

Association Between Two Anatomical Landmark Measurements and Tibial Osteotomy Thickness in Total Knee Arthroplasty

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AIM: This study preliminarily explores the statistical association between measurements derived from the apex of the tibial tubercle and the most lateral point of the fibular head, as anatomical reference landmarks, and tibial osteotomy thickness in total knee arthroplasty (TKA), while also evaluating the limitations of their predictive value.

METHODS: We analyzed the computed tomography (CT) scan data from 20 patients in the TKA Group and 30 patients in the Non-surgical Group. Key anatomical measurements were performed: the distance from the tibial tubercle apex to the osteotomy surface in the sagittal plane (tibial tubercle distance [TD]), and the distance from the most lateral point of the fibular head to the osteotomy surface in the coronal plane (fibular head distance [FD]). Statistical analysis was performed using SPSS 22.0 software. The primary aim was to assess the association between these measurements and the tibial osteotomy thickness and to evaluate the strength and limitations of this association for exploratory estimation of tibial osteotomy thickness.

RESULTS: Measurements showed good to excellent inter-observer reliability (intraclass correlation coefficient [ICC]: 0.89–0.91). A modest inverse association was observed. The multiple regression model combining both landmarks was significant ($F = 3.303$, $p = 0.041$), but demonstrated very limited explanatory power (adjusted $R^2 = 0.041$), and neither landmark emerged as an independent significant predictor (normalized tibial tubercle distance [TDJ]: $p = 0.078$; normalized fibular head distance [FDJ]: $p = 0.098$). In an exploratory time-series analysis, an Auto Regressive Integrated Moving Average (ARIMA) (0,1,0) model demonstrated a high goodness-of-fit on the historical data ($R^2 = 0.896$, Mean Absolute Percentage Error [MAPE] = 1.137%), whereas its near-zero stationary R^2 suggests that its goodness-of-fit may be attributed more to the intrinsic continuity of the data series rather than the predictive utility of the anatomical landmarks.

CONCLUSIONS: This study demonstrates a modest inverse association between the measurements derived from the tibial tubercle apex/the most lateral point of the fibular head and the tibial osteotomy thickness. However, linear regression reveals that these variables are weak standalone predictors, and their clinical predictive utility likely depends on integration into multifactorial models.

Keywords: tibial tubercle; fibular head; bony landmarks; total knee arthroplasty; osteotomy line

Introduction

Total knee arthroplasty (TKA) is the gold standard for treating end-stage knee joint diseases, effectively alleviating severe knee pain, correcting deformities, and restoring knee joint function [1]. With advancements in surgical techniques and the introduction of innovatively designed knee prostheses, an increasing number of surgeons are adopt-

ing TKA to treat more complex knee pathologies. Concurrently, as the annual volume of TKA surgeries rises, the number of revision surgeries is also increasing [2]. Whether in primary or revision TKA, accurately determining the position and volume of the tibial osteotomy is a critical initial step that significantly affects the joint line height, femoral osteotomy volume, and rotation. Therefore, improper handling at this stage can lead to serious complications [3]. Current methods for determining the tibial osteotomy line often rely on the tibial cartilage surface or the exposed subchondral bone surface, which may not provide a reliable reference in challenging primary or revision cases, thereby increasing surgical complexity and uncertainty—a significant challenge for surgeons [4]. To address this challenge, this study introduces a dual-reference system based on palpable bony landmarks: the apex of the tibial tubercle and the most lateral point of the fibular head. This study aimed

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to preliminarily assess the feasibility and statistical association of using these landmarks as potential references for tibial osteotomy through CT imaging and statistical modeling.

Methods

Inclusion and Exclusion Criteria for TKA Group

Inclusion Criteria

This retrospective study reviewed cases from January 2018 to December 2019 at Beijing Royal Integrative Medicine Hospital, People's Hospital of Zhongzhan District, and Beijing Tsinghua Changgung Hospital who underwent primary TKA.

