MENTORS IN ORTHOPEDICS

# PERSONALIZED ALIGNMENT IN TKA: CURRENT CONCEPTS

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## SUMMARY

**Background:** Total knee arthroplasty (TKA) traditionally utilized mechanical alignment (MA) to achieve a neutral hip-knee-ankle (HKA) angle of 180°. Although MA provides high implant survivorship, a significant proportion of patients report residual pain and functional dissatisfaction. Recent anatomical studies demonstrate that native coronal alignment is highly variable, leading to the development of personalized alignment strategies that prioritize individual kinematics over systematic neutral positioning.

**Objective:** This review aims to define the principles of personalized alignment concepts in TKA, including kinematic, inverse kinematic, restricted kinematic, and functional alignment, while summarizing current clinical outcomes and surgical methodologies.

**Key Points:** Kinematic alignment (KA) aims to restore pre-arthritic joint lines and ligamentous tension by resurfacing the femur and tibia based on individual anatomy. To mitigate risks of aseptic loosening associated with extreme varus, restricted KA (rKA) limits bone resections to within ±5° of the mechanical axis and HKA to within ±3° of neutral. Inverse kinematic alignment (IKA) prioritizes native tibial joint line obliquity, adjusting femoral resections to achieve gap balance. Functional positioning utilizes robotic-assisted technology to fine-tune implant placement based on intraoperative soft tissue tension. Comparative studies indicate that KA may offer superior patient-reported outcomes, such as the Forgotten Joint Score, compared to MA, though long-term data for restricted and inverse techniques remain limited.

**Conclusion:** Personalized alignment strategies represent a shift toward restoring patient-specific kinematics in TKA. While early clinical results are encouraging, long-term follow-up is essential to evaluate the impact of non-neutral alignment on implant longevity and aseptic failure rates.

## KEYWORDS

Arthroplasty, Replacement, Knee; Knee Joint; Biomechanical Phenomena; Robotic Surgical Procedures; Bone Malalignment

## INTRODUCTION

Traditionally in total knee arthroplasty (TKA) a post-operative neutral alignment was a standard principle [1],[2],[3]. To obtain a neutral (mechanical) alignment the femoral and tibial components are positioned perpendicular to the femoral and tibial mechanical axis. This alignment philosophy for TKA was driven by equalizing load on the implant to decrease wear and loosening rather than restoring normal knee kinematics and function. Mechanical alignment (MA) in TKA has demonstrated good long-term implant survival [2],[4],[5]. However, functional outcomes of the TKA are inconsistent. Bonnin et al. found 75 to 89% of patients with TKA reported significant discomfort [6]. Discomfort during activities of daily living is a significant cause of patient's dissatisfaction after TKA [6],[7],[8].

Several recent studies have described limb alignment in non-osteoarthritic and osteoarthritic populations. A systematic review by Moser et al reported that the mean hip knee ankle angle (HKA) ranged from 176.7° to 180.7° in a native non-osteoarthritic knee [9]. The majority of studies in the review (12 of 15 ) did not report a neutral native limb alignment of 180°, apart from Hovinga et al [10] or Khattak et al [11]. The variability of coronal alignment in non-osteoarthritic knees raises the question if an alignment of 180° really is "normal" and should be the target in TKA for all patients. Moser et al in a second paper reviewed femorotibial alignment in osteoarthritic knees and concluded there was a large variation in overall coronal limb alignment as well as isolated femoral and tibial coronal alignments [12]. This observation continues to fuel the discussion and classification of limb alignment. In an asymptomatic cohort of 250 adults, Bellemans et al. defined a neutral alignment as 180° ± 3°, constitutional varus < 177°, and constitutional valgus > 183° [13]. Hirschmann et al. in more recent studies further classified the HKA alignment to include the femoral mechanical angle (FMA) and the tibial mechanical angle (TMA) [14],[15],[16]. This classification is more useful and is an explanation how current concepts of alignment variations in both femoral and tibial cuts will affect the final alignment. As the concept of MA was questioned in the 1980s anatomical alignment was introduced by Hungerford and Krackow with the goal to improve functionality by closer mimicking the native knee alignment [1], but alignment was similar for all and not personalized. This lead to the development of several concepts of personalized alignment: kinematic, inverse kinematic, restricted kinematic and functional. The distinction between these different concepts of alignment is sometimes difficult to interpret and reporting inconsistent in the literature.

