Review

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Alignment Techniques in Total Knee Arthroplasty: Where do We Stand Today?

Hemanta Dhungana*, Subhash Jangid, Meghal Goyal

Department of Orthopedics, Fortis Hospital, Gurgaon, Haryana, India

ABSTRACT

Achieving optimal alignment in total knee arthroplasty (TKA) is a critical factor in ensuring optimal outcomes and long-term implant survival. Traditionally, mechanical alignment has been favored to achieve neutral post-operative joint alignment. However, contemporary approaches, such as kinematic alignments and hybrid techniques including adjusted mechanical, restricted kinematic, inverse kinematic, and functional alignments, are gaining attention for their ability to restore native joint kinematics and anatomical alignment, potentially leading to enhanced functional outcomes and greater patient satisfaction. The ongoing debate on optimal alignment strategies considers the following factors: long-term implant durability, functional improvement, and resolution of individual anatomical variations. Furthermore, advancements of computer-navigated and robotic-assisted surgery have augmented the precision in implant positioning and objective measurements of soft tissue balance. Despite ongoing debates on balancing implant longevity and functional outcomes, there is an increasing advocacy for personalized alignment strategies that are tailored to individual anatomical variations. This review evaluates the spectrum of various alignment techniques in TKA, including mechanical alignment, patient-specific kinematic approaches, and emerging hybrid methods. Each technique is scrutinized based on its fundamental principles, procedural techniques, inherent advantages, and potential limitations, while identifying significant clinical gaps that underscore the need for further investigation.

Key words: total knee arthroplasty; hybrid alignment; functional alignment; kinematic alignment; alignment axes; anatomical alignment; mechanical alignment

INTRODUCTION

Knee osteoarthritis is recognized as a prevalent degenerative joint disease that imposes a significant socio-economic burden on both society and healthcare systems. In recent decades, growing global rates of obesity and population aging cause the incidence of knee osteoarthritis to rise notably[1,2].

Total knee arthroplasty (TKA) stands as a highly effective treatment option for individuals suffering from severe osteoarthritis. It offers favorable outcomes, including the ability to resume daily activities and notable functional improvement. However, despite significant advancements of surgical techniques and postoperative care, up to 20% of TKA patients still report dissatisfaction with their outcomes[3]. The success of TKA is determined by several factors that contribute to a pain-free knee, better function, patient satisfaction, and long-term implant longevity[4].

Proper alignment of the knee joint is one of the utmost crucial factors in determining the long-term survival of the implant following TKA[5]. It is believed that optimal alignment helps reduce both mechanical and shear stresses exerted on bearing surfaces within the knee joint as well as bone-prosthesis interface[6,7]. Poor alignment in TKA has been associated with reduced implant survivor and suboptimal functional outcomes[6,8,9].

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*Corresponding author E-mail: hemantadhungana@gmail.com

Achieving stable postoperative knee neutral alignment has been a standard principle of TKA[10,11], but emerging evidence suggests that a significant proportion of adult men (32%) and women (17%) have constitutional varus in the knees after TKA, which highlights the need for a more individualized approach to alignment correction[12]. Various personalized alignment concepts, such as kinematic alignment (KA), inverse kinematic alignment (iKA), restricted kinematic alignment (rKA), and functional alignment, have been developed to tailor alignment strategies for TKA based on each patient's unique anatomy and kinematics (**Fig. 1**).

In this narrative review, by delving into the fundamental principles underlying different alignment techniques employed in TKA, we aim to gain a comprehensive understanding of their application in TKA.

ALIGNMENT AXES

Vertical axis

Vertical axis refers to a vertical line extending from the center of the pubic symphysis (located in the pelvis) to the ground in a normal anteroposterior radiograph taken during weight-bearing. This line serves as a reference for assessing the alignment and positioning of the lower limb relative to the rest of the body[13].

Mechanical axis

Mechanical axis of the lower limb is an imaginary line from the center of the femoral head (located at the hip joint) to the center of the ankle joint. This line typically exhibits a slight inclination of approximate 3 degrees relative to vertical axis[14]. The mechanical axis of the lower extremity can be further subdivided into femoral mechanical axis and tibial mechanical axis. Femoral mechanical axis extends from the head of the femur to the intercondylar notch of the distal femur. Tibial mechanical axis extends from the center of the proximal tibia to the center of the ankle joint. Hip-knee-ankle angle, also known as mechanical alignment angle, is formed by medial angle between femoral mechanical axis and tibial mechanical axis. The hip-knee-ankle angle of a normal knee is typically slightly less than 180 degrees[15,16].