Patients were included if they met all of the following conditions:

1. **Diagnosis:** A primary diagnosis of end-stage knee osteoarthritis or rheumatoid arthritis, documented in the surgical notes.
2. **Surgery:** Underwent primary, unilateral TKA for the indicated diagnosis.
3. **Imaging Data:** Available complete postoperative computed tomography (CT) scans of the surgical knee joint performed at the participating institutions during the follow-up. This was required for precise anatomical measurements.
4. **Clinical Records:** Available complete clinical records, including surgical reports that specified the implanted femoral component size (for prosthesis width, femoral prosthetic width [PW], retrieval), and Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) score records.

Exclusion Criteria

- (1) Severe intra- or extra-articular deformity or bone defect on the tibial or femoral side preoperatively;
- (2) Postoperative 3–6-month follow-up WOMAC score >60 points;
- (3) Lack of postoperative knee joint CT scan imaging data;
- (4) Tibial tubercle osteotomy performed during the replacement surgery;
- (5) Patients requiring rehospitalization during follow-up due to severe joint effusion, hematoma, periprosthetic fracture, infection, or dislocation.

Rationale for Non-surgical Group Selection and Sample Size

The primary rationale for including a non-surgical group in this study was to establish an anatomical reference baseline that more closely approximates the pre-operative status of actual surgical candidates. Patients undergoing TKA present with substantial anatomical and morphological alterations due to end-stage osteoarthritis. Using healthy volunteers as controls would yield anatomical parameters with limited clinical applicability due to marked differences from the target patient population. Therefore, we deliberately selected control subjects with symptomatic knees who had not yet met the surgical threshold or opted for conserva-

tive management. The anatomical state of this non-surgical group represents a critical phase in disease progression—the “immediate pre-surgical” or “surgical-threshold” stage. The measured relationships between the tibial tubercle, fibular head, and the predefined osteotomy planes derived from this group are thus more directly generalizable to pre-operative planning for actual surgical patients.

Regarding sample size, this study is an exploratory, hypothesis-generating anatomical measurement study. To our knowledge, no prior studies have used the tibial tubercle and fibular head as landmarks to predict tibial osteotomy thickness, precluding a formal a priori sample size calculation based on an established effect size. Consequently, our sample size was estimated primarily based on feasibility and the robustness of descriptive statistics. Referring to the similar anatomical measurement study [5], a sample of 20–30 per group is generally sufficient to detect moderate anatomical variations and ensure reasonable stability of the measured means. We ultimately included the TKA group (20 knees) and the Non-surgical group (30 knees). By simulating three osteotomy depths for each knee in the Non-surgical group (generating 3 data points per knee), the final analytical dataset comprised 110 observations. These simulated osteotomy thicknesses were used as predefined anatomical scenarios for exploratory analysis rather than as observed clinical surgical outcomes. This approach effectively enhanced the stability of the statistical model and provided an adequate data foundation for the preliminary exploration of variable relationships. See Table 1.

Table 1. General demographic data.

Demographic data	TKA group	Non-surgical group	p value
Number of cases	20	30	
Age (years)*	68 (56–80)	58 (45–83)	0.001**
Body mass index (kg/m ²)	27.3 ± 3.8	26.1 ± 4.2	0.309
Sex ratio (Female/Male)	16/4	21/9	0.430
Diagnosis			
OA	16 (80.0%)	28 (93.3%)	0.202
RA	4 (20.0%)	2 (6.7%)	
Kellgren-Lawrence Grade			0.010
Grade II	0	3 (10%)	
Grade III	8 (40%)	22 (73.3%)	
Grade IV	12 (60%)	5 (16.7%)	

*: Expressed as median (minimum–maximum).

** indicates a statistically significant result.

Abbreviations: OA, osteoarthritis; RA, rheumatoid arthritis; TKA, total knee arthroplasty.

Measurement Methods

Measurement Methods for the TKA Group

CT images were reviewed using standardized reconstruction settings, and measurements were performed on multiplanar reconstructed images according to predefined anatomical planes to ensure consistency across cases.

1. Tibial tubercle distance (TD): linear distance from the apex of the tibial tubercle to the tibial osteotomy plane, measured on the sagittal image that best displayed the entire tubercle profile (Fig. 1).
2. Fibular head distance (FD): The linear distance from the most lateral point of the fibular head to the tibial osteotomy plane, measured on the image where the fibular head was best visualized (Fig. 2).
3. Femoral prosthetic width (PW): The overall width from the medial to the lateral edge of the femoral component, measured on the coronal image at the level of the articular surface.
4. The tibial osteotomy thickness: the values were extracted from surgical records. The actual tibial osteotomy thickness was defined as the intraoperatively recorded thickness of tibial bone resection and was obtained directly from the operative record.



Fig. 1. Measurement of TD (the sagittal distance between the most prominent anterior point of the tibial tubercle and the tibial osteotomy line in post-arthroplasty patients). The red line indicates the tibial osteotomy plane. A line parallel to this plane was drawn through the highest point of the tibial tubercle, represented by the green line. A segment connecting these two parallel lines is shown as the short green line segment. The length of this segment was defined as TD. TD, tibial tubercle distance.

Measurement Methods for the Non-Surgical Group

The identification of the anatomical landmarks—specifically, the most lateral point of the fibular head



Fig. 2. Measurement of FD (the coronal distance between the most lateral point of the fibular head and the tibial osteotomy line in post-arthroplasty patients). The red line indicates the tibial osteotomy plane. The blue line represents the simulated mechanical axis of the lower limb. The most lateral prominence of the fibular head was identified, and a line segment (shown in green) was drawn from this point to the red line. The length of this green segment was defined as FD. FD, fibular head distance.

and the apex of the tibial tubercle—on CT images was performed in accordance with the previously outlined protocol.

The simulated osteotomy planes were defined on preoperative CT images of the Non-surgical Group. In the coronal plane, using the highest point of the lateral tibial plateau as the proximal reference, a line was drawn perpendicular to the tibial anatomical axis. This line was then translated distally to positions corresponding to osteotomy thicknesses of 8 mm, 9 mm, and 10 mm, thereby establishing the coronal level of the simulated osteotomy.

In the sagittal plane, the orientation of the osteotomy line was set parallel to the native posterior slope of the medial tibial plateau. The intersection of the defined coronal level and sagittal orientation defined the complete three-dimensional simulated osteotomy surface for each resection thickness.

Subsequently, the following measurements were obtained relative to this simulated surface:

1. Tibial tubercle distance (TD): The perpendicular distance from the apex of the tibial tubercle to the simulated osteotomy surface, measured in the mid-sagittal plane (Fig. 3A).