The aim of this current concepts paper is to clarify the different types of current personalized alignments, summarize their main principles and report their results.

## KINEMATIC ALIGNMENT

### Principles

Kinematic alignment (KA), described in 2006 by Howell et al., as an 'individualized' or patient-specific technique [17]. The aim of KA is knee resurfacing with restitution of the pre-arthritic anatomy and preservation of the ligamento-muscular envelope. In this technique the knee is represented in three kinematic axes with respect to the joint lines of the distal and posterior femur (Figure 1): one transverse axis in the femur about which the tibia flexes and extends, one about which the patella flexes and extends, and one longitudinal axis about which the tibia internally and externally rotates on the femur. All three axes are either perpendicular or parallel to the joint lines

[18]. By resurfacing the knee joint, KA technique aims to co-align the axes and joint lines of the components with the three 'kinematic' axes and joint lines of the pre-arthritic joint. The surgeon resurfaces the femur maintaining the native femoral joint line obliquity, and adjusts the flexion and extension gaps with the tibial resection. In some cases, KA involves complex algorithms to balance the flexion and extension gaps [19]. The tibial compensation can result in more oblique tibial varus resections with an increased medial tibial bone cut compared to MA.

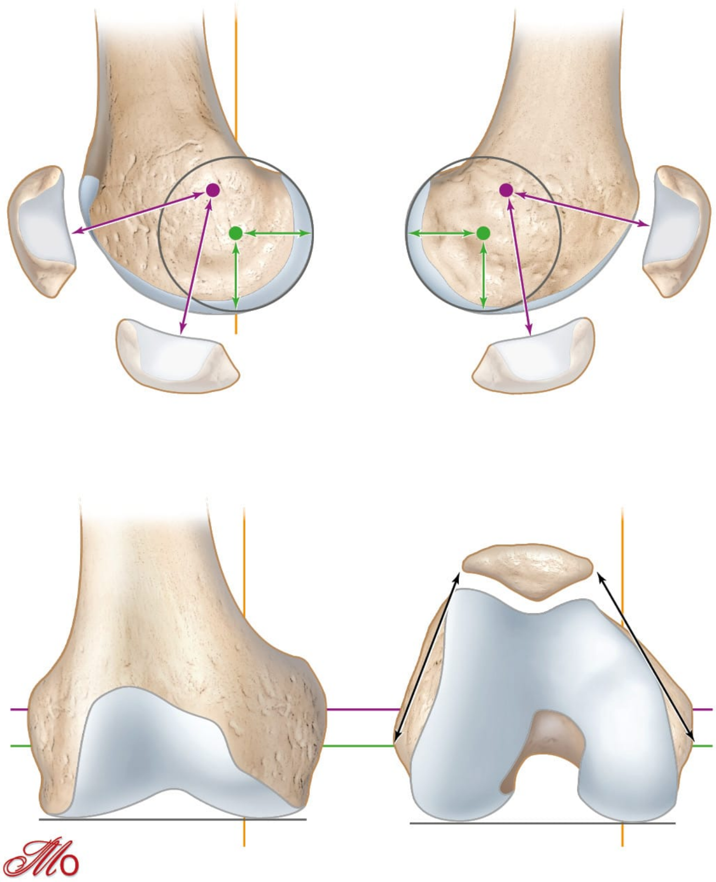

Figure 1: The transverse axis in the femur about which the tibia flexes and extends is the most distal and posterior (Green line). The transverse axis in the femur about which the patella flexes and extends is more proximal and anterior (Violet line). The longitudinal axis about which the tibia internally and externally rotates on the femur passes through the medial femorotibial compartment (Yellow line). All three axes are either parallel or perpendicular to the joint lines (Black line).

Femoral and tibial bone resection thicknesses are checked with caliper measurements and should match the thickness of the components after compensating for wear and saw cut. Intrinsically, it restores native ligament lengthening, does not create gap imbalance and minimizes the need for ligament release [20],[21],[22],[23]. In his protocol, Howell does not place restrictions on the patient's anatomy and post-operative correction. For this reason, KA requires a precise surgical technique and can be performed by multiple methods: conventional instrumentation, computer navigation, personalized instruments, or robotic assisted technique.

