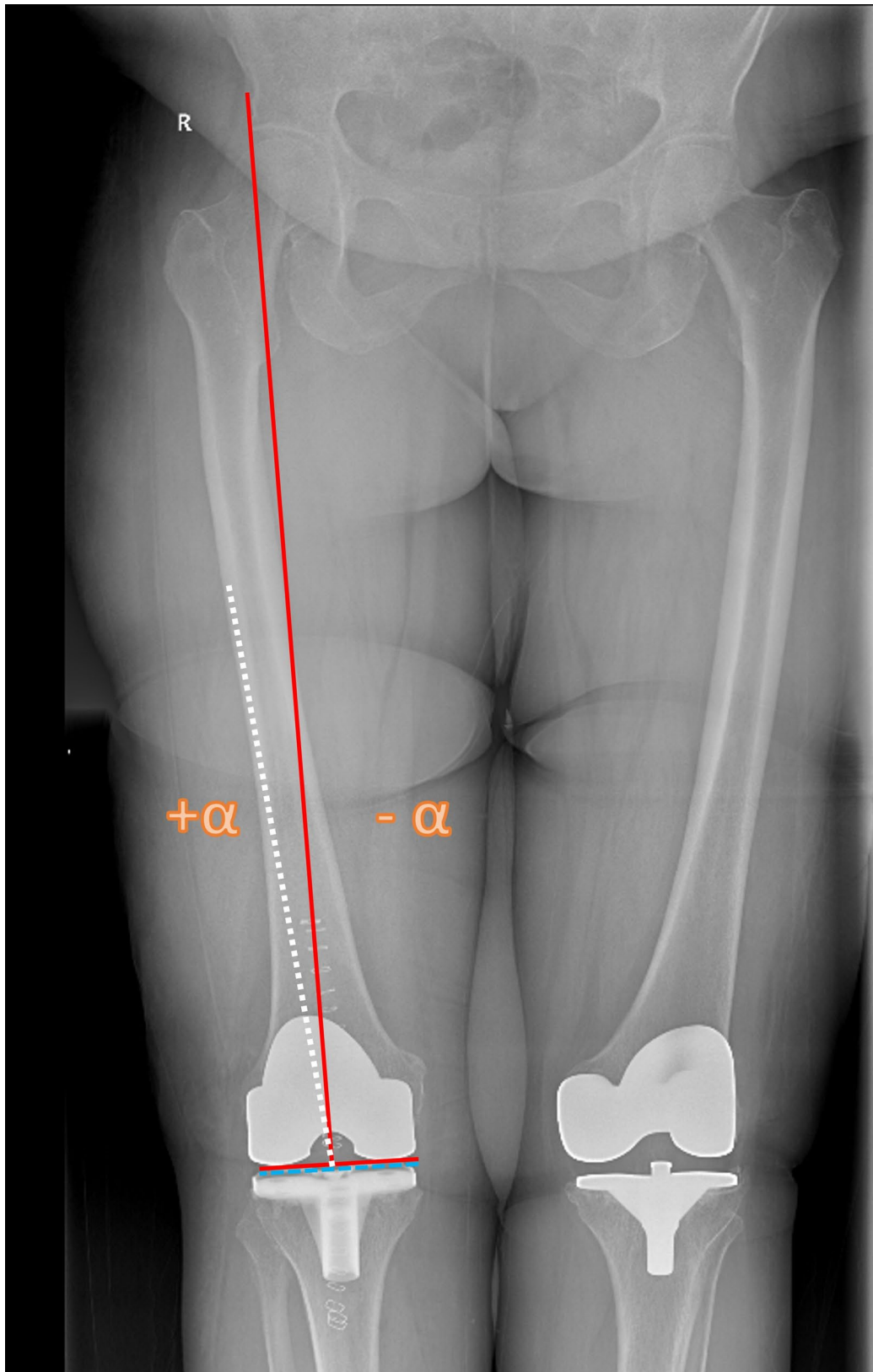


Fig. 3 Measurement of the quadriceps vector on standing long leg radiographs. The continuous line depicts the quadriceps vector (a line connecting the anterior inferior iliac spine to the distal end of the trochlear groove at the centre of the femoral component) and the dotted line depicts the implants prosthetic trochlear angle (in this case 7 degrees). A lateral deviation was denoted as a positive value (+ α) while a medial deviation was denoted as a negative one (- α)

