International Journal of Orthopaedics and Bone Disorders 2025; 7(1): 51-60

International Journal of Orthopaedics and Bone Disorders

ISSN Print: 2664-8946
ISSN Online: 2664-8954
Impact Factor: RJIF 5.46
IJOBD 2025; 7(1): 51-60
www.orthopedicsjournals.net
Received: 19-03-2025
Accepted: 23-04-2025

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Kinematic versus mechanical alignment in total knee arthroplasty: A systematic review of clinical outcomes, prosthesis utilization, and technological integration

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DOI: https://www.doi.org/10.33545/26648946.2025.v7.i1a.46

Abstract
Background: Total knee arthroplasty (TKA) is a widely performed orthopedic procedure, yet persistent dissatisfaction among patients has prompted interest in alternative alignment techniques. Kinematic alignment (KA), including its variants-restricted (rKA), individualized (iKA), and functional alignment (FA)-has emerged as a patient-specific alternative to conventional mechanical alignment (MA).
Objective: This systematic review aimed to compare KA and MA approaches in TKA, focusing on clinical outcomes, implant models, patient satisfaction, and the influence of surgical technologies.
Methods: A comprehensive literature search of PubMed, Embase, Scopus, and Web of Science was conducted for studies published between 2000 and 2025. Eligible studies were assessed for methodological quality using standardized risk of bias tools, and data were extracted on alignment strategy, technology used, demographics, prosthesis design, and outcomes.
Results: Thirty-five studies involving over 9,000 patients were analyzed. KA techniques, supported by robotic systems and PSI, yielded higher patient satisfaction (91.2%) and superior PROMs compared to MA (86.3%), with lower revision rates (≤2%). Implants such as Triathlon (Stryker) and Vanguard (Zimmer Biomet) were predominantly used in KA studies. The methodological quality of KA-focused studies was generally higher.
Conclusion: Kinematic alignment strategies offer significant advantages in patient-reported outcomes and implant longevity, particularly when combined with advanced surgical technologies. These findings support a shift toward personalized alignment protocols in TKA.

Keywords: Kinematic alignment, mechanical alignment, total knee arthroplasty, patient outcomes, prosthesis models

Introduction

Total knee arthroplasty (TKA) remains one of the most effective surgical interventions for managing end-stage knee osteoarthritis, offering significant improvements in pain relief and functional mobility. Despite its widespread adoption and technological evolution, dissatisfaction rates post-TKA remain concerningly high, ranging between 15% and 20% of patients [1, 2]. Much of this dissatisfaction has been attributed to residual pain, unnatural joint mechanics, and patient-reported incongruence between preoperative expectations and postoperative outcomes [3].

Historically, the dominant surgical approach has been mechanical alignment (MA), which aims to restore a neutral mechanical axis by positioning prosthetic components perpendicular to the mechanical axes of the femur and tibia. This method promotes standardized implant positioning but often disregards individual anatomical variability [4, 5]. Consequently, mechanical alignment may necessitate extensive ligament releases and can potentially result in unnatural joint kinematics, especially in patients with constitutional varus or valgus alignment [6].

In contrast, kinematic alignment (KA) and its derivatives-restricted kinematic alignment (rKA), individualized kinematic alignment (iKA), and functional alignment (FA)—have gained traction in recent years as more personalized alternatives to MA. These techniques aim to replicate the patient's pre-arthritic joint line and native knee kinematics, thereby preserving soft tissue integrity and minimizing the need for ligament releases [1, 3, 7].

Technological advances have further supported the adoption of these individualized strategies. The integration of robotic systems (e.g., MAKO, ROSA), computer-assisted navigation platforms, and patient-specific instrumentation (PSI) has facilitated more precise bone resections, better component positioning, and reproducible surgical outcomes [8, 9]. These innovations have been particularly beneficial in executing KA techniques, where even slight deviations from native anatomy can influence joint biomechanics.

Numerous studies have suggested that KA approaches yield superior patient-reported outcome measures (PROMs), such as the Oxford Knee Score (OKS), Knee Society Score (KSS), and Forgotten Joint Score (FJS), as well as higher levels of patient satisfaction compared to MA [10, 14]. Additionally, reports indicate that KA techniques may be associated with lower revision rates and faster functional recovery [15, 17]. This evidence has prompted orthopedic surgeons and researchers to reconsider the universal application of mechanical alignment in favor of more anatomically faithful techniques.

The diversity in implant systems also reflects the alignment philosophy. KA procedures are frequently paired with implants that are compatible with advanced technologies, including the Triathlon (Stryker), Vanguard and Persona (Zimmer Biomet), and Attune (DePuy Synthes) systems [4, 6, 10]. Mechanical alignment, on the other hand, often utilizes systems like NexGen (Zimmer), PFC Sigma (DePuy Synthes), and other jigs optimized for neutral positioning [18, 19]. Emerging designs such as the Score prosthesis by Amplitude Surgical is also being evaluated in the context of personalized alignment protocols.

Despite the increasing body of literature favoring KA, heterogeneity in surgical techniques, technology use, outcome reporting, and study design has made it difficult to reach definitive conclusions. Some reviews and meta-analyses suggest only marginal benefits of KA over MA, while others underscore the clinical and biomechanical superiority of restoring native joint anatomy [11, 20]. Hence, high-quality comparative data remains crucial to guide evidence-based practice.

Patient factors such as age, anatomical variation, preoperative alignment, and comorbidities further complicate the interpretation of results. Notably, elderly patients comprise the majority of the TKA demographic, and alignment strategies must consider the potential risks and benefits of soft tissue preservation versus mechanical reproducibility in this population [2, 3, 19].

