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Impact of Alignment Strategies on Trochlear Morphology Following Robotic-Assisted Total Knee Arthroplasty

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Abstract: ***Purpose**: Restoration of native trochlear morphology remains a challenge in total knee arthroplasty (TKA), especially given the variability in coronal alignment strategies, including mechanical alignment (MA), adjusted mechanical alignment (aMA), kinematic alignment (KA), and functional alignment (FA). Emerging evidence suggests that kinematic-based techniques may better replicate native trochlear orientation compared to mechanical approaches [1, 2]. This study aimed to evaluate the impact of these four alignment techniques on postoperative trochlear orientation in patients undergoing robotic-assisted TKA (RAS-TKA). We hypothesised that FA would demonstrate the fewest deviations from native trochlear parameters. **Methods**: A prospective analysis was conducted on 96 patients undergoing RAS-TKA using a single prosthetic design. Preoperative planning incorporated both mechanical and kinematic alignment considerations. Intraoperative alignment was achieved through aMA in 68 patients and FA in 28 patients following robotic balancing protocols. Preoperative transverse CT imaging was employed to assess native anatomical parameters, including posterior condylar axis (PCA), lateral trochlear inclination (LTI), sulcus angle (SA), and anterior trochlear line (ATL) angle. Postoperative measurements were derived from intraoperative robotic software and photographic implant analysis. Deviation from native orientation was quantified, with outliers defined as ≥3° deviation. Trochlear dysplasia was classified by LTI <12°1. **Results**: The median native values were: PCA 2°, LTI 18°, SA 137°, and ATL 4°. Outlier prevalence for LTI ranged from 47% to 60% across alignment types, with KA producing the fewest outliers, followed by FA, aMA, and MA. Similar trends were observed for ATL deviation (outlier range: 40.5%–85%). SA exhibited the highest alteration, with 81% of cases classified as outliers. Only LTI under KA alignment did not significantly differ from the native anatomy (p > 0.05). **Conclusion**: Significant deviation from native trochlear orientation occurs after RAS-TKA irrespective of alignment strategy. Kinematic alignment yielded the most accurate replication of lateral trochlear inclination, although a substantial rate of outliers remained. The standardised design of contemporary implants may necessitate trade-offs between flexion balance and anatomical restoration of the trochlea. Further longitudinal studies are warranted to determine the clinical impact of these anatomical compromises on patellofemoral function and patient outcomes.***

Level of Evidence: Level II, prospective cohort study.

Keywords: alignment, patellofemoral joint, robotic-assisted, total knee arthroplasty, trochlea orientation

1. Introduction

Achieving optimal coronal alignment has historically been the cornerstone of total knee arthroplasty (TKA) since its widespread adoption, with mechanical alignment (MA) considered the traditional standard [1, 2]. MA aims to position the femoral and tibial components perpendicular to the mechanical axes, thereby achieving a neutral alignment relative to the ground. This approach has been associated with reliable long-term survivorship and consistent clinical outcomes [3, 4].

However, kinematic alignment (KA), which aligns the prosthesis based on the patient's native joint kinematics across three anatomical axes, has emerged as a viable alternative. Proponents argue that KA may better restore physiological knee motion and soft tissue tension1. Despite theoretical benefits, both mid-term and long-term studies, along with national joint registry data, suggest that clinical outcomes between MA and KA are broadly equivalent [6, 7, 8].

The advent of robotic-assisted surgery (RAS) has enabled a more nuanced application of alignment philosophies. By offering real-time intraoperative feedback and precise bone preparation, RAS has facilitated the rise of alternative strategies such as adjusted mechanical alignment (aMA) and functional alignment (FA). In aMA, the procedure starts with MA as a reference, but intraoperative modifications are made to one or both components, typically within a 3° threshold, to accommodate individual soft-tissue laxity. FA, on the other hand, represents a more personalized approach that integrates principles of both MA and KA, adjusting implant positioning dynamically based on intraoperative soft-tissue envelope characteristics. This method seeks to avoid ligament releases while achieving balanced flexion-extension gaps [10, 11].