Table 1 Demographic characteristics of the study groups

	Study Cohort (n=222)
Age	
Mean ± SD	66.0±7.5
Median (min-max)	66 (48–87)
Sex	
Men	40 (18.1%)
Women	182 (81.9%)
Kellgren-Lawrence Classification	
2	7 (3.1%)
3	83 (37.4%)
4	132 (59.5%)
Body Mass Index	
Mean ± SD	32.0±5.1
Median (min-max)	31.3 (18.0–50.6)
Side (%)	
Right	109 (49.1%)
Left	113 (50.9%)
Follow-up period (months)	
Mean ± SD	63.5±3.5
Median (min-max)	64.0 (60.0–73.0)

gathered during outpatient visits by the and the scores obtained at the last follow-up were included in the final analysis.

Data analyses

Statistical analyses were conducted using the Statistical Package for Social Sciences (SPSS) software, version 22.0, for Windows (IBM, Chicago, Illinois, USA). Numeric variables are presented as means with standard deviations, while categorical data are reported as frequencies and percentages. Since the data did not meet the criteria for normal distribution according to the Shapiro–Wilk test, non-parametric methods were employed. Specifically, the Mann-Whitney U test, a non-parametric alternative to the independent two-sample t-test, was utilized to assess relationships between parameters. Categorical variables were analyzed using the Chi-square test. Interobserver reliability was assessed using the Intraclass Correlation Coefficient. An ICC value of 0.996 showed optimal reliability between the observers. Correlation analysis was performed between the various QV deviation angles and clinical scores for the overall cohort as well as for the subtypes of the CPAK classification using the Spearman Correlation test. A p-value < 0.05 was accepted as statistically significant.

Results

Demographics

Mean age at the time of surgery for the included cohort was 66.0±7.5 with the great majority being women (n=182, 81.9%). The patients were followed up for an

Table 2 Postoperative clinical scores of the stud cohorts as recorded on their last follow-up visit

	Mechanically Aligned(n=222)
Knee Society Score	
Mean ± SD	83.2 ± 12.2
Median (min-max)	87.0 (41 – 100)
Knee Society Score - Functional	
Mean ± SD	81.4 ± 17.8
Median (min-max)	90.0 (20 – 100)
Forgotten Joint Score	
Mean ± SD	71.6 ± 17.6
Median (min-max)	77.0 (38 – 100)
Flexion angle (degrees)	
Mean ± SD	112.2 ± 9.9
Median (min-max)	120 (90 – 130)
Extension angle (degrees)	
Mean ± SD	0.2 ± 1.3
Median (min-max)	0.0 (-5 – 10)
QV deviation angle	
Mean ± SD	5.6 ± 2.4
Median (min-max)	5.7 (-1.1 – 13.1)
QV quadriceps vector	

Table 3 Preoperative and postoperative alignment characteristics of the study groups

	Preoperative CPAK	Postoperative CPAK
I	114 (51.4%)	4 (1.8%)
II	24 (10.8%)	2 (0.9%)
III	5 (2.3%)	3 (1.4%)
IV	65 (29.3%)	95 (42.8%)
V	10 (4.4%)	52 (23.4%)
VI	2 (0.9%)	11 (4.9%)
VII	2 (0.9%)	43 (19.4%)
VIII	0 (0.0%)	12 (5.4%)
IX	0 (0.0%)	0 (0.0%)

CPAK coronal plane alignment of the knee

average of 63.5±3.5 months. Demographic data is presented in Table 1.

