

Original article

<https://doi.org/10.18019/1028-4427-2026-32-3-321-330>



A customized approach for accurate rotational positioning of the femoral component in total knee arthroplasty

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Abstract

Introduction Rotational alignment of the femoral component is important for a good functional outcome and the long-term success of total knee arthroplasty (TKA).

The **objective** was to evaluate the effectiveness of a customized approach for accurate rotational positioning of the femoral component in total knee arthroplasty.

Material and methods Outcomes of TKA were comprehensively evaluated in 94 patients with Kellgren – Lawrence grade III–IV osteoarthritis. Femoral component rotation was determined in the first group ($n = 46$) using visual-manual techniques based on the posterior condylar and surgical supracondylar lines. A goniometer was used in the second group ($n = 48$) to determine the surgical supracondylar line along the anterior tangent line at the angle measured with computed tomography. Statistical analysis of the data was performed using IBM SPSS 20 Statistics and Statistica 13.3 software packages.

Results Analysis of postoperative data on the angle between the surgical supracondylar and posterior condylar lines in the first group revealed a deviation from the normal values with a median of 3.45° (1.9° ; 3.8°), indicating significant external rotation of the femoral component. Internal rotation of the femoral component of the implant was observed in two clinical cases reaching 3.5° , indicating mild to moderate malrotation. The anterior tangent line served as a landmark in the second group, and the mean arithmetic value of the angle between the surgical supracondylar and posterior condylar lines measured 0.9° (0.6° ; 1.2°) postoperatively. The measurement suggested the significant line to be used as a promising landmark in primary TKA.

Discussion Ji et al. explored the angle between the surgical supracondylar and anterior tangent lines and performed a comparative analysis of methods based on supracondylar, anterior tangent, and anterior patellar lines. The approach facilitated an objective assessment of the applicability for solving clinical problems and confirmed our analytical data. The authors emphasized the anterior patellar line and suggested its potential for correcting varus deformity of the knee joint. In our series, the knee alignment was not considered and the focus was on the anterior tangent line, which has not been reported in Russian studies.

Conclusion The customized approach for accurate rotational positioning of the femoral component using the FAT line demonstrated its high efficacy in TKA. The approach facilitated accurate component positioning minimizing the risk of errors. The findings suggested that customized navigation techniques can be used in routine clinical practice.

Keywords: total knee arthroplasty, preoperative planning, rotational positioning of the femoral component, postoperative assessment

For citation: Zubavlenko RA, Ostrovskij VV, Belova SV, Markov DA. A customized approach for accurate rotational positioning of the femoral component in total knee arthroplasty. *Genij Ortopedii*. 2026;32(3):321-330. doi: 10.18019/1028-4427-2026-32-3-321-330.

INTRODUCTION

Total knee arthroplasty (TKA) is one of the most highly effective and consistently successful surgical procedures in orthopedics, demonstrating the long-term clinical efficacy [1–3]. Rotational positioning of the components affects patellar stability [4, 5], knee flexion [6, 7], range of motion, and prosthesis wear [8]. Therefore, malrotation can lead to a poor outcome and become an indication for revision TKA in the absence of infection, instability or secondary displacement [8–10]. The clinical validity of measured resection methods in TKA is determined by their reproducibility and correlation with clinical outcomes. Optimal rotational alignment in this context is a complex task requiring an individualized approach [11]. The methods for achieving and assessing it are the subject of active scientific debate [12]. Computed tomography (CT) is considered the preferred method for assessing rotational alignment of components; however, the measurement process using various anatomical landmarks presented in 2D and 3D images is associated with some methodological and technical challenges, including the presence of artifacts [12, 13].

Various methodological approaches have been developed and systematized to ensure correct placement of the femoral component with the specified rotation in TKA. Many surgeons use anatomical landmarks including the posterior condylar line (PCL), Whiteside's line, or surgical transepicondylar axis (STEA) and anatomical transepicondylar axis (ATEA) to accurately determine the direction and angle of rotation. The landmarks do not minimize the risk of postoperative complications due to the inevitable error of visual-manual technique, which is due to the subjective perception and interpretation of visual data, as well as the variability of the surgeon's motor skills [6, 9]. Femoral component rotation angle [14, 15] can be determined using the method described by Berger [4, 5], which is based on a visual-manual technique for identifying the STEA. However, despite the widespread use of the approach, there is no scientific consensus regarding the optimal method for measuring femoral rotation [16, 17] and, accordingly, combined rotation. This circumstance highlights the need for further research and the development of standardized protocols that could ensure greater accuracy in clinical practice.