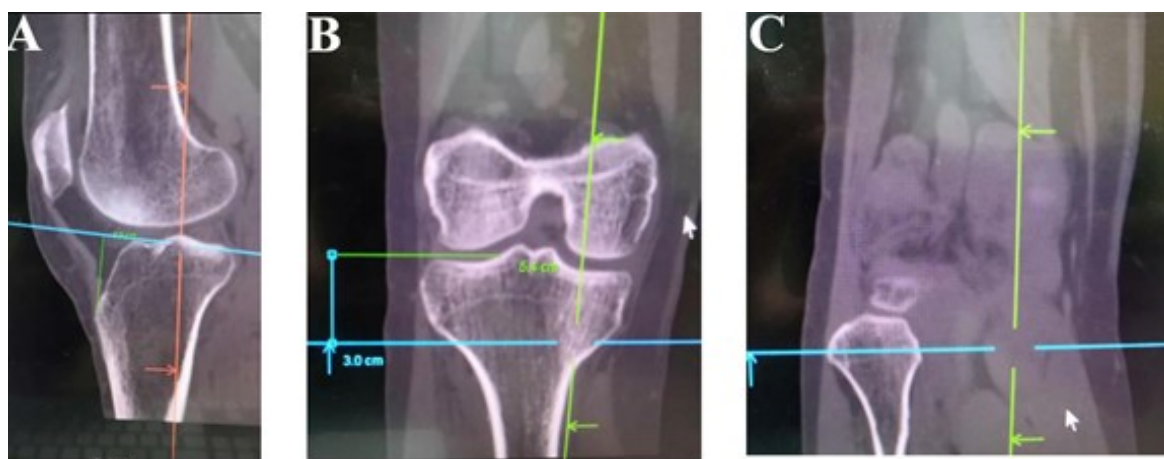


Fig. 3. Measurement of TD and FD in the Non-surgical group. (A) TD: after identifying the apex of the tibial tubercle, a perpendicular line (green) was drawn to the proximal tibial articular surface (blue line). The red line with short arrows represents the lower limb mechanical axis. (B,C) FD: after identifying the most lateral point of the fibular head, a perpendicular line (blue) was drawn to the same reference line (green). FD was measured on the selected image plane where the fibular head was clearly identified. For both measurements, simulated osteotomy at 8-, 9-, and 10-mm distal translations was applied, and the perpendicular distance was measured at each level, yielding three values per parameter.

2. Fibular head distance (FD): The linear distance from the most lateral point of the fibular head to the simulated osteotomy surface, measured on the image plane where the center of the fibular head was clearly identified (Fig. 3B,C).

3. The width of the distal femoral condylar articular surface (FW): The maximum mediolateral width of the distal femoral articular surface, measured on the selected image plane at the level of the posterior condyles.

All radiographic measurements were performed by two independent investigators using a dedicated picture archiving and communication system (PACS) workstation. Inter-observer reliability was assessed using the intraclass correlation coefficient (ICC), and the mean of the two measurements was used for the final analysis.

Data Analysis

Data Preparation and Model Construction

All statistical analyses were performed using SPSS version 22.0 (IBM Corp., Chicago, IL, USA). Continuous variables were assessed for normality using the Shapiro-Wilk test and were presented as mean $\pm$ standard deviation for normally distributed data or as median (interquartile range) for non-normally distributed data. Group comparisons of continuous variables were conducted using the independent samples *t*-test (for normal distributions) or the Mann-Whitney U test (for non-normal distributions).

Inter-observer reliability for the key measurements (TD, FD, PW and FW) was assessed by two independent raters across all 50 cases. Inter-observer reliability was quantified using a two-way random-effects ICC for absolute agreement. ICC values were interpreted as follows: <0.50, poor; 0.50–0.75, moderate; 0.75–0.90, good; >0.90, excellent.

Data from the TKA Group ($n = 20$ knees, with actual osteotomy thickness) and the Non-surgical group ($n = 30$ knees, with three simulated osteotomy thicknesses per knee) were combined, resulting in a final analytical dataset of $N = 110$ observations. Because the three simulated osteotomy thickness measurements from each non-surgical knee were derived from the same anatomical structure, potential within-knee correlation was considered. A linear mixed-effects model with a random intercept for each knee was performed as a sensitivity analysis to evaluate the robustness of the primary regression findings.

In the Non-surgical Group, each simulated osteotomy thickness (8, 9, and 10 mm) represents a clinically plausible surgical scenario. In clinical practice, the final osteotomy thickness is influenced by surgeon preference and intraoperative findings and may vary by 1–2 mm even under similar anatomical conditions. Therefore, these three thicknesses were included to capture the range of clinically relevant variability.

No missing data were identified for the primary anatomical and surgical variables analyzed in this study. A two-tailed p -value < 0.05 was considered statistically significant throughout the analysis.