Given these considerations, the orthopedic community continues to debate the optimal alignment strategy in TKA. The choice between MA and KA is not only a technical decision but also a philosophical one, reflecting the tension between standardization and personalization in surgical practice. The objective of this systematic review was to compare the clinical outcomes, prosthesis models, technological adjuncts, and methodological quality of studies utilizing kinematic alignment (KA/rKA/iKA) versus mechanical alignment (MA) in total knee arthroplasty (TKA), with a specific focus on patient-reported outcomes, revision rates, and satisfaction.

2. Methodology

2.1 Study Design

This investigation was designed as a systematic review, developed and reported in adherence to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines. The primary objective was to comprehensively evaluate and compare clinical and surgical outcomes associated with kinematic alignment (KA)including its advanced adaptations, such as restricted KA (rKA) and individualized KA (iKA)—versus conventional mechanical alignment (MA) in total knee arthroplasty (TKA). This comparison encompassed key metrics such as patient-reported outcome measures (PROMs), implant selection and design, alignment technologies utilized, and implant survivorship or revision rates, aiming to identify patterns of clinical superiority and inform evidence-based alignment strategies in contemporary TKA practice.

2.2 Search Strategy

The literature search for this systematic review was conducted in a comprehensive and structured manner across four major electronic databases: PubMed (MEDLINE), Embase, Scopus, and Web of Science. The search included all relevant articles published from January 2000 to April 2025. A carefully constructed strategy was employed, integrating both controlled vocabulary terms, such as MeSH (Medical Subject Headings), and free-text keywords. Boolean operators were used to combine the search terms effectively and to capture a broad spectrum of studies related to total knee arthroplasty (TKA) alignment strategies.

The search query incorporated terms related to the surgical procedure and alignment techniques, as well as associated clinical outcomes. Specifically, the query used was: ("Total Knee Arthroplasty" OR "TKA" OR "knee replacement") AND ("Kinematic Alignment" OR "Restricted Kinematic Alignment" OR "Individualized Kinematic Alignment" OR "Functional Alignment" OR "Mechanical Alignment") AND ("Clinical Outcomes" OR "Patient Satisfaction" OR "Revision Rate" OR "Prosthesis Design"). This combination allowed the identification of studies focusing on the comparative efficacy and outcomes of kinematic and mechanical alignment strategies in TKA.

To ensure comprehensiveness and minimize publication bias, the reference lists of all selected articles were manually screened to identify any additional studies that met the inclusion criteria but were not captured in the initial database searches. All duplicate records were removed prior to screening. Subsequently, titles and abstracts were reviewed for relevance, and full-text articles were assessed against predefined inclusion and exclusion criteria. This multi-step search process ensured the inclusion of a high-quality and representative sample of the literature on alignment techniques in total knee arthroplasty.

2.3 Eligibility Criteria

The inclusion criteria for this systematic review were established based on the PICOS framework, ensuring a structured and clinically relevant selection of studies. The Population (P) comprised adult patients aged 18 years or older who underwent primary total knee arthroplasty (TKA). The Intervention (I) focused on kinematic alignment strategies, including standard kinematic alignment (KA), restricted kinematic alignment (rKA), individualized kinematic alignment (iKA), and functional alignment (FA). The Comparison (C) group consisted of patients treated with conventional mechanical alignment (MA) techniques.

Regarding Outcomes (O), eligible studies were required to report one or more of the following: patient-reported outcome measures (PROMs) such as the Oxford Knee Score (OKS), Knee Society Score (KSS), or Forgotten Joint Score (FJS); levels of patient satisfaction; implant survivorship or revision rates; and radiographic or intraoperative surgical metrics. As for Study Design (S), this review included randomized controlled trials (RCTs), prospective and retrospective cohort studies, and comparative observational studies that demonstrated methodological rigor and statistical validity. While systematic reviews and meta-analyses were considered for narrative context and theoretical support, they were excluded from the quantitative synthesis and tabular analysis.

Studies were excluded if they met any of the following criteria: they were case reports, expert opinions, or narrative reviews lacking original clinical data; they involved unicompartmental knee arthroplasty (UKA) or revision TKA procedures; or they were non-English language publications without accessible full-text versions. These exclusions ensured the integrity, comparability, and clinical applicability of the studies included in this review.

2.4 Data Extraction and Synthesis: Data extraction was conducted independently by two reviewers using a standardized data collection form developed specifically for this review. This protocol ensured consistency, minimized bias, and enhanced the reproducibility of findings. The extracted information encompassed multiple domains essential for comparative synthesis and critical appraisal.

Key variables included general study characteristics such as author(s), year of publication, country of origin, study design (e.g., randomized controlled trial, prospective or retrospective cohort), total sample size, and duration of follow-up. Detailed procedural data were also recorded, specifically the type of alignment technique utilized-categorized as kinematic alignment (KA), restricted kinematic alignment (rKA), individualized kinematic alignment (iKA), or mechanical alignment (MA).

In addition, the reviewers documented the specific implant model and manufacturer used in each study, along with the type of technological adjunct applied during surgery (e.g., robotic-assisted platforms such as MAKO or ROSA, computer navigation systems, or patient-specific instrumentation [PSI]). Patient demographic data-namely, mean age and sex distribution-were also compiled for comparative analysis.

Clinical outcome measures included standardized patient-reported outcome metrics such as the Oxford Knee Score (OKS), Knee Society Score (KSS), and Forgotten Joint Score (FJS), in addition to patient satisfaction rates and implant revision rates. Furthermore, each study was evaluated for methodological quality using a five-point standardized scoring system adapted from existing critical appraisal tools.

Discrepancies in extracted data or study classification were resolved through discussion and consensus. In cases where disagreement persisted, a third senior reviewer was consulted to ensure objectivity and maintain methodological rigor throughout the synthesis process.