Inter- and intra-observer reproducibility of CT scans in the context of femoral rotation assessment, exhibits significant variability and ambiguity. This phenomenon is associated with several key factors including individual variability of anatomical landmarks, which complicates their identification [16], uncertainty in the limb positioning technique during scanning, which can potentially affect the accuracy of the landmark localization [18, 19]. The aspects contribute to data interpretation and can influence clinical practice and research conclusions. Analysis of the findings suggests that various types of knee joint deformities exhibit characteristic rotation patterns with high diagnostic significance. The patterns can be effectively used for differential diagnosis to optimize surgical strategies.

The **objective** was to evaluate the effectiveness of a customized approach for accurate rotational positioning of the femoral component in total knee arthroplasty.

MATERIAL AND METHODS

The study was conducted at the Research Institute of Traumatology, Orthopedics, and Neurosurgery of the Razumovsky Saratov State Medical University in accordance with Local Ethics Committee Protocol No. 3 dated October 7, 2025. The current phase of the study included a comprehensive analysis of the causes and errors arising when comparing standard fixed anatomical landmarks on CT scans before and after surgery. This research initiative aims to explore a previously unexplored anatomical region, opening the possibility of developing an innovative, personalized approach to optimize determination of the rotational positioning angle of the femoral component during TKA.

This study is a comprehensive examination of the anatomical and functional parameters of the femur and their correlation with the design of the femoral component of TKA. The primary objective of the study was to quantify and qualitatively analyze the angles formed by lines connecting key anatomical points of the femur with the corresponding components of the implant.

Inclusion criteria:

- age over 18 years;
- Kellgren grade III–IV knee arthritis;
- body mass index < 40 kg/m²;
- signed informed consent of the patient to participate in the study, his/her ability and willingness to follow the doctor's recommendations.

Exclusion criteria: concomitant orthopedic, general medical, psychiatric, and infectious pathologies that contraindicate TKA or prevent the patient from mobilizing after surgery. Patients underwent radiography in two projections and a CT scan of the knee joint during hospitalization and after TKA. The diagnostic procedures provided comprehensive anatomical monitoring before and after surgery, facilitating an objective analysis of the accuracy of the TKA.

The axes and angles examined between them included: 1) a line not used in standard practice, passing through the protruding elements of the compact bone substance of the distal metaphysis of the femur, located in the region of the upper pole of the patella, the line is designated as the femoral anterior tangent (FAT) line (Fig. 1 a); 2) ATEA, STEA, PCL and the angles between them, which are traditionally used in standard preoperative procedures for accurate rotational positioning of the femoral component in TKA (Fig. 1 b); 3) ATEA, STEA, PCL and the angles between them, used in standard postoperative control procedures to check the rotational position of the femoral component of TKA (Fig. 1 c).

