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Primary Knee

Joint Line Obliquity Affects Survivorship Following Total Knee Arthroplasty: 12.7-Year Follow-Up of 800 Cases

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A B S T R A C T

Background: The purpose of this study was to evaluate the influence of joint line obliquity (JLO) on survivorship following total knee arthroplasty (TKA) over a mean follow-up of 12.7 years

Methods: We reviewed the records for 800 patients who had undergone TKA for primary knee osteoarthritis between January 2004 and December 2010. Based on postoperative alignment, patients were categorized into two groups: the mechanically aligned group (mechanical axis of $0 \pm 3^\circ$) and the outlier group (mechanical axis beyond $0 \pm 3^\circ$). In addition, patients were stratified into four groups according to joint line obliquity (JLO), as measured on full-length standing weight-bearing radiographs using both the original classification (sum of lateral distal femoral angle and medial proximal tibial angle) and a modified classification (joint surface angle relative to the hip–knee–ankle axis). Kaplan–Meier survival analysis was used to estimate implant survival, with aseptic revision for mechanical failure defined as the endpoint.

Results: Mechanical failure occurred in 3.5% of cases (28 of 800) over a mean follow-up of 12.7 years. Although the original JLO classification was not associated with aseptic revision, the modified classification revealed significant differences within the outlier group. Notably, lateral joint line inclination was associated with the highest failure rate (5.2% [10 of 193]; $P = 0.01$). Implant survival was significantly higher in the mechanically aligned group (98.6%) than in the outlier group (92.6%) ($P < 0.001$, log-rank test). Within the outlier group, the lowest survival rate (87.7%, $P < 0.001$) was found in knees with nonparallel JLO, particularly those with lateral inclination. Multivariate Cox regression analyses identified postoperative JLO (hazard ratio, 1.58; $P = 0.042$) as an independent risk factor for mechanical failure.

Conclusion: When applying the modified JLO classification, postoperative JLO was associated with high survival rates following TKA at a mean follow-up of 12.7 years. Outlier alignment in combination with nonparallel JLO, particularly lateral inclination, demonstrated the poorest survival rate.

Level of evidence: Retrospective cohort study; Level III.

Traditionally, achieving a neutral mechanical axis has been regarded as a fundamental goal for ensuring reliable and successful outcomes in total knee arthroplasty (TKA) [1,2]. Within the framework of mechanical alignment, orthopaedic surgeons have aimed to establish neutral lower limb alignment, typically represented by a hip–knee–ankle (HKA) angle of 0° [2–4]. This approach is predicated on the rationale that neutral alignment minimizes mechanical imbalance between the medial and lateral compartments of the knee joint, potentially reducing polyethylene wear and the risk of implant loosening [5].

Despite generally acceptable outcomes following TKA with the mechanical alignment, approximately 20% of patients report dissatisfaction postoperatively [6–9]. A pivotal study by Bellemans et al. [10] initiated substantial discourse within the orthopaedic community regarding the optimal alignment target. They found that 34% of men and 20% of women in a healthy population exhibited native limb alignment that fell outside the $0 \pm 3^\circ$ range from neutral. As such, imposing a neutral mechanical axis may not

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reflect a patient's natural anatomical alignment, potentially inducing a soft-tissue imbalance. Ongoing debate persists regarding the ideal alignment strategy to enhance patient satisfaction, supported by clinical studies suggesting that postoperative varus alignment does not necessarily compromise functional outcomes or implant survival [4,11–16].

Joint line obliquity (JLO), influenced by the positioning of the tibial and femoral components, also plays a critical role in knee biomechanics. Malalignment of these components can lead to deviations in JLO, resulting in uneven joint surface loading that may negatively impact patient-reported outcomes and implant longevity [3,5,17,18]. Ritter et al. [19] emphasized the importance of achieving neutral alignment in both components to optimize TKA survivorship. More recently, Bae et al. [20] classified nine postoperative phenotypes based on alignment and JLO, identifying one phenotype, characterized by varus alignment and lateral joint line inclination, as being associated with inferior implant survival. These findings suggest that both overall alignment and JLO may critically influence long-term outcomes after TKA. Several clinical investigations have since proposed modified alignment strategies as reproducible methods for preserving preoperative knee phenotypes while accounting for coronal alignment and JLO [17,21–24]. Nevertheless, there remain a limited number of studies evaluating the effect of JLO on long-term survivorship following TKA.

The aim of the present study was to evaluate the influence of JLO on survivorship following TKA for osteoarthritic knees, with a mean follow-up of 12.7 years. We hypothesized that achieving a postoperative parallel JLO would be associated with superior survivorship after TKA compared to medial or lateral JLO.

Materials and Methods

Patients

The arthroplasty database of a tertiary academic referral center was reviewed after institutional review board approval. A total of 1,003 patients who underwent mechanically aligned TKA for primary osteoarthritis with a cruciate-retaining prosthesis (NexGen CR; Zimmer, Warsaw, Indiana) between January 6, 2004, and December 21, 2010, were identified. Only patients who had complete full-length standing weight-bearing radiographs available for radiographic analysis were eligible for inclusion. As the primary objective was to investigate whether postoperative alignment and JLO were associated with the risk of aseptic revision for mechanical failures (defined as polyethylene wear, implant loosening, or instability), patients who underwent revision surgery due to periprosthetic joint infection or periprosthetic fractures were excluded. Additional exclusion criteria were as follows: (1) prior open knee procedures; (2) absence of preoperative or postoperative full-length standing weight-bearing radiographs; (3) inappropriate measurements, such as rotated radiographs; and (4) inability to contact the patient or refusal to participate in follow-up. Based on these criteria, a total of 800 knees were included in the final analysis, with a mean follow-up duration of 12.7 years (Figure 1).