Despite growing interest in these techniques, one key limitation across all alignment strategies is the use of standardized, off-the-shelf prosthetic components. These implants have a predetermined trochlear design, limiting the extent to which native trochlear anatomy can be replicated, particularly in the axial plane3. Although intraoperative RAS software enables visualization of trochlear component positioning, achieving a flexion gap balance often takes precedence, potentially at the expense of anatomical restoration of the femoral trochlea4.

Recent three-dimensional (3D) analyses have shown that both MA and KA often fail to reproduce native trochlear orientation [12, 14]. To date, no large-scale comparative study has evaluated the impact of four alignment strategies—MA, aMA, KA, and FA—on trochlear morphology restoration following RAS-TKA. This knowledge gap is clinically relevant, as the patella articulates over the femoral trochlea along a secondary kinematic axis located proximal and anterior to the surgical transepicondylar axis [15, 16, 17].

This prospective study aims to assess how different alignment techniques influence the restoration of native trochlear orientation in patients undergoing RAS-TKA. By employing preoperative CT-based planning and intraoperative robotic data, we compare the performance of MA, KA, aMA, and FA strategies in replicating native trochlear angles. We hypothesize that FA will result in the fewest deviations from the native trochlear orientation, thus providing the most anatomically accurate reconstruction.

2. Methods

This prospective study was conducted at a high-volume arthroplasty center performing approximately 400 total knee arthroplasties (TKAs) annually, with an even distribution between robotic-assisted surgery (RAS) and computer-assisted techniques. Patients undergoing primary RAS-TKA using the MAKO system (Stryker, Kalamazoo, MI, USA) between March 2023 and February 2024 were included. A total of 96 consecutive patients met the inclusion criteria. Surgeries were performed or directly supervised by single fellowship-trained orthopedic surgeon.

Alignment Strategies Mechanical alignment (MA) and kinematic alignment (KA) were preoperatively simulated using MAKO 3D planning software based on CT imaging [27]. Femoral and tibial resections followed manufacturer-recommended protocols using the most distal and dorsal points as references. The surgeon reviewed and approved all plans to ensure accuracy with preoperative imaging.

For MA, both components were aligned perpendicular to the mechanical axis in the coronal plane, with the femoral component externally rotated by 3° relative to the posterior condylar axis (PCA). Bone resections were standardized to 7 mm from the more prominent condyle.

KA followed principles of unrestricted kinematic alignment [28], preserving native joint lines by removing equal amounts of bone (7 mm) from both condyles without adjustment for soft-tissue tension. Both MA and KA positions were recorded intraoperatively.

In aMA, minor adjustments (within 3°) from MA were made intraoperatively based on virtual gap balancing as per established protocols [29]. FA, in contrast, began from a KA-based template and was intraoperatively adjusted to achieve soft tissue balance without releases where possible. However, in valgus knees where the hip–knee–ankle (HKA) angle exceeded 3°, targeted soft tissue releases were employed to restore mechanical balance [30].

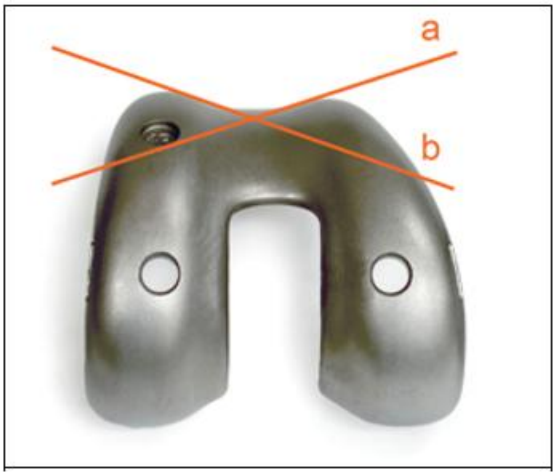
Posterior osteophytes were routinely excised in all cases. All patients received the cementless Triathlon TKA prosthesis (Stryker).