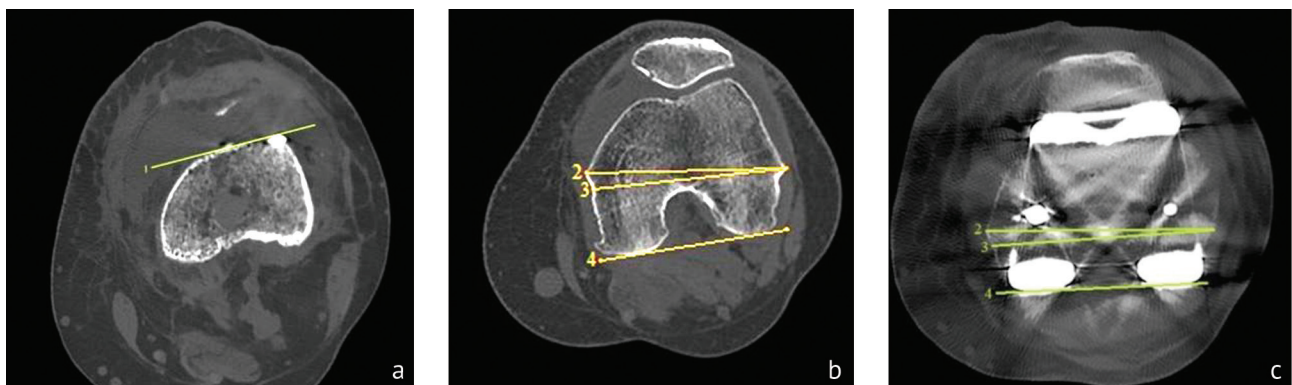


Fig. 1 Axes drawn through the anatomical fixed landmarks of the femur on CT scan: (a) FAT visualized at the superior pole of the patella; (b) standard visualization of the ATEA, STEA, PCL before surgery; (c) standard visualization of the ATEA, STEA, PCL after surgery. Designations: (1), FAT; (2), ATEA; (3), STEA; (4), PCL

The study included a comprehensive quantitative and qualitative assessment of the knee joint in 94 patients with Kellgren–Lawrence grade III–IV osteoarthritis (OA) [20]. All patients underwent TKA. A comparative evaluation of the methods for determining the rotation of the femoral component in TKA was conducted. In the first group ($n = 46$), the rotation of the femoral component was determined using a standard navigation system based on the installation of a 4/1 resection block relative to the PCL axis and/or visually and manually along the STEA axis (Fig. 2 a, b). A standard goniometer was used in the second group ($n = 48$) to measure the rotation of the femoral component of TKA along the angle between the STEA and FAT axes (Fig. 2 c).

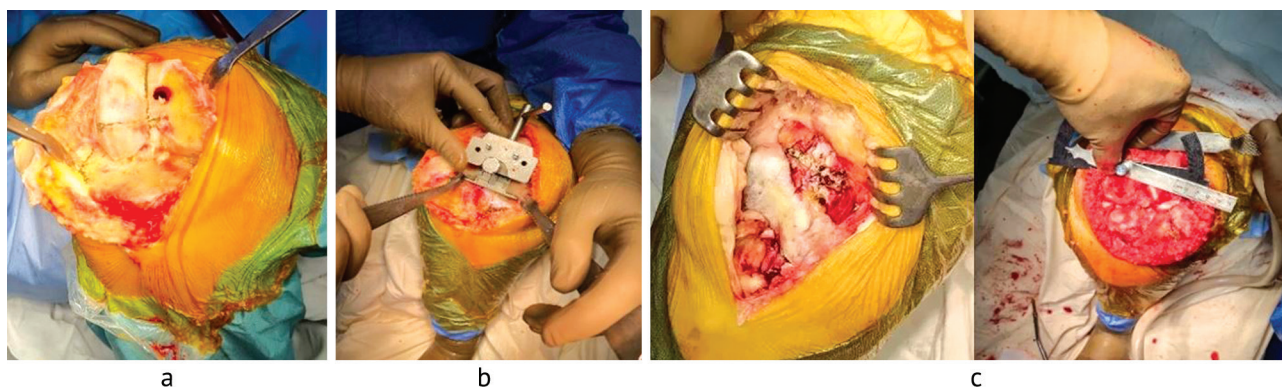


Fig. 2 Methodological intraoperative approaches to determining the rotation of the femoral component of the TKA: (a) determining STEA using visual-manual technique; (b) determining STEA relative to the posterior condyles using a standard measuring device; (c) determining STEA along the FAT line using a standard goniometer

Statistical analysis of the data was performed using the IBM SPSS 20 Statistics and Statistica 13.3 software packages. The Shapiro – Wilk (Sh–W) and Kolmogorov – Smirnov (K–S) tests were used to test hypotheses about the normal distribution. If at least one of the parameters did not correspond to the normal distribution, the result was classified as negative. Comparison of statistically significant parameters was performed by calculating the Spearman rank correlation coefficient (S). R values less than 0.3 suggested a weak relationship between the variables, values in the range of 0.3–0.7 indicated a moderate relationship, and values greater than 0.7 indicated a strong relationship. The results were considered statistically significant at $p < 0.05$, which meets the criteria for clinical trials and validation of scientific data.

RESULTS

Analysis of the rotation angles of FAT/STEA, FAT/ATEA, FAT/PCL, STEA/A TEA, and ATEA/PCL in the first group confirmed their compliance with the normal distribution. This allowed us to conclude that the most representative characteristics of these parameters included $M \pm SD$ and 95 % confidence interval. However, the angles, STEA/PCL, and STEA/PCL after surgery did not follow the normal distribution. In these cases, the median and quartiles were used to describe the central tendency of the data (Table 1).