Anatomic axis

The anatomic axis of the femur or the tibia is an imaginary line centered on the diaphysis or the shaft of each bone. Two methods are commonly employed to determine the anatomic axis of the femur; one is to draw a line from the proximal to the distal end of the femur within the intramedullary canal, and the other is to draw a line passing through two points, one point located at the center of the femoral shaft and the other 10 cm above the knee joint, *i.e.*, at an equidistant distance between the medial and lateral cortex of the femur[14].

In anteroposterior evaluation, the mechanical and anatomic axes of the tibia are generally parallel to each other. However, in the case of the femur, there is typically a 5–7 degrees inclination difference between anatomic axis and mechanical axis[17].

Anatomic tibiofemoral angle is determined by measuring the angle between the anatomic axes of the femur and the tibia. This angle provides valuable

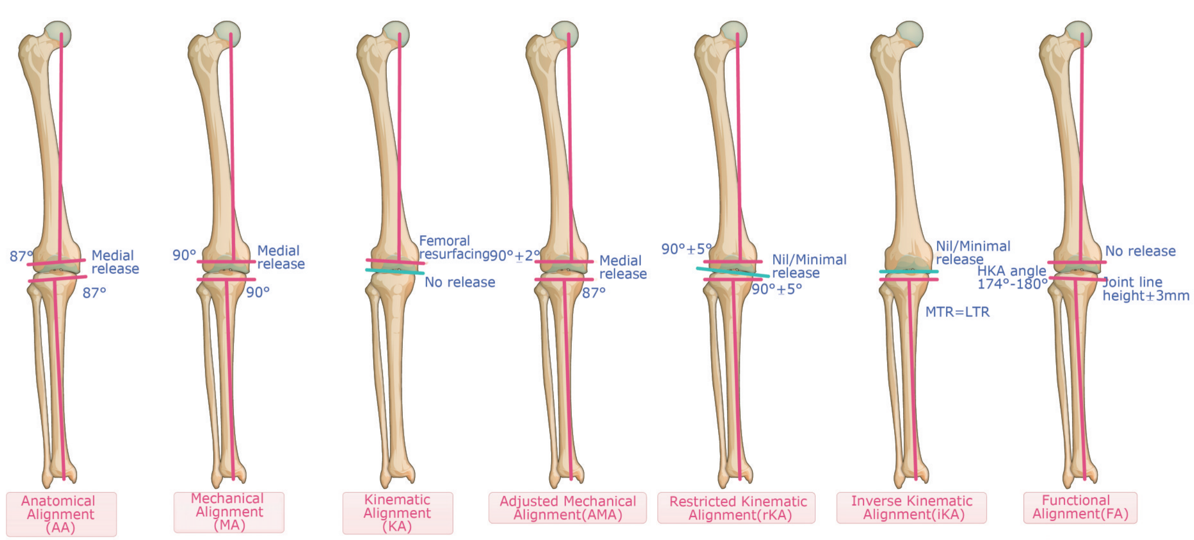

Figure 1. A summary illustration of various alignment techniques employed in total knee arthroplasty.

information about the alignment and potential deformity of the knee joint. On average, anatomic tibiofemoral angle is approximately 173–175 degrees. This physiological value serves as a reference for assessing any deviation from normal alignment[14].

Kinematic axis

Mechanical and anatomical axes can be well visualized and described using plain X-rays. These axes provide important information about the structural alignment of the knee joint. However, when it comes to understanding the dynamic motion of the knee, a different concept—kinematic axis—comes into play[18,19].

Knee kinematics focuses on the relative motion and position of the femur, patella, and tibia at different flexion angles rather than on the forces in the knee. Kinematic alignment is based on three functional kinematic axes that describe the motion of the knee joint[19,20]. The first kinematic axis of the knee is the transverse femoral axis in the femur, around which the tibia flexes and extends. It passes through the center of a circle that coincides with the articular surface of the femoral condyles. The second kinematic axis is the transverse axis of tibia, around which the patella flexes and extends relative to the femur. It is located proximally anterior to and parallel to the first transverse axis. The third axis is longitudinal axis of the tibia, around which the tibia rotates internally and externally on the femur. This axis is perpendicular to the first two axes. Together, these three kinematic axes capture the complex and dynamic movements of the knee, including flexion, extension, patellar motion, and tibial rotation[13,21,22].

ALIGNMENT TECHNIQUES IN TKA

Anatomical alignment

In 1985, Hungerford and Krackow introduced the concept of anatomical alignment in total knee replacement surgery[23]. They introduced the idea of aligning the components of the knee prosthesis in a manner that closely mimics the natural anatomy of the knee joint. This technique focuses on achieving an oblique joint line that is typically positioned at a 2°–3° valgus angle relative to the mechanical axis of the limb[23]. This systematic approach involves restoring the entire limb alignment to a neutral position and eliminating the need for external rotation of the femoral component.

Anatomical alignment strategy is believed to offer several advantages, including the optimization of load distribution within the tibial component and the enhancement of patellofemoral biomechanics. By anatomically aligning the components to replicate the joint line, forces exerted on the knee joint during weight-bearing can be distributed more evenly across the tibial surface, thereby reducing the risk of excessive stress on specific areas of the implant. Additionally, the technique is designed to align the patella in a manner that reduces the risk of stretching lateral retinacular ligament during knee flexion[10].

Although short-term outcomes appeared favorable, it is worth noting that catastrophic wear of polyethylene component has been reported to occur in 5% of cases, leading to the need for additional interventions and early revision surgey[24]. However, a study by Yeo *et al*. confirmed that the wear characteristics and durability of modern-day polyethylene and implants have improved. The use of robotics in TKA allows for precise alignment of implant components. This contributes to better functional outcomes and improved joint stability[24].

In the past, technical challenge of achieving precise osteotomies posed the risk of excessive varus alignment of the limb or improper positioning of tibial implant[25,26]. However, recent advances in surgical techniques such as navigation systems and robotics have addressed these challenges[27,28].

Mechanical alignment

Mechanical alignment technique in TKA, originally described by Insall *et al*., involves making a femoral osteotomy and a tibial resection perpendicular to the mechanical axes of the femur and tibia, respectively[29]. Insall *et al*. believed that anatomical alignment could result in failure of medial tibial plateau fixation due to uneven loading forces. Additionally, they advocated external rotation of femoral component by 3° in TKA to achieve a balance between flexion and extension gaps[29]. Femoral component is commonly positioned to align with trans-epicondylar axis, which serves as the reference axis for flexion-extension movements in the knee[30]. The optimal distal femoral incision is commonly performed at a 2°–7° valgus angle to femoral shaft axis. This valgus alignment helps to obtain a neutral mechanical alignment of the knee joint[31].

Restoring a neutral mechanical axis is commonly believed to be beneficial in terms of implant durability and patient function after TKA[32]. The achievement of load symmetry by restoring a neutral mechanical axis has been instrumental in preventing asymmetrical wear and tear of polyethylene platform, which has been a significant and common complication in the past[33].

Maintaining alignment within ± 3° of neutral mechanical axis is believed to minimize the risk of complications such as excessive wear, implant loosening, and instability. This long-held belief has served as a guideline for surgeons when determining optimal alignment during the surgical procedure[34]. Studies have shown that both computer-assisted TKA and robot-assisted TKA achieve higher mechanical axis alignment and more precise component placement than conventional surgical techniques[35,36].

Nevertheless, despite these improvements, it must be acknowledged that functional outcomes are not satisfactory, with around 50% of patients experiencing residual symptoms including pain, instability, stiffness, and swelling following mechanical alignment TKAs. Additionally, 10% to 20% of patients expressed dissatisfaction with the procedure's outcomes[37]. Moreover, the relationship between alignment within ± 3° of neutral mechanical axis and functional outcomes in TKA has been a subject of investigation. Although achieving alignment within the ± 3° range may be considered ideal, it is not the sole determinant of functional success[36,38].

Accurate assessment of mechanical alignment in TKA requires comprehensive imaging of the entire limb, including the hip, knee, and ankle. CT or radiographic imaging of the whole limb allows for a more thorough evaluation of limb alignment and component positioning. However, it is noteworthy that many studies on TKA outcomes have primarily relied on short X-rays. The extensive reliance on short X-rays in studies of TKA outcome suggests a potential gap in the analysis of mechanical alignment. Limited imaging may not capture a complete picture of component position and limb axis, leading to incomplete assessment and potential inaccuracies in alignment[39,40].