Predictive Modeling

The correlation between anatomical measurements (TD/FD) and osteotomy thickness was evaluated using Pearson's correlation coefficient (for normally distributed pairs) or Spearman's rank correlation coefficient (for non-normally distributed pairs). A multiple linear regression model was further constructed with osteotomy thickness as the dependent variable. The model was employed to quantify the relationship and predictive utility of the

anatomical landmarks. The model took the following form: Osteotomy thickness = $\beta_0 + \beta_1(\text{TDJ}) + \beta_2(\text{FDJ}) + \varepsilon$, where β_0 is the intercept, β_1 and β_2 are the standardized regression coefficients, and ε is the error term. The normalized variables TDJ and FDJ were calculated by dividing TD and FD by the corresponding width measurement (PW in the TKA Group and FW in the Non-surgical Group), respectively, and were used as predictors in the regression model. The model was constructed using the Enter method in SPSS (version 22.0, IBM, Chicago, IL, USA), with all predictors entered simultaneously to assess their combined explanatory power. Model assumptions, including linearity, normality of residuals, and homoscedasticity, were evaluated graphically and statistically.

Model Evaluation

The overall performance of the predictive model was evaluated using the adjusted R^2 value, which indicates the proportion of variance in osteotomy thickness explained by the predictors, penalized for the number of predictors. The overall significance of the regression model was tested using an analysis of variance (ANOVA) F-test. The individual contribution of each predictor was assessed based on its standardized regression coefficient (Beta) and the corresponding p -value. A p -value < 0.05 was considered statistically significant. Variance inflation factors (VIFs) were calculated for each predictor to diagnose potential multicollinearity, with VIF values < 5 indicating acceptable collinearity levels.

Results

Reliability of Anatomical Measurements

Inter-observer reliability was assessed using the intraclass correlation coefficient (ICC) with a two-way random-effects model for absolute agreement. The average-measures ICC was 0.911 (95% CI: 0.863–0.945) for TD and 0.894 (95% CI: 0.836–0.935) for FD, indicating good to excellent reproducibility. The mean value of the repeated measurements was used in all subsequent analyses. After establishing acceptable measurement reliability, the study population and the derived anatomical variables were evaluated for the primary analysis.

Study Population, Descriptive Statistics, and Adjusted Anatomical Variables

The TKA Group (20 knees) and the Non-surgical group (30 knees) were included. The demographic and clinical characteristics of the two groups are summarized in Table 1. The distribution of primary diagnosis (osteoarthritis [OA] vs. rheumatoid arthritis [RA]) showed no significant difference between groups ($p = 0.202$, Fisher's exact test).

To control for the influence of individual physique, the raw anatomical measurements were normalized. The normalized tibial tubercle distance (TDJ) and normalized fibular head distance (FDJ) were calculated by normalizing TD and

FD to the corresponding width measurement, using PW in the TKA Group and FW in the Non-surgical Group, respectively. For the entire combined dataset ($N = 110$), the descriptive statistics for these adjusted predictors were: $\text{TDJ} = 0.3643 \pm 0.047$ and $\text{FDJ} = 0.2729 \pm 0.037$. These adjusted variables were then entered into a multiple linear regression model to evaluate their predictive value for osteotomy thickness. The dataset comprised 110 observations derived from 50 knees, with each non-surgical knee contributing three simulated osteotomy thicknesses.

Primary Analysis: Predictive Value of Adjusted Anatomical Landmarks

A multiple linear regression analysis was performed to evaluate the joint predictive utility of TDJ and FDJ for the tibial osteotomy thickness (THICKNESS). The key finding is that these landmarks, while showing a modest inverse association, possess very limited standalone predictive value.

The overall regression model was statistically significant ($F(2, 107) = 3.303$, $p = 0.041$). However, its explanatory power was minimal, with an adjusted R^2 of 0.041, indicating that TDJ and FDJ together accounted for approximately 4.1% of the variance in osteotomy thickness. Within this model, neither TDJ (standardized coefficient $\beta = 0.168$, $p = 0.078$) nor FDJ ($\beta = 0.157$, $p = 0.098$) was a statistically significant independent predictor. Although the direction of the FDJ coefficient differed from its unadjusted correlation with THICKNESS, this finding should be interpreted cautiously given the limited explanatory power of the model. The variance inflation factor ($\text{VIF} = 1.010$ for both) indicated no substantial multicollinearity. The complete regression results are detailed in Table 2. Thus, the primary analysis demonstrates that while a statistical association exists, these anatomical landmarks lack sufficient predictive power for clinical application. The sensitivity analysis using a linear mixed-effects model with a random intercept for each knee showed consistent results with the primary regression analysis, with no substantial changes in the direction, magnitude, or statistical significance of the regression coefficients.

Exploratory Time-Series Analysis: Interrogating the Data Structure

To further explore whether the ordering structure of the analytical dataset influenced the observed model fit, an exploratory Auto Regressive Integrated Moving Average [ARIMA] analysis was conducted.

The expert modeler selected a simple time-series, corresponding to an ARIMA (0,1,0) specification. While this model demonstrated an exceptionally high goodness-of-fit to the historical data ($R^2 = 0.896$), the model statistics indicated a "Number of Predictors" of 1 and a stationary R-squared of 0.085. This pattern suggests that the high goodness-of-fit may mainly reflect the ordering characteristics and internal structure of the osteotomy thickness

Table 2. Linear regression analysis for predicting osteotomy thickness.

Variable	Mean $\pm$ SD	Correlation with THICKNESS $\dagger$	unstandardized coefficient B (SE)	Standardized coefficient β	p value
(Constant)	—	—	6.998 (0.786)	—	<0.001*
TDJ	0.3643 $\pm$ 0.047	-0.184 (0.053)	2.913 (1.636)	0.168	0.078
FDJ	0.2729 $\pm$ 0.037	-0.174 (0.070)	3.480 (2.087)	0.157	0.098
Model Summary			R ² = 0.058 F(2, 107) = 3.303	Adjusted R ² = 0.041 p = 0.041*	

N = 110.

Abbreviations: SD, standard deviation; SE, standard error; THICKNESS, tibial osteotomy thickness; TDJ, normalized tibial tubercle distance; FDJ, normalized fibular head distance.

Notes: $\dagger$ Values are Pearson correlation coefficients (r) with p-values in parentheses. * indicates a statistically significant difference at $p < 0.05$.

The variance inflation factor (VIF) was 1.010 for both TDJ and FDJ, indicating no substantial multicollinearity.

dataset rather than providing evidence of substantial predictive value from the anatomical measurements. The Ljung-Box Q test confirmed the residuals were white noise ($p = 0.338$). These ARIMA model statistics, summarized in Table 3, are consistent with the conclusion from the regression analysis, indicating that the apparent model fit primarily reflects the underlying structure of the data, rather than the predictive utility of the anatomical landmarks.

Table 3. Goodness-of-fit statistics for the time series (ARIMA) model.

Fit statistic	Value
Model type	Simple (expert modeler)
Number of predictors in Model	1
Stationary R-squared	0.085
R-squared	0.896
RMSE	0.263
MAPE	1.137%
MAE	0.1027
Normalized BIC	-2.581
Ljung-Box Q(18)	
Statistic	19.910
DF	18
p	0.338

Notes: The stationary R-squared measures the model's predictive performance relative to a simple mean model. A positive value (0.085) indicates that the model provides a modest improvement over the mean model. The high R-squared (0.896) reflects the model's excellent fit to the historical data. The model included one predictor, yet the relatively low stationary R-squared suggests that the high fit is predominantly driven by the intrinsic temporal structure (e.g., trend or autocorrelation) within the osteotomy thickness data series itself, rather than by substantial predictive power from the anatomical landmarks (TDJ and FDJ). The non-significant Ljung-Box Q statistic ($p = 0.338$) confirms that the residuals are white noise, indicating that the model has adequately captured the available information in the series. RMSE, Root Mean Square Error; MAPE, Mean Absolute Percentage Error; MAE, Mean Absolute Error; BIC, Bayesian Information Criterion; DF, Degrees of Freedom; ARIMA, Auto Regressive Integrated Moving Average.