Clinical Scores

Patient reported outcome measures, recorded as KSS, KSS-F and FJS showed good overall clinical outcomes during the follow up period. Of the study cohort, 166 patients had KSS scores ≥ 80 (i.e. excellent scores) while 14.4% and 10.8% of the patients reported fair and good results respectively. The prosthetic trochlear angle showed a mean lateral deviation of 5.6 ± 2.4 degrees from the quadriceps vector, with only one patient exhibiting a negative (medial) deviation. Relevant clinical data is presented in Table 2.

Table 3. Postoperative clinical scores of the stud cohorts as recorded on their last follow-up visit.

Overall alignment

Alignment evaluation during the preoperative phase showed that 51.4% of patients had a varus lower limb alignment and an apex distal joint line obliquity (CPAK I) with the CPAK type IV (varus alignment and neutral joint line obliquity) being the second most frequent alignment type (29.3%). During the postoperative phase, the most frequent alignment type was that of CPAK IV (42.8%) followed by type V (23.4%) with a neutral lower limb alignment and a neutral joint line obliquity. All data regarding preoperative and postoperative alignment types are presented in Table 3; Fig. 2.

Mean preoperative mLDFA was 90.7 ± 3.0 while mean postoperative value was 92.1 ± 2.3 degrees. The MPTA mean values during the preoperative and postoperative phase, on the other hand, were 83.9 ± 3.4 and 89.0 ± 1.7 respectively (Table 4). The change in the distal femur, directly affecting the deviation of the PTA relative to the QV, was towards a varus in most of the patients. Of the study cohort, 126 patients (56.8%) had a distal femur with a varus alignment (mLDFA < 85 degrees) while postoperatively 178 patients (80.2%) showed a varus distal femoral line (i.e. a femoral component placed in varus, relative to the mechanical line) (Fig. 4).

Deviation from the quadriceps vector

Correlation analysis showed an expected significant correlation between the deviation angle from the quadriceps

Table 4 Preoperative and postoperative individual radiological parameters of the stud cohort

	n = 222
Preoperative mLDFA	
Mean \pm SD	90.7 \pm 3.0
Median (min-max)	90.9 (81.6–101.5)
Postoperative mLDFA	
Mean \pm SD	92.1 \pm 2.3
Median (min-max)	92.2 (85.2–99.0)
Preoperative MPTA	
Mean \pm SD	83.9 \pm 3.4
Median (min-max)	84.1 (68.6–94.1)
Postoperative MPTA	
Mean \pm SD	89.0 \pm 1.7
Median (min-max)	89.1 (84.0–94.4)
Change in mLDFA (Δ)	
Mean \pm SD	1.3 \pm 2.8
Median (min-max)	1.3 (-8.2–12.4)
Change in MPTA (Δ)	
Mean \pm SD	5.0 \pm 3.5
Median (min-max)	4.7 (-2.3–25.8)

mLDFA mechanical lateral distal femoral angle, MPTA – medial proximal tibial angle

vector and the final HKA angle ($r = 0.672$, 95% CI 0.417–0.559, $p < 0.001$). Aside from the expected correlation between PTA–QV deviation angle and final HKA angle, PTA–QV deviation was not significantly correlated with

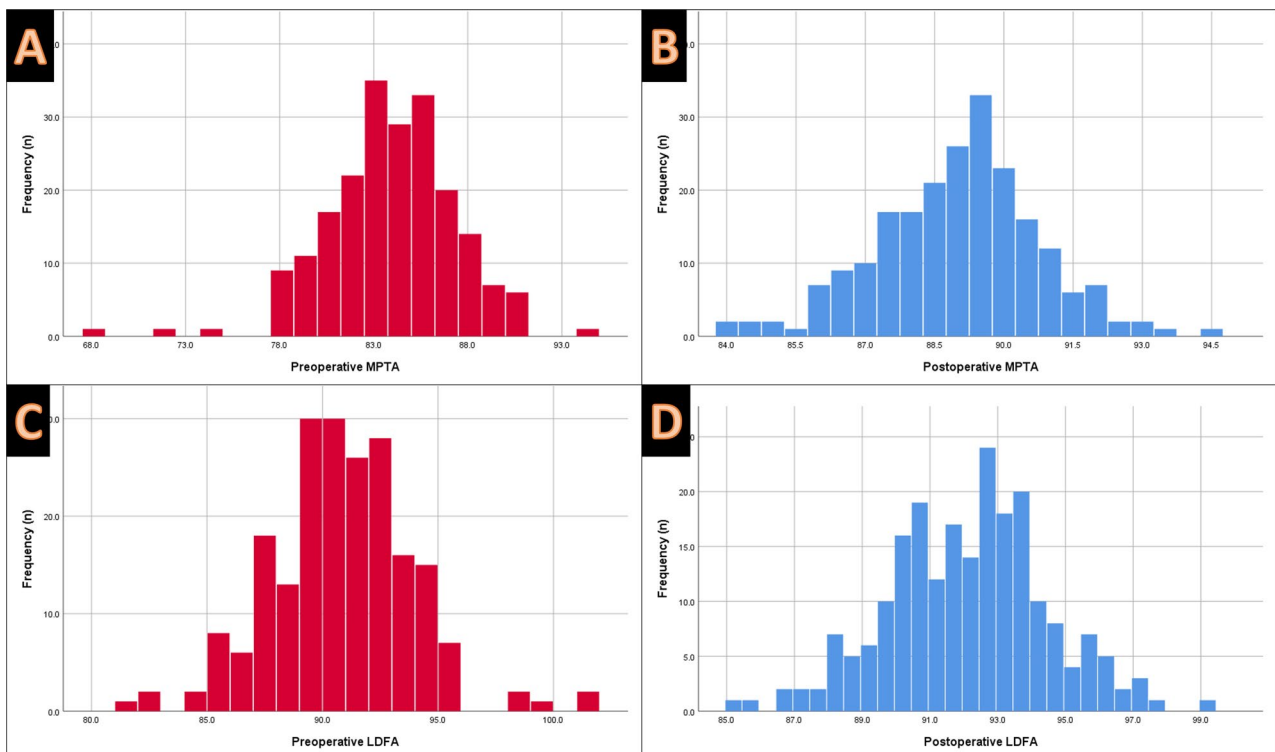


Fig. 4 Preoperative and postoperative LDFA (A&B) and MPTA (C&D) values of the study cohort and their frequencies

Table 5 Correlation analysis between the quadriceps vector deviation angle and the study variables

		Final HKA angle	Δ HKA	KSS	KSS-F	FJS	Flexion angle
Quadriceps vector deviation angle	Spearman correlation	0.672	-0.095	-0.005	-0.002	-0.038	0.009
	p-value	<0.001	0.167	0.938	0.978	0.574	0.896

HKA Hip-Knee-Ankle angle, KSS Knee Society Score, FJS Forgotten Joint Score

Δ HKA, Knee Society Score, KSS-Function, Forgotten Joint Score, or flexion angle (Table 5).

Discussion

The most important finding of this study is that the prosthetic trochlear angle exhibits a lateral deviation from the native quadriceps vector in mechanically aligned TKA. In our cohort, the magnitude of PTA–QV deviation was correlated with final HKA angle, but it was not associated with patient-reported outcomes at last follow-up. Although a positive PTA–QV deviation effectively increases the functional Q-angle, the two measurements are conceptually distinct. The traditional Q-angle reflects the global extensor mechanism alignment and is influenced by both femoral and tibial anatomy [8], whereas the PTA–QV deviation specifically quantifies the relationship between the prosthetic trochlear orientation and the quadriceps line of force at the distal femur [7]. As such, PTA–QV deviation represents an implant-specific, patellofemoral parameter that refines the classical Q-angle concept and may better explain patellofemoral behavior following total knee arthroplasty.

