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An Asymmetric Medio-Lateral Flexion Laxity Target Yields Excellent Results in Robotic-Assisted Total Knee Arthroplasty With Functional Knee Positioning

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ABSTRACT

Background: Functional knee positioning (FKP) in robotic-assisted (RA) total knee arthroplasty (TKA) aims to optimize soft-tissue balance through patient-specific implant fine-tuning. However, it remains unclear (1) how intraoperative ligament laxity affects joint awareness and (2) whether the discrepancy between intraoperative planned and achieved laxity is affected by preoperative coronal limb alignment or fixed flexion deformity (FFD).

Methods: This retrospective study analyzed 130 patients undergoing image-based RA TKA with FKP using a cementless cruciate-retaining implant. Intraoperative adjustments were made to balance the flexion-extension laxity, targeting one to two mm larger lateral flexion laxity. Medial and lateral gaps before and after implant positioning were recorded at near extension and 90° flexion. Patient-reported outcome measures (PROMs), including the Forgotten Joint Score (FJS-12) and a 5-point Likert scale for satisfaction, were assessed at a minimum of one year postoperatively to investigate correlations between PROMs and final intraoperative laxities. The impact of preoperative coronal limb alignment, measured on long-leg radiographs, and FFD on final laxities was also evaluated.

Results: Final laxities were: median medial extension laxity 1.5 mm (1.0 to 2.0), lateral extension laxity 1.5 mm (1.1 to 2.0), medial flexion laxity 1.0 mm (0.5 to 1.5), and lateral flexion laxity 2.0 mm (1.5 to 2.5). At one year, the FJS-12 was 87.4 ± 14.5. A weak inverse correlation was observed between medial flexion laxity and FJS-12 ($r = -0.18$, $P = 0.047$); no other laxities were associated with PROMs. Sensitivity analyses showed no relevant laxity cutoffs influencing PROMs. Valgus knees exhibited larger changes between planned and final medial extension laxity compared with varus knees ($P < 0.002$). Unlike cases without FFD, those with preoperative FFD $>10^\circ$ showed no discrepancy between planned and final extension laxities ($P < 0.003$).

Conclusions: Image-based RA TKA using FKP achieves good-to-excellent clinical outcomes at one year, with a balanced symmetric extension laxity. Coronal limb alignment and FFD significantly influence the deviation between planned and final extension laxity and should be considered during surgical planning.

Total knee arthroplasty (TKA) has long been established as an effective surgical treatment for end-stage knee osteoarthritis, with the primary goal of reducing pain and restoring function [1]. Over the last decade, however, the focus in TKA has increasingly shifted toward personalization, broadening the traditional mechanical alignment philosophy to a spectrum of patient-specific alignment strategies [2]. These emerging techniques aim to restore a well-functioning joint through the concept of a "balanced soft-tissue

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envelope", tailored to each patient's individual anatomy and functional demands.

Among these innovative approaches is functional knee positioning (FKP), a three-dimensional (3D) alignment philosophy that attempts to restore the patient's prearthritic or functional alignment [3,4]. This strategy leverages advanced technologies such as image-based planning and robotic-assisted (RA) surgery to refine component placement and to optimize tibio-femoral and patello-femoral soft-tissue balancing intraoperatively. Despite these advancements, a substantial knowledge gap remains: the inherent ligamentous laxity of each patient before the onset of arthritis is typically unknown. Biomechanical evidence demonstrates that the medial collateral ligament behaves isometrically, while lateral laxity is more variable, establishing the principle of preserving medial stability with modest lateral laxity in flexion as relative, rather than absolute, targets [5]. Current approaches to assessing individual knee laxity predominantly depend on intraoperative evaluations, which may be affected by pathological deformities, degenerative changes, and surgical technique [6,7].

The evidence linking knee laxity to patient-reported outcome measures (PROMs) remains limited and heterogeneous, particularly when considering the wide array of alignment philosophies in use today [8–19]. In this setting, measures of joint awareness and satisfaction may be especially relevant, as they could capture subtle instability or imbalance more directly than broader functional outcome scores, which are often influenced by broader factors such as age, comorbidities, or rehabilitation potential [20]. Yet, in the context of FKP, it remains unclear to what extent intraoperative ligament laxity impacts clinical outcomes [7]. Furthermore, while robotic systems now allow for highly individualized planning and adjustment of implant position to achieve targeted laxity, discrepancies between planned and achieved laxity are frequently observed. These inconsistencies may arise due to several intraoperative factors, such as fixed flexion deformity (FFD), altered coronal alignment, or the presence of extensive osteophytes, which may compromise the accuracy of the intraoperative soft-tissue assessment [6,21].

Given this context, the present study aimed to investigate two primary questions within the framework of image-based RA TKA with FKP: (1) what is the relationship between intraoperative knee laxity, expressed in terms of tibio-femoral gaps, and both joint awareness and patient satisfaction at one year postoperatively? and (2) what are the differences between planned and achieved knee laxity, and how are these influenced by both an FFD and coronal lower limb alignment? It was hypothesized that, within the context of RA TKA, intraoperative knee laxity patterns influence clinical outcomes and that coronal and sagittal limb deformities impact the assessment of intraoperative laxity.

Materials and Methods

Study Design and Population

This retrospective study of a prospectively collected database was conducted at a single tertiary arthroplasty center and included all consecutive patients who underwent RA-TKA for end-stage primary knee osteoarthritis. All procedures were performed between June 1, 2023 and June 30, 2024 using the Triathlon Tritanium (Stryker, Michigan) cementless cruciate-retaining (CR) or cruciate-stabilized (CS) knee design with the MAKO robotic system (Stryker, Michigan). Exclusion criteria included posterior cruciate ligament or collateral ligamentous insufficiency, previous infection, previous femoral/tibial osteotomy or previous femoral/tibial fracture, inflammatory joint diseases, neurological conditions, the need for higher constraint than a CR/CS design, or severe osteopenia/osteoporosis.