## Surgical technique

KA implantation is traditionally a measured resection technique with the femur first (Figure 2). Initially, the surgeon must estimate the individual physiological knee laxity throughout the knee range of motion and amount of bone loss. The first cut is the distal femoral cut which is parallel to the joint line after correcting for the estimated bone loss. The posterior femoral cut is then performed parallel to the posterior condylar plane (usually no wear posteriorly). Resection of bone (corrected for wear) from the distal and posterior femur is equal in thickness to the femoral component condyle which kinematically aligns the femoral component. The surgeon then cuts the tibia parallel to the articular surface again correcting for wear. The tibial resected bone (corrected for wear) is equal in thickness to the tibial component will kinematically align the tibial component [18].

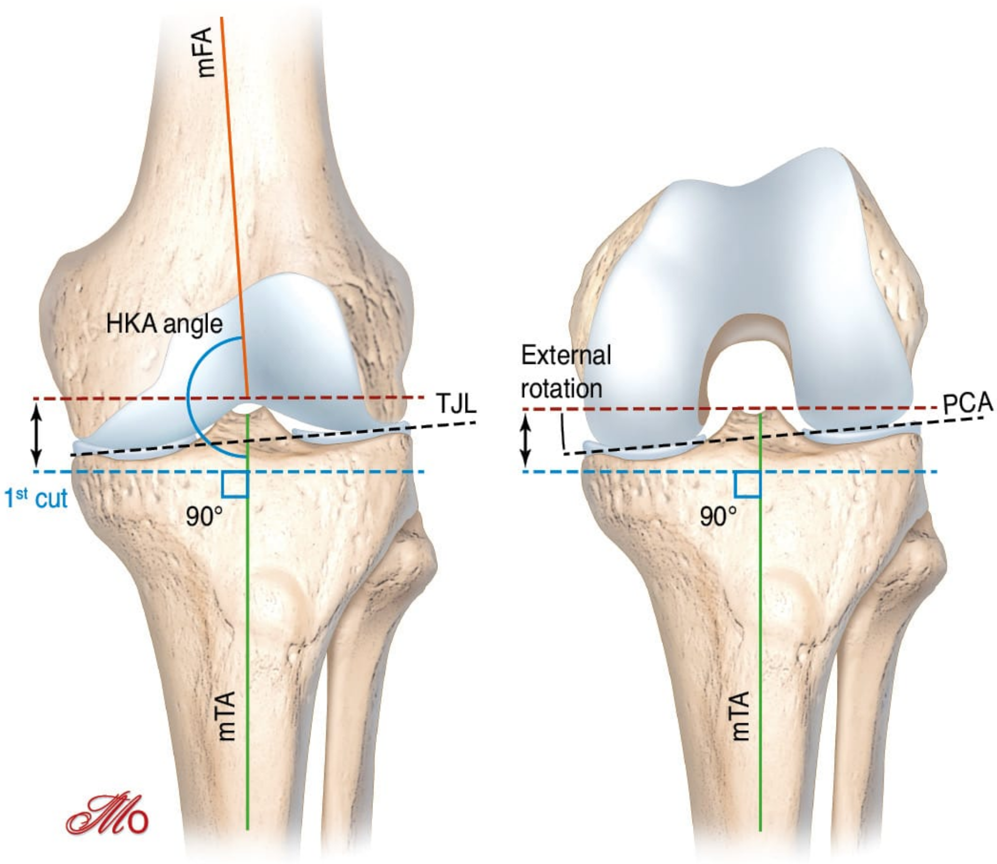


Figure 2: Mechanical alignment cuts

The surgeon must always measure each bone resection with a caliper. The thickness of the bone cut is calculated by deducting 1 mm from the implant thickness for the saw blade thickness and by estimating the amount of articular surface wear. The cartilage thickness is frequently approximately 2 mm on the distal and posterior parts of the femoral condyles.