Radiographic Assessments

Preoperative Imaging Preoperative HKA angle, lateral distal femoral angle, and medial proximal tibial angle were measured using standardized full-length standing anteroposterior radiographs and classified by phenotype [31]. All patients underwent lower limb CT scans following MAKO protocol [27]. Transverse CT sections at the level of maximal epicondylar prominence were used to calculate the surgical transepicondylar axis-PCA angle (TEA-PCA), lateral trochlear inclination (LTI) angle, sulcus angle (SA), and anterior trochlear line (ATL) angle [26, 32, 33]. Trochlear dysplasia was defined as LTI <12° [32, 34].
Measurements were independently performed by two trained evaluators with a minimum interval of two weeks between readings. All angle values were rounded to the nearest integer.

Implant Analysis

Since the manufacturer did not supply the relevant CAD files, the ATL, SA, and LTI angles of the Triathlon femoral implant were measured using high-resolution axial photographs captured with a 56mm f/1.2 lens (Fujifilm, Minato, Japan). These images were analyzed using professional photo-editing software (Adobe Lightroom, Adobe Inc., USA), a validated technique in prior biomechanical studies [35]. An architectural engineer (M. K.) conducted two independent measurement sessions, separated by four weeks. The measured implant angles were: SA 143°, ATL 2°, and LTI 18°.



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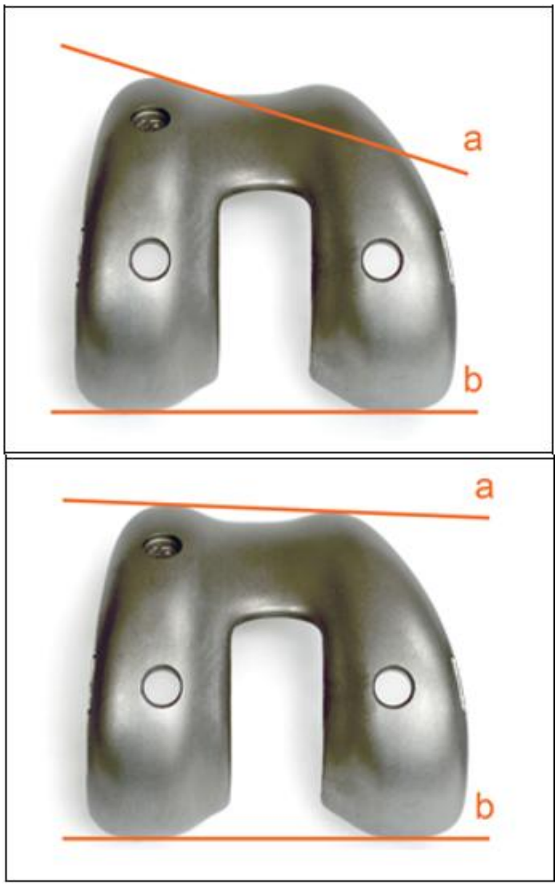

Figure 1: Photographic analysis with the lines added. Angles were measured between line a and b.

Postoperative Assessments

Postoperative ATL and LTI angles were derived by combining intraoperative PCA-referenced implant positioning data with photographic implant angle measurements. SA remained constant as determined by the fixed prosthesis design. Differences between pre-and postoperative values were calculated. Outliers were defined as deviations ≥3° in any angular parameter [31].

Patients with preoperative trochlear dysplasia (LTI <12°) were excluded from LTI outlier classification, given the necessity of angle correction in such cases [32, 34].

