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Functional Alignment in Robotic Total Knee Arthroplasty: From Precision Bone Resection to Phenotype-Specific Reconstruction: A Narrative Review of Current Concepts, Clinical Evidence, and Unresolved Controversies

Dr. Nishant

Assistant Professor of Orthopedics at Netaji Subhash Chandra Bose Medical College and Hospital, Bihta, Bihar, India

Abstract: ***Background**: Mechanical alignment has traditionally served as the reference strategy for total knee arthroplasty (TKA). While this approach ensures reproducible implant positioning and durable survivorship, it imposes a uniform neutral-axis target on knees that exhibit significant anatomical and soft-tissue variability. Functional alignment has emerged as a personalized strategy that employs robotic planning and intraoperative gap assessment to adjust component position within predefined boundaries, restore patient-specific joint-line orientation, minimize ligament releases, and achieve balanced flexion and extension gaps. **Purpose**: This narrative review evaluates the principles, surgical workflow, clinical evidence, safety considerations, phenotype-specific applications, and future directions of functional alignment in robotic TKA. **Methods**: A targeted narrative search of PubMed/MEDLINE and major orthopaedic journals was conducted for publications available through June 30, 2026. Search terms included "functional alignment," "functional positioning," "personalized alignment," "robotic total knee arthroplasty," "mechanical alignment," "CPAK," "gap balancing," and "kinematic alignment." Priority was given to randomized trials, comparative studies, large clinical cohorts, alignment-boundary investigations, and recent systematic reviews. **Results**: Functional alignment consistently reduces the frequency and extent of collateral ligament releases and enhances the ability to achieve predefined gap targets. Several small randomized studies have reported improved early pain scores, Forgotten Joint Scores, satisfaction, or Knee Injury and Osteoarthritis Outcome Scores compared to mechanical alignment. However, two larger randomized trials did not demonstrate clinically significant superiority in primary patient-reported outcome measures at two years. The 2026 RASKAL factorial randomized trial involving 303 TKAs found no difference in Knee Injury and Osteoarthritis Outcome Score-12 between functional and mechanical alignment, although mechanical alignment required substantially more soft-tissue releases. A recent systematic review of 5,155 functionally aligned robotic TKAs reported favorable short- to mid-term scores and an early aseptic revision proportion of approximately 0.35%. However, most included evidence was observational and follow-up duration was limited. **Conclusion**: Functional alignment is a technically reproducible approach for achieving a balanced TKA with reduced soft-tissue disruption. Current evidence supports its safety over short- to mid-term follow-up but does not establish universal clinical superiority over mechanical alignment. At present, functional alignment should be considered a controlled, phenotype-aware method of personalization rather than a single standardized alignment target. Long-term randomized and registry-based studies employing standardized definitions are necessary.*

Keywords: functional alignment; robotic total knee arthroplasty; personalized alignment; mechanical alignment; CPAK; ligament balancing; knee arthroplasty

1. Introduction

Total knee arthroplasty remains one of the most successful procedures for relieving pain and restoring function in end-stage knee osteoarthritis. Nevertheless, a proportion of patients continue to report residual pain, stiffness, instability, or an unnatural perception of the replaced knee despite technically uncomplicated surgery. This discrepancy has prompted renewed scrutiny of the traditional assumption that every arthritic knee should be reconstructed to a neutral mechanical axis.

Mechanical alignment positions the femoral and tibial components perpendicular to their respective mechanical axes. The technique prioritises reproducibility, load distribution, and implant durability but may alter the patient's constitutional limb alignment, joint-line obliquity, femoral rotation, tibial slope, and native ligament laxity pattern. Personalised alignment strategies, in contrast, aim to account for the considerable anatomical variation observed among normal and arthritic knees.