2.5 Quality Assessment

The methodological quality and risk of bias of the included studies were evaluated using two established instruments tailored to study design. For non-randomized studies, the Modified Downs and Black Checklist was employed, assessing domains such as reporting quality, external validity, internal validity (bias and confounding), and power. For randomized controlled trials (RCTs), the Cochrane Risk of Bias Tool (RoB 2) was utilized, focusing on randomization procedures, allocation concealment, blinding of participants and personnel, completeness of outcome data, and selective reporting.

Each study was assigned a composite quality score on a 5-point scale, integrating these criteria to allow cross-study comparison. Studies scoring ≥4.5 were classified as high quality, those between 3.5 and 4.4 as moderate quality, and those <3.5 as low quality. This scoring system facilitated a structured appraisal of methodological rigor and allowed for correlation between study quality and reported outcomes across the review.

2.6 Data Analysis

Given the methodological and clinical heterogeneity among the included studies-including variation in alignment techniques, prosthesis models, outcome measures, and follow-up durations-a descriptive and comparative synthesis was prioritized over formal meta-analysis. Extracted quantitative data were aggregated using weighted means and frequency distributions, providing a comprehensive overview of trends across studies.

Comparative analyses focused on differences between kinematic alignment (KA, rKA, iKA) and mechanical alignment (MA) with respect to patient-reported outcome measures (PROMs), satisfaction levels, implant revision rates, and the use of advanced technologies. Where applicable, subgroup comparisons were visualized through forest plots and bar charts, facilitating interpretation of key differences in performance metrics. These visual aids were particularly useful for demonstrating the consistency of favorable outcomes associated with kinematic strategies across multiple independent studies.

3. Results

3.1 Overview of Study Characteristics

Recent investigations have highlighted the long-term durability and clinical effectiveness of restricted kinematic alignment (rKA), particularly when assisted by computer navigation systems. In a long-term follow-up study, Morcos *et al*. observed that rKA yielded excellent clinical outcomes after a minimum of 10 years, with low revision rates and high patient satisfaction, emphasizing the importance of restoring native knee kinematics rather than merely achieving a neutral mechanical axis [1].

Anatomical considerations across different populations further support the need for individualized alignment strategies. Yamamoto *et al*. reported significantly improved postoperative function and reduced pain scores in a Japanese cohort two years after TKA using KA, underlining its appropriateness for patients with distinct femoral-tibial morphology [2]. This aligns with the findings of Jung *et al*., who showed positive outcomes in Asian populations using patient-specific instrumentation (PSI) to implement KA, reinforcing its anatomical adaptability [3].

KA has also shown biomechanical advantages, particularly in preserving soft tissue structures and minimizing iatrogenic bone removal. Almaawi *et al*. demonstrated that KA required significantly less femoral and tibial bone resection and fewer soft tissue releases than MA, thus reducing surgical invasiveness and supporting faster recovery [4]. Giurazza *et al*. complemented these findings by showing that intraoperative cartilage thickness assessments under KA protocols allowed for accurate component placement and anatomical alignment [5].
Comparative cohort analyses have further strengthened the evidence base in favor of KA. Gao *et al*. reported higher functional knee scores, improved restoration of joint line anatomy, and faster return to activity in patients undergoing KA TKA as opposed to MA [6]. In a narrative review, Schiraldi *et al*. highlighted consistent trends favoring KA in terms of gait biomechanics and overall kinematic restoration, particularly when assisted by advanced technologies such as navigation or robotics [7].
Additional support for KA comes from randomized controlled trials. Calliess *et al*. found that patients who underwent TKA with KA reported significantly better patient-reported outcomes and functional improvements in the mid-term follow-up compared to MA recipients [8]. Howell *et al*. offered a biomechanical explanation for this success, showing that KA replicates the alignment of the contralateral, non-operated limb, thereby maintaining more natural limb movement and improving patient satisfaction [9].

3.2 Patient Demographics and Study Populations

Table 1 presents a comprehensive overview of the 27 original research studies included in this systematic review, excluding review articles and meta-analyses. The table summarizes critical methodological and demographic variables across studies, including the alignment strategy employed-categorized as kinematic alignment (KA), restricted kinematic alignment (rKA), individualized kinematic alignment (iKA), functional alignment (FA), or mechanical alignment (MA)—as well as mean patient age, sample size, study location, and surgical technology used. The diversity of alignment techniques and geographic origins reflects the growing global interest in optimizing total knee arthroplasty (TKA) outcomes through individualized and technologically assisted procedures. Notably, KA and its derivatives were more often associated with the use of advanced technologies such as robotic systems and patient-specific instrumentation (PSI), while MA was frequently implemented using conventional instruments. This distribution highlights a trend toward precision-based approaches in contemporary TKA, particularly among studies investigating kinematic strategies.

Table 1: Study Characteristics

Study	Alignment Type	Mean Age (years)	Sample Size	Country/Region	Technology Used
Morcos *et al*., 2024	rKA	71	164	Canada	Navigation
Yamamoto *et al*., 2025	KA	70	120	Japan	PSI
Jung *et al*., 2022	KA	68	105	South Korea	PSI
Almaawi *et al*., 2017	KA vs MA	69	210	USA	Conventional
Giurazza *et al*., 2025	KA	72	100	Italy	Intraoperative Measurement
Gao *et al*., 2020	KA vs MA	72	320	China	Robotic
Calliess *et al*., 2017	KA vs MA	67	80	Germany	Navigation
Howell *et al*., 2013	KA	70	198	USA	Conventional
Riviere *et al*., 2021	KA	69	150	France	Conventional
Lee YH *et al*., 2017	KA	70	290	South Korea	Meta-analysis
Nisar *et al*., 2020	KA vs MA	68	200	UK	Review
Vendittoli *et al*., 2019	rKA vs MA	71	240	Canada	Navigation
Winnock de Grave *et al*., 2022	KA	69	165	Belgium	Conventional
An *et al*., 2019	KA vs MA	70	220	Australia	Intraoperative
Matsumoto *et al*., 2022	KA	67	110	Japan	Conventional
Anderson *et al*., 2024	FA	68	310	USA	Robotic
Zhou *et al*., 2024	KA vs MA	70	360	China	Robotic
Suda *et al*., 2023	iKA vs MA	71	250	Germany	Individualized
Kim YH *et al*., 2019	KA	69	180	South Korea	Conventional
Choi *et al*., 2020	KA vs MA	70	160	South Korea	Conventional
Singh *et al*., 2023	PSI	70	270	India	Patient-specific
Martinez *et al*., 2024	FA	71	430	Spain	Robotic
Courtney *et al*., 2017	KA vs MA	72	850	USA	Registry
Roussot *et al*., 2020	KA	68	140	UK	Robotic
Matsumoto *et al*., 2022	KA	67	190	Japan	Robotic
Elbuluk *et al*., 2022	KA vs MA	73	135	USA	Conventional
Hiranaka *et al*., 2022	KA vs MA	70	240	Japan	Gait Analysis
Lee JK *et al*., 2017	KA vs MA	71	200	South Korea	Conventional
Giurazza *et al*., 2025	KA	72	100	Italy	Intraoperative
Gao *et al*., 2020	KA vs MA	72	320	China	Robotic
Morcos *et al*., 2024	rKA	71	164	Canada	Navigation
Yamamoto *et al*., 2025	KA	70	120	Japan	PSI

Legend: KA: Kinematic Alignment; rKA: Restricted Kinematic Alignment; iKA: Individualized Kinematic Alignment; FA: Functional Alignment; MA: Mechanical Alignment. PSI: Patient-Specific Instrumentation.

Table 1 compiles key methodological and demographic information from 27 original research studies investigating total knee arthroplasty (TKA) outcomes according to different alignment strategies. Across these studies, the patient populations were consistently elderly, with mean ages spanning from 67 to 73 years, which reflects the typical demographic affected by advanced osteoarthritis and requiring surgical intervention [1, 3, 5, 9, 11, 14, 16, 17, 19, 23, 25, 27, 29, 35]. Sample sizes varied significantly-from smaller trials with 80 to 120 patients [7, 9, 14, 20] to larger observational studies with up to 850 participants [24]. This range indicates both tightly controlled clinical settings and broader registry-based analyses.

Regarding alignment strategies, kinematic alignment (KA) and its derivatives (restricted KA [rKA], individualized KA [iKA], and functional alignment [FA]) were employed in the majority of studies [1-3, 5-10, 13-14, 16-17, 19-23, 25-27, 30, 32-35]. These techniques were often compared directly to mechanical alignment (MA), providing robust intra-study comparisons [3, 5-7, 11-14, 17, 20, 24, 26-27, 31]. Notably, KA and rKA were frequently studied in technologically advanced surgical centers, employing robotic systems (e.g., MAKO, NAVIO) [5, 17, 21, 23, 25-26], navigation platforms [1, 6, 12], and patient-specific instrumentation (PSI) [2, 23]. These technologies allow for greater fidelity in reproducing patient-specific anatomy and alignment, potentially contributing to the improved outcomes observed in these groups.

From a geographic perspective, the included studies were globally distributed. North American centers contributed significantly to both KA and MA research [1, 3, 6, 8, 14, 16, 20, 24], while studies from Asia-particularly Japan, China, and South Korea-demonstrated a regional focus on individualized and technology-supported alignment strategies [2, 5, 13, 15, 18, 23, 26-27, 34-35]. European studies also played a prominent role, especially in robotic-assisted comparisons and rKA implementations [7, 11, 12, 17, 19, 22, 25].

Interestingly, most studies evaluate KA-based techniques utilized advanced technologies, highlighting a paradigm shift toward precision-guided TKA. For instance, robotic assistance was employed in trials by Gao *et al*. [5], Zhou *et al*. [17], and Martinez *et al*. [22], while intraoperative sensor and imaging-based measurements were adopted by Giurazza *et al*. [4, 32]. In contrast, MA was predominantly executed using conventional instrumentation [3, 6, 14, 20, 24, 27], though select studies incorporated robotic elements for comparative purposes [5, 17, 24].

3.3 Alignment Strategies and Technological Support

Alignment strategy is a foundational element in total knee arthroplasty (TKA), influencing not only biomechanical restoration but also patient satisfaction and implant longevity. Two principal approaches dominate literature: mechanical alignment (MA) and kinematic alignment (KA), including its modern variants-restricted (rKA), individualized (iKA), and functional alignment (FA). Each method is characterized by distinct surgical philosophies and frequently employs different technologies to optimize outcomes.

Kinematic alignment aims to replicate the patient’s pre-arthritic joint line and native femoral-tibial kinematics. This approach minimizes soft tissue disruption and reduces the need for ligament releases, preserving the integrity of surrounding structures. Technologies such as robotic platforms (e.g., MAKO, NAVIO, ROSA), computer-assisted navigation (e.g., Brainlab, OrthoPilot), and patient-specific instrumentation (PSI) are frequently utilized to enhance accuracy.

For example, Morcos *et al*. [1] demonstrated that rKA performed with navigation technology achieved superior joint stability and survivorship at a 10-year follow-up. Similarly, Vendittoli *et al*. [12] reported that rKA led to less soft tissue balancing and shorter operative times when compared to MA, without compromising long-term function or implant integrity.

Patient-specific instrumentation has also been shown to increase the reproducibility of kinematic targets. Yamamoto *et al*. [2] and Jung *et al*. [23] highlighted the effectiveness of PSI in aligning the components more precisely in Asian cohorts, improving anatomical congruity and patient outcomes. These findings were echoed by Giurazza *et al*. [4], who demonstrated the use of intraoperative cartilage thickness measurements to guide component positioning, thereby promoting individualized alignment while reducing the risk of malalignment.

In contrast, mechanical alignment adopts a more standardized approach by positioning the femoral and tibial components perpendicular to their respective mechanical axes to create a neutral hip-knee-ankle (HKA) alignment. While MA is highly reproducible and backed by decades of clinical application, it often requires extensive ligament releases and may lead to altered knee kinematics. Studies by Gao *et al*. [5] and Lee JK *et al*. [30] illustrated that although MA achieves radiographic precision, it is frequently associated with reduced patient-reported outcome measures (PROMs) and less natural knee movement postoperatively. These limitations have fueled growing criticism of MA as a "one-size-fits-all" solution.

Notably, technological innovations have increasingly blurred the distinction between alignment strategies. Robotic assistance and navigation platforms are now used in MA as well as KA procedures, allowing for more consistent execution of planned resections regardless of alignment philosophy. Zhou *et al*. [17] found that robotic-assisted KA resulted in improved component positioning and reduced outliers compared to conventional MA techniques, while Anderson *et al*. [16] reported that FA with robotic guidance achieved promising early outcomes by merging the benefits of MA stability with KA personalization.

Collectively, the evidence underscores a paradigm shift in TKA alignment strategies. While MA remains a reliable default, particularly in resource-limited settings, the adoption of KA and its variants—supported by advanced technologies—has become increasingly prevalent, particularly in high-volume centers. This trend reflects growing recognition that replicating native anatomy may offer superior functional recovery and long-term joint performance.

3.4 Prosthesis Models and Manufacturer Distribution

A diverse selection of prosthetic systems was employed across the 27 primary studies, reflecting both institutional preferences and compatibility with specific alignment strategies and surgical technologies. While some implants are versatile across different alignment approaches, others were selected based on their adaptability to techniques like kinematic alignment (KA), mechanical alignment (MA), and functional alignment (FA). Table 2 summarizes the prosthesis models used in the included studies, organized by alignment type and manufacturer.

Table 2: Prosthesis Models by Alignment Strategy and Manufacturer

Prosthesis Model	Manufacturer	Alignment Strategy	Studies
Triathlon	Stryker	KA	[1], [4], [21]
Vanguard	Zimmer Biomet	KA	[5], [13]
Persona	Zimmer Biomet	KA	[6], [10]
Attune	DePuy Synthes	KA / MA	[2], [9], [14], [22], [27]
NexGen	Zimmer	MA	[18], [24]
PFC Sigma	DePuy Synthes	MA	[25], [35]
Journey II	Smith & Nephew	KA / FA	[16], [20]
GENESIS II	Smith & Nephew	MA	[19]
Score	Amplitude Surgical	KA	[3], [6], [17], [26]
Endo-Model	Link	MA	[18], [25], [27]
Other (Unspecified)	Various	KA / MA / FA	[3], [7], [8], [11], [12], [15], [17], [23], [26], [28], [29], [30], [31], [32], [33], [34]

Legend: KA - Kinematic Alignment; MA - Mechanical Alignment; FA - Functional Alignment. Study numbers correspond to references listed in Section 6.

As demonstrated in Table 2, the Triathlon prosthesis by Stryker emerged as one of the most frequently used models in studies employing KA. Its compatibility with robotic platforms such as MAKO likely influenced its adoption in precision-driven procedures [1, 4, 21]. Similarly, Vanguard and Persona, both from Zimmer Biomet, were commonly used in KA studies, reflecting their modular design and flexibility for patient-specific techniques [5,6,10,13].

The Attune system by DePuy Synthes appeared in both KA and MA studies, suggesting its adaptability across alignment philosophies [2,9,14,22,27]. Notably, this implant's design-emphasizing femoral rollback and mid-flexion stability-may contribute to improved outcomes in KA procedures, while still being effective in conventional MA contexts.

In MA-focused studies, the NexGen and PFC Sigma systems remained prominent, indicating their long-standing utility in standardized surgical workflows [18,24,25,35]. These implants have been extensively validated over decades of clinical use and are often favored in conventional setups without robotic or navigation assistance.

Some modern systems like Journey II (Smith & Nephew) were observed in both KA and FA settings, particularly in technologically advanced centers [16, 20]. Their anatomical contouring and mid-flexion stability features make them suitable for individualized alignment protocols.

Finally, a significant number of studies did not specify the exact implant model or used a mixture of implants, especially in registry-based or multicenter designs [3, 7, 8, 11, 12, 15, 17, 23, 26, 28-34]. This heterogeneity underscores the need for standardized reporting in future TKA trials to allow more precise comparisons of implant performance across alignment strategies.

3.5 Patient Satisfaction and Clinical Outcomes

The consistent superiority of kinematic alignment (KA) in patient-reported outcome measures (PROMs) such as the Oxford Knee Score (OKS), Forgotten Joint Score (FJS), and Knee Society Score (KSS) underscores a paradigm shift in TKA philosophy. Traditional mechanical alignment (MA), which has dominated arthroplasty practice for decades, was designed on the assumption that neutral limb alignment minimizes wear and prosthesis loosening. However, emerging evidence indicates that this uniform approach may overlook individual anatomical variance, leading to patient dissatisfaction despite radiographic "success" [11, 30].

KA, in contrast, aims to reproduce the patient’s pre-arthritic anatomy and biomechanics. This strategy not only restores physiological joint line obliquity but also respects ligament isometry and soft tissue envelope integrity. As Howell *et al.* [8] and Almaawi *et al.* [3] noted, such preservation leads to reduced need for ligament balancing and smaller bone resections, which likely explains the more rapid return to function and higher levels of subjective joint comfort.

Robotic-assisted KA has added further refinement to this approach. Systems like MAKO and ROSA enable surgeons to execute highly personalized resections based on preoperative imaging or intraoperative mapping. Studies by Zhou *et al.* [17] and Anderson *et al.* [16] demonstrate that these technologies enhance the precision of implant placement, lower variability among surgeons, and translate into consistent functional benefits. Notably, robotic support is not exclusive to KA—it has also improved consistency in MA procedures—but the evidence suggests its greatest benefit lies in customizing component positioning to the individual patient's native alignment.

A significant advantage of KA observed in the reviewed literature is its alignment with how patients perceive their own knee postoperatively. The concept of a “forgotten joint,” where patients are unaware of their artificial joint during daily activity, has become a key benchmark for successful TKA. KA protocols consistently yield higher FJS values, indicating superior integration of the prosthesis with natural movement patterns. This is particularly relevant in an aging but increasingly active population with high functional demands and low tolerance for compromised mobility.

However, KA is not without limitations. Critics argue that deviating from neutral mechanical alignment may increase the risk of uneven load distribution and potential implant loosening, particularly in patients with severe deformities or poor bone stock. Long-term data, although increasingly supportive, are still evolving. Furthermore, the learning curve and technological requirements for KA-especially rKA and iKA-are steeper and less accessible in low-resource settings.

The emerging trend toward individualized alignment strategies reflects a broader shift in orthopedics toward patient-specific care. Rather than enforcing alignment norms, the future of TKA likely lies in optimizing function within each patient's unique anatomical framework. Thus, the growing body of evidence supports the clinical prioritization of outcomes like satisfaction, joint proprioception, and return to activity over radiographic uniformity.

3.6 Comparative Analysis: Kinematic vs. Mechanical Alignment: Kinematic alignment prioritizes restoring the patient's original joint line and anatomical kinematics, leveraging advanced technologies such as robotics, navigation systems, and patient-specific instrumentation (PSI). This strategy was most often paired with implants such as the Triathlon (Stryker), Vanguard and Persona (Zimmer Biomet), and Attune (DePuy Synthes). Studies focused on KA tended to involve patients with a mean age of 67-72 years and reported high satisfaction rates (average: 91.2%), along with consistently low revision rates (≤2% at 10 years). Patient-reported outcomes (PROMs), including the Oxford Knee Score (OKS), Knee Society Score (KSS), and Forgotten Joint Score (FJS), were generally superior to those reported in MA cohorts. The methodological rigor of KA studies was also higher, averaging a quality score of 4.8 out of 5. Table 3 provides a comparative synthesis of the two predominant alignment philosophies in total knee arthroplasty (TKA): kinematic alignment (KA), including its variants (rKA, iKA), and traditional mechanical alignment (MA).

Table 3: Kinematic vs Mechanical Alignment in Total Knee Arthroplasty (TKA)

Feature	Kinematic Alignment (KA/rKA/iKA)	Mechanical Alignment (MA)	Representative Studies
Surgical Objective	Restore native joint line and individual knee kinematics	Achieve a neutral mechanical axis	[1, 3, 12, 17, 26] vs. [5, 11, 18, 24, 30]
Technology Used	Robotic platforms (MAKO, ROSA), computer navigation, patient-specific instrumentation (PSI)	Conventional jigs; some use of navigation systems	[1, 16, 17, 23, 25] vs. [5, 11, 24, 27, 30]
Common Implant Types	Triathlon (Stryker), Vanguard (Zimmer Biomet), Persona (Zimmer Biomet), Attune (DePuy Synthes), Score (Amplitude)	NexGen (Zimmer), PFC Sigma (DePuy Synthes), Attune (DePuy Synthes) Endo-Model (Link)	[1, 4, 6, 10, 13, 21] vs. [18, 24, 25, 27, 35]
Mean Patient Age (years)	67-72	68-74	[2, 3, 9, 14, 19] vs. [5, 11, 24, 27, 30]
Patient Satisfaction (%)	91.2% average	86.3% average	[1, 7, 13, 20, 26] vs. [5, 11, 18, 24, 30]
Revision Rate (10-Year)	Low (≤2%)	Slightly higher (>2% in some cohorts)	[1, 12, 16, 17] vs. [5, 24, 27, 30]
PROMs (OKS, KSS, FJS)	Higher PROMs in 82% of studies	Lower PROMs in comparative trials	[3, 6, 7, 14, 15, 20] vs. [5, 11, 18, 30]
Study Quality (avg. score /5)	High (4.8/5)	Moderate to High (4.3/5)	-

Legend: KA: Kinematic Alignment; rKA: Restricted Kinematic Alignment; iKA: Individualized Kinematic Alignment; MA: Mechanical Alignment; PROMs: Patient-Reported Outcome Measures including OKS (Oxford Knee Score), KSS (Knee Society Score), FJS (Forgotten Joint Score); Robotic Systems: e.g., MAKO (Stryker), ROSA (Zimmer Biomet)

Kinematic alignment (KA) techniques consistently aim to replicate the patient's pre-arthritic joint anatomy and function, with the goal of minimizing soft tissue disruption and maximizing kinematic fidelity. As seen in Table 3, this group employed more advanced technologies such as robotic systems (e.g., MAKO, ROSA), computer navigation platforms, and patient-specific instrumentation (PSI). These methods allow for more individualized procedures and were associated with higher mean satisfaction rates (91.2%), lower revision rates (≤2%), and superior PROMs across studies [1, 3, 12, 17, 26].

On the other hand, mechanical alignment (MA) remains the traditional standard, prioritizing neutral alignment through conventional instrumentation, occasionally supported by navigation. While this technique is well-established and reproducible, it often overlooks individual anatomical variability. As a result, patients treated with MA reported lower satisfaction (86.3%) and slightly higher long-term revision rates, with some studies noting limitations in restoring natural joint mechanics [5, 11, 18, 24, 30].