Patient Demographics

A total of 149 patients who underwent RA TKA were included. Of these, 19 patients lacked the complete availability of intraoperative laxity data. Of these 130 remaining patients, 117 patients had complete preoperative long-leg radiographs for coronal alignment assessment, and 117 patients completed 1-year postoperative PROMs. There was one patient who died prior to completing the 1-year PROMs follow-up and was excluded from further analysis.

The mean age at the time of surgery was 73 years (range, 42 to 89). The cohort comprised 49 men (38%) and 81 women (62%). Laterality was evenly distributed, with 66 knees (51%) operated on the left side and 64 knees (49%) on the right side. The mean body mass index was 29.9 (range, 17.4 to 44.9). The mean value for the hip-knee-ankle angle (HKA) was 3.1 degrees varus (range, 22 degrees varus to 16 degrees valgus).

Surgical Technique

All patients underwent a preoperative computed tomography scan of the hip, knee, and ankle to allow for 3D reconstruction and surgical planning. All surgeries were performed by three experienced arthroplasty surgeons who had a caseload of more than 50 TKA per year, using an FKP technique for TKA alignment, without a tibial precut for knee balancing. The tourniquet was not applied in any of the cases included. After a medial parapatellar approach, femoral and tibial tracker arrays were securely attached to the patient's femur and tibia, followed by bone registration. After medial and lateral femoral and tibial osteophyte removal, a laxity assessment was performed. Extension laxity was assessed in between 10 and 20 degrees of knee flexion to decouple the posterior capsule from the femoral condyles and posterior osteophytes and prevent false tight gaps caused by posterior capsule tension. A manual varus/valgus correction force was then applied to tension the soft tissues. At 90 degrees of flexion, spoons were used to tension the soft tissues by applying a distraction of the medial and lateral tibio-femoral compartments. During the laxity assessment, care was taken to tension the medial and lateral collateral ligaments by removing slack without entering the linear region of the stress–strain curve, thereby avoiding excessive distraction or tissue damage [22]. The force applied to balance the knee was not influenced by the values of the flexion/extension gaps displayed on the robotic system screen. Intraoperative laxity values were displayed in real-time on the robotic system screen. These values represent the gap measured by the robotic system between the most prominent points of the femoral component's distal (in extension) and posterior (in flexion) condyles and the deepest point of the tibial polyethylene insert, based on the virtual patient-specific implant configuration. Intraoperative adjustments were made to the 3D implant positioning to balance the flexion-extension laxity, aiming for a 0.5 to 1.5 mm symmetric gap in extension and an asymmetric gap in flexion, with a 0.5 to one mm gap medially and a one to two mm larger gap laterally. These values were used as practical safe reference ranges rather than rigid thresholds [23]. For cases with FFD greater than 10 degrees, a larger extension gap was planned, either by a proximal shift of the distal femoral cut or by a distal shift of the tibial cut. These adjustments were performed while carefully preserving joint line height and maintaining target flexion balance.

In the coronal plane, the tibial component matched the native mechanical medial proximal tibial angle within a boundary of two degrees valgus to four degrees varus, after consideration of possible bony wear. The tibial resection landmarks were chosen close to the constitutional tibial anatomy to reproduce both joint line orientation (medial proximal tibial angle) and joint line height, with landmarks referenced approximately two-thirds posteriorly on the tibial plateau. In the sagittal plane, the tibial component position recreated the native tibial slope of the unaffected compartment within a boundary of zero to seven degrees. Femoral component coronal alignment was fine-tuned within a safe zone ranging from five degrees valgus to five degrees varus. The sagittal position of the femoral component was adjusted to prevent anterior notching and modify component sizing to balance the flexion gap and restore the posterior condylar offset. Femoral component axial rotation was referenced to the posterior condylar axis and subsequently adjusted to achieve flexion gap balance while respecting native trochlear orientation. After femoral and tibial components' fine-tuning, all bone cuts were performed at a single stage using the haptically controlled robotic arm and preserving the posterior cruciate ligament insertion. Trial components were inserted, after which alignment and soft-tissue balance were reverified. In the axial plane, the tibial component was rotated to ensure tibio-femoral congruency in extension. Lateral patellar facetectomy was performed, while patellar resurfacing was not performed [24]. In cases of suboptimal patellar tracking, reshaping of the patella was undertaken, reducing its thickness to prevent overstuffing and improving patello-femoral tracking. Final cementless components were then implanted. By default, a CR insert was used (117 out of 130, 90%). A CS insert was used in case the intraoperative assessment suggested insufficient posterior cruciate ligament competence (e.g., excessive posterior drawer after trialing; 13 out of 130, 10%). With the final implants in place, the laxity assessment was repeated using the same method as before the bone cuts.

In varus knees, a limited release was performed of the deep fibers of the medial collateral ligament for exposure of the proximal tibia to the level of the tibial cut. In five patients (five of 130, 3.8%), an additional release was performed before any of the bony cuts and implant fine-tuning (three ilio-tibial band releases in valgus knees and two medial collateral ligament releases in varus knees).

All patients followed a standardized rehabilitation protocol, starting mobilization on postoperative day one with weight-bearing as tolerated and a structured physiotherapy program with frequent follow-up and home exercises.

Outcomes

Intraoperative laxity data were routinely recorded by the robotic system and expressed as tibio-femoral gaps, taking into account the planned femoral and tibial component positioning and the selected polyethylene insert thickness. Medial extension laxity (MEL) and lateral extension laxity (LEL) were measured in millimeters near full extension, whereas medial flexion laxity (MFL) and lateral flexion laxity (LFL) represented the tibio-femoral gaps at 90° of flexion.

There were two sets of values stored: the planned laxity, measured before bone resections, and the final laxity, measured after implantation of the definitive components with the final insert in place.

Following Graichen et al. [25], four laxity phenotypes (LP) were calculated.

- LPext = MEL−LEL (medio-lateral balance in extension),
- LPflex = MFL−LFL (medio-lateral balance in flexion),
- LPmed = MEL−MFL (medial balance between extension and flexion),
- LPlat = LEL−LFL (lateral balance between extension and flexion).

If the final insert thickness differed from the 9-mm insert used in the planning phase, this difference was incorporated into the calculation of planned-to-final laxity changes.

Extension was measured as the maximal passive knee extension without the application of external force, defined as the smallest angle between the mechanical axes of the femur and tibia in the sagittal plane, as reported by the robotic software. For analysis, any loss of full extension (0°) was defined as FFD.

Preoperative coronal limb alignment was assessed by two trained orthopaedic surgery residents on full-length standing radiographs using the HKA, the angle formed between the femoral and tibial mechanical axes. The mean values of the two assessors were used for further analysis. Knees were categorized as varus (HKA $>$ 3° varus), valgus (HKA $>$ 3° valgus), and neutral (3° varus $\leq$ HKA $\leq$ 3° valgus).

At 1-year follow-up, clinical outcomes were assessed using the Forgotten Joint Score (FJS-12) [26], and a 5-point Likert scale for patient satisfaction was made of five items: "very satisfied," "satisfied," "neutral," "not satisfied," and "strongly not satisfied." Patients were contacted by telephone in case they did not attend follow-up visits. If unresponsive, they were considered lost to follow-up.

Ethics Statement

The present study adheres to the principles outlined by the Declaration of Helsinki and follows Good Clinical Practice guidelines for each step performed during the study, including data collection, analysis, and reporting. Ethics approval was obtained from the institutional review board (7/2024/OSS*/AOUMO, transmitted with protocol N. 4527/2024).

Data Analyses

All statistical analyses were performed using the Statistical Package for Social Sciences (SPSS, Version 23.0, IBM, New York, USA). Using GPower (Version 3.1, Universität Düsseldorf, Germany) for a two-tailed Pearson correlation with α of 0.05 and power of 0.78, the required sample size was 117 cases to detect a modest correlation of $r = 0.25$ between final laxity and the clinical outcomes in this study [27]. Data normality was assessed using the Shapiro–Wilk test and visually inspected using boxplots. Correlation analyses were performed to assess the relationship between final laxity and both FJS-12 and satisfaction. In these analyses, cases exhibiting greater than 10° of FFD following final component implantation (n = two) were excluded. This exclusion criterion was applied because an FFD exceeding 10° compromises the surgeon's capacity to reliably assess joint laxity near extension. A threshold analysis was conducted to determine whether specific laxity thresholds (laxity above versus below cutoffs incrementally increasing by 0.5) were associated with superior outcomes. The influence of FFD was evaluated via a correlation between FFD and the differences between planned and achieved laxity values (Pearson or Spearman correlation based on normality). As well, a sensitivity analysis comparing the differences between planned and achieved laxity above and below selected FFD thresholds was performed. The influence of coronal alignment was assessed by comparing differences between planned and achieved laxity across varus, neutral, and valgus groups. For the latter analysis, patients who had a preoperative or final FFD greater than 10° were excluded from the study, as a preoperative FFD exceeding this threshold limits the ability to accurately assess laxity before bony cuts, while a final FFD greater than 10° impairs the assessment of laxity following final implant insertion. Parametric data were analyzed using Student's *t*-tests, and results were reported as means with standard deviations (SDs). Nonparametric data were analyzed using Mann–Whitney *U*-tests and reported as medians with interquartile ranges (IQR: Q1 to Q3). A *P*-value below 0.05 was considered statistically significant. A Bonferroni correction was applied for multiple comparisons where appropriate.

Results

Relationship Between Final Laxity and Clinical Outcomes

Preoperative FFD averaged four degrees (range, −6 (hyperextension) to 31 (FFD)), whereas postoperative FFD was recorded at a mean of two degrees (range, −5 (hyperextension) to 16 (FFD)). In total, 13 cases exceeded 10 degrees of FFD preoperatively. Final laxities were MEL median 1.5 mm (1.0 to 2.0), LEL 1.5 mm (1.1 to 2.0), MFL 1.0 mm (0.5 to 1.5), and LFL 2.0 mm (1.5 to 2.5). At one year postoperatively, FJS-12 averaged 87.4 ± 14.5, and 113 out of 117 patients (97%) were satisfied or very satisfied with the result of surgery.

Excluding cases with more than 10 degrees of FFD after implantation of final components (n = two), a weak negative correlation was observed between final MFL and the FJS-12 at one year postoperatively ($r = -0.18$; $P = 0.047$; Figure 1). No other gap measurements showed an association with either the FJS-12 or satisfaction at one year postoperatively ($P = 0.061$ to 0.55). Sensitivity analyses did not identify specific laxity thresholds associated with superior FJS-12 when comparing patients above versus below the threshold (Figure 2). Likewise, LPext, LPflex, LPmed, and LPlat had no impact on FJS-12 or satisfaction scores at one year.

Role of FFD on the Change Between Planned and Final Laxity

Using a sensitivity analysis, a threshold of 8 to 10 degrees of preoperative FFD was found to influence the change from planned to achieved MEL ($P = 0.004$) and LEL ($P < 0.001$) (Table 1), with the final laxity being larger than the planned laxity in the cases without FFD. The change from planned to final laxity in extension was weakly correlated to the difference between preoperative and postoperative FFD ($P = 0.03$ and < 0.001 for MEL and LEL, respectively; Table 2), whereas this was not the case for MFL or LFL.