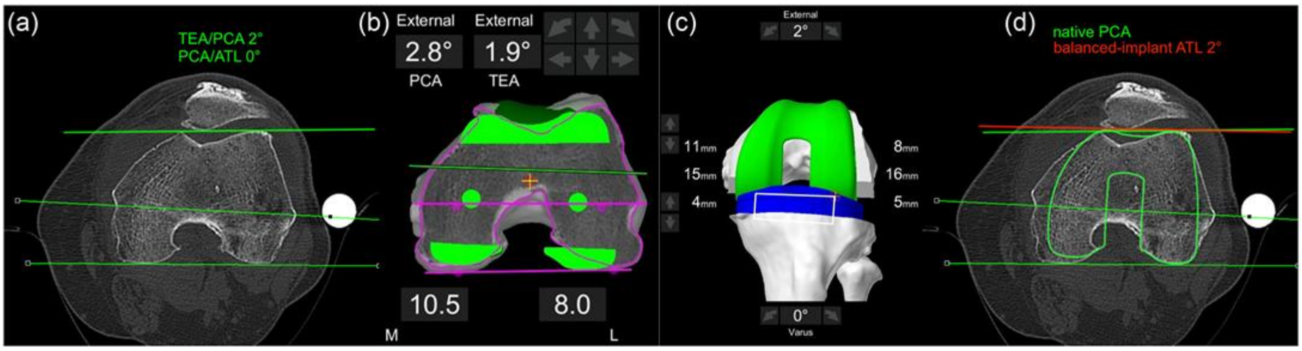

Figure 2: Measurement technique of the alteration of trochlear orientation, on the example of anterior trochlear line (ATL). (a) Native computed tomography (CT) measurements. (b) Implant position, mechanical alignment (MA), prebalancing, using the intraoperative software. (c) Balancing using the intraoperative software. (d) Position after balancing (adjusted mechanical alignment), using the CTscans. The change in ATL was calculated using the implant ATL, adjusted for the change of the position postbalancing (in this case, 2°). PCA, posterior condylar axis; TEA, transepicondylar axis.

Statistical Analysis

Data normality was evaluated using the Shapiro–Wilk test. Normally distributed variables are presented as mean ± standard deviation (SD), and non-normally distributed variables as median with interquartile range (IQR). Between-group comparisons were performed using independent t-tests or Mann–Whitney U tests, as appropriate. Categorical data were analyzed using the χ^2 test. Linear regression assessed the influence of phenotypic alignment on native trochlear geometry.

While a formal power analysis was not conducted, previous studies have demonstrated significant trochlear differences using sample sizes as small as 10–13 knees [29, 30], and all measurements in this cohort reached statistical significance [36].

All statistical analyses were performed using SPSS version 28.0.1.0 (IBM Corp., Armonk, NY, USA). A p-value <0.05 was considered statistically significant.

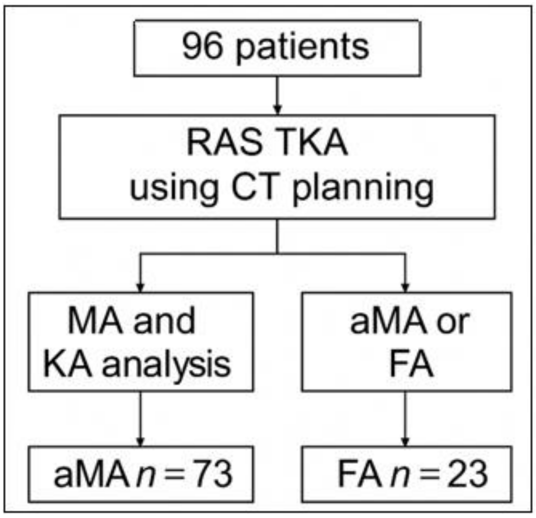

Figure 3: Flow chart of patient inclusion and group distribution. aMA, adjusted mechanical alignment; CT, computed tomography; FA, functional alignment; KA, kinematic alignment; MA, mechanical alignment; TKA, total knee arthroplasty.

3. Results

Following the application of inclusion criteria, 96 patients were analyzed (Figure 3). The mean patient age was 68.3 ± 9.2 years, with a BMI of 28.1 ± 9.8. Of these, 49.5% were female. The mean hip–knee–ankle (HKA) angle was 175.5° ± 5.6, femoral mechanical angle (FMA) was 91.6° ± 2.6, and tibial mechanical angle (TMA) was 87.1° ± 2.9. Distribution according to the phenotype classification is presented in Table 1 [31].

All 96 patients were planned and analyzed using both mechanical alignment (MA) and kinematic alignment (KA) through preoperative planning. As per the study protocol, each patient underwent robotic-assisted TKA using either adjusted mechanical alignment (aMA) or functional alignment (FA), and were analyzed in these subgroups accordingly (Figure 1).

Patients receiving FA were significantly younger than those receiving aMA ($p < 0.05$); however, no significant differences were observed in gender distribution or in preoperative alignment parameters (HKA, FMA, and TMA) between these groups (Table 2).