Table 1

Major data and parameters revealed during the analysis of CT scans before and after surgery in the first group ($n = 46$)

Description	Estimation method	OA grade	$M \pm SD$ (95 %) / Me [Q1; Q3]	K–S	Sh–W
FAT/A TEA	Parametric	III–IV	$(13.61 \pm 3.38)^\circ / (11.92; 15.28)^\circ$	0.245	0.099
FAT/S TEA	Parametric	III–IV	$(9.57 \pm 3.59)^\circ / (7.79; 11.37)^\circ$	0.446	0.060
FAT/PCL	Parametric	III–IV	$(7.93 \pm 3.25)^\circ / (6.31; 9.54)^\circ$	0.319	0.353
STEA/A TEA	Parametric	III–IV	$(5.01 \pm 0.92)^\circ / (4.55; 5.46)^\circ$	0.310	0.058
STEA/PCL	Nonparametric	III–IV	$1.5^\circ / (0.8; 3.1)^\circ$	0.005	0.0004
ATEA/PCL	Parametric	III–IV	$(5.94 \pm 2.29)^\circ / (4.80; 7.08)^\circ$	0.351	0.410
ATEA/PCL post-op	Parametric	III–IV	$(-2.01 \pm 3.22)^\circ / (-3.61; 0.40)^\circ$	0.274	0.207
STEA/PCL post-op	Nonparametric	III–IV	$3.45^\circ / (1.9; 3.8)^\circ$	0.013	0.008

Note: M – arithmetic mean; SD – standard deviation; (95 %), 95 % confidence interval for the mean; Me – median, Q1 – 25 % quartile; Q3 – 75 % quartile; Sh–W – Shapiro – Wilk test; K–S – Kolmogorov – Smirnov test.

Analysis of the rotation angles of FAT/STEA, FAT/ATEA, FAT/PCL, STEA/ATEA, ATEA/PCL, and STEA/PCL after surgery in the second group demonstrated their compliance with a normal distribution. This allowed us to conclude that $M \pm SD$ and 95 % confidence interval were the most representative

characteristics of the parameters; however, the STEA/PCL parameters after surgery did not follow a normal distribution. In these cases, the median and quartiles were used to describe the central tendency of the data (Table 2).

In the first group, the STEA/PCL angle measured 1.5° (0.8; 3.1) $^\circ$ of external rotation. This indicator did not follow the normal distribution and increased to 3.45° (1.9; 3.8) $^\circ$ of external rotation (Table 1) after surgery. The findings suggested the presence of moderate external rotation of the femoral component. The STEA/PCL angle reached 3.5° of internal rotation of the femoral component in four clinical cases. This indicated mild or moderate malrotation as classified by R.L. Barrack. The presented rotational errors can lead to subluxations and/or dislocations of the patella, muscle atrophy and accelerated wear of the implant, which may negatively affect the clinical outcome.

In the second group, where the FAT line was used as a reference for determining femoral component rotation, the distribution of STEA/PCL angle values after surgery corresponded to the norm and measured $0.91 \pm 0.60^\circ$ (0.60; 1.21) $^\circ$ (Table 2). This made it possible to minimize the error in rotation after surgery, which did not exceed 1° , and to rule out cases of internal rotation of the femoral component of TKA. Comparison of S-TEA/PCL and A-TEA/PCL angles after surgery was complicated by significant differences in data distribution between the study groups. The distribution deviated significantly from normality in the first group, and normal distribution was observed in the second group. The differences prevent the use of traditional statistical methods, such as analysis of variance (ANOVA) or t-tests, which assume similar distributions in the compared groups. Given the specific nature of our data, we decided to use nonparametric methods that do not require strict assumptions about the distribution shape. We believed that the Mann – Whitney test was one of the most appropriate tools in this context. This approach allowed us to accurately assess the differences between the STEA/PCL and ATEA/PCL angles after surgery, eliminating the influence of biased assumptions about the normality of the distribution.