Surgical Techniques and Postoperative Management

All TKAs were performed by two experienced orthopaedic surgeons using a conventional mechanical alignment technique and cruciate-retaining prostheses (NexGen CR; Zimmer, Warsaw, Indiana). A standard medial parapatellar arthrotomy was performed via a midline skin incision. Tibial resection was performed using an extramedullary guide system, with the proximal tibia cut perpendicular to the mechanical axis and a posterior slope of 7°. Distal femoral resection was performed using an intramedullary guide, with the valgus angle set at 4 to 6° according to the angle between the mechanical and anatomical axes of the femur. Femoral component rotation was determined based on balanced flexion gap principles. After bony resection, soft-tissue balancing was carried out as needed to achieve medial and lateral gap symmetry within ±2 mm [25]. Once stability was confirmed in both full extension and 90° of flexion, all components were fixed using tobramycin-impregnated cement.

A standardized postoperative rehabilitation protocol was implemented for all patients. Isometric exercises commenced immediately after surgery, and active and passive range of motion exercises began on postoperative day one, progressing as tolerated. Full weight-bearing ambulation, initially with the assistance of a walker, was also encouraged from the first postoperative day as tolerated.

Radiographic Assessment

Standardized anteroposterior, lateral, and Merchant views of the knee, as well as full-length standing weight-bearing radiographs, were obtained preoperatively; at one, three, six, and 12 months postoperatively; and annually thereafter. The postoperative mechanical HKA angle was measured as the angle formed by the mechanical axes of the femur and tibia, with positive values indicating varus alignment. Based on this measurement, patients were stratified into two groups: (1) the mechanically aligned group, defined by a postoperative mechanical axis within $\pm$ 3° of neutral (0 $\pm$ 3°), and (2) the outlier group, comprising patients whose mechanical axis fell outside this range. The postoperative lateral distal femoral angle (LDFA) and medial proximal tibial angle (MPTA) were assessed to determine the femoral and tibial component alignment in the coronal plane. Lateral distal femoral angle was defined as the lateral angle between the distal femoral joint line and the femoral mechanical axis, whereas MPTA was defined as the medial angle between the proximal tibial joint line and the tibial mechanical axis. These angular measurements were used to calculate the original JLO, which reflects the overall slope of the joint surface. Based on the classification system proposed by MacDessi et al. [24], JLO was categorized as follows: less than 177° as apex distal, 177 to 183° as neutral, and greater than 183° as apex proximal.

Although various methods for measuring JLO have been described in the literature, the most reliable and standardized approach remains unclear. MacDessi et al. [24] proposed the Coronal Plane Alignment of the Knee classification, which incorporates the axes of constitutional knee phenotypes and defines JLO as the sum of the LDFA and MPTA measured during bipedal stance, with 180° indicating a neutral joint line (Figure 2). However, this method does not quantify the deviation angle of the joint line from the horizontal plane and therefore may not accurately reflect the actual degree of JLO relative to the ground. To address these limitations, Bae et al. [20] proposed a modified JLO measurement, calculated by subtracting 90° from the angle formed between the mechanical limb axis (connecting the centers of the hip and ankle) and the tibial joint surface (Figure 3). This method quantifies the inclination of the tibial joint surface relative to the mechanical axis of the lower limb, but does not directly capture the balance between the femoral and tibial components. Using this approach, modified JLO was classified as medial joint line inclination (less than −2°), parallel (−2 to 2°), or lateral joint line inclination (greater than 2°). As shown in Figure 4, postoperative phenotypes were then categorized into nine groups based on the combined assessment of HKA (varus, neutral, or valgus) and the modified JLO (medial joint line inclination, parallel, or lateral joint line inclination). Radiographic measurements were independently performed by two orthopaedic surgeons blinded to the study objectives. Each surgeon repeated all