Table 1: Phenotype classification distribution.

Classification	Count (n)	Percentage (%)
HKA Phenotypes		
NEU HKA 0°	6	6.00%
VAL HKA 3°	6	6.5% (rounded)
VAL HKA 6°	4	4.5% (rounded)
VAL HKA 9°	3	3.5% (rounded)
VAL HKA 12°	0	0.5% (round to 0)
VAL HKA 15°	0	0.5% (round to 0)
VAR HKA 3°	20	21%
VAR HKA 6°	27	28%
VAR HKA 9°	19	19.5% (rounded)
VAR HKA 12°	8	8.00%
VAR HKA 15°	1	1.50%
VAR HKA 21°	0	0.5% (round to 0)

Native Trochlear Orientation

The native TEA–PCA angle had a median of 2° [IQR 3°], lateral trochlear inclination (LTI) was 18° [IQR 7°], sulcus angle (SA) was 137° [IQR 12°], and anterior trochlear line (ATL) was 4° [IQR 4°]. There was no significant association between any of the preoperative phenotype classifications and native trochlear orientation measurements (Table 3) [31, 32].

Table 2: Group differences.

Variable	aMA (n = 64)	FA (n = 32)	p-Value
Mean Age (± SD)	69.0 ± 10.7 years	65.7 ± 8.7 years	0.04
Female (%)	33 (51.6%)	13 (40.6%)	n. s.
BMI (± SD)	29.4 ± 8.5	27.8 ± 7.5	n. s.
HKA (± SD)	175.6° ± 5.4°	175.5° ± 6.1°	n. s.
FMA (± SD)	91.5° ± 2.4°	93.2° ± 2.9°	n. s.
TMA (± SD)	87.2° ± 2.7°	86.7° ± 3.4°	n. s.

Table 3: Linear regression of phenotype measurements and native trochlear orientation.

Phenotype	SA β (95% CI)	p Value	LTI β (95% CI)	p Value	ATL β (95% CI)	p Value
HKA	0.200 (−0.137 to 0.184)	n. s.	0.044 (−0.058 to 0.111)	n. s.	0.044 (−0.203 to 0.387)	n. s.
FMA	0.013 (−0.035 to 0.042)	n. s.	0.020 (−0.083 to 0.063)	n. s.	0.008 (−0.079 to 0.088)	n. s.
TMA	−0.009 (−0.143 to 0.127)	n. s.	0.070 (−0.077 to 0.230)	n. s.	−0.009 (−0.143 to 0.127)	n. s.

Measurement Reliability

Intraobserver reliability for trochlear angle measurements was high with a mean intraobserver intraclass correlation coefficient (ICC) of 0.92, and interobserver ICC of 0.88. For implant measurements, the intraobserver ICC was 0.98. The phenotype analysis also demonstrated strong reliability with intraobserver and interobserver ICC values of 0.97.

Lateral Trochlear Inclination (LTI)

Trochlear dysplasia, defined as LTI < 12°, was identified in 22 patients (11.0%) [33, 34]. KA and FA demonstrated a lower number of LTI outliers than MA and aMA (Table 4). No statistically significant difference was found between KA and FA (p = n. s.) or between MA and aMA (p = n. s.). However, KA significantly reduced the number of outliers compared to both aMA ($p = 0.02$) and MA ($p = 0.01$). In contrast, FA did not produce a statistically significant reduction in outliers compared to MA or aMA.

Compared to the native LTI, only KA (p = n. s.) preserved the median angle without significant alteration. In contrast, MA ($p < 0.001$), FA ($p = 0.04$), and aMA ($p < 0.001$) significantly altered the LTI relative to the native anatomy [30, 33].

Table 4: Lateral trochlear inclination angle values and outliers.

Alignment Strategy	Outliers (n/N, %)	Median LTI Value (°) [IQR]
MA	58/96 (60.4%)	15 [0]
KA	45/96 (46.9%)	18 [0]
aMA	57/96 (59.4%)	15 [2]
FA	21/96 (21.9%)	15 [4]

Anterior Trochlear Line (ATL)
A demonstrated the lowest percentage of ATL outliers, whereas MA showed the highest proportion ($p < 0.001$) (Table 5). A statistically significant difference in outlier rates was also observed between KA and FA ($p < 0.001$).