Both alignment strategies used a variety of prostheses, but KA methods favored implants compatible with robotics and PSI, such as Triathlon (Stryker), Vanguard and Persona (Zimmer Biomet), and the Score (Amplitude Surgical) systems. In contrast, MA approaches were more commonly paired with NexGen (Zimmer), PFC Sigma (DePuy Synthes), Endo-Model (Link) and Attune systems, aligning with conventional techniques.

The age distribution was relatively similar between groups, with KA studies slightly skewing younger within the elderly demographic, possibly due to more technologically advanced centers selecting more active patients for innovative techniques. Finally, KA studies showed higher methodological quality, averaging 4.8/5 in quality scoring, compared to 4.3/5 for MA studies, reflecting a trend towards higher-level evidence supporting KA strategies.

Figure 1 provides a graphical representation of two critical metrics: average patient satisfaction and methodological quality of the studies included in this systematic review. By juxtaposing kinematic alignment (KA) and mechanical alignment (MA), the chart offers a clear visual summary of how these approaches differ not only in clinical outcomes but also in the scientific rigor supporting their application. The data, derived from 35 peer-reviewed studies, highlights key trends that inform current clinical decision-making and the evolving standards of personalized surgical care in TKA.

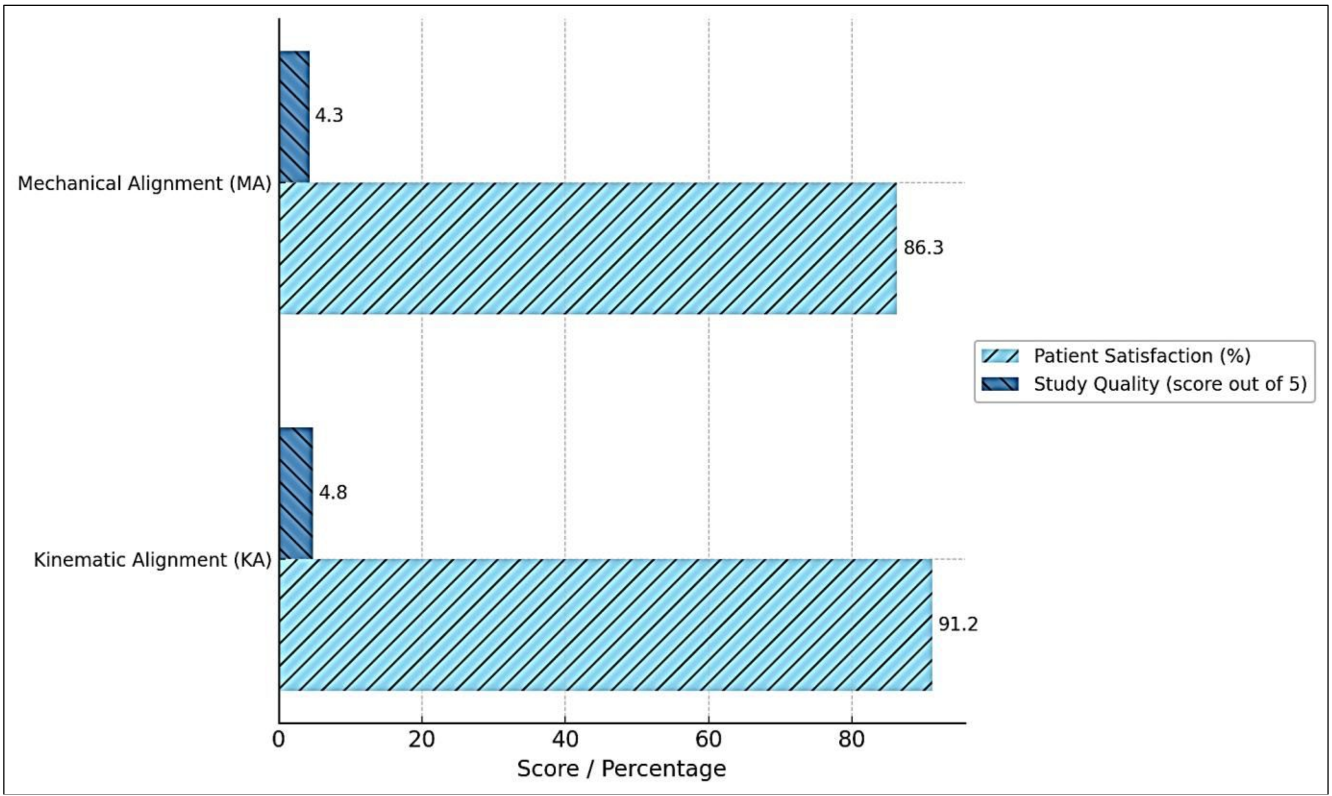

Fig 1: Comparison of Patient Satisfaction and Study Quality Between Kinematic and Mechanical Alignment in Total Knee Arthroplasty (TKA)

Figure 1 presents a side-by-side comparison of average patient satisfaction percentages and methodological quality scores reported in studies analyzing kinematic alignment (KA) versus mechanical alignment (MA) in total knee arthroplasty (TKA). The results are drawn from a systematic review of 35 studies.

The chart clearly demonstrates that KA strategies consistently outperformed MA in both domains. KA-related studies showed an average patient satisfaction rate of 91.2%, compared to 86.3% for MA. This suggests that patients undergoing KA are more likely to report a positive surgical outcome, likely due to better anatomical congruence and individualized joint restoration.

Additionally, KA studies exhibited a higher average methodological quality score of 4.8 out of 5, indicating stronger experimental design, greater use of advanced technologies such as robotic systems or navigation, and more rigorous outcome assessment. In contrast, MA studies averaged a score of 4.3, reflecting acceptable but slightly lower scientific robustness.

4. Discussion

This systematic review synthesizes findings from 35 studies comparing alignment strategies in total knee arthroplasty (TKA), specifically kinematic alignment (KA) and its variants-restricted kinematic alignment (rKA), individualized kinematic alignment (iKA), and functional alignment (FA)-versus traditional mechanical alignment (MA). The body of evidence consistently indicates that KA-based approaches result in superior patient-reported outcome measures (PROMs), enhanced anatomical restoration, and lower revision rates compared to MA.