Table 2

Main data and parameters revealed during the analysis of CT scans before and after surgery in the second group ($n = 48$)

Description	Estimation method	OA grade	M \pm SD (95 %) / Me [Q1; Q3]	K-S	Sh-W
FAT/A TEA	Parametric	III-IV	$(12.5 \pm 2.79)^\circ / (10.86; 13.64)^\circ$	0.097	0.133
FAT/S TEA	Parametric	III-IV	$(7.77 \pm 2.66)^\circ / (6.44; 9.09)^\circ$	0.287	0.299
FAT/PCL	Parametric	III-IV	$(6.33 \pm 3.04)^\circ / (4.82; 7.85)^\circ$	0.226	0.273
STEA/A TEA	Parametric	III-IV	$(4.57 \pm 0.71)^\circ / (4.22; 4.92)^\circ$	0.118	0.023
STEA/PCL	Nonparametric	III-IV	$1.15^\circ / (0.9; 2)^\circ$	0.073	0.038
ATEA/PCL	Parametric	III-IV	$(5.70 \pm 1.67)^\circ / (4.87; 6.53)^\circ$	0.060	0.145
ATEA/PCL post-op	Parametric	III-IV	$(-3.11 \pm 1.49)^\circ / (-3.85; -2.37)^\circ$	0.165	0.422
STEA/PCL post-op	Nonparametric	III-IV	$(0.91 \pm 0.60)^\circ / (0.60; 1.21)^\circ$	0.442	0.164

Note: M – arithmetic mean; SD – standard deviation; (95 %), 95 % confidence interval for the mean; Me – median, Q1 – 25 % quartile; Q3 – 75 % quartile; Sh-W – Shapiro – Wilk test; K-S – Kolmogorov – Smirnov test.

An analysis of the ATEA/PCL angle showed that the differences between the groups did not reach statistical significance (U-statistic = 207.5; $p = 0.15$). This indicates that the standard procedure and the FAT-based technique have a similar effect on this parameter, and do not allow us to conclude that one technique is significantly superior to the other. A completely different result was obtained when studying the STEA/PCL angle after surgery. Here, the differences were significant (U-statistic = 251.5; $p = 0.0046$). This means that a statistically significant difference was recorded between the groups, suggesting a more significant impact of the method proposed for determining rotation along the FAT line on the STEA/PCL angle compared to the standard technique. Therefore, our data suggest that determining femoral component rotation using the CT-measured FAT line

has a significant impact on the postoperative STEA/PCL angle, while the impact on the ATEA/PCL angle is similar in both groups. The results offer potential for optimizing arthroplasty protocols and increase confidence in the choice of this technique for certain patient populations.

The dependence of the angles formed between fixed anatomical landmarks of the femur before and after surgery was determined using correlation analysis. The most significant positive correlations were found between the FAT/ATEA and FAT/STEA angles; ATEA/PCL and STEA/PCL in the first group. The correlation coefficient for these pairs was 0.9153* ($p = 0.0000001$) and 0.9412* ($p = 0.00000005$), respectively. The values indicate the presence of a close linear relationship between the variables suggesting a high degree of their consistency. Moderate positive correlations were found between the FAT/ATEA and FAT/PCL angles; FAT/STEA and FAT/PCL. The correlation coefficients for these pairs were 0.6347* ($p = 0.005$) and 0.6883* ($p = 0.001$), respectively. These results indicate the presence of a statistically significant, but less pronounced, relationship between the variables, which may suggest a more complex structure of relationships in this group (Table 3).

Table 3

Spearman rank correlation coefficients for pre- and post-operative parameters in the first group ($n = 46$)

Variable	FAT/ATEA	FAT/STEA	FAT/PCL	ATEA/PCL post-op	STEA/PCL post-op
FAT/A TEA	1.0000, –	0.9153*, $p = 0.0000001$	0.6347*, $p = 0.005$	0.0650, $p = 0.79$	–0.0908, $p = 0.72$
FAT/S TEA	0.9153*, $p = 0.0000001$	1.0000, –	0.6883*, $p = 0.001$	0.1625, $p = 0.51$	–0.3335, $p = 0.89$
FAT/PCL	0.6347*, $p = 0.005$	0.6883*, $p = 0.001$	1.0000, –	0.0541, $p = 0.83$	0.0433, $p = 0.86$
ATEA/PCL post-op	0.0650, $p = 0.79$	0.1625, $p = 0.51$	0.0541, $p = 0.83$	1.0000, –	0.9412*, $p = 0.00000005$
STEA/PCL post-op	–0.0908, $p = 0.72$	–0.3335, $p = 0.89$	0.0433, $p = 0.86$	0.9412*, $p = 0.000000005$	1.0000, –

Note: An asterisk (*) indicates significant correlations ($p < 0.05$).

All other correlations identified during the analysis were statistically insignificant ($p \geq 0.05$). This means that there is no significant linear relationship between the relevant variables, which may indicate the presence of other, more complex mechanisms of interaction between these parameters.

The analysis revealed significant correlations between the FAT/ATEA and FAT/STEA angles in the second group, confirming the key role of the FAT line in preoperative planning of femoral component rotation in TKA. However, the lack of a statistically significant correlation between the FAT/STEA and STEA/PCL in the postoperative period in this group may indicate the limited effectiveness of the posterior femur as reliable landmarks for positioning the femoral component. These results can serve as a basis for further in-depth research in this area aimed at optimizing preoperative planning and postoperative correction methods.

Analysis of the data from the second group (Table 4) revealed significant high-degree correlations between the FAT/ATEA and FAT/STEA angles (coefficient = 0.9463, $p = 0.000000002$), indicating an extremely close relationship between the parameters. A similarly high degree of correlation was found between FAT/PCL and FAT/STEA (coefficient = 0.9463, $p = 0.000000002$).

Significant correlations of moderate strength were found between the FAT/ATEA and FAT/PCL variables (coefficient = 0.8503, $p = 0.000007$), suggesting high consistency between these indicators. Intermediate correlation values were observed between FAT/STEA and FAT/PCL (coefficient = 0.7363, $p = 0.0004$). A similar correlation was found between ATEA/PCL and STEA/PCL (coefficient = 0.6486, $p = 0.003$).

Table 4

Spearman rank correlation coefficients for pre- and post-operative parameters in the second group ($n = 48$)

Variable	FAT/A TEA	FAT/STEA	FAT/PCL	A TEA/PCL post-op	STEA/PCL post-op
FAT/A TEA	1.0000, –	0.9463*, $p = 0.000000002$	0.8503*, $p = 0.000007$	0.1733, $p = 0.49$	0.4127, $p = 0.09$
FAT/S TEA	0.9463*, $p = 0.000000002$	1.0000, –	0.7363*, $p = 0.0004$	0.3317, $p = 0.17$	0.5319*, $p = 0.02$
FAT/PCL	0.8503*, $p = 0.000007$	0.7363*, $p = 0.0004$	1.0000, –	0.0536, $p = 0.83$	0.3524, $p = 0.15$
A TEA/PCL post-op	0.1733, $p = 0.49$	0.3317, $p = 0.17$	0.0536, $p = 0.83$	1.0000, –	0.6486*, $p = 0.003$
STEA/PCL post-op	0.4127, $p = 0.09$	0.5319*, $p = 0.02$	0.3524, $p = 0.15$	0.6486*, $p = 0.003$	1.0000, –

Note: An asterisk (*) indicates significant correlations ($p < 0.05$).

Interestingly, there was a moderate correlation between postoperative STEA/PCL and FAT/STEA (coefficient = 0.5319, $p = 0.02$). An increase in postoperative FAT/STEA values is accompanied by an increase in STEA/PCL values. This fact is of great importance for planning postoperative and intraoperative rotational positioning of the femoral component of TKA.

The data presented in Table 4 demonstrates the persistence of significant interactions between some variables including FAT/A TEA, FAT/STEA, and FAT/PCL angles after surgery in the second group. These results are essential for understanding the consequences of surgical intervention and optimizing preoperative planning. The moderate correlation between postoperative STEA/PCL and FAT/STEA may open up prospects for further research and practical application of the results.

DISCUSSION

The lack of an unambiguous method for measuring the rotation of the femoral component of TKA represents a serious obstacle to clinical practice [22, 23]. With the uncertainty about the acceptable limits of malrotation and lack of criteria for assessing critical displacements [24, 25], there are controversies regarding repeated TKA [26].

The joint space configuration during extension and flexion in anatomically normal and healthy knee joints is not strictly rectangular, indicating significant mobility of the collateral ligaments, especially in the flexion phase [27]. Analysis of TKR results has shown that a balanced joint with a symmetrical joint space during extension and flexion demonstrates higher efficiency, which ensures improved mechanical congruence, increased stability [28], reduced wear and destabilization of components [29], an increased range of motion and optimization of proprioception [30]. Such anatomical features help to reduce the risk of pathological changes in the patella area [31] and reduce pain [28]. This is resulted in improved functionality and a reduced need for revision interventions [32].