Compared to the native ATL, all four alignment strategies—MA, KA, FA, and aMA—significantly altered the median ATL (all $p < 0.001$) [30].

Table 5: Anterior trochlear line angle values and outliers

Alignment Strategy	Outliers (n/N, %)	Median ATL Value (°) [IQR]
MA	82/96 (85.4%)	−1 [0]
KA	39/96 (40.6%)	2 [0]
aMA	79/96 (82.3%)	−1 [2]
FA	69/96 (71.9%)	−1 [4.5]

Sulcus Angle (SA)
The implant SA was constant at 143°, resulting in an 81% outlier rate when compared to native values. The difference between the native and implant median SA was statistically significant ($p < 0.001$), consistent across all alignment strategies. Given the fixed trochlear design of the implant, SA could not be individualized to match native morphology [29, 30, 35, 36].

4. Discussion

The most important finding of the present study is that use of an off-the-shelf femoral implant results in a high number of outliers in trochlear orientation when compared to the native trochlear anatomy. This was consistent regardless of the alignment strategy employed, and is primarily attributable to the uniform design of the femoral component, which lacks trochlear morphologic individualization [7, 29, 30, 32]. Notably, the lowest number of outliers was produced by kinematic alignment (KA). Furthermore, KA was the only strategy that did not significantly alter the lateral trochlear inclination (LTI) angle when compared to native anatomy. Therefore, the initial hypothesis—that functional alignment (FA) would best restore native trochlear morphology—was refuted.

Robotic-assisted TKA allows for highly precise, individualized component positioning, which facilitates implementation of personalized alignment strategies such as KA and FA [19, 22, 25, 37]. However, the current evidence on whether this translates into superior clinical outcomes remains limited and inconsistent [19, 22, 33]. This is likely due to the heterogeneity of existing studies, which compare alignment philosophies (MA, KA, FA, etc.) with or without robotic assistance, using various protocols and definitions [4, 19]. To address this, some authors recommend that comparative alignment studies should be performed using the same robotic delivery system in a blinded and standardized manner [25, 41].

FA is a hybrid alignment technique that builds on KA principles but permits fine-tuned intraoperative adjustments according to the patient’s soft-tissue envelope [25]. While guidelines for femoral and tibial positioning in FA are defined [25], actual implementation varies across centers. In contrast to inverse KA, which modifies only the femur [39], FA can adjust both the tibial and femoral components to achieve soft-tissue balance. In our cohort, FA was performed with the femur initially placed in a KA-derived position, but the need for flexion gap balancing led to additional component rotations. This likely explains why FA generated more trochlear outliers than unrestricted KA, although fewer than MA and aMA.

While unmodified KA preserves native rotational axes, it may result in undesirable varus or valgus positioning, leading to increased medial load or coronal mismatch, particularly in patients with extreme native deformities [20, 34]. Thus, even though KA best reproduces native trochlear orientation, its mechanical implications on other compartments of the knee must be considered.

Shatrov et al. evaluated MA, KA, and FA using the same robotic platform as this study, measuring trochlear translation and depth across multiple positions [35]. They found that KA caused the least "understuffing" of the trochlea, while MA resulted in the most lateral displacement. FA and KA showed no significant difference in translation, but KA placed 13% of femoral components outside the 6°/3° rotational safe zone [35]. Nonetheless, KA patients had superior early clinical outcomes, suggesting that restoration of native morphology may outweigh minor deviations from alignment "safe zones" [19].

It is well established that native trochlear morphology varies significantly across individuals, as does native coronal alignment [11, 13, 24]. For coronal alignment, "neutral" has been defined as HKA $179.2° \pm 2.8–5.6°$ in males and $180.5° \pm 2.8–5.6°$ in females [12], but no such classification exists for trochlear anatomy. Unlike coronal alignment, which can be modulated by altering femoral and tibial cuts, trochlear shape is fixed by implant design, creating limited flexibility and potential compromise [7].

The primary surgical goal for the femoral component is to balance the knee in both extension and flexion, with the flexion phase being most critical for restoring trochlear anatomy [35]. Riviere et al. demonstrated that even KA significantly alters the trochlear groove, producing a shallower and more valgus-oriented sulcus than native anatomy [30]. This is relevant because the patella tracks within the trochlear groove by rotating around a secondary kinematic axis, which lies anterior and proximal to the trans-epicondylar axis (TEA) [5]. Ideally, the anterior trochlear line (ATL) should maintain a consistent orientation toward both the TEA and secondary axis throughout knee flexion [5, 26].

However, our data showed that all alignment strategies, including KA and FA, increased the sulcus angle (SA), indicating understuffing of the medial and lateral facets. This underfilling reduces medio-lateral patellar stability, even in the absence of overt lateral maltracking [1]. Riviere et al. corroborated this, showing that even with morphometric femoral implants, the trochlea often remains underfilled and valgus-shifted, even using KA [29].

Contrary to the authors' expectations, FA did not restore trochlear orientation as effectively as KA. Although FA aims to optimize soft-tissue balance in flexion, it often requires external rotation of the femoral component, which alters the ATL away from its native configuration [7]. This creates a trade-off between achieving a balanced flexion gap and maintaining correct trochlear orientation. Based on these findings, the authors posit that modifications in ATL relative to PCA may have a greater impact on patellar tracking than the coronal flange orientation.

A second major finding is the overall high rate of trochlear orientation outliers (up to 85%), regardless of alignment strategy. While coronal alignment outliers are conventionally defined as deviations beyond 3° [13], no such thresholds exist for trochlear parameters. Shatrov et al. proposed a 6°/3° rotational safe zone, but did not define outliers for trochlear translation [35]. Riviere et al. used repeated measures ANOVA and Bonferroni-corrected t-tests to assess trochlear orientation, but also did not define specific thresholds [29, 30]. Dejour et al. analyzed 14 femoral component designs using radiographic projections, not 3D CT, and likewise did not establish outlier definitions [7].

Rosa et al. evaluated 45 implant designs and 4116 CT scans, finding that 41.5% of native trochlear angles fell outside the prosthetic design range, raising concerns about mechanical mismatch and patellar tracking compromise [32].

5. Limitations

This study has several limitations. First, clinical outcomes were not evaluated, which would be essential to determine whether morphologic preservation (KA) or gap balancing (FA) translates into superior function [19, 35]. Second, trochlear angles were measured on 1-mm transverse CT slices, using validated indices for patellar instability, although small variations in slice plane may affect reproducibility. However, consistency was ensured by using a standardized measurement protocol across all patients.

Outliers were defined as deviations ≥3°, based on accepted coronal alignment thresholds [13]. An alternative statistical approach using Tukey's method (1.5 IQR) would yield more lenient outlier thresholds (e. g., SA > 19.5°, LTI < 10.5°, ATL > 6°) [17]. However, this would result in clinically unacceptable classifications, such as excluding an LTI of 9° from being dysplastic. Lastly, not all patients received FA or aMA, due to varying alignment philosophies among participating surgeons [2].

6. Conclusion

This study demonstrates that trochlear orientation is significantly altered following total knee arthroplasty (TKA), irrespective of the alignment strategy employed. Among the techniques evaluated, kinematic alignment (KA) yielded the fewest outliers, yet a substantial proportion of implants still deviated from native trochlear morphology, underscoring the inherent limitations of current off-the-shelf femoral component designs [7, 29, 30, 32].

The findings suggest that surgeons are often forced to compromise between achieving optimal flexion gap balance and preserving native trochlear alignment, particularly during femoral component rotation in functional alignment (FA) [25, 35]. This trade-off may have important implications for patellofemoral biomechanics, potentially contributing to maltracking or instability, even when coronal alignment and gap balance are optimized [1, 5, 26, 29].

Given the high prevalence of trochlear outliers, further clinical investigations are warranted to determine whether restoring native trochlear orientation—as most closely achieved with KA—translates into improved patient-reported outcomes, patellar tracking, and long-term prosthesis survivorship [19, 29, 35].

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