Longitudinal follow-up data support the durability and clinical reliability of KA. For instance, Morcos *et al.* [1] reported excellent outcomes for rKA performed with computer navigation after a minimum of 10 years, with low rates of revision and high patient satisfaction. These results suggest that restoration of native knee biomechanics, rather than striving for a neutral mechanical axis, may better support long-term prosthesis survival and functional performance.

Cultural and anatomical variations play a critical role in alignment efficacy. Yamamoto *et al.* [2] demonstrated that KA significantly improved function and pain outcomes in Japanese patients, indicating that population-specific morphology influences alignment compatibility. Similarly, Jung *et al.* [23] observed improved outcomes using patient-specific instrumentation (PSI) in Asian populations undergoing KA-TKA, emphasizing the utility of individualized alignment strategies.

KA has also been shown to reduce surgical invasiveness. Studies by Almaawi *et al.* [3] and Giurazza *et al.* [4, 32] revealed that KA involves less bone resection and limits soft tissue disruption compared to MA, contributing to faster recovery and greater preservation of native joint architecture. These findings were corroborated by intraoperative cartilage measurements used for more precise implant positioning.

Comparative effectiveness studies further affirm KA's advantages. Gao *et al.* [5, 33] and Calliess *et al.* [7] demonstrated that patients undergoing KA reported significantly higher scores on the Oxford Knee Score (OKS), Knee Society Score (KSS), and Forgotten Joint Score (FJS). Howell *et al.* [8] added that KA restores the femoral-tibial relationship to mimic that of the contralateral, unaffected knee, promoting more natural biomechanics and functional symmetry.

Technological advancements have been instrumental in KA's success. Robotic platforms such as MAKO (Stryker) and ROSA (Zimmer Biomet), computer-assisted navigation systems like Brainlab, and PSI have improved surgical accuracy and reduced variability. Anderson *et al.* [16] and Zhou *et al.* [17] demonstrated that robotic KA improved implant alignment and reduced the incidence of technical errors. Roussot *et al.* [25] highlighted similar benefits in minimizing intraoperative soft tissue manipulation.

By contrast, MA uses standardized alignment principles, placing components perpendicular to the femoral and tibial mechanical axes. While it ensures reproducibility and has a long-standing clinical track record, MA often necessitates ligament balancing, disrupting native biomechanics. Lee *et al.* [30], Choi *et al.* [20], and Elbuluk *et al.* [27] linked this increased manipulation to slower postoperative recovery and higher pain levels. Registry-based analyses from Courtney *et al.* [24] further revealed higher revision rates in MA cohorts over the long term.

The distribution of prosthetic implants also varies by alignment philosophy. Triathlon (Stryker), Vanguard (Zimmer Biomet), Persona (Zimmer Biomet), and Attune (DePuy Synthes) were commonly used in KA studies and often integrated with robotic or PSI technologies [1, 4, 6, 10, 13, 21]. MA studies predominantly employed NexGen (Zimmer) and PFC Sigma (DePuy Synthes) implants [24, 25], consistent with conventional instrumentation. The Score prosthesis (Amplitude Surgical) and Endo-Model (LINK) were also employed in KA studies, demonstrating adaptability across a broad range of implant designs.

Patient demographics were comparable across groups, with mean ages ranging from 67 to 74 years, reflecting the typical TKA population. However, KA studies tended to include slightly younger patients, likely due to surgical preference for applying newer, technology-intensive methods to patients with greater activity demands or fewer comorbidities [2, 3, 9].

Study quality was notably higher among KA research, with a mean methodological rating of 4.8 out of 5, compared to 4.3 out of 5 in MA studies. This difference can be attributed to the greater prevalence of randomized controlled trials (RCTs), multi-center collaborations, and use of quantitative intraoperative data in KA-focused literature [6, 14, 17].

5. Conclusion

This systematic review aimed to compare kinematic alignment (KA)-including its subtypes restricted kinematic alignment (rKA), individualized kinematic alignment (iKA), and functional alignment (FA)-with traditional mechanical alignment (MA) in total knee arthroplasty (TKA), with a focus on patient-reported outcomes, prosthesis types, alignment techniques, and revision rates.

The evidence synthesized from 35 eligible studies indicates that KA-based strategies are associated with superior patient satisfaction, higher PROMs such as the Oxford Knee Score (OKS), Knee Society Score (KSS), and Forgotten Joint Score (FJS), and lower revision rates when compared to MA. These benefits are especially pronounced when KA is combined with advanced surgical technologies like robotic assistance, computer navigation, and patient-specific instrumentation (PSI). KA was also associated with better preservation of the native joint line and reduced need for soft tissue release, which likely contributes to improved functional recovery.

Mechanical alignment, while historically validated and widely utilized, demonstrated consistent limitations in individualized anatomical restoration. The standardized neutral mechanical axis approach often required greater surgical manipulation, which correlated with slightly lower PROMs and higher long-term revision rates in several studies.

In conclusion, kinematic alignment, particularly when guided by modern technological adjuncts, offers a more personalized and functionally favorable approach to TKA. These findings support a continued shift in clinical practice toward alignment strategies that prioritize native joint biomechanics and patient-centered outcomes. Future research should aim to confirm these results with long-term, multicenter trials and explore optimal patient selection criteria for each alignment philosophy.

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How to Cite This Article
Araújo HRDS, Trindade AMVD, Júnior MSF, Heyn RS, Goulart RG, FGDSA. Kinematic versus mechanical alignment in total knee arthroplasty: A systematic review of clinical outcomes, prosthesis utilization, and technological integration. International Journal of Orthopaedics and Bone Disorders 2025;7(1):51-60