International Journal of Orthopaedics Research
www.orthopaedicsjournal.in
E-ISSN: 2663-0923
Received: 10-06-2026, Accepted: 10-07-2026, Published: 25-07-2026
Volume 8, Issue 3, 2026, Page No. 1-4

Lower limb alignments in total knee arthroplasty (TKA): A critical review of evolving philosophies

Abbas Bhatia M S[1], Kuldeep Rathor[2]
[1] Orthopedic Surgeon, Sports Injury Centre, VMMC, Safdurjung Hospital, New Delhi, India
[2] Assistant Professor, Department of Orthopaedics, AIIMS Bhopal, Madhya Pardesh, India
Corresponding author: Abbas Bhatia
DOI: https://doi.org/10.66856/ijor.2026.8.3.8030

Abstract

Background: While total knee arthroplasty (TKA) remains a highly successful intervention for end-stage knee osteoarthritis, patient dissatisfaction rates consistently hover around 20%. To address this, surgeons have increasingly transitioned from uniform mechanical reconstruction to personalized, patient-specific alignment strategies. This paper reviews the underlying principles, technical execution, and clinical evidence of emerging alignment paradigms.
Methods: A comprehensive literature synthesis was conducted utilizing the PubMed database to evaluate mechanical, anatomical, kinematic, inverse kinematic, restricted kinematic, and functional alignment techniques in primary TKA.
Results: Traditional mechanical alignment (0 ± 3 degrees relative to the mechanical axis) prioritizes implant longevity, though its strict superiority regarding survivorship remains debated. Conversely, personalized techniques—such as kinematic alignment (KA) and functional alignment (FA)—prioritize physiological soft-tissue tension and constitutional anatomy. Short-term randomized controlled trials demonstrate comparable or superior patient-reported outcome measures (PROMs) with personalized strategies. However, concerns persist regarding outlier wear and early tibial component loosening in extreme varus configurations.
Conclusion: Personalized alignment paradigms show promising early-to-midterm efficacy and high patient satisfaction. Nevertheless, the definitive boundaries of safe biomechanical deviation for long-term implant survival remain undefined, necessitating ongoing long-term clinical trials.

Keywords: Total knee arthroplasty (TKA) alignment strategies robotic assisted surgery kinematic alignment personalized knee arthroplasty

Introduction

Total knee arthroplasty (TKA) is widely recognized as a highly cost-effective surgical intervention for restoring joint function and relieving pain in patients suffering from advanced knee osteoarthritis [1]. Joint registry data reveals outstanding long-term durability, with cumulative revision rates of only 4% to 5% at 10 years and approximately 6% at 15 years [1].

Despite these impressive survivorship figures, post-operative dissatisfaction affects nearly 20% of patients. This subset of patients often experiences a persistent "unnatural" joint sensation, residual pain, or mild instability. Historically, surgeons adhered to the concept of Mechanical Alignment (MA), which establishes a neutral mechanical axis perpendicular to the joint line. While MA minimizes structural wear by distributing load evenly across the tibial tray, it disregards individual anatomical variations and can significantly alter a patient's pre-arthritic kinematics.

Recent morphometric studies have demonstrated that the native human knee exhibits highly variable joint line obliquity and coronal orientation [3]. Forcing a standard, neutral mechanical alignment on a patient with constitutional varus or valgus can disrupt native soft-tissue balance, necessitating extensive ligamentous releases. To address this issue, various personalized alignment strategies—such as anatomical, kinematic, inverse kinematic, restricted kinematic, and functional alignment—have emerged.

The purpose of this review is to systematically clarify the fundamental principles, surgical methodologies, clinical efficacy, and biomechanical safety of these contemporary TKA alignment philosophies.

Alignment Paradigms: Principles and Evidence

1. Mechanical Alignment (MA)

Introduced in the 1970s, MA remains the benchmark paradigm for primary TKA. The primary goal of MA is to position both the distal femoral and proximal tibial bone cuts perpendicular (90°) to their respective mechanical axes in the coronal plane. This aligns the overall hip-knee-ankle (HKA) angle to 180 ± 3°.

By ensuring the mechanical axis passes directly through the center of the prosthetic joint, MA aims to equalize stress distribution across the polyethylene insert, thereby mitigating risks of asymmetric wear, component subsiding, or aseptic loosening. To manage the flexion gap and maintain patellofemoral tracking, surgeons employ either a measured resection or gap balancing technique.

Despite its biomechanical rationale, the clinical necessity of maintaining a strict 0 ± 3° "safe zone" has been questioned:

- Ritter *et al.* [4] evaluated 6,070 TKAs over a mean of 8 years and concluded that a postoperative HKA alignment of 2.5° to 7.4° valgus exhibited lower overall failure rates compared to extreme varus or valgus outliers. Significantly, they warned against "compensating" cuts (e.g., creating tibial varus to offset femoral valgus), which drastically increased failure rates.
- Conversely, Bonner *et al.* [5] reported on 501 TKAs at a 15-year follow-up and found no statistically significant

difference (p = 0.47) in aseptic loosening rates between knees within the neutral zone and those deviating by > 3°.
- Supporting this, Parratte *et al.* [6] and Abdel *et al.* [7] tracked 398 TKAs over 15 and 20 years respectively, demonstrating that an alignment outside the 0° ± 3° threshold did not correlate with higher revision rates or poorer clinical scores.

2. Anatomical Alignment (AA)

First proposed in 1985 by Hungerford and Krackow [8], Anatomical Alignment seeks to combine a neutral lower limb mechanical axis with a joint line oriented in 2° to 3° of varus relative to the mechanical axis, mirroring native joint line orientation during gait. This orientation allows the prosthetic joint line to remain parallel to the ground during single-leg stance.

Early iterations of AA faced complications, including catastrophic polyethylene wear, which was heavily influenced by outdated insert designs and materials. However, modern robotic-assisted surgical systems have renewed interest in this paradigm:
- Yim *et al.* [9] conducted a randomized controlled trial (RCT) comparing robotic-assisted AA (2° tibial varus, 2° femoral valgus, and 2° internal rotation relative to the transepicondylar axis) with MA. At 2 years postoperatively, no significant differences were detected in range of motion (ROM), ligament laxity, or PROMs.
- Yeo *et al.* [10] confirmed these findings in an 8-year follow-up study, demonstrating comparable survivorship, complication rates, and gait kinematics between AA and MA cohorts.

3. Kinematic Alignment (KA)

Kinematic Alignment, introduced by Howell *et al.* [11], seeks to restore the native, pre-arthritic three-dimensional orientation of the knee joint. The philosophy is based on three fundamental kinematic axes of the femur:
1. The transverse axis around which the tibia flexes and extends.
2. The transverse axis around which the patella moves.
3. The longitudinal axis around which the tibia rotates relative to the femur.

KA aims to replicate the pre-arthritic joint line without performing soft-tissue releases. Initially, this was accomplished using MRI-based Patient-Specific Instrumentation (PSI). Today, surgeons widely utilize a calipered kinematic alignment technique. In calipered KA, the thickness of the distal and posterior femoral bone cuts matches the exact thickness of the femoral component implants (typically 8 to 9 mm), factoring in 2 mm for arthritic cartilage wear and 1 mm for the saw blade kerf.

Clinical Performance of KA
- Dossett *et al.* [12] reported significantly superior WOMAC, Knee Society, and functional scores, alongside improved flexion angles (121° ± 10° vs. 113° ± 13°), for KA over MA at both 6-month and 2-year milestones.
- Calliess *et al.* [13] also observed superior combined KSS and WOMAC scores in their KA cohort at 1 year.
- In contrast, trials by Waterson *et al.* [14] and Young *et al.* [15] reported equivalent clinical outcomes, ROM, and satisfaction scores at 1 and 5 years postoperatively.
- Regarding long-term survival, Howell *et al.* [16] reported a 10-year implant survivorship of 97.5% for revision of any cause and 98.4% specifically for aseptic loosening, suggesting that accommodating a patient's natural varus anatomy does not necessarily jeopardize implant longevity.

Inverse Kinematic Alignment (IKA)

While traditional KA primarily utilizes the femur as the reference point and adjusts the tibia accordingly (which can sometimes lead to excessive tibial bone resection or joint instability), Inverse Kinematic Alignment reverses this paradigm. Using robotic-arm assistance, IKA first plans a tibial cut that matches the patient's pre-arthritic tibial joint line (restricted to a safe range of 6° varus to 2° valgus relative to the mechanical axis).

Following the tibial cut, the extension and flexion gaps are balanced intraoperatively by dynamically adjusting the distal lateral and posterior lateral femoral resections.
- Winnock de Grave *et al.* [17] reported high patient satisfaction and comparable clinical scores at 1 year in a comparative study evaluating robotic IKA against adjusted mechanical alignment. This strategy minimizes tibial bone loss while maintaining customized ligament balance.

Restricted Kinematic Alignment (rKA)

To mitigate the potential risk of rapid implant wear or early loosening in patients with severe constitutional deformities, Restricted Kinematic Alignment was introduced as a "compromise" protocol. rKA attempts to restore native anatomy but establishes strict boundaries or "safe zones" to prevent extreme outliers:
- Independent femoral and tibial cuts are restricted to within ±5° of their mechanical axes.
- The cumulative postoperative HKA angle must fall within ±3° (or 5° varus to 4° valgus depending on the specific protocol).
- If a patient's pre-arthritic planning falls outside these parameters, the surgical plan is systematically adjusted back toward the boundary limits:
- MacDessi *et al.* [18] demonstrated in an RCT that rKA successfully achieved superior quantitative soft-tissue balance and fewer bone recuts than MA, without compromising clinical outcomes at 1 year.
- However, Sappey-Marinier *et al.* [19] reported a concerning 16% aseptic tibial loosening rate in a posterior-stabilized rKA cohort at a 50-month follow-up compared to just 4% in an MA cohort, highlighting the ongoing debate regarding bone-implant interface stress in non-orthogonal configurations.

Modified Kinematic Alignment (mKA)

Modified Kinematic Alignment (often termed "pseudo-kinematic" alignment) was specifically developed to accommodate East Asian patient populations, who exhibit a high prevalence of constitutional varus.
- In mKA, the tibial resection is capped at a fixed 3° of varus with a 7° posterior slope.
- The femoral cuts are then performed using kinematic principles (matching implant thickness).

- Matsumoto *et al*. [20] conducted an RCT showing that mKA resulted in significantly improved post-operative flexion angles (129° ± 9° vs. 116° ± 13°) and superior 2011 Knee Society functional scores at 1 year compared to traditional MA.

Functional Alignment (FA)

Functional Alignment is an evolution of personalized TKA that leverages advanced robotic-assisted technology and real-time sensor feedback. Rather than adhering to strict pre-determined bone cut angles, FA positions the components to optimize soft-tissue tension throughout the entire range of motion, keeping bone resections within conservative boundaries:

- The femoral component is adjusted between 0° and 3° to balance the coronal extension gap, and within ±3° of the transepicondylar axis to balance the flexion gap.
- The tibial component is planned along the mechanical axis and adjusted up to 3° varus to equalize the mediolateral gaps.
- Choi *et al*. [21] demonstrated that robotic-assisted FA resulted in superior Knee Society satisfaction, expectation, and functional scores, alongside improved FJS-12 metrics at 2 years compared to manual MA.

Discussion

The development of primary TKA alignment techniques represents a shift from implant-centered

Alignment Strategy	Coronal Tibial Resection Limit	Coronal Femoral Resection Limit	Overall HKA Target	Balancing Focus
Mechanical (MA)	Perpendicular (90° to MA)	Perpendicular (90° to MA)	0° ± 3°	Soft-Tissue Release
Anatomical (AA)	2° to 3° Varus	2° to 3° Valgus	0° (Neutral)	Structural Alignment
Kinematic (KA)	Restores Native Joint Line	Restores Native Joint Line	Restores Constitutional Axis	Measured Resection
Inverse Kinematic (IKA)	Restores Native Joint Line (6° Varus to 2° Valgus)	Adjusted based on Tibial Cut	6° Varus to 3° Valgus	Femoral Gap Adjustment
Restricted Kinematic (rKA)	Restores Native (Limit: ±5°)	Restores Native (Limit: ±5°)	0° ± 3°	Boundary-Restricted KA
Modified Kinematic (mKA)	Fixed 3° Varus	Restores Native (Implant Thickness)	Constitutional Varus	Native Femoral Focus
Functional (FA)	0° to 3° Varus	0° to 3° Valgus/Varus	Custom Balanced Axis	Real-Time Gap Balancing

Balancing Longevity and Natural Kinematics

Traditional MA simplifies ligament balancing by providing a symmetric bone platform, but it frequently requires extensive soft-tissue releases that can compromise dynamic joint stability. Conversely, KA and FA minimize the need for ligament releases by preserving individual joint line obliquity, resulting in a more natural joint feel and higher early patient satisfaction.

However, leaving a tibial component in substantial varus increases shear stress at the medial bone-implant interface. While modern cement techniques and highly cross-linked polyethylene decrease wear, long-term survival data (> 15 years) for unrestricted kinematic strategies remains sparse.

Technological Integration and Future Directions

Personalized alignment paradigms are highly dependent on surgical precision. Manual instrumentation introduces variability that can easily turn a planned kinematic configuration into an extreme outlier. The integration of 3D preoperative CT planning, optical navigation, and haptic robotic-arm assistance has significantly improved the reproducibility of these complex cuts.

Furthermore, traditional assessment of post-operative alignment has relied on 2D plane radiographs. Recent literature indicates a high rate of error when identifying true anatomical outliers using 2D imaging compared to 3D CT reconstruction. Future studies must incorporate standardized 3D alignment measurements alongside objective soft-tissue tension tracking to accurately evaluate the clinical and radiographic outcomes of these alignment philosophies.

Conclusion

Personalized TKA alignment paradigms—such as kinematic, restricted kinematic, and functional alignment—offer promising short-to-medium-term outcomes, often demonstrating superior patient satisfaction and joint kinematics compared to traditional mechanical alignment. However, the precise boundaries of safe anatomical deviation required to guarantee long-term implant survival remain unknown. Continued multicenter randomized trials with long-term follow-ups are necessary to establish definitive guidelines for personalized arthroplasty.