With the growing adoption of navigation and robotic-assisted TKA, surgeons can reproduce planned target angles more accurately and with fewer outliers than conventional instrumentation, improving restoration of postoperative limb alignment [24]. Clinical studies and meta-analyses show smaller deviations from the intraoperative plan for coronal component positioning and sagittal parameters, together with improved control of rotational (axial) alignment—an important consideration as modern alignment philosophies increasingly rely on precise, patient-specific targets [11].

Mechanical alignment has long been the cornerstone of TKA, aiming to position the femoral and tibial components perpendicular to the mechanical axis to achieve a neutral hip–knee–ankle (HKA) angle of 180°. Numerous studies have reported satisfactory clinical outcomes and implant survival rates ranging from 89% to 99% at 10 years and 85% to 97% at 20 years of follow-up [12, 14]. However, recent research has highlighted that up to 20% of patients remain dissatisfied after TKA, potentially due to the uniform application of MA disregarding individual anatomical variations [16, 23]. This persistent dissatisfaction suggests that factors beyond global limb alignment may contribute to suboptimal results, including patellofemoral kinematics and trochlear–extensor mechanism congruence. Investigating the relationship between the

prosthetic trochlear angle and the quadriceps vector in mechanically aligned TKAs is therefore clinically relevant, as it allows identification of systematic patellofemoral deviations inherent to MA principles and helps determine whether these deviations are clinically tolerated or may contribute to residual symptoms. Personalized alignment strategies, such as kinematic alignment (KA) and functional alignment, which seek to restore the patient's native joint line and knee kinematics have shown promising results [10, 15, 17, 22]. The results of this study are, similar to previous ones, showed optimal clinical results with the mechanical alignment strategy obtaining good-to-excellent results in over 83.3% of the patients. Recent comparative studies indicate that alternative alignment strategies may further optimize functional outcomes in selected populations [25].

Femoral component rotation plays a critical role in aligning the quadriceps mechanism, and appropriate external rotation has been shown to improve patellar tracking and reduce lateral patellofemoral contact pressures [5]. The spherical axis, on the other side, provides a robust descriptor of femoral kinematics and flexion–extension behavior, whereas femoral component rotation directly influences trochlear orientation and patellofemoral engagement. Quadriceps malalignment, as reflected by deviation between the PTA and the QV, represents a patellofemoral-specific construct that is not fully captured by global kinematic descriptors such as the spherical axis [19]. Accordingly, femoral rotation, spherical axis orientation, and quadriceps vector alignment should be regarded as interrelated but distinct contributors to patellofemoral mechanics after total knee arthroplasty.

Traditional approach has mandated that this angle aligns with the QV after a mechanically aligned TKA, however, this standardized approach does not account for individual anatomical variations, leading to potential mismatches between the PTA and the patient's native QV, especially in kinematically aligned TKAs. After all, we still kinematically implant femoral components designed for mechanical alignment. Howell et al. [7] showed that patients had better FJS scores when the angle of the prosthetic trochlea was lateral to the quadriceps vector in kinematically aligned knees. Medial deviation was correlated with poorer results. More recently, Jeremic et al. [9] showed that a medial deviation of the 6° PTA relative to the QV occurred in over half of the cases, particularly among certain coronal plane alignment of the knee (CPAK) types. Although recent evidence

suggests that deviation from native CPAK phenotypes may negatively impact outcomes [25], the present study was not designed to assess CPAK preservation or migration, and our findings should therefore be interpreted independently of CPAK-based outcome frameworks. In the present study, all mechanically aligned knees, except from one case, exhibited lateral deviation of the PTA relative to the QV and the deviation as well as the FJS scores seemed not to be correlated with any of the subtypes of the CPAK classification. This is due to the fact that the majority of patients had a distal femoral varus preoperatively. When augmented with femoral components postoperatively, the deviation amount from the QV only increases. It is a known fact in the literature that eastern and Asian populations have a higher prevalence of bowed femora as well as varus knee alignment [1, 18]. In response to these findings, some implant designs have evolved to incorporate 'S'-shaped trochlear designs, aiming to more closely replicate the complex geometry of the native trochlear groove.