Discussion

Restoring the normal joint line on the tibial side or accurately determining the tibial osteotomy surface is a core aspect of revision or primary TKA and a focus of numerous studies [5,6,7]. In primary TKA, the high point of the lateral tibial plateau or the low point of the medial plateau is typically used as a reference to determine the osteotomy thickness and plane, a method whose accuracy and effectiveness have been widely validated. However, in some complex TKA cases, due to potential damage to the proximal tibial bone surface from wear, trauma, erosion, or osteolysis, these traditional reference points may no longer be reliable [8,9]. Therefore, researchers have proposed using bony landmarks such as the femoral epicondyles, the inferior pole of the patella, the tibial tubercle, and the fibular head as auxiliary references, and have demonstrated their effectiveness [10,11]. Nonetheless, some deep bony landmarks, such as the adductor tubercle and the inferior patellar pole, may be suitable for preoperative planning because of their deep location or susceptibility to knee joint movement, with intraoperative use potentially increasing error [12,13]. Furthermore, some readily palpable landmarks, such as the tibial tubercle and fibular head, have also been considered insufficiently reliable when used alone as effective reference landmarks during surgery [14,15]. In contrast to previous studies that mainly evaluated the anatomical relationship or reliability of individual bony landmarks, the present study quantitatively assessed their predictive performance for tibial osteotomy thickness. Although TDJ and FDJ showed modest inverse associations with osteotomy thickness, the regression model demonstrated limited explanatory ability (adjusted R² = 0.041), and neither TDJ nor FDJ showed an independent significant contribution (TDJ: $\beta = 0.168$, $p = 0.078$; FDJ: $\beta = 0.157$, $p = 0.098$). These findings suggest that, compared with using anatomical landmarks as reference points alone, their predictive value for individualized osteotomy thickness determination may be limited and likely requires integration with additional clinical or biomechanical factors.

The multivariate linear regression model achieved overall statistical significance ($F(2, 107) = 3.303$, $p = 0.041$).

However, this finding must be interpreted with caution for two reasons. First, the model showed limited explanatory power, with an adjusted R^2 of 0.041, suggesting that over 95% of the variance in osteotomy thickness was attributable to factors outside our model. Second, and more importantly, neither of the hypothesized anatomical predictors demonstrated a statistically significant independent contribution to the model (TDJ: $\beta = 0.168$, $p = 0.078$; FDJ: $\beta = 0.157$, $p = 0.098$).

The ability of these anatomical measurements to estimate tibial osteotomy thickness remains limited within the exploratory framework of this study. The difference between the unadjusted correlation and the adjusted regression coefficient for FDJ may reflect the influence of multivariable adjustment; however, the lack of statistical significance and the low explanatory power of the model prevent further interpretation of this directional change. Therefore, these results support the presence of a modest inverse association between the anatomical measurements and tibial osteotomy thickness rather than a robust, standalone predictive tool. Clinically, although these landmarks may provide supplementary information, they are insufficient on their own for precise, individualized preoperative planning.

The exploratory time-series analysis yielded a model with exceptionally high goodness-of-fit ($R^2 = 0.896$), a result that requires careful interpretation to avoid misinterpretation. Crucially, the model statistics indicated a “Number of Predictors” of 1, whereas the stationary R-squared was 0.085. This combination revealed that the expert modeler selected a “Simple” model (effectively a random walk or naive model) and that its goodness-of-fit may be influenced by the ordering characteristics and internal structure of the osteotomy thickness dataset, and should not be interpreted as evidence of strong predictive utility of the anatomical measurements. Thus, these results should not be interpreted as evidence supporting the predictive utility of the anatomical landmarks. Instead, they underscore the smooth, continuous nature of the dataset—a separate property that does not enhance the predictive performance observed in the primary regression analysis. Accordingly, conclusions regarding the clinical and predictive values of these anatomical landmarks should be based on the multivariate linear regression analyses.