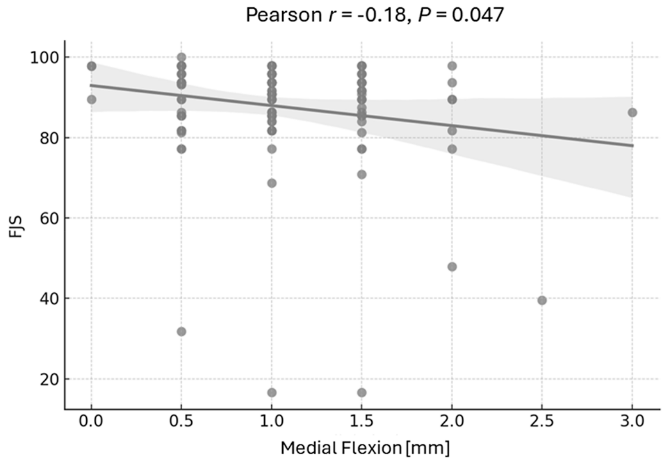

Figure 1. Correlation analysis between Forgotten Joint Score and the Medial Flexion Laxity. FJS-12, Forgotten Joint Score.

Role of Coronal Alignment on the Change Between Planned and Final Laxity

For this analysis, cases with either a preoperative or final FFD greater than 10 degrees were excluded based on prior findings. Valgus knees exhibited a greater MEL difference from planning to final measurement compared with varus knees: 2.0 (1.0 to 3.0) versus 1.0 mm (0.5 to 1.5; $P = 0.002$) (Table 3). There were no other planned-to-final laxity changes that differed across coronal alignment categories.

Discussion

This study demonstrates that image-based RA TKA using the FKP technique enables the surgeon to plan for and achieve a symmetric extension laxity (MEL median, 1.5 mm (IQR: 1.0 to 2.0), LEL 1.5 mm (IQR: 1.1 to 2.0)) and an asymmetric flexion laxity pattern (MFL 1.0 mm (IQR: 0.5 to 1.5), LFL 2.0 mm (IQR: 1.5 to 2.5)), resulting in good-to-excellent clinical outcomes at one year. Unlike traditional target-based methods, FKP does not rely on fixed laxity values but rather permits a deliberate slight lateral laxity in flexion (mean LPflex 0.8 mm). The IQR illustrates that successful clinical results can still be achieved despite a certain variability in soft-tissue balance. In addition, a statistically significant inverse correlation between MFL and the FJS-12 suggests that increased medial laxity in flexion may negatively impact joint awareness. This finding reinforces the importance of medial stability in achieving favorable functional outcomes [8,9,12–17,28–31]. A possible explanation lies in the anatomical and functional differences between the medial and lateral compartments. Unlike the lateral compartment, which benefits from dynamic stabilizers, the medial compartment relies solely on the medial collateral ligament for stability. Any loss of medial stability can affect overall balance, highlighting the importance of achieving optimal medial compartment balance. Although prior literature has emphasized the relevance of medial laxity to patient satisfaction across various implants and alignment philosophies, this is the first study to establish such an association within the context of FKP. Although chosen laxity targets in this study reflect an empirically derived safe range from the literature—emphasizing the importance of medial stability while acknowledging the greater tolerance of the lateral compartment—these values are not fixed thresholds, and reproducible boundaries for laxity remain to be defined. Conversely, no significant associations were found between other laxity parameters and clinical outcomes. This is consistent with the findings by Manara et al., who also reported favorable mean FJS-12 outcomes in a balanced cohort without identifying specific laxity thresholds predictive of PROMs [7]. Nevertheless, the clinical relevance of lateral laxity, particularly in flexion, remains debated. Although physiological in native knees, lateral laxity post-TKA has shown mixed associations in the literature, with some studies suggesting a positive influence on PROMs, others linking excessive laxity to suboptimal results, and some advocating for symmetric medial-lateral balancing [9,10,12–14,18,29,31–33]. These discrepancies may be partly attributable to the predominance of mechanical alignment in previous studies, which tends to preserve lateral laxity in typical varus osteoarthritis unless a medial release is performed.

The observed differences between planned and achieved intraoperative laxity values in our cohort may also account for the variation in final laxities and could be attributed to the FKP surgical technique without tibial precut: the removal of large posterior femoral and tibial osteophytes after bone resections may result in recorded laxity values being greater than the planned gaps. Notably, robotic systems employ digital tensioning, which has been shown to be reproducible [7], yet intraoperative factors

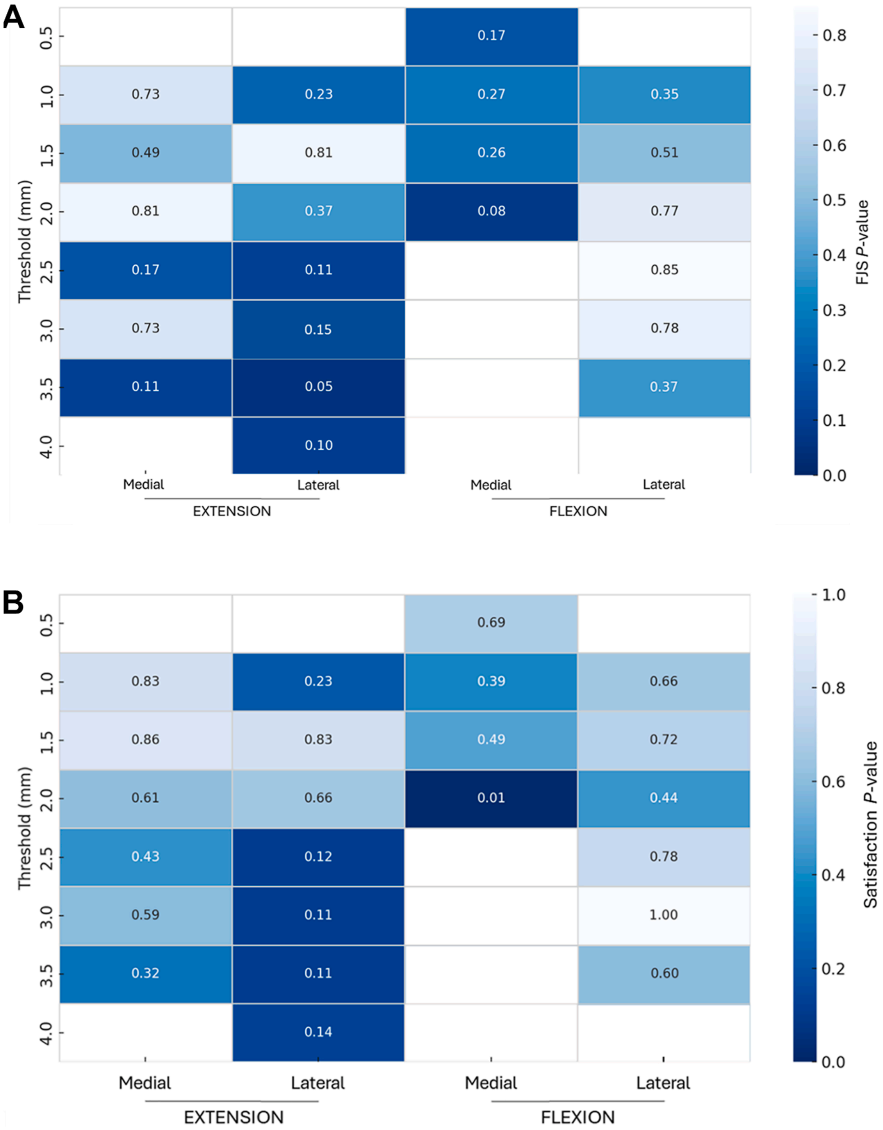

Figure 2. Heatmap of threshold analysis showing *P* values for the difference in Forgotten Joint Score (A) and Satisfaction (B) at one year postoperatively between the group above versus below each laxity threshold. A Bonferroni correction was applied, setting the significance level at $P < 0.006$. FJS-12, Forgotten Joint Score.

can still introduce a mismatch. Prior studies suggest that posterior osteophyte removal may subtly alter laxity by releasing posterior capsular tension [6]. Gustke et al. argue that this effect may be minimal for coronal balance but acknowledge the possibility of minor increases in joint laxity [21].

This study further explored the effect of FFD on the discrepancy between planned and achieved laxity. In cases with FFD, surgeons typically aimed for greater MEL and LEL to facilitate full extension postoperatively [34]. Interestingly, in these cases, the planned gaps more closely matched final measurements, whereas in cases without FFD, the final laxity was usually slightly larger than planned, likely reflecting the more constrained planning with wider gaps in FFD and the greater influence of intraoperative factors in knees without FFD.

Coronal alignment was another factor associated with discrepancy between planned and achieved laxity, particularly in

Table 1
Results of the Threshold Analysis Indicating the Change in Planned to Final Laxity for a Threshold of 10° of Preoperative Fixed Flexion Deformity.

Threshold of 10°	Group ≤ Threshold	Group > Threshold	*P*-Value
Medial extension	1.0 (0.5; 1.5) (n = 117)	0 (−0.5; 1.0) (n = 13)	0.004
Lateral extension	1.0 (0; 1.5) (n = 117)	−0.5 (−0.5; 0) (n = 13)	<0.001
Medial flexion	0.5 (0.5; 1.0) (n = 117)	0.5 (0; 1.0) (n = 13)	0.2
Lateral flexion	0.5 (0; 1.5) (n = 117)	0 (−0.5; 0.5) (n = 13)	0.01

A Bonferroni correction was applied with a level of significance of 0.005.
Results are indicated as median (Q1, Q3), and expressed in millimeters.

Table 2
Correlation Analysis Between the Change From Planned to Final Laxity and the Change in Preoperative to Final Fixed Flexion Deformity.

ΔNative FFD−Final Extension FFD	r	*P*-Value
Medial extension	0.26	0.03
Lateral extension	0.35	0.001
Medial flexion	0.13	0.15
Lateral flexion	0.10	0.26

FFD, fixed flexion deformity.

Table 3
Change From Planned to Final Laxity by Coronal Alignment Category.

Variable	Comparator 1	C1 Results	Comparator 2	C2 Results	*P*-Value
Medial extension	Varus (n = 69)	1.0 (0.5; 1.5)	Neutral (n = 20)	1.0 (0.5; 1.8)	0.94
Medial extension	Varus (n = 69)	1.0 (0.5; 1.5)	Valgus (n = 28)	2.0 (1.0; 3.0)	0.002[a]
Medial extension	Neutral (n = 20)	1.0 (0.5; 1.8)	Valgus (n = 28)	2.0 (1.0; 3.0)	0.02
Lateral extension	Varus (n = 69)	1.0 (0.5; 2.0)	Neutral (n = 20)	1.5 (0.9; 2.0)	0.96
Lateral extension	Varus (n = 69)	1.0 (0.5; 2.0)	Valgus (n = 28)	0.5 (0.0; 1.5)	0.09
Lateral extension	Neutral (n = 20)	1.5 (0.9; 2.0)	Valgus (n = 28)	0.5 (0.0; 1.5)	0.19
Medial flexion	Varus (n = 69)	0.5 (0.5; 1.5)	Neutral (n = 20)	0.8 (0.5; 1.1)	0.93
Medial flexion	Varus (n = 69)	0.5 (0.5; 1.5)	Valgus (n = 28)	1.0 (0.5; 2.1)	0.18
Medial flexion	Neutral (n = 20)	0.8 (0.5; 1.1)	Valgus (n = 28)	1.0 (0.5; 2.1)	0.23
Lateral flexion	Varus (n = 69)	1.0 (0.0; 1.5)	Neutral (n = 20)	1.0 (0.0; 1.5)	0.72
Lateral flexion	Varus (n = 69)	1.0 (0.0; 1.5)	Valgus (n = 28)	1.2 (0.5; 2.0)	0.14
Lateral flexion	Neutral (n = 20)	1.0 (0.0; 1.5)	Valgus (n = 28)	1.2 (0.5; 2.0)	0.11

Results are presented as median (Q1, Q3) in millimeters.
Comparisons Were Performed Between Comparator 1 (C1) and Comparator 2 (C2), With Results Shown in the Respective Columns.
C = Comparator.
[a] Indicates statistical significance after Bonferroni correction.

valgus knees. Compared with varus deformities, valgus knees exhibited greater variation in medial extension laxity from plan to final outcome. This may partly reflect the use of a medial parapatellar approach, which can act as a functional "release" of the medial collateral ligament [35]. This effect was less pronounced in varus knees, where the MCL is typically tighter and more robust, potentially resisting unintended changes. In contrast, in valgus knees, the medial collateral ligament is often less competent and more susceptible to alterations induced by the surgical approach. These subtle surgical differences may lead to incremental laxity changes that are more pronounced in valgus alignment.

This study has several potential limitations. There were three different surgeons who contributed to patient care, introducing potential interoperator variability. The preresection gap assessment was not standardized, and no objective force-measurement tools were used during tensioning. This introduces variability in gap measurements, despite efforts to avoid any excessive stress during the assessment. In addition, the ideal laxity targets for each individual patient remain unknown, which is a primary reason this study was conducted. Although a slightly looser LFL was generally accepted and still associated with good-to-excellent clinical outcomes, these specific laxity values may not be generalizable to all implant designs or alignment strategies. Also, the retrospective design inherently limits control over confounding factors. Key contributors to outcomes such as implant positioning or joint line obliquity were not evaluated, though they likely interact with laxity to influence PROMs. Although we did not classify patients by native knee phenotype [36,37] due to sample size restrictions, such a classification may offer insight into individualized alignment strategies. Similarly, because of the relatively small effect sizes and the limited number of knees in some subgroup analyses, the possibility of type II error cannot be excluded. Prospective studies are needed to clarify these interactions. Furthermore, clinical outcomes in this cohort were generally favorable, which may have limited the ability to detect any meaningful relationship between laxity values and clinical outcomes. Follow-up was limited to one year; while this time frame is valuable for early outcomes, longer-term data collection is ongoing. It should also be recognized, however, that the incremental value of long-term PROMs is debated, as recent evidence has suggested they may offer little additional information beyond two years after arthroplasty [38]. Moreover, this study did not include preoperative baseline PROMs or functional outcome scores, which limits the interpretability and comparability of results. In addition, data on preoperative patient expectations, which are a known determinant of postoperative satisfaction, were not collected [39]. This may confound observed associations between laxity and PROMs. In addition, radiographic severity of osteoarthritis was not systematically assessed [40]. Baseline joint degeneration could affect native soft-tissue tension and influence both planning and final laxity values. Furthermore, ligamentous release was performed in five out of 130 patients (3.8%). Though not standardized and potentially impacting laxity assessment, these releases occurred before any implant adjustment and bone cuts. This might have a minor influence on the reported results. In addition, mid-resection workflow, with posterior osteophyte removal after the initial resections, might have produced different results regarding the effect of FFD on planned versus achieved laxities (Supplementary Table 1). Furthermore, the robotic system used in this study rounded off gap values to the nearest half of a millimeter may contribute to measurement imprecision, with a potential rounding error of up to 0.25 mm. Also, a potential optimism bias exists in outcome assessment, as postoperative satisfaction was collected via contact with the surgical team. This may have inadvertently influenced patient responses and inflated satisfaction scores.

Conclusions

Image-based RA TKA using the FKP technique achieved good-to-excellent clinical outcomes at one year with a well-balanced symmetric extension gap and an asymmetric flexion gap with slight lateral laxity. Although variability exists, the technique allowed consistent achievement of symmetric extension and modest lateral flexion laxity across the cohort. However, coronal limb alignment and preoperative FFD influenced the deviation between the planned and final laxity pattern. Knees with a preoperative FFD of more than 10° showed no significant deviation between planned and final extension laxities, whereas other cases demonstrated measurable differences. These factors should be carefully accounted for during surgical planning and intraoperative decision-making, as they may affect the ability to achieve the intended soft-tissue balance.

CRediT authorship contribution statement

H. Vermue: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **F. Zambianchi:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **S. Clemenza:** Writing – review & editing, Methodology, Data curation. **M. Clò:** Writing – review & editing, Methodology, Data curation. **J. Victor:**

Writing – review & editing. **F. Catani:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

References

[1] Carr AJ, Robertsson O, Graves S, Price AJ, Arden NK, Judge A, et al. Knee replacement. Lancet 2012;379:1331–40. https://doi.org/10.1016/S0140-6736(11)60752-6.

[2] Rivière C, Iranpour F, Auvinet E, Howell S, Vendittoli P-A, Cobb J, et al. Alignment options for total knee arthroplasty: a systematic review. Orthop Traumatol Surg Res 2017;103:1047–56. https://doi.org/10.1016/j.otsr.2017.07.010.

[3] Shatrov J, Battelier C, Sappey-Marinier E, Gunst S, Servien E, Lustig S. Functional Alignment Philosophy in total Knee Arthroplasty - rationale and technique for the varus morphotype using a CT based robotic platform and individualized planning. SICOT J 2022;8:11. https://doi.org/10.1051/sicotj/2022010.

[4] Koutserimpas C, Andriollo L, Gregori P, Zambianchi F, Tsiridis E, Catani F, et al. Revisiting terminology: the transition from “functional alignment” to “functional knee positioning”. Knee Surg Sports Traumatol Arthrosc 2025;33:1948–53. https://doi.org/10.1002/ksa.12667.