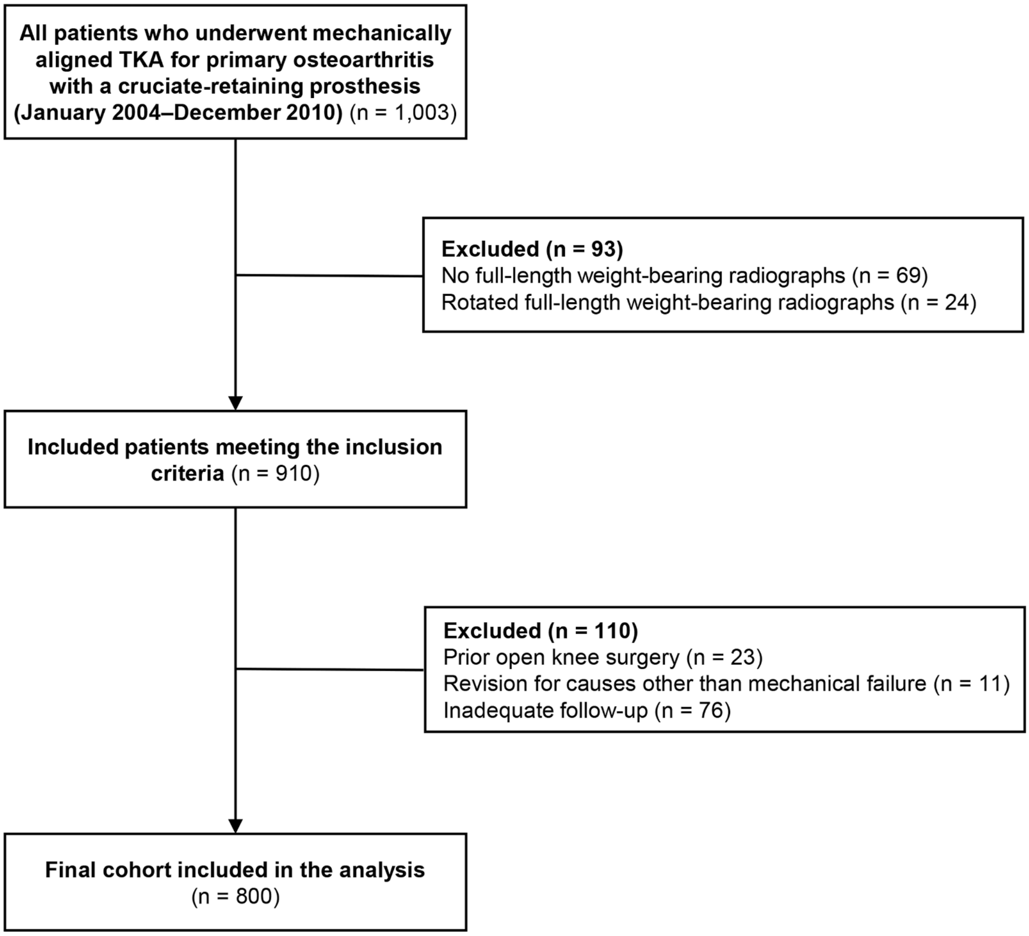

Figure 1. Flow diagram illustrating the patient enrollment process in the study. TKA, total knee arthroplasty.

measurements twice, with a 4-week interval between assessments, to determine intraobserver and interobserver reliability. Intraobserver and interobserver reliability were assessed using intraclass correlation coefficients, all of which indicated good agreement (intra-class correlation coefficient >0.80).

Survival

Survival analysis was performed using the Kaplan–Meier method, with revision surgery for nontraumatic mechanical failure (defined as revision due to aseptic loosening, polyethylene wear, or instability) serving as the endpoint. Revisions attributed to periprosthetic joint infection or periprosthetic fractures were excluded. Risk factors that affected survival were as follows: age, body mass index, gender, American Society of Anesthesiologists grade, preoperative mechanical HKA angle, preoperative MPTA, preoperative LDFA, postoperative mechanical HKA angle, change in mechanical HKA angle (ΔmHKA), postoperative MPTA, postoperative LDFA, and postoperative JLO.

Data Analyses

Paired and independent *t*-tests were applied to assess differences in continuous variables with normal distribution. For nonnormally distributed variables, the Mann–Whitney *U*-tests and Wilcoxon signed-rank tests were used. Differences in categorical variables were analyzed using the *Chi*-square tests or Fisher exact tests, as appropriate. The Kaplan–Meier survivorship analysis was used to estimate the cumulative implant survival rate over the study period, with revision for mechanical failure as the endpoint and a 95% confidence interval (CI). Hazard ratios (HRs) were calculated using Cox proportional hazards models to evaluate the association between potential risk factors and survival rates. Statistical significance was defined as $P < 0.05$.

Results

Patient demographic characteristics and clinical data are summarized in Table 1 and Figure 5.

Radiographic Results

With respect to postoperative alignment, 800 knees were analyzed. Of these, 694 knees demonstrated limb alignment within the target range of $0 \pm 3^{\circ}$ and were categorized as the aligned group. The remaining 106 knees exhibited a deviation from the mechanical axis exceeding 3° and were classified as the outlier group.

Based on the original JLO classification, 79 knees (9.8%) exhibited apex distal orientation (less than 177°), 467 knees (58.4%) displayed a neutral joint line (177 to 183°), and 254 knees (31.8%) demonstrated apex proximal orientation (greater than 183°). In contrast, using the modified JLO classification, 25 knees