The focus of mechanical alignment is to achieve a neutral hip-knee-ankle axis where the mechanical axes of the femur and tibia should ideally form an angle of 180°, indicating a perfectly alignment of the knee joint. However, it has been observed that only a very small percentage of individuals are born with this neutral alignment. MacDessi *et al*. discovered that only a small percentage of normal knees (15.4%) and arthritis-affected knees (14.6%) achieved mechanically neutral alignment and joint line. This means that for the majority of individuals (approximately by 85%), mechanically neutral joint replacement does not fully restore native joint alignment[41]. This highlights the need for further investigation into alternative alignment methods and strategies to improve outcomes for these patients.

Kinematic alignment

Howell *et al*. have advocated kinematically aligned total knee replacements with the aim of restoring the alignment of knee joint to its pre-arthritic state, without the need to release collateral ligaments. By replicating the pre-arthritic axis, KA aims to restore the natural kinematics of knee joint and potentially improve postoperative functional outcomes. Additionally, KA helps to achieve physiological patellar tracking, as it take into account the restoration of the native Q angle (the angle between the quadriceps tendon and the patellar tendon)[21,42,43].

Unlike previous mechanical and anatomic alignment techniques, KA is a three-dimensional approach to aligning the components in TKA[13]. This means that the implant components are positioned in a way that replicates the patient's pre-arthritic joint geometry[21]. During KA procedure, the objective is to remove an appropriate amount of bone and cartilage in the distal, posterior, and tibial regions. This resection takes into account the degree of wear and damage to the cartilage that will be replaced by the TKA components[21,42,44]. These systems can assist in achieving precise bone resections and component placement[45,46].

KA in total knee replacement has been recognized as having several potential benefits, with one of the advantages being the potential for better functional outcomes. By restoring natural alignment and joint kinematics, KA may help improve range of motion, joint stability, and overall knee function. In addition, KA has the potential to reduce postoperative pain compared to other alignment techniques[47]. This approach is particularly favorable for valgus-aligned knees. Its approach minimizes the need for extensive soft tissue manipulation and simplifies an otherwise complex surgical procedure[48].

In the study conducted by Dossett *et al.*[13] in 2012, the six-month follow-up showed significant improvements in various outcome measures in the KA group compared to the mechanical alignment group. The KA group had a 16-point improvement in the WOMAC (pain, stiffness, and physical function) score, a 7-point improvement in the Oxford Knee score, and a 25-point improvement in the combined Knee Society score. Additionally, the KA group demonstrated a 5° greater flexion compared to the mechanical alignment group. Similarly, KA has better functional outcomes compared to mechanical alignment. However, a meta-analysis by Courtney and Lee found similar complication rates between KA and mechanical alignment TKA over a two-year follow-up[49]. The majority of revision cases in that study were attributed to patellofemoral problems accounting for 1.2% of the total cases. According to the first published ten-year follow-up, KA demonstrated a remarkable success rate with a survival rate of 97.5%. This indicates the long-term durability and effectiveness of KA technique in TKA[50].

In a study by Shelton *et al.*[51], satisfaction rate was evaluated in patients who underwent a kinematically aligned TKA on one knee after previously receiving a mechanically aligned TKA on the other knee[51]. They found that 83% of the patients expressed satisifaction with mechanically aligned TKA during the transition to kinematically aligned approach. Furthermore, during follow-up evaluation, kinematically aligned TKA achieved a notable increased satisfaction rate, with 92% of patients expressing satisfaction[52]. Similarly, Bellemans *et al.*[53] investigated KA in TKA customized to native knee phenotypes and showed that KA applied in TKA improves early clinical outcomes, including pain relief and functional recovery, surpassing traditional methods, emphasizing its role in personalized TKA.

While KA has shown promise in TKA, the optimal range for component positioning remains uncertain. It is important to determine a safe and effective range for KA of total knee components. Additionally, it should be noted that the biomechanics of the osteoarthritic knee may differ from its pre-arthritic state, which further adds to the complexity of alignment considerations in KA[10].

Mechanical alignment has been extensively studied with long-term follow-up of authors from diverse backgrounds, but KA has not been investigated at the same level. The short follow-up period for KA limits our understanding of its long-term outcomes and the potential implications of larger follow-up on outcomes[52].

Adjusted mechanical alignment

It is recognized that the knee joint line in most individuals is not parallel to the ground, but instead has a natural tendency towards varus, typically around 3 degrees. To address this concern adjusted mechanical alignment (aMA) approach emerged in the field of TKA[53]. The aMA technique is a considerable modification of conventional mechanical alignment technique. In order to achieve optimal correction, aMA usually corrects frontal deformity on the femoral side to less than 3 degrees of maximum correction by adjusting implant positioning, which consequently correcting tibial deformity to neutral mechanical alignment[54-57].

Several studies have reported that aMA technique successfully addressed anatomical constitutionaly varus or valgus knees deformity with favorable outcomes in terms of survivor and patient satisfaction. However, these studies were non-comparative and lacked direct comparisons to other alignment techniques[55,56]. A recent study conducted by Graichen *et al.*[57] showed that the aMA technique successfully achieve desired hip-knee-ankle alignment and gap balance in more than 90% of cases. However, non-anatomical tibial resection in aMA may lead to patients dissatisfaction after TKA. Long-term studies involving a large number of cases are necessary to thoroughly assess the short-term outcomes of this technique[58].

Restricted kinematic alignment

rKA has emerged as a viable option for patients with extreme anatomy and can serve as an alternative to KA, rKA protocol is primarily focused on replicating patient's natural knee anatomy within a safe range[46]. The primary concern with rKA protocol is the boundaries of hip-knee-ankle (HKA) angle. Previous studies have shown that implant survivorship does not have a substantial negative effect as long as the HKA angle remain within a 3-degree range[59]. Therefore, firstly rKA protocol need to achieve replication of individual lower limb anatomy while ensuring that overall alignment remains within ± 3° of neutral alignment[60]; secondly, in order to accommodate the majority of patients and replicate their individual anatomy, rKA protocol should emphasize maintaining independent incisions in the proximal tibia and distal femur within 5 degrees of mechanical axis[46].

Moreover, rKA technique applied in TKA has achieved a more anatomically accurate and biomechanically favorable reconstruction of knee joint. This is accompanied by preserving the natural shape and anatomy of the femur while making any necessary adjustments to the tibia[60]. Additionally, it has shown significant improvement in achieving a more balanced load distribution across knee joint. In the study by MacDessi *et al*.[61], 80% of the participants in the KA group achieved optimal knee balance, compared to only 35% in the mechanical alignment group. However, it is worth noting that the long-term clinical outcomes of rKA in TKA have not been extensively studied.

Inverse kinematic alignment

iKA technique involves achieving an equal amount of resection of medial and lateral bone during tibial resurfacing to ensure the natural obliquity of tibial joint line to be preserved. By adjusting the resection of the posterior and distal femurs, iKA achieves a balanced flexion-extension gap. Therefore, this technique is effective in preventing tibial over-resection and subsequent complications[46,62].

Winnock de Grave *et al*.[62,63] introduced and detailed the concept and technique of iKA utilizing a robotic-assisted system. This technique effectively restores pre-arthritic medial proximal tibial angle, maintaining it within a safe range of 84°–92°. Additionally, tibial slope is aligned to be parallel and equal to native medial tibial slope. After tibial resection, the procedure follows a traditional gap balancing method. Femoral incision is adjusted to equalize extension and flexion gaps without the need for soft tissue releases. KA and iKA differ in the way they balance the knee, with KA balancing the knee by adjusting tibial incision, while iKA balancing the knee by modifying femoral incision. Moreover, iKA has the advantage of external rotation of femoral component, which has the potential to improve functional outcomes, especially in the case of knee valgus, distinguishing it from traditional KA techniques.

Winnock de Grave *et al*.[63] specifically reported the efficacy of iKA and showed that there was no significant difference in clinical outcomes between iKA and aMA at 12 months of TKA; however, restricted iKA showed greater patient satisfaction and significant improvment in postoperative Oxford Knee score.

Further research and long-term follow-up studies are needed to validate these findings and explore the potential benefits of restricted iKA in a larger patient population.

Functional alignment

Functional alignment is a ralatively new approach in TKA that is built upon the principles of KA. It incorporates advanced technology and precision-guided techniques to achieve a more accurate and personalized alignment of the knee joint[64,65].

Functional alignment in TKA is a dynamic intraoperative process, in which surgeon uses robotic-assisted systems to manipulate various factors to restore a balanced extension-flexion gap and equalize medio-lateral soft tissue tension[64]. Robotic-assisted systems in TKA provide real-time feedback and guidance to the surgeon throughout the procedure, thus enabling surgeon to make an accurate intraoperative assessment and necessary adjustments to achieve optimal implant sizing, positioning, gap balance, and joint line height[66,67].

Early knee arthroplasty alignment strategies lacked clear targets for joint line obliquity and height and often relied on subjective assessment of soft tissue. In contrast, functional alignment addresses this issue by incorporating unique variations in joint line obliquity into alignment considerations and emphasizing the importance of maintaining the natural height of joint line[29,43,68]. Funtional alignment takes into account the fact that each individual has unique constitutional bony anatomy and soft-tissue characteristics and develops individualized alignments based on these factors rather than using a "one-size-fits-all" approach[68].

Functional alignment is a novel approach that focuses on restoring the natural three-dimensional alignment of the knee joint while preserving the integrity of the soft tissue envelope. Maintaining the integrity of the soft tissue envelope is to preserve the natural tension and balance of the ligaments and surrounding structures[64,68]. One of the main advantages of robotic platform is the ability to pre-assess and correct errors in final implant position before any bone cut are made. This help minimize the occurrence of errors and misalignments during the surgery[67,69].

In the study conducted by Sires and Wilson[69], the accuracy of intraoperative component alignment using a robotic-assisted TKA system was assessed using postoperative CT scans. The results showed that 93% of surgical measurements were within 3 degrees of CT measurements, indicating the high precision in the alignment achieved with the robotic-assisted system.

However, the issue of safe limits for implant positioning in TKA remains a concern. A study by Jeon *et al*.[70] found that robot-assisted TKA did not show significant improvement in long-term clinical and radiologic outcomes compared to traditional methods. These results highlight the limitations of current robotic technology in achieving superior patient outcomes in knee replacement surgeries. The lack of clear definitions and limited evidence for rigid limits pose challenges in determining optimal thresholds. Further research is necessary to establish precise guidelines for implant positioning in TKA and to determine the optimal range that ensures favorable outcomes[68].

CONCLUSIONS

Conventional alignment techniques in TKA have shown improved durability of implants but come with functional limitations. Personalized alignment strategies such as KA, which address these limitations by considering individual patient anatomy, are gaining popularity. KA has been demonstrated promising early clinical outcomes, but its effectiveness in patients with anatomical variations is still under evaluation. Hybrid alignment techniques like aMA, rKA, and iKA have also gained attention, but long-term clinical outcomes require further research. Early knee arthroplasty alignment lacked specific targets for joint line obliquity and height, relying on subjective assessment. The concept of functional alignment has emerged to address this limitation by acknowledging individual variations and tailoring alignment based on patient factors, optimizing outcomes and preserving natural joint line height.

In the evolving field of TKA, the quest for determining optimal co-alignment remains a topic of ongoing debate and divergence. Further research is essential to determine the optimal alignment ranges for TKA using modern implants. The goal is to strike a balance between restoring patient-specific kinematics to improve functional outcomes and adhering to the safe boundaries of neutral mechanical alignment to optimize implant durability. Surgeons must consider individual patient factors such as bone quality, ligament balance, and preexisting deformities, when determining the appropriate alignment targets for each patient.

This narrative review summarizes the current understanding, techniques, and outcomes of alignment methods in TKA. It explores the principles and techniques associated with each alignment method, shedding light on their advantages and limitations.

Take-home messages

- Mechanical alignment and anatomical alignment techniques have shown better long-term implant durability but come with functional limitations.
- New approaches in total knee arthroplasty (TKA) are shifting towards personalized alignment strategies that consider the unique anatomy of each patient.
- Kinematic alignment (KA) technique in TKA has demonstrated promising early clinical outcomes. However, its effectiveness in patients with significant anatomical variations is yet to be proven.
- Hybrid alignment techniques, such as adjusted mechanical alignment, restrict KA, and inverse KA emerge as attractive options for addressing unique anatomical variations. However, further research is necessary to evaluate the mid- and long-term clinical outcomes.
- Unlike previous approaches, functional alignment in TKA modifies alignment based on individual bony anatomy and soft-tissue laxity assessment, aiming for definable and reproducible targets.

ARTICLE INFORMATION

Conflict of interests

The authors declare no conflict of interest.

Authors' contributions

Hemanta Dhungana drafted, revised, and proofed the manuscript; Subhash Jangid and Meghal Goyal revised the manuscript. All authors read and approved the published version of the manuscript.

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