References

1. Price AJ, Alvand A, Troelsen A, *et al*. Knee replacement. Lancet. 2018:392(10158):1672-1682.
2. Minoda Y. Alignment techniques in total knee arthroplasty. Journal of Joint Surgery and Research,2023:1(1):108-116.
3. Bellemans J, Colyn W, Vandenneucker H, Victor J. The Chitranjan Ranawat award: is neutral mechanical alignment normal for all patients? The concept of constitutional varus. Clin Orthop Relat Res,2012:470(1):45-53.
4. Ritter MA, Davis KE, Meding JB, *et al*. The effect of alignment and BMI on failure of total knee replacement. J Bone Joint Surg Am,2011:93(17):1588-1596.
5. Bonner TJ, Eardley WG, Patterson P, *et al*. The effect of post-operative mechanical axis alignment on the survival of primary total knee replacements after a follow-up of 15 years. J Bone Joint Surg Br,2011:93(9):1217-1222.
6. Parratte S, Pagnano MW, Trousdale RT, Berry DJ. Effect of postoperative mechanical axis alignment on the fifteen-year survival of modern, cemented total knee replacements. J Bone Joint Surg Am,2010:92(12):2143-2149.
7. Abdel MP, Ollivier M, Parratte S, *et al*. Effect of postoperative mechanical Axis alignment on survival and functional outcomes of modern total knee

arthroplasties with cement: a concise follow-up at 20 years. J Bone Joint Surg Am,2018:100(6):472-478.
8. Hungerford DS, Krackow KA. Total joint arthroplasty of the knee. Clin Orthop Relat Res,1985:(192):23-33.
9. Yim JH, Song EK, Khan MS, *et al*. A comparison of classical and anatomical total knee alignment methods in robotic total knee arthroplasty: classical and anatomical knee alignment methods in TKA. J Arthroplasty,2013:28(6):932-937.
10. Yeo JH, Seon JK, Lee DH, Song EK. No difference in outcomes and gait analysis between mechanical and kinematic knee alignment methods using robotic total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc,2019:27(4):1142-1147.
11. Howell SM, Kuznik K, Hull ML, Siston RA. Results of an initial experience with custom-fit positioning total knee arthroplasty in a series of 48 patients. Orthopedics,2008:31(9):857-863.
12. Dossett HG, Estrada NA, Swartz GJ, *et al*. A randomised controlled trial of kinematically and mechanically aligned total knee replacements: two-year clinical results. Bone Joint J,2014:96-B(7):907-913.
13. Calliess T, Bauer K, Stukenborg-Colsman C, *et al*. PSI kinematic versus non-PSI mechanical alignment in total knee arthroplasty: a prospective, randomized study. Knee Surg Sports Traumatol Arthrosc,2017:25(6):1743-1748.
14. Waterson HB, Clement ND, Eyres KS, *et al*. The early outcome of kinematic versus mechanical alignment in total knee arthroplasty: a prospective randomised control trial. Bone Joint J,2016:98-B(10):1360-1368.
15. Young SW, Sullivan NPT, Walker MIL, *et al*. No difference in 5-year clinical or radiographic outcomes between kinematic and mechanical alignment in TKA: a randomized controlled trial. Clin Orthop Relat Res,2020:478(6):1271-1279.
16. Howell SM, Shelton TJ, Hull ML. Implant survival and function ten years after kinematically aligned total knee arthroplasty. J Arthroplasty,2018:33(12):3678-3684.
17. Winnock de Grave P, Kellens J, Luyckx T, *et al*. Inverse kinematic alignment for total knee arthroplasty. Orthop Traumatol Surg Res,2022:108(5):103305.
18. MacDessi SJ, Griffiths-Jones W, Chen DB, *et al*. Restoring the constitutional alignment with a restrictive kinematic protocol improves quantitative soft-tissue balance in total knee arthroplasty: a randomized controlled trial. Bone Joint J,2020:102-B(1):117-124.
19. Sappey-Marinier E, Shatrov J, Batailler C, *et al*. Restricted kinematic alignment may be associated with increased risk of aseptic loosening for posterior-stabilized TKA: a case-control study. Knee Surg Sports Traumatol Arthrose,2022:30(8):2838-2845.
20. Matsumoto T, Takayama K, Ishida K, *et al*. Radiological and clinical comparison of kinematically versus mechanically aligned total knee arthroplasty. Bone Joint J,2017:99-B (5):640-646.
21. Choi BS, Kim SE, Yang M, *et al*. Functional alignment with robotic-arm assisted total knee arthroplasty demonstrated better patient-reported outcomes than mechanical alignment with manual total knee arthroplasty. Knee Surg Sports Traumatol Arthrose,2022:30(11):3810-3818.