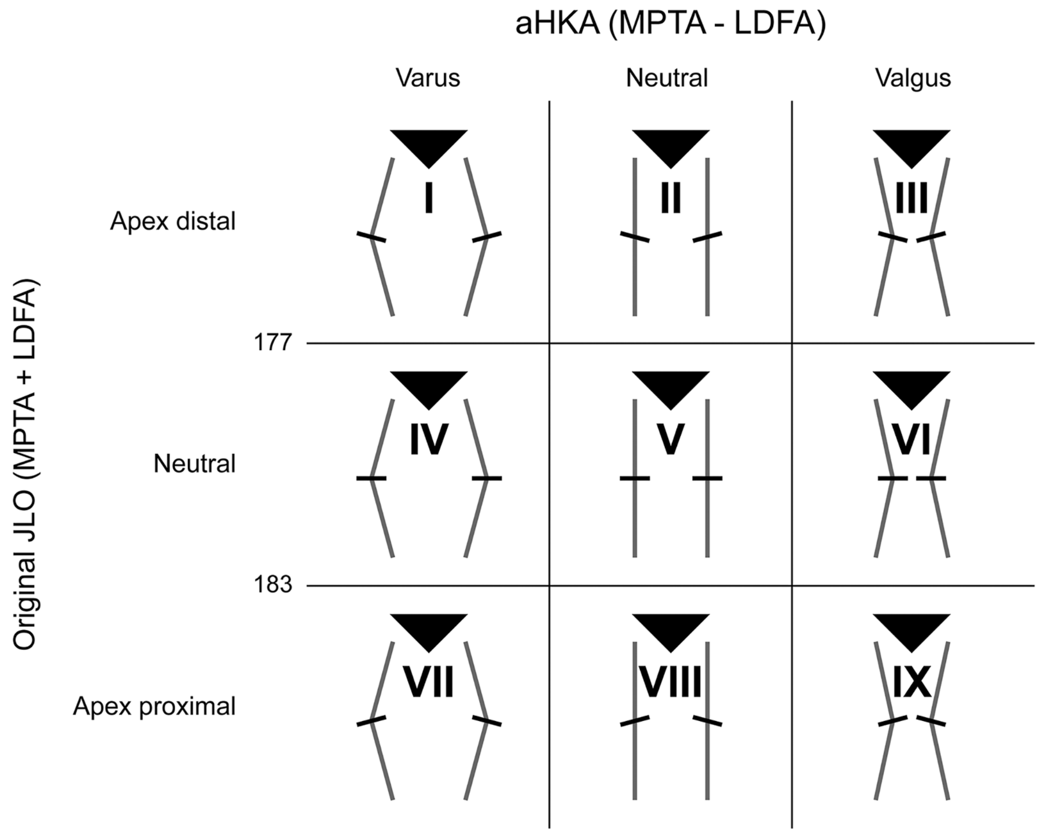

Figure 2. The CPAK classification showing nine theoretical types of knee based on aHKA and original JLO measurements. Original JLO was calculated as the sum of MPTA and LDFA. CPAK, Coronal Plane Alignment of the Knee; aHKA, arithmetic hip–knee–ankle angle; JLO, joint line obliquity; MPTA, medial proximal tibial angle; LDFA, lateral distal femoral angle.

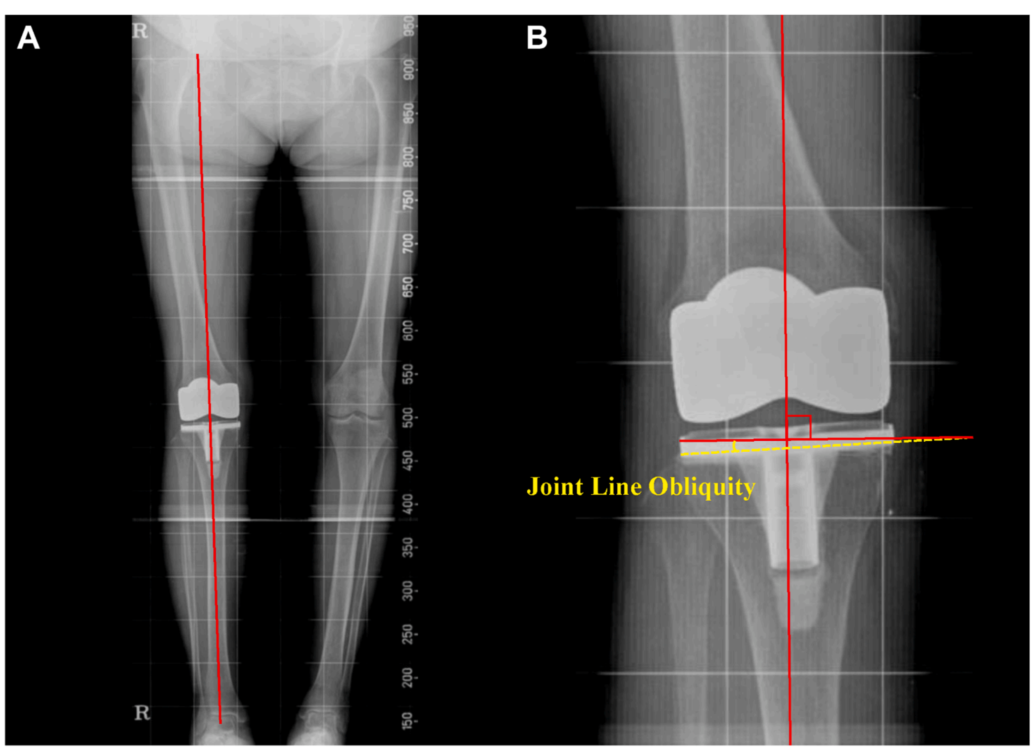

Figure 3. Modified JLO measurement. (A) The hip–knee–ankle axis (represented by the solid red line) was determined by extending the line from the center of the femoral head to the center of the ankle. (B) Joint line obliquity was calculated by subtracting 90° from the angle between the tibial joint surface (represented by the dashed yellow line) and the hip–knee–ankle axis. JLO, joint line obliquity.

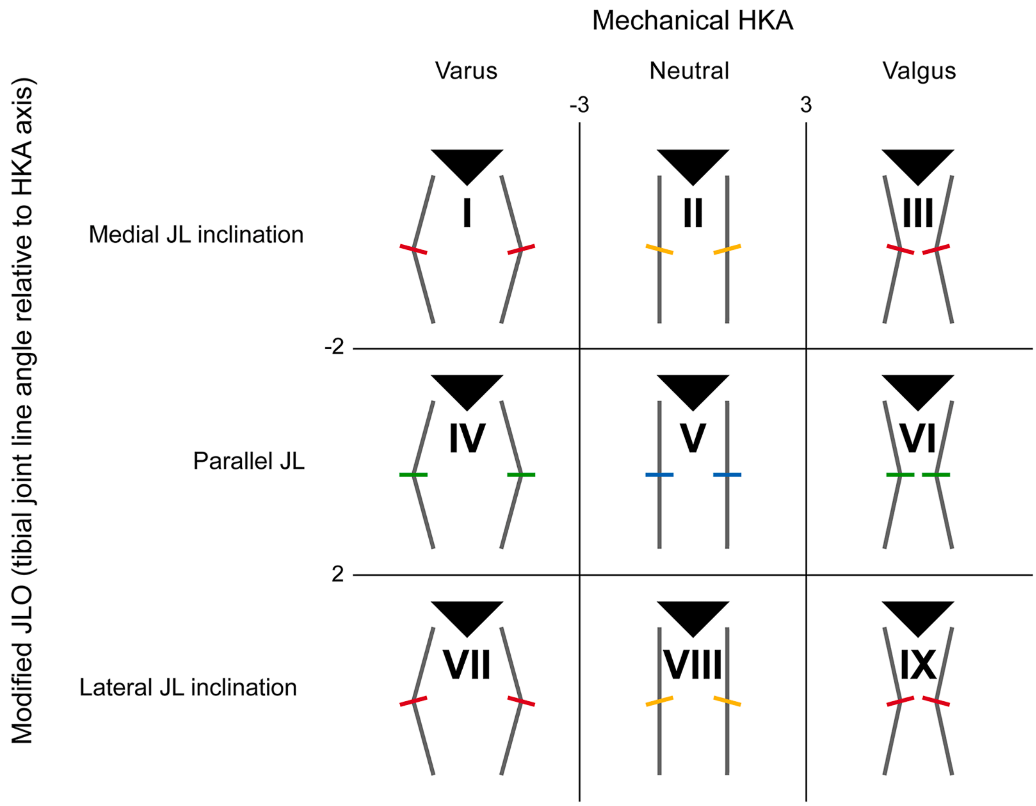

Figure 4. Postoperative phenotype configuration based on the HKA angle and modified JLO. Blue indicates mechanically aligned + parallel; yellow, mechanically aligned + non-parallel; green, outlier + parallel; and red, outlier + non-parallel. HKA, hip–knee–ankle; JLO, joint line obliquity; JL, joint line.

(3.1%) showed medial inclination, 566 knees (70.8%) had parallel orientation, and 209 knees (26.1%) exhibited lateral inclination.

Effect of JLO on Aseptic Revision

Over the follow-up period, the overall rate of mechanical failure was 3.5% (28 of 800 cases). Specifically, there were 18 cases of aseptic loosening (10 femoral only, four tibial only, and four with loosening of both components), eight cases of polyethylene wear, and two cases of instability. A total of 13 knees (2.1% of 607 cases) in the aligned group underwent revision, whereas 15 knees (7.8% of 193 cases) in the outlier group required revision, with a statistically significant difference between the groups ($P < 0.001$). Using the aligned plus parallel group as the reference, the odds ratios for revision were 1.00 (95% CI, 0.23 to 3.24) for aligned plus nonparallel, 1.61 (95% CI, 0.49 to 5.29) for outlier plus parallel, and 7.16 (95% CI, 2.91 to 17.61) for outlier plus nonparallel. The corresponding HRs were 1.00 (95% CI, 0.28 to 3.62), 1.69 (95% CI, 0.52 to 5.50), and 6.73 (95% CI, 2.79 to 16.25), respectively.

Table 1
Demographic[a] Characteristics.

Variables	Value
Age (years)	69 (46 to 92)
Women (no. of patients)	730 (91.2)
Body mass index	25.7 (16.9 to 42.0)
ASA grade (no. of patients)	
I	72 (9.0)
II	664 (83.0)
III	64 (8.0)
Follow-up period (years)	12.7 ± 3.6
Preoperative radiographic parameters (deg)	
Mechanical HKA angle[b]	9.9 ± 5.9
LDFA	90.1 ± 2.8
MPTA	84.8 ± 3.3

ASA, American Society of Anesthesiologists; HKA, hip–knee–ankle; LDFA, lateral distal femoral angle; MPTA, medial proximal tibial angle.
[a] Values are presented as mean (range), mean ± SDs or No. (%), as appropriate.
[b] A positive angle indicates varus alignment; a negative angle indicates valgus alignment.

As detailed in Tables 2 and 3, the relationship between JLO and aseptic revision was further examined within each coronal alignment phenotype using both the original and modified JLO classification systems. According to the original JLO classification, no significant association with aseptic revision was observed in either the mechanically aligned group ($P = 0.450$) or the outlier group ($P = 0.700$). However, the application of the modified JLO classification revealed a significant difference in failure rates within the outlier group ($P = 0.010$), where knees with lateral joint line inclination demonstrated the highest failure rate (5.2%) compared to those with parallel (2.1%) or medial joint line inclination (0.5%). In contrast, within the aligned group, differences in failure rates by modified JLO classification were not statistically significant ($P = 0.770$).