The inter-observer reliability for the key anatomical measurements was reassessed and found to be satisfactory, with average-measures ICC values of 0.911 (95% CI: 0.863–0.945) for TD and 0.894 (95% CI: 0.836–0.935) for FD. These results indicate good to excellent reproducibility, confirming that the measurement protocol was sufficiently consistent for subsequent analyses. Given this acceptable reliability, the limited explanatory power of the regression model (adjusted $R^2 = 0.041$) can be interpreted with greater confidence as reflecting the genuinely limited standalone predictive value of these anatomical landmarks, rather than being an artifact of excessive measure-

ment noise. Nevertheless, it must be acknowledged that manual measurements on two-dimensional CT images inherently involve some degree of subjectivity and precision constraints. Future studies employing semi-automated or three-dimensional measurement techniques could further refine the precision of these assessments.

Several limitations of this study should be acknowledged. First, the sample size was relatively small, particularly for the TKA group ($n = 20$ knees), which limits the statistical power to detect smaller effect sizes and may affect the generalizability of the findings.

Second, in the Non-surgical Group, each knee contributed three observations corresponding to simulated osteotomy thicknesses of 8, 9, and 10 mm. Although these measurements originated from the same anatomical structure and are not fully independent, we chose this approach to reflect the clinical reality that a range of osteotomy thicknesses may be selected for the same knee depending on intraoperative surgical judgment. To assess the potential impact of within-knee correlation, we conducted a sensitivity analysis using a linear mixed-effects model with a random intercept for each knee. The results were consistent with the primary ordinary least squares regression analysis, with no substantive change in the direction, magnitude, or significance of the regression coefficients. Nevertheless, readers should interpret the precision of our estimates with this limitation in mind.

Third, the use of simulated osteotomy planes in the non-surgical group, while necessary for ethical and practical reasons, may not fully reproduce the intraoperative conditions encountered during TKA. Furthermore, the simulated osteotomy thicknesses (8, 9, and 10 mm) were predefined scenarios rather than actual clinical resection outcomes. Because the anatomical measurements were derived relative to these simulated osteotomy planes, potential geometric dependency should be considered when interpreting the observed associations. Future studies using independently measured intraoperative osteotomy thicknesses are required to validate the predictive applicability of these landmarks. Fourth, this study focused on only two anatomical landmarks. Other factors known to influence osteotomy thickness — including soft tissue tension, ligamentous balance, implant design, and surgeon preference — were not incorporated into the predictive model.

Despite these limitations, this study provides preliminary evidence regarding the association between extra-articular bony landmarks and tibial osteotomy thickness, and offers direction for future research incorporating more comprehensive, multi-factorial predictive models.

Conclusions

In summary, this study demonstrates a modest inverse association between measurements derived from the tibial tubercle and fibular head and tibial osteotomy thickness. The limited explanatory power of the regression model high-

lights the multifactorial nature of tibial osteotomy level determination in TKA, with bony landmarks representing only one of many contributing factors. Future research aimed at developing predictive models should integrate these landmarks with a broader set of variables, including those related to soft-tissue and dynamic intraoperative assessment, to move toward more comprehensive and clinically reliable planning aids.

Availability of Data and Materials

The data analyzed are available from the corresponding authors upon reasonable request.

Author Contributions

Conceptualization, FJ and XC; methodology, JLS and XC; validation, JLS and HL; formal analysis, JLS and HL; investigation, JLS, PL and HL; data curation, JLS; writing—original draft preparation, JLS; writing—review and editing, JLS and FJ; visualization, JLS; supervision, FJ, XC; project administration, HL and FJ; funding acquisition, HL and FJ. All authors contributed to the critical revision of the manuscript for important intellectual content. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

This study was approved by the Ethics Committee of People's Hospital of Zhongzhan District (No. 2024001). Since this study is based on retrospective anonymized data without identifiable information, the informed consent was waived in accordance with relevant regulations. The study conformed to the provisions of the Declaration of Helsinki.

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Conflict of Interest

The authors declare no conflict of interest.

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