Recent advancements in total knee arthroplasty have increasingly emphasized the importance of the patellofemoral joint congruence, what is often referred to as the "third compartment" of the knee [2]. Traditionally, surgical focus has been on balancing the flexion and extension gaps, sometimes overlooking the patellofemoral articulation, however, growing awareness of the third compartment's role has led to a reevaluation of surgical techniques and implant designs to enhance patient outcomes [6]. Aligning the PTA with the QV, or apparently keeping it laterally deviated, ought to be only one of the goals to achieve and studies have shown that improper management of this compartment can lead to anterior knee pain and compromised function, highlighting the need for precise balancing during surgery [7, 9].

The results of this study should be interpreted in light of its limitations. The study is limited by its retrospective design, which inherently carries a risk of selection bias, and by the absence of a comparative cohort treated with an alternative alignment strategy. Consequently, causal inferences regarding the effect of PTA–QV deviation on clinical outcomes should be made with caution. We tried to diminish these limitations by including almost all patients operated in the defined time period. Additionally, radiographic measurements on plain X rays can often be misleading since they depend heavily on the way the radiographs are performed and on who performs them. While the QV and the preoperative trochlear angle, despite having been reported to be parallel to each other, might therefore slightly change depending on the radiograph. To mitigate this, we measured both the QV and the PTA with the subsequent deviation on a single postoperative optimal long leg radiograph. The use of three different posterior-stabilized implant designs

with varying post-cam geometries represents a source of heterogeneity that may have influenced femoral rollback, axial rotation, and patellofemoral kinematics. In addition, the routine application of 3° of external rotation relative to the posterior condylar axis may have resulted in unintended internal or external rotation relative to the patient-specific trochlear and quadriceps anatomy, thereby affecting patellar tracking. An additional limitation is the lack of skyline views to confirm better patellar tracking in patients with a lateral deviation of the PTA. Preoperative patient-reported outcome scores were not available for all patients, precluding assessment of postoperative improvement. Finally, our cohort was predominantly female, limiting thus the generalizability of the results. Future studies with comparing and larger cohorts will provide the opportunity to make more accurate comments on the deviation from the quadriceps vector and on its potential effect on clinical results.

Conclusion

Prosthetic trochlear angle exhibits a lateral deviation from the native quadriceps vector in total knee arthroplasty patients operated with a mechanical alignment strategy. This deviation is only associated with the final HKA angle, but not with poorer outcomes.

Ethical Review Committee Statement

The Local Ethics Committee (Number 1 Ethics Committee of Ankara City Hospital, decision nr. TADEB-1-25-1267) has approved the study design.

Authors' contributions

EV: Conceived the idea, wrote the main text, ES: Revised and wrote part of the original draft, supervised the study, HU: Revised and wrote part of the original draft, supervised the study, WC: Revised and wrote part of the original draft, supervised the study, FF: Gathered data, performed measurements and statistics, BAS: Gathered data, performed measurements and statistics, AG: Gathered data, performed measurements and statistics, AF: Contributed patients, mentored the study and revised the final draft.

Funding

No funding was available for this study.

Data availability

Data regarding this manuscript will be made available upon request from the Editor.

Declarations

Ethics approval and consent to participate

The study was conducted in accordance with the Declaration of Helsinki and the study design was approved by the Local Ethics Committee of Ankara Bilkent City Hospital (decision nr. TADEB-1-25-1267). All patients included in this study gave their written and verbal consent to participate and for their data to be used in this study.

Consent for publication

All patients included in this study gave their written and verbal consent to participate and for their data to be used in this study.

Competing interests

The authors declare no competing interests.

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