Survival

At a mean follow-up of 12.7 years, the outlier group demonstrated significantly lower survival rates (92.6% [95% CI, 87.4 to 95.8]) compared to the mechanically aligned group (98.6% [95% CI, 97.1 to 99.3]) ($P < 0.001$, log-rank test). As shown in Figure 6, postoperative alignment (mechanically aligned versus outlier) with modified JLO classification (parallel versus nonparallel, the latter including both medial and lateral inclinations) indicated that knees with outlier alignment and nonparallel JLO demonstrated

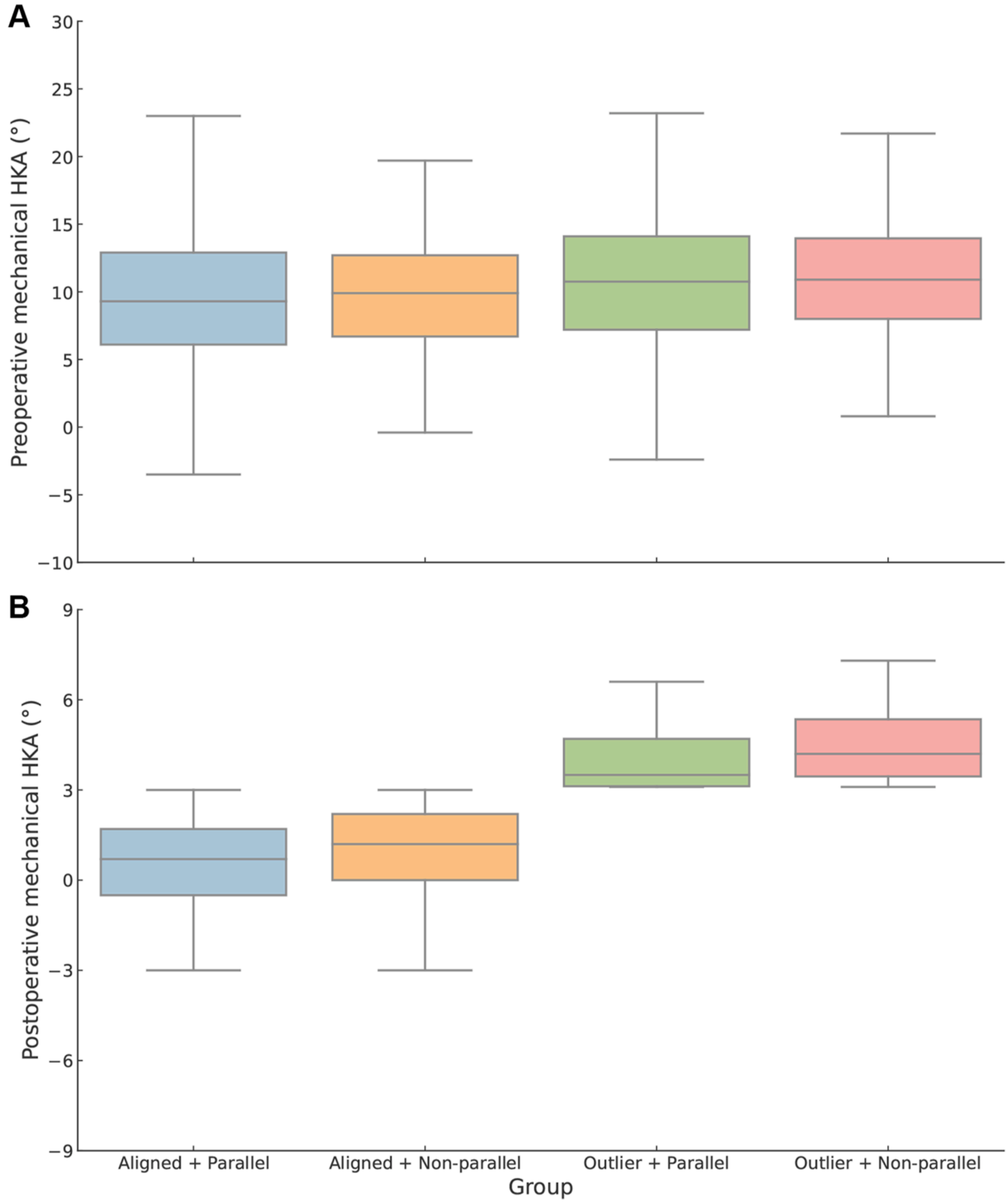

Figure 5. Box plots of (A) preoperative and (B) postoperative mechanical HKA angles for the four subgroups: blue indicates aligned + parallel; yellow, aligned + non-parallel; green, outlier + parallel; and red, outlier + non-parallel. HKA, hip–knee–ankle.

the lowest survival rate (87.7%) among all groups ($P < 0.001$, log-rank test). This subgroup substantially reduced the overall survivorship of the outlier group, underscoring the adverse effect of nonparallel JLO in malaligned knees. Multivariate Cox regression analyses identified postoperative JLO (HR, 1.58; $P = 0.042$) as an independent risk factor for mechanical failure. The JLO cutoff value predictive of aseptic failure was 2.5° (area under the curve [AUC], 0.700), with a sensitivity of 78.0% and specificity of 55.0%.