The terminology surrounding personalised TKA has become increasingly complex. Kinematic alignment seeks to resurface the knee and reproduce its estimated pre-arthritic articular geometry. Restricted kinematic alignment restores this anatomy within predefined safety limits. Inverse kinematic alignment generally begins with the tibial resection and subsequently adjusts femoral positioning to obtain balance. Functional alignment uses computer-assisted or robotic technology to integrate constitutional anatomy with quantitative soft-tissue behaviour, modifying component position before bone resection to achieve specified gap and alignment targets. Importantly, functional alignment is an umbrella term rather than one universally standardised operative protocol. [1–5]

2. From Mechanical Neutrality to Personalized Reconstruction

2.1 Limitations of a universal neutral target

Neutral mechanical alignment is not the native phenotype for every patient. Constitutional varus, valgus femoral morphology, variable medial proximal tibial angles, and differences in joint-line obliquity occur in asymptomatic populations. Consequently, mechanically aligning every TKA may require asymmetric bone resections or collateral ligament releases to convert a constitutionally oblique joint line into one that is perpendicular to the limb mechanical axis.

The central argument for functional alignment is not that neutral mechanical alignment invariably fails. Rather, a uniform reconstruction may be unnecessarily disruptive in certain phenotypes. A knee that appears radiographically neutral after mechanically aligned TKA may have undergone substantial alteration of its native distal femoral and proximal tibial geometry.

2.2 The CPAK classification

The Coronal Plane Alignment of the Knee classification describes nine phenotypes based on:
1) **Arithmetic hip-knee-ankle angle**, representing constitutional varus, neutral, or valgus alignment.
2) **Joint-line obliquity**, classified as apex distal, neutral, or apex proximal.

CPAK provides a practical language for examining whether the effect of an alignment strategy varies across preoperative phenotypes. It is particularly relevant because early evidence suggests that certain phenotypes, especially CPAK type I knees with constitutional varus and apex-distal joint-line orientation, may derive greater benefit from joint-line preservation than other groups. Nevertheless, CPAK remains a coronal-plane classification and does not fully describe sagittal alignment, femoral version, tibial rotation, ligament competence, or dynamic laxity. [2,7]

3. What is Functional Alignment?

Functional alignment can be defined as the patient-specific positioning of TKA components using quantitative intraoperative information to achieve a planned limb alignment and soft-tissue balance while minimising unnecessary ligament releases.

Its major principles are:
- Restoration, where appropriate, of the patient's constitutional joint-line orientation.
- Assessment of medial and lateral compartment laxity before bone resection.
- Virtual modification of femoral and tibial component position in the coronal, sagittal, and axial planes.
- Preservation of the native soft-tissue envelope whenever a satisfactory balance can be achieved by safe component adjustments.
- Use of boundaries to avoid extreme component orientation or limb alignment.
- Verification of bone resections, gap balance, range of motion, stability, and component position.

Functional alignment differs from unrestricted kinematic alignment because component position can be deliberately adjusted away from the estimated native articular surfaces to accommodate the patient's soft-tissue behavior. It differs from conventional gap balancing because both the anatomical reconstruction and the final ligament envelope influence the plan. It also differs from adjusted mechanical alignment because neutral mechanical positioning is not necessarily the initial or preferred target.

The desired extension gap is generally symmetric and rectangular. In flexion, either a rectangular gap or a controlled trapezoidal gap with physiological lateral laxity may be accepted. However, the definition of "balanced" differs among surgeons, robotic platforms, implant designs, and studies. This heterogeneity is one of the principal obstacles to comparing reported outcomes. [4,5]

4. Role of Robotic Technology

Robotic systems permit precise registration of osseous anatomy, virtual component positioning, prediction or measurement of compartment gaps, controlled bone resection, and verification of the executed plan. Image-based systems use preoperative CT-derived three-dimensional models, whereas imageless systems construct the anatomical model from intraoperative registration.
The robot does not independently select the ideal alignment. It increases the precision with which the surgeon's selected plan can be executed. Therefore, robotic TKA and functional alignment should not be treated as interchangeable interventions. A robot can execute mechanical, kinematic, restricted kinematic, inverse kinematic, or functional alignment. Conversely, some principles of personalized balancing may be applied using navigation, pressure sensors, patient-specific instrumentation, or conventional techniques.

Meta-analytic evidence shows that robotic TKA reduces alignment outliers and increases accuracy relative to conventional instrumentation, but improved precision has not consistently translated into superior short- or medium-term patient-reported outcomes. This distinction is crucial: accuracy describes conformity to a plan, whereas clinical effectiveness depends on whether the selected plan was appropriate for that patient.

5. 5. Suggested Surgical Workflow

5.1 Preoperative evaluation

Preoperative planning should include:
- Standing hip-to-ankle radiographs.
- Assessment of the mechanical axis, medial proximal tibial angle, lateral distal femoral angle, and joint-line obliquity.
- Identification of the CPAK phenotype.
- Evaluation of fixed versus correctable deformity.
- Analysis of flexion contracture, recurvatum, tibial slope, posterior condylar offset, and patellofemoral anatomy.
- Clinical assessment of the medial collateral, lateral collateral, and posterior cruciate ligaments.

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- Identification of extra-articular deformity, retained hardware, bone loss, or previous osteotomy.

CT-based systems additionally allow three-dimensional assessment of femoral and tibial morphology, rotational landmarks, osteophytes, and implant fit.

5.2 Registration and initial plan

After registration, osteophytes that mechanically tension the collateral structures should be removed before definitive gap assessment. The initial component plan may begin from:
- A kinematic or resurfacing position.
- A tibia-first inverse kinematic plan.
- Restricted kinematic boundaries.
- Adjusted mechanical positioning.

The starting philosophy should be explicitly reported because different initial plans may ultimately be described under the same label of functional alignment.

5.3 Quantitative soft-tissue assessment

Compartment gaps are assessed in extension, mid-flexion, and flexion under a controlled force. Important variables include:
- Medial-lateral differential in extension.
- Medial-lateral differential at 90°.
- Change in gap dimensions through the arc of motion.
- Presence of excessive medial opening.
- Physiological lateral laxity in flexion.
- Fixed flexion deformity.
- Effect of posterior cruciate ligament preservation or resection.

Measurements are meaningful only when limb position, applied force, osteophyte removal, capsular tension, and anaesthetic muscle relaxation are reasonably standardized.

5.4 Component adjustment

Common virtual adjustments include:
- Coronal modification of the tibial component to reproduce or partially restore the native medial proximal tibial angle.
- Coronal adjustment of the distal femoral component.
- Femoral external rotation to alter the flexion gap.
- Modification of tibial slope.
- Femoral flexion or extension.
- Proximal-distal translation affecting extension-gap dimensions and joint-line level.
- Anterior-posterior femoral translation affecting posterior condylar offset and flexion balance.

These modifications should be iterative. Correcting one compartment may produce an undesirable change elsewhere, including femoral internal rotation, excessive femoral valgus, joint-line elevation, anterior notching, posterior overstuffing, or excessive tibial varus.

5.5 Safety boundaries

There is no universally accepted safety envelope for functional alignment. This absence of consensus is clinically important. A simulation involving 692 robotic TKAs found that progressively widening allowable tibial coronal boundaries increased the proportion of femoral components positioned in marked valgus or internal rotation. When tibial boundaries were expanded to 84°–92°, combined femoral valgus and internal rotation occurred more frequently, particularly in CPAK types I and II. Component freedom should therefore not be increased without considering the compensatory position required on the opposite side of the articulation.

The following should generally trigger reassessment of the plan:
- Excessive varus or valgus of either component.
- Femoral internal rotation.
- Excessive external rotation resulting in medial flexion instability.
- Excessive tibial slope or unintended slope reduction.
- Joint-line elevation.
- Anterior femoral notching.
- Excessive posterior condylar offset.
- Uncorrected severe coronal deformity.
- Residual medial instability.
- Excessive lateral tightness in flexion.
- Component overhang or poor bone coverage.

These represent pragmatic surgical safeguards rather than validated universal thresholds.

6. Gap Balance and Soft-Tissue Preservation

One of the most reproducible findings supporting functional alignment is reduced soft-tissue release. By adjusting component position before bone resection, the surgeon can accommodate the existing ligament envelope rather than forcing the soft tissues to conform to neutral mechanical cuts.

In a 2025 study of 100 robotic TKAs, modification of a restricted kinematic plan according to functional principles increased the proportion of balanced knees from 86% to 99% in extension and from 43% to 98% in flexion. Femoral external rotation was one of the principal adjustments required to improve flexion balance. However, the investigation did not demonstrate that the observed balance differences directly produced superior clinical outcomes compared with another alignment group.

Soft-tissue preservation offers several theoretical advantages:
- Reduced collateral ligament trauma.
- Lower risk of iatrogenic instability.
- Preservation of proprioceptive structures.
- Less alteration of native joint-line orientation.
- Reduced need for constrained implants.
- Potentially faster early recovery.

Nevertheless, fewer releases should not automatically be interpreted as better surgery. A component should not be placed in an unsafe position merely to avoid a necessary release. In severe fixed deformity, selective soft-tissue correction may be more appropriate than extreme component compensation.

7. Clinical Evidence

7.1 Randomized controlled trials

The 2025 John N. Insall Award randomized trial compared 123 functionally aligned and 121 mechanically aligned robotic TKAs. At two years, the primary outcome- the Forgotten Joint Score- did not differ significantly between groups. Functional alignment required markedly fewer soft-tissue releases and produced modest improvements in selected KOOS domains and willingness to recommend surgery. A prespecified or exploratory phenotype analysis showed better Forgotten Joint and quality-of-life scores with functional alignment among CPAK type I knees, suggesting that the effect may be phenotype dependent rather than universal.

A randomized bilateral study assigned opposite knees in 30 patients to functional or mechanical alignment. Functional alignment produced fewer posteromedial releases, a joint line that was more parallel to the floor, and better Forgotten Joint Scores at three and six months. The paired design reduced interpatient variability, but the sample was small and follow-up was limited to six months.

Another 2025 randomized trial involving 99 patients found that functional alignment reduced the frequency and extent of soft-tissue releases and was associated with better six-month KOOS subscales, Forgotten Joint Scores, and stair-climbing pain. Subgroup findings suggested greater early benefit among patients with obesity or greater preoperative varus, although subgroup results require external validation.

The most substantial contemporary evidence is the 2026 RASKAL registry-nested, multicentre, blinded, 2 × 2 factorial randomized trial. A total of 303 patients were assigned to robotic or computer-assisted surgery and to functional or mechanical alignment. Functional alignment was not superior to mechanical alignment for change in KOOS-12 at three months, six months, one year, or two years. No differences were found in Oxford Knee Score, Forgotten Joint Score, satisfaction, pain, or general quality-of-life measures. Mechanical alignment nevertheless required soft-tissue release in 44.8% of cases compared with 8.1% in the functional group. These results indicate that reducing surgical disruption does not necessarily yield a detectable population-level improvement in conventional PROMs at two years.

7.2 Summary of major comparative evidence

Young et al., 2025	Randomized trial; 244 TKAs	2 years	Similar primary Forgotten Joint Score; fewer releases with functional alignment; possible benefit in CPAK type I
Chompoosang et al., 2025	Bilateral randomized trial; 30 patients	6 months	Better early Forgotten Joint Score and fewer releases with functional alignment
Wang et al., 2025	Randomized trial; 99 TKAs	6 months	Better selected early KOOS and pain outcomes; fewer releases
MacDessi et al., 2026	Multicentre 2 × 2 factorial randomized trial; 303 TKAs	2 years	No PROM superiority; markedly fewer releases with functional alignment

The divergent results may reflect sample size, follow-up duration, definitions of functional alignment, surgeon technique, implant design, balancing targets, patient phenotype, and the ceiling effects of modern TKA. A small early difference may disappear with rehabilitation, while conventional PROMs may be insufficiently sensitive to detect more subtle changes in knee awareness or dynamic stability.

8. Varus and Valgus Phenotypes

Most early functional-alignment literature concentrated on varus osteoarthritis. In a 2025 analysis of 355 functionally aligned robotic TKAs, varus and valgus knees required different component modifications and resection patterns. Varus knees were reconstructed with greater tibial varus, whereas valgus knees required greater femoral valgus. Despite these differences, postoperative functional scores and short-term survivorship were comparable between groups, with reported survivorship exceeding 98% in both cohorts.

Functional alignment may be particularly useful in valgus knees because conventional mechanical alignment can require extensive lateral releases. However, valgus deformity is heterogeneous. It may originate predominantly from the distal femur, proximal tibia, intra-articular wear, extra-articular deformity, lateral ligament contracture, medial ligament attenuation, or combinations of these factors.

Functional alignment should be applied cautiously when valgus deformity is associated with:

- Medial collateral ligament incompetence.
- Severe fixed lateral contracture.
- Major bone loss.
- Extra-articular deformity.
- Neuromuscular imbalance.
- Patellar instability.
- Requirement for constrained fixation.

A robot can quantify the deformity but cannot restore a deficient ligament.

9. Implant Survivorship and Safety

Long-term survivorship remains the principal unresolved question. A 2025 systematic review and meta-analysis included 20 studies and 5,155 robotic TKAs performed using functional alignment. The weighted mean follow-up was approximately 2.5 years. Reported functional scores were generally favorable, and only 18 aseptic revisions were identified, corresponding to a pooled early aseptic revision proportion of approximately 0.35%. Obese patients accounted for the reported mechanical failures.

These findings are reassuring but should be interpreted cautiously because:

- Most included studies were nonrandomized.

- All procedures in the review used an image-based robotic platform.
- Several cohorts originated from high-volume specialist centres.
- Definitions and boundaries varied.
- Mean follow-up was insufficient to assess polyethylene wear, progressive radiolucency, late ligament attenuation, or aseptic loosening.
- Single-arm survivorship cannot determine superiority over established mechanical alignment.

The absence of an early failure signal supports continued controlled use, but it does not prove equivalence over 10–20 years.

10. Current Controversies

10.1 Functional alignment lacks a single definition

Two surgeons may describe procedures as functional alignment despite using different starting points, gap targets, component boundaries, implant designs, or release thresholds. Future publications should report:
- Initial alignment philosophy.
- Preoperative phenotype.
- Final hip-knee-ankle angle.
- Medial proximal tibial angle.
- Lateral distal femoral angle.
- Joint-line obliquity.
- Femoral rotation.
- Tibial slope.
- Flexion and extension gaps.
- Applied distraction force.
- Soft-tissue releases.
- Planned versus executed component position.

10.2 Balance is not synonymous with normal kinematics

A rectangular gap is easy to conceptualize and measure, but the native knee does not demonstrate identical medial and lateral behavior throughout flexion. The medial compartment is relatively constrained, whereas the lateral compartment permits greater posterior translation and rotational freedom. Excessive pursuit of mathematical symmetry may create a knee that is technically balanced yet physiologically abnormal.

10.3 Component positioning versus ligament release

Functional alignment transfers part of the balancing burden from the soft tissues to component position. The critical question is how much component deviation is preferable to a controlled release. At present, this trade-off is determined largely by surgeon judgment and platform-specific protocols.

10.4 Phenotype-specific treatment

The mixed results of randomized trials may arise because functional alignment is being tested as a universal intervention. Patients whose constitutional anatomy already approximates neutral mechanical alignment may experience little difference. Patients with marked joint-line obliquity or CPAK type I morphology may be more likely to benefit. Future trials should therefore be designed and powered for phenotype-treatment interaction.

10.5 Implant design

The optimal alignment may depend on whether the implant is cruciate retaining, posterior stabilized, medial pivot, bicruciate retaining, or ultracongruent. A strategy appropriate for a medial-stabilized design may not be transferable to an implant that depends on symmetrical femorotibial conformity.

10.6 Cost and accessibility

Robotic systems involve capital expenditure, maintenance, disposables, imaging in some platforms, theatre workflow changes, and training. Economic value will depend on case volume, reduced complications, length of stay, revision avoidance, and whether personalized planning produces meaningful clinical gains rather than radiographic precision alone.

11. Patient Selection

At present, the most straightforward candidates for functional alignment are patients undergoing primary TKA for osteoarthritis who have:
- Correctable varus or valgus deformity.
- Competent collateral ligaments.
- Adequate bone stock.
- No major extra-articular deformity.
- No requirement for high constraint.
- Anatomy that can be reconstructed within reasonable component boundaries.

Greater caution is appropriate in:
- Severe fixed deformity.
- Collateral ligament insufficiency.
- Major bone loss.
- Previous osteotomy.
- Post-traumatic malunion.
- Inflammatory destruction with ligament attenuation.
- Neuropathic arthropathy.
- Revision TKA.
- Severe recurvatum or multiplanar instability.

These selection criteria reflect current surgical reasoning rather than validated indications.

12. Future Directions

12.1 Standardized terminology and reporting

Consensus definitions should distinguish functional alignment according to its starting plan, balancing method, numerical boundaries, and final reconstruction. Without this information, meta-analysis will continue to combine clinically dissimilar procedures.

12.2 Long-term randomized and registry studies

Randomized trials should be linked to arthroplasty registries to evaluate revision, fixation, instability, patellofemoral

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complications, and implant-specific failure over at least 10 years.

12.3 Three-dimensional phenotyping

CPAK is useful but incomplete. Future classification systems should incorporate:

- Sagittal femoral bow.
- Native tibial slope.
- Femoral version.
- Tibial torsion.
- Trochlear morphology.
- Dynamic laxity.
- Gait characteristics.
- Foot and ankle compensation.
- Hip-spine-knee interaction.

12.4 Dynamic rather than static balance

Current robotic platforms principally quantify gaps at selected flexion angles. Future systems should evaluate continuous laxity curves, contact forces, femorotibial rollback, axial rotation, and patellar tracking throughout the arc of motion.

12.5 Data-driven decision support

Large datasets linking preoperative phenotype, intraoperative gap patterns, component position, implant design, and postoperative outcomes could support predictive planning. Such systems may eventually recommend a patient-specific alignment envelope, although algorithmic recommendations will require external validation and transparent safety constraints.

12.6 Better outcome measures

Traditional PROMs may not detect subtle differences among well-functioning TKAs. Future studies should include:

- Forgotten Joint Score.
- Activity-specific pain.
- Objective gait analysis.
- Wearable-derived activity.
- Stair and sit-to-stand testing.
- Patient-specific functional goals.
- Instability symptoms.
- Return to recreational activity.
- Satisfaction adjusted for preoperative expectations.

13. Conclusion

Functional alignment represents an important evolution in TKA planning. It uses robotic precision not merely to reproduce a predetermined neutral axis but to integrate patient anatomy, component positioning, and quantitative ligament balance.

The most consistent demonstrated advantage is a reduction in soft-tissue releases and an improved ability to achieve predefined gap targets. Smaller randomized studies suggest better early recovery or knee awareness in selected patients, while larger two-year trials have not demonstrated universal superiority in their primary patient-reported outcomes. Early survivorship appears reassuring, but long-term evidence remains inadequate.

Functional alignment should therefore not be presented as a replacement for mechanical alignment in every patient. It is better understood as a controlled framework for personalized reconstruction. The surgeon must balance preservation of constitutional anatomy against safe component orientation, implant mechanics, ligament competence, and the consequences of residual deformity. The central future objective is not to identify one ideal alignment for all TKAs, but to determine which reconstruction is appropriate for each knee phenotype.

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