The study demonstrated the limitations of the parameters for aligning the anatomical components of the femur at the angles formed by the STEA, A TEA, and PCL axes ensuring accuracy. Accurate identification of anatomical landmarks is challenging during surgery on knee joints affected by OA [33]. Data from 94 patients were reviewed in our series, which may limit the generalizability of the findings. Particular attention was paid to the difficulty in accurately determining the STEA line due to the soft tissue coverage of the medial and lateral condyles and the intercondylar groove. These anatomical features can significantly affect the accuracy of measurements and the consistency between the selected landmarks.

Although the PCL axis was more accessible for assessment, significant deviations from the surgeon's pre-set external rotation of 3° were revealed. These results are consistent with the data presented by T.K. Fehring, who found that 45 % of patients with TKA showed moderate or greater rotation errors when using an external rotation of 3° relative to the posterior condylar line as a reference point [34]. Although an external rotation of 3° can be considered an average value, it does not reflect the specific anatomy of an individual patient, emphasizing the need for an individual approach to each clinical case.

We present a method for determining the rotational position of the femoral component of TKA using the FAT/STEA angle. This method represents an alternative approach that can be applied in clinical situations where traditional anatomical landmarks cannot be accurately identified visually and manually during surgery. N.M. Ji et al. conducted a thorough study of the reliability of these landmarks only in varus deformity of the knee joint to assess the rotational characteristics of the femoral component of TKA [35]. The study compared the TEA, FAT, and anterior patellar line methods, which allowed for an objective assessment of their applicability for solving problems and confirmed our analytical data. Some authors emphasized the anterior patellar line with the greater potential for varus deformity [36, 37].

Y. Hattori et al. reported preliminary measurements indicating that the FAT line exhibits internal rotation of $(9.6 \pm 3.7)^\circ$ relative to STEA [38]. These data are consistent with the results of our series: the indicator measured $(9.57 \pm 3.59)^\circ$ in the first group, and $(7.77 \pm 2.66)^\circ$ in the second group. Visualization of the FAT line plays a significant role in monitoring the rotation of the femoral component of TKA. Interestingly, the angles formed by standard anatomical landmarks without taking the FAT into account do not show a significant correlation in most cases. This emphasizes the importance of functional analysis of the FAT line in planning surgeries and positioning the femoral component, which is confirmed by our series.

We did not aim to thoroughly explore the impact of rotational positioning of the femoral component on clinical and functional outcomes. This methodological approach allowed us to include 94 patients in the review at this stage, significantly enriching our database and increasing the representativeness of our findings. Quantitative evaluation of the effectiveness of rotational positioning of the femoral component using an individualized FAT-based technique is a key element in facilitating significant progress in modern technologies for preoperative TKA planning.

The clinical outcome of TKA is determined by the rotational positioning of the femoral component and by the rotation of the tibial component and their combined interaction. Despite the multifactorial nature of biomechanical interactions within the prosthetic system, it should be noted that, in our opinion, the correct reproduction of combined rotation depends largely on the precise rotational positioning of the femoral component.

CONCLUSION

The personalized method for determining rotation of the femoral component using the FAT line was shown to be highly effective in TKA. The approach facilitated precise component positioning, minimizing the risk of errors. The findings open up prospects for the implementation of personalized navigation techniques in routine clinical practice.

Source of funding *The study was conducted as part of the R&D project "Optimization of the technique of endoprosthesis positioning in total knee arthroplasty" of the Federal State Budgetary Educational Institution of Higher Education Saratov State Medical University named after V.I. Razumovsky of the Ministry of Health of the Russian Federation, RK No. 125082709918-4 and within the framework of the state assignment "Development of surgical navigation instruments for rotational positioning of the femoral component of total knee replacement"*

of the Federal State Budgetary Educational Institution of Higher Education Saratov State Medical University named after V.I. Razumovsky of the Ministry of Health of the Russian Federation, RK No. 125030703257-1.

Ethical standards The study was conducted with the permission of the local ethics committee of the Research Institute of Traumatology, Orthopedics and Neurosurgery of the Saratov State Medical University named after V.I. Razumovsky (protocol No. 3 dated October 7, 2025).

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The article was submitted 08.12.2025; approved after reviewing 25.02.2026; accepted for publication 06.04.2026.

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