Table 2
Postoperative Distribution of Survival and Mechanical Failure Rate Based on Alignment and Original JLO[a] Classification.

Variable	Aligned Group (Mechanical Axis, 0 ± 3°)				Outlier Group (Beyond 0 ± 3°)			
	JLO < 177°	177° ≤ JLO ≤ 183°	JLO > 183°	Total	JLO < 177°	177° ≤ JLO ≤ 183°	JLO > 183°	Total
Survival	59 (9.8)	356 (58.6)	179 (29.5)	594 (97.9)	18 (9.3)	94 (48.7)	66 (34.2)	178 (92.3)
Failure	0	8 (1.3)	5 (0.8)	13 (2.1)	2 (1.0)	9 (4.7)	4 (2.1)	15 (7.7)
Total	59 (9.8)	364 (59.9)	184 (30.3)	607	20 (10.4)	103 (53.3)	70 (36.3)	193

JLO, joint line obliquity.
[a] Values are presented as percentages.

Table 3
Postoperative Distribution of Survival and Mechanical Failure Rates Based on Alignment and Modified JLO[a] Classification.

Variable	Aligned Group (Mechanical Axis, 0 ± 3°)				Outlier Group (Beyond 0 ± 3°)			
	JLO < −2°	−2° ≤ JLO ≤ 2°	JLO > 2°	Total	JLO < −2°	−2° ≤ JLO ≤ 2°	JLO >2°	Total
Survival	22 (3.6)	442 (72.8)	130 (21.4)	594 (97.9)	2 (1.0)	110 (57.0)	66 (34.2)	178 (92.2)
Failure	0 (0)	10 (1.7)	3 (0.5)	13 (2.1)	1 (0.5)	4 (2.1)	10 (5.2)	15 (7.8)
Total	22 (3.6)	452 (74.5)	133 (21.9)	607	3 (1.5)	114 (59.1)	76 (39.4)	193

JLO, joint line obliquity.
[a] Values are presented as percentages.

Discussion

The principal finding of the present study was that outlier alignment in combination with nonparallel JLO, particularly lateral inclination, demonstrated the poorest long-term survival rate of TKA. This subgroup substantially reduced the overall survivorship of the outlier group, underscoring the detrimental effect of nonparallel JLO in malaligned knees. When applying the modified JLO classification, postoperative JLO was associated with survival rates following TKA at a mean follow-up of 12.7 years. Moreover, multivariate Cox regression analysis identified postoperative JLO as an independent risk factor for mechanical failure. Our findings underscore the clinical importance of considering alignment and JLO during TKA to optimize long-term outcomes.

Historically, TKA survivorship has been primarily assessed in relation to coronal limb alignment, with neutral alignment considered essential for maximizing implant longevity and clinical outcomes. Numerous prior studies have reported improved long-term survival in patients who achieved postoperative neutral mechanical alignment [2,5,19,26–31]. Our findings are consistent with earlier evidence demonstrating that varus malalignment of the mechanical HKA angle is associated with an elevated risk of aseptic revision [1,2,29]. Despite the prevailing view that neutral alignment is the optimal surgical target, this concept remains subject to debate. Several clinical studies have indicated that residual postoperative varus alignment may not compromise the durability of modern knee prostheses [13,32]. Abdel et al. [16], for example, found no difference in the 20-year implant survival between patients who had neutral alignment (0 ± 3°) and those who had malalignment (beyond 0 ± 3°), suggesting that neutral mechanical axis alignment may not necessarily confer superior implant longevity or functional outcomes. Similarly, our findings showed no association between the change in alignment (ΔmHKA) and survival rates. Although conventional TKA approaches have emphasized the importance of achieving a neutral HKA alignment, emerging alignment strategies, such as Coronal Plane Alignment of the Knee phenotype restoration, focus on reproducing the native JLO. Recent clinical studies have shown that these modified alignment techniques are reliable and reproducible in restoring the preoperative knee phenotype, particularly with regard to coronal alignment and JLO [17,21–24].

The clinical relevance of JLO has been demonstrated in multiple studies [21,23,33,34]. Matsumoto et al. [21] reported that maintaining joint line orientation parallel to the floor following TKA equalizes load distribution across the medial and lateral tibial compartments, potentially contributing to improved implant durability. Konishi et al. [33] demonstrated that the apex proximal JLO negatively affected clinical outcomes after TKA and that it should be avoided to optimize postoperative outcomes. In a retrospective analysis of 936 patients, Sappey-Marinier et al. [23] demonstrated reduced postoperative knee pain in patients who had restored JLO compared to those without restoration, underscoring the clinical relevance of restoring native knee phenotypes. They further observed that mechanical alignment shifted most knees to a neutral phenotype, with restoration of the constitutional phenotype achieved in only 18% of the cohort. Consistent with this finding, the surgical target in the present study was mechanical alignment in all cases; thus, the outlier group should be regarded not as an individualized alignment strategy but as unintended deviations from the intended mechanical alignment. Several studies have associated femoral or tibial component malalignment with reduced TKA survival rates [3,5,19,20]. Collectively, these findings suggest that JLO is a key determinant of knee biomechanics in TKA patients, with marked obliquity associated with suboptimal clinical outcomes.

Recently, increasing attention has been directed toward categorizing preoperative knee phenotypes in patients who have primary osteoarthritis [24,35–39]. Despite identical overall alignment, individual variation in JLO may arise due to differences in femoral and tibial anatomy. MacDessi et al. [24] were the first to introduce a standardized classification system for constitutional knee phenotypes. However, their method of calculating JLO as the sum of the LDFA and MPTA may be unintuitive and prone to measurement exaggeration. To address these limitations, Bae et al. [20] proposed a modified postoperative phenotype classification that enables more intuitive interpretation of TKA configurations by using direct measurements of HKA and JLO from full-length standing weight-bearing radiographs. Unlike the original classification, the modified JLO system revealed significant differences in mechanical failure rates, particularly among outlier subgroups. Although the modified JLO does not directly assess the balance between femoral and tibial components, our findings indicate that nonparallel JLO, especially lateral inclination, may be associated with inadequate soft-tissue balancing during TKA and may disrupt

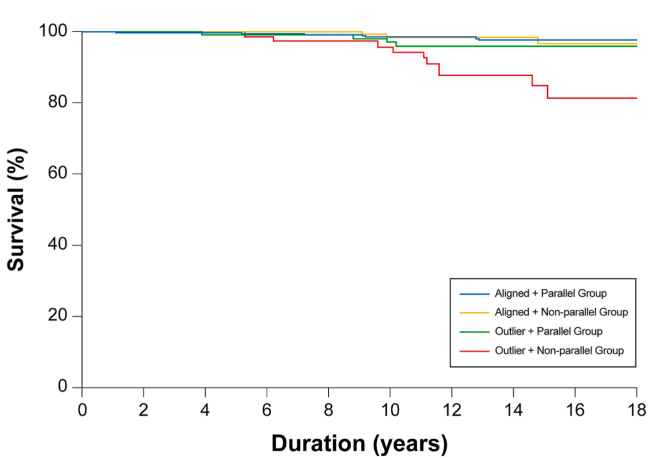

Figure 6. Kaplan–Meier survivorship curve comparing four subgroups based on alignment (mechanically aligned versus outlier) and modified JLO classification (parallel versus nonparallel, with the latter including both medial and lateral joint line inclinations). JLO, joint line obliquity.

load distribution across the knee joint. Additional studies incorporating intraoperative balancing assessments are warranted to validate this relationship and clarify its clinical significance. Biomechanically, lateral JLO is theorized to increase joint shear forces during single-leg stance, consistent with findings by Niki et al. [40], who reported reduced knee adduction moments in the presence of a horizontally oriented joint line. They proposed that a horizontal joint line yields a more vertical ground reaction force, which reduces the lever arm and knee adduction moment. Similarly, Nakayama et al. [41] used a three-dimensional finite element model to demonstrate that altered JLO markedly increases shear stress in the medial compartment. To our knowledge, this study represents one of the largest cohort series to examine the relationship between alignment, JLO, and implant survivorship according to the knee phenotype following TKA. Avoidance of lateral JLO may be essential in minimizing the mechanical failure risk after TKA [35,42,43]. Nevertheless, existing literature on the long-term impact of JLO remains inconclusive, and the debate regarding optimal leg alignment and orientation techniques in TKA continues. Further studies are warranted to elucidate the influence of individualized alignment and JLO strategies on patient satisfaction and implant longevity following TKA.

This study has several potential limitations. The non-randomized, retrospective design introduces the potential for selection bias. In addition, the use of two-dimensional radiological measurements on full-length standing weight-bearing radiographs represents a methodological limitation, as measurement accuracy may be affected by variations in limb rotation. Validation using three-dimensional modalities, such as computed tomography, is warranted. Also, the study population was predominantly Asian with varus knee deformities, which may limit the generalizability of the findings to other demographic groups. Furthermore, the demographic profile of the cohort may have been biased due to a disproportionate predominance of women, which should be taken into account when interpreting the results [44,45]. Moreover, multiple postoperative radiographs were obtained during the first year in accordance with our institutional protocol; however, no interval differences in alignment or JLO were observed. In addition, this study focused exclusively on static coronal plane alignment; other important factors such as sagittal alignment, anatomical variations, and ligament balancing were not assessed, despite their known contributions to the success of TKA [46]. Nevertheless, the present study offers meaningful insights supported by a sufficiently long follow-up period, enabling a robust investigation of the impact of alignment and JLO on implant survivorship following TKA.

When applying the modified JLO classification, postoperative JLO was associated with high survival rates following TKA at a mean follow-up of 12.7 years. Outlier alignment in combination with non-parallel JLO, particularly lateral inclination, demonstrated the poorest survival rate. Future investigations with longer follow-up are needed to further elucidate the combined effects of alignment and JLO on patient-reported outcomes and implant longevity.

CRediT authorship contribution statement

Hong Yeol Yang: Writing – original draft, Investigation, Formal analysis. **Eun Kyoo Song:** Validation, Resources, Formal analysis, Conceptualization. **Ji Ho Seo:** Visualization, Methodology, Investigation, Data curation. **Sung Ju Kang:** Software, Methodology, Investigation, Data curation. **Jong Keun Seon:** Writing – review & editing, Supervision, Resources, Project administration, Conceptualization.

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