[5] Okazaki K, Miura H, Matsuda S, Takeuchi N, Mawatari T, Hashizume M, et al. Asymmetry of mediolateral laxity of the normal knee. J Orthop Sci 2006;11:264–6. https://doi.org/10.1007/s00776-006-1009-x.

[6] Lee JH, Jung HJ, Lee JK, Hwang JH, Kim Il J. Large osteophytes over 10 mm at posterior medial femoral condyle can lead to asymmetric extension gap following bony resection in robotic arm-assisted total knee arthroplasty with pre-resection gap balancing. J Clin Med 2023;12:5980. https://doi.org/10.3390/jcm12185980.

[7] Manara JR, Goonatillake M, Marley M, Pretty W, Collopy D, Clark G. Virtual assessment of coronal balance prior to bone resection with the MAKO robotic-assisted system accurately predicts final balance in TKA. J Robot Surg 2023;17:2849–54. https://doi.org/10.1007/s11701-023-01705-9.

[8] Campi S, Papalia R, Esposito C, Candela V, Gambineri A, Longo UG. The correlation between objective ligament laxity and the clinical outcome of mechanically aligned TKA. J Clin Med 2023;12:6007. https://doi.org/10.3390/jcm12186007.

[9] Watanabe M, Kuriyama S, Nishitani K, Nakamura S, Matsuda S. What is the optimal posterior cruciate ligament tension to achieve patient satisfaction in cruciate-retaining total knee arthroplasty? J Arthroplasty 2023;38:S183–9. https://doi.org/10.1016/j.arth.2023.01.050.

[10] Ueyama H, Nakagawa S, Minoda Y, Fukunaga K, Takemura S, Koyanagi J, et al. Association of intraoperative medial joint gap laxity in the flexion position with subjective knee instability after fixed-bearing posterior-stabilised total knee arthroplasty. Knee 2024;51:65–73. https://doi.org/10.1016/j.knee.2024.08.005.

[11] Kaneko T, Mochizuki Y, Hada M, Toyoda S, Takada K, Ikegami H, et al. Greater postoperative relatively medial loose gap at 90° of flexion for varus knees improves patient-reported outcome measurements in anatomical bi-cruciate retaining total knee arthroplasty. Knee 2020;27:1534–41. https://doi.org/10.1016/j.knee.2020.08.005.

[12] Tsubosaka M, Muratsu H, Takayama K, Maruo A, Miya H, Kuroda R, et al. Effect of intraoperative soft tissue balance on postoperative recovery of ambulatory and balancing function in posterior-stabilized total knee arthroplasty. J Orthop Sci 2019;24:507–13. https://doi.org/10.1016/j.jos.2018.10.024.

[13] Takagi K, Taketomi S, Yamagami R, Kawaguchi K, Sameshima S, Kage T, et al. Both intraoperative medial and lateral joint stabilities at midflexion influence postoperative patient-reported outcome measures following Bi-Cruciate stabilized total knee arthroplasty. J Knee Surg 2023;36:857–65. https://doi.org/10.1055/s-0042-1744191.

[14] Seki K, Seki T, Imagama T, Okazaki T, Kaneoka T, Yamazaki K, et al. The factors impacting on patient-reported outcomes after bicruciate-stabilized total knee arthroplasty for Varus knee osteoarthritis. Indian J Orthop 2024;58:1395–401. https://doi.org/10.1007/s43465-024-01186-4.

[15] Randall AL, Wakelin EA, Kah J, Keggi JM, Koenig JA, DeClaire JH, et al. Impact of joint laxity on 2-Year KOOS outcomes of posterior stabilized total knee arthroplasty. J Knee Surg 2024;37:941–8. https://doi.org/10.1055/a-2376-7085.

[16] Jagota I, Al-Dirini RMA, Taylor M, Twiggs J, Miles B, Liu D. Functional preoperative assessment of coronal knee laxity better predicts postoperative patient outcomes than intraoperative surgeon-defined laxity in total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc 2025;33:621–33. https://doi.org/10.1002/ksa.12400.

[17] Inui H, Taketomi S, Yamagami R, Kono K, Kawaguchi K, Tanaka S. Preoperative and intraoperative factors contributing to patient satisfaction after bi-cruciate stabilized total knee arthroplasty. J Orthop Surg (Hong Kong) 2021;29:23094990211034004. https://doi.org/10.1177/23094990211034004.

[18] Okamoto N, Nakamura E, Masuda T, Hisanaga S, Miyamoto T. Lateral laxity in flexion influences patient-reported outcome after total knee arthroplasty. Indian J Orthop 2024;58:24–9. https://doi.org/10.1007/s43465-023-01045-8.

[19] Hao K, Niu Y, Feng A, Wang F. Coronal laxity at flexion is larger after posterior-stabilized total knee arthroplasty than with cruciate-retaining procedures. J Arthroplasty 2023;38:1267–72. https://doi.org/10.1016/j.arth.2022.12.041.

[20] Cook CE, Wright A, Wittstein J, Barbero M, Tousignant-Laflamme Y. Five recommendations to address the limitations of patient-reported outcome measures. J Orthop Sports Phys Ther 2021;51:562–5. https://doi.org/10.2519/jospt.2021.10836.

[21] Gustke KA, Cherian JJ, Simon P, Morrison TA. Effect of posterior osteophytes on total knee arthroplasty coronal soft tissue balance: do they matter? J Arthroplasty 2022;37:S226–30. https://doi.org/10.1016/j.arth.2022.01.034.

[22] Woo SL, Debski RE, Withrow JD, Janaushek MA. Biomechanics of knee ligaments. Am J Sports Med 1999;27:533–43. https://doi.org/10.1177/03635465990270042301.

[23] Inokuchi T, Muratsu H, Kamenaga T, Tsubosaka M, Nakano N, Hayashi S, et al. Intraoperative lateral laxity greater than 4° is associated with inferior functional improvement in posterior-stabilised total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc 2025;33:296–307. https://doi.org/10.1002/ksa.12327.

[24] Gunderson ZJ, Sokrab R, Landis TG, Buller LT, Deckard ER, Meneghini RM. Outcomes of selectively unresurfaced patellae with a partial lateral facetectomy in primary total knee arthroplasty. J Arthroplasty 2025;40:S229–34. https://doi.org/10.1016/j.arth.2025.04.024.

[25] Graichen H, Grau T, von Eisenhart-Rothe R, Lustig S, Calliess T, Clatworthy M, et al. A three-dimensional scoring system for assessment of individual bony and laxity phenotype restoration (knee SIPR) in personalised TKA as a base for treatment guidance. Knee Surg Sports Traumatol Arthrosc 2025;33:2204–13. https://doi.org/10.1002/ksa.12601.

[26] Sansone V, Fennema P, Applefield RC, Marchina S, Ronco R, Pascale W, et al. Translation, cross-cultural adaptation, and validation of the Italian language Forgotten Joint Score-12 (FJS-12) as an outcome measure for total knee arthroplasty in an Italian population. BMC Musculoskelet Disord 2020;21:23. https://doi.org/10.1186/s12891-019-2985-2.

[27] Cohen J. Statistical Power Analysis for the Behavioral Sciences. New York: Lawrence Erlbaum Associates; 1988. https://doi.org/10.4324/9780203771587. Rev. ed.

[28] Tsukiyama H, Kuriyama S, Kobayashi M, Nakamura S, Furu M, Ito H, et al. Medial rather than lateral knee instability correlates with inferior patient satisfaction and knee function after total knee arthroplasty. Knee 2017;24:1478–84. https://doi.org/10.1016/j.knee.2017.09.004.

[29] Kamenaga T, Muratsu H, Kanda Y, Miya H, Kuroda R, Matsumoto T, et al. The influence of postoperative knee stability on patient satisfaction in cruciate-retaining total knee arthroplasty. J Arthroplasty 2018;33:2475–9.

[30] Mizu-Uchi H, Kawahara S, Ishibashi S, Colwell CWJ, Nakashima Y, D'Lima DD. Postoperative Valgus laxity and medial pivot kinematics are significantly associated with better clinical outcomes. J Arthroplasty 2022;37:S187–92. https://doi.org/10.1016/j.arth.2022.02.088.

[31] Ueyama H, Kanemoto N, Minoda Y, Nakagawa S, Taniguchi Y, Nakamura H. Association of a wider medial gap (medial laxity) in flexion with self-reported knee instability after medial-pivot total knee arthroplasty. J Bone Joint Surg Am 2022;104:910–8. https://doi.org/10.2106/JBJS.21.01034.

[32] Matsumoto T, Takayama K, Muratsu H, Ishida K, Hashimoto S, Hayashi S, et al. Relatively loose flexion gap improves patient-reported clinical scores in cruciate-retaining total knee arthroplasty. J Knee Surg 2018;31:573–9. https://doi.org/10.1055/s-0037-1604446.

[33] Kaneko T, Kono N, Mochizuki Y, Hada M, Toyoda S, Musha Y, et al. Bi-cruciate substituting total knee arthroplasty improved medio-lateral instability in mid-flexion range. J Orthop 2017;14:201–6.

[34] Liu DW, Reidy JF, Beller EM. The effect of distal femoral resection on fixed flexion deformity in total knee arthroplasty. J Arthroplasty 2016;31:98–102. https://doi.org/10.1016/j.arth.2015.07.033.

[35] Whiteside LA. Selective ligament release in total knee arthroplasty of the knee in valgus. Clin Orthop Relat Res 1999;367:130–40.

[36] MacDessi SJ, Griffiths-Jones W, Harris IA, Bellemans J, Chen DB. Coronal Plane Alignment of the Knee (CPAK) classification. Bone Joint J 2021;103-B:329–37. https://doi.org/10.1302/0301-620X.103B2.BJJ-2020-1050.R1.

[37] Hirschmann MT, Hess S, Behrend H, Amsler F, Leclercq V, Moser LB. Phenotyping of hip-knee-ankle angle in young non-osteoarthritic knees provides better understanding of native alignment variability. Knee Surg Sports Traumatol Arthrosc 2019;27:1378–84. https://doi.org/10.1007/s00167-019-05507-1.

[38] Spece H, Kurtz MA, Piuzzi NS, Kurtz SM. Patient-reported outcome measures offer little additional value two years after arthroplasty : a systematic review and meta-analysis. Bone Joint J 2025;107-B:296–307. https://doi.org/10.1302/0301-620X.107B3.BJJ-2024-0910.R1.

[39] Noble PC, Conditt MA, Cook KF, Mathis KB. The John Insall Award: patient expectations affect satisfaction with total knee arthroplasty. Clin Orthop Relat Res 2006;452:35–43. https://doi.org/10.1097/01.blo.0000238825.63648.1e.

[40] Rehman Y, Lindberg MF, Arnljot K, Gay CL, Lerdal A, Aamodt A. More severe radiographic osteoarthritis is associated with increased improvement in patients' health State following a total knee arthroplasty. J Arthroplasty 2020;35:3131–7. https://doi.org/10.1016/j.arth.2020.06.025.

Appendix

Supplementary Table 1
Overview of the study population’s distribution in the Coronal Plane Alignment of the Knee (CPAK) classification.

CPAK Class	Number (n (%))
I	29 (24.8)
II	31 (26.5)
III	31 (26.5)
IV	12 (10.3)
V	8 (6.8)
VI	6 (5.1)
VII-IX	0 (0)