During the trials, if there is femoro-tibial soft-tissue imbalance (tightness and/or excessive laxity) and the knee soft-tissue envelope remains intact (no release/deficiency), the proximal tibia should be recut to compensate. A kinematic femoral component implantation is relatively straightforward and highly reproducible compared to a kinematic tibial cut and component insertion. A common technique for this method is to use personalized (patient specific) cutting guides that enable additional degrees of varus/valgus/slope. In summary, the ligament balancing is performed by the bone cuts and adjusted as required by the tibial cut. This results in two important limitations that can occur with KA and have led to the development of restricted KA and inverse KA which is discussed later.

## Results

Sappey Marinier et al. performed a systematic review of the clinical and radiological outcomes after TKA with KA versus with MA at 2 years of follow-up [24]. They reported that four of five prospective randomized controlled trials studies did not find any significant difference between the two groups (MA or KA) for all the scores [25],[26],

[27],[28]. One study reported that kinematically aligned TKA had significantly better scores for pain, function, and ROM than those who underwent mechanically aligned TKA [29]. Young et al. [25] found no significant difference between KA (n=49) and MA (n=50) in OKS (42±6 and 41±6, respectively) at 24-month follow-up. Conversely, a randomized controlled trial by Dossett et al. [29] revealed a significant (p=0.005) difference with KA (n=44) outcomes greater than MA (n=44) in OKS (40±10.2 and 33±11.1, respectively) at 24-month follow up. Of note 90% of knees in the latter study were preoperatively in varus alignment and at 24 months there were no difference concerning the complication and revision rates, postoperative gait analysis and tibial component migration.

Shelton et al have assessed the functional outcomes and satisfaction rate of patients treated with a KA TKA that already had a contralateral mechanically aligned TKA [30]. 83% of patients were satisfied with the MA TKA when they were treated with the KA TKA and 92% were satisfied with the KA TKA at final follow-up. The median forgotten joint score (FJS) for KA TKA was higher than MA TKA by a significant difference of 15 points (p=0.006). 56% favored the KA TKA, 8% favored the MA TKA, and 36% rated both knees the same (p<0.001). 74% of patients favored the recovery of the KA TKA, 6% favored the recovery of the MA TKA.

A concern with kinematic alignment is the risk of developing aseptic loosening due to the increased varus alignment. Howell et al reported implant survival of 220 (unrestricted) KA TKA at 10 years of follow-up of 97.5% for revision for any reason and 98.4% for aseptic failure[22]. Tibial component loosening occurred in one patient, with a reverse tibial slope. Using MA criteria, the percentage postoperatively aligned in the varus (valgus) outlier range (>3°) was 78% (0%) for the tibial component, 31% (5%) for the femoral component knee, and 7% (21%) for the HKA (unknown mean varus).

## INVERSE KINEMATIC ALIGNMENT

### Principles

A limitation of correcting ligament balancing with a tibial recut is that the “resurfacing” of the femur is at the expense of adjustment with the tibial cut. Two difficulties can occur if a tibial recut is necessary for ligament rebalance. Firstly, a more oblique and deeper recut will sacrifice medial tibial bone stock. Sappey-Marinier has demonstrated that an increased tibial resection depth is associated with significantly greater valgus laxity between 30° to 90° of flexion, particularly with a tibial resection of 14 mm or more [31]. Increasing the tibial resection could jeopardize the medial collateral ligament and could complicate TKA revision if required. The risk of early loosening with tibial secondary displacement is increased with a severe varus tibial alignment [32]. The second difficulty concerns gap balancing where an increased tibial recut impacts the flexion and the extension gaps. In the majority of “standard” cases the difference between gaps is small. But in complex cases where the recut may be asymmetrical it could lead to laxity which may lead to instability.

The principle of the “inverse kinematic alignment” is to “resurface” the tibia with equal medial and lateral resections after correcting for wear, maintaining the native tibial joint line obliquity. The gap balancing is then performed by adjusting the femoral distal and posterior resections (Figure 2c). This technique could avoid tibial over resection and tibia-related postoperative complications. This technique has the advantage to manage independently the flexion and extension gaps. However, to perform an inverse KA accurately with conventional instrumentation or patient specific guides is challenging and complex while robotic-assisted system enables intraoperative planning of bone resections and gap balancing before the cuts.

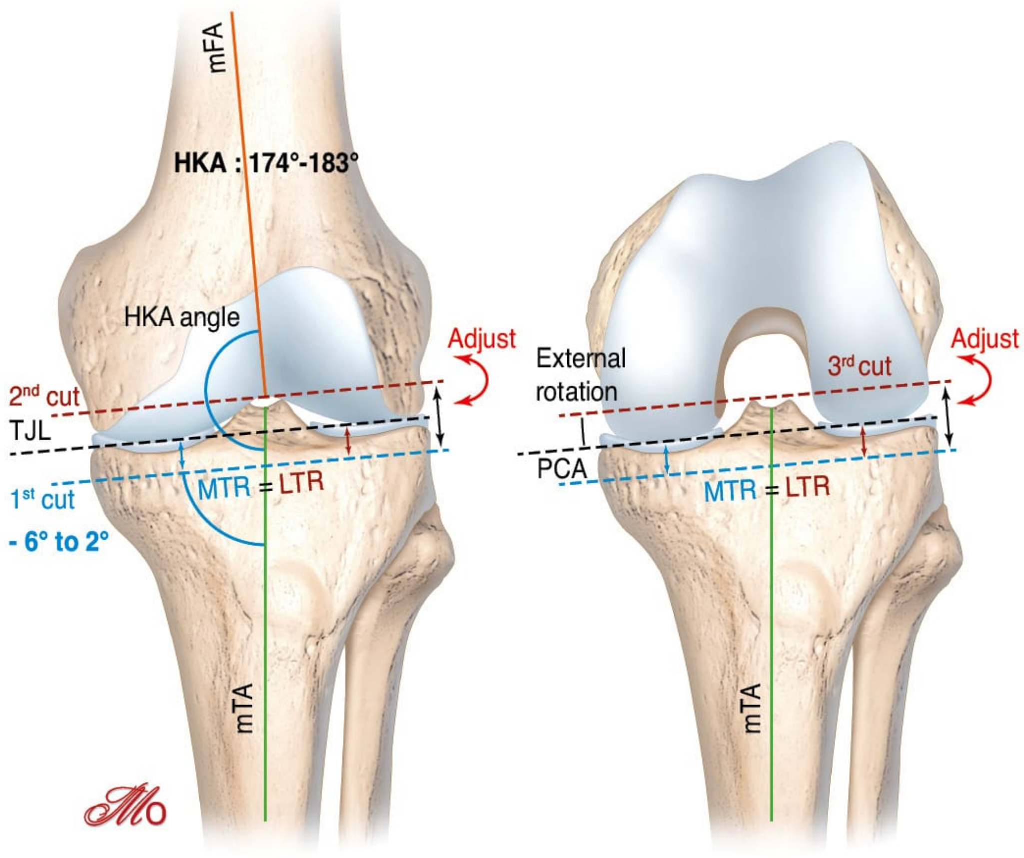


Figure 3: Inverse kinematic alignment cuts

## Surgical technique

Winnock de Grave et al. described this new concept and technique with a robotic-assisted system [33]. The tibial component is positioned first by planning a resection of equal amounts of bone medial and lateral on the tibia, after correcting for bone wear. The aim is to restore the pre-arthritic medial proximal tibial angle, within a safe zone of 84° to 92°. The tibial slope is determined by the native medial tibial slope. On the femoral side, the femoral component is positioned to restore the medial joint line height both in extension and flexion. The flexion and extension gaps are balanced by adjusting the distal and posterior resection levels of the femur. For the flexion gap, the aim is to achieve with the robotic-assisted system residual laxity of 1–2 mm in the medial compartment and 1–3 mm in the lateral compartment. For the extension gap, the aim is to achieve with the robotic-assisted system residual laxity of 1–2 mm in both compartments. The target for the HKA angle remains in a safe zone between 174 to 183°. Readjustment of the femoral cuts a second time after the first cuts after trialing is difficult with a conventional resection guides. The robotic assisted system estimates gap balancing prior to the cuts but also to potentially estimate and perform an adjustment and recuts after initial resections and trial.

## Results

Only Winnock de Grave et al. have reported the outcomes of the inverse KA. They found no significant difference of clinical outcomes at one year between inverse KA and adjusted MA [33]. They reported a higher rate of satisfaction and significant improvement in postoperative OKS for restricted inverse KA, compared to adjusted MA. Of note, knees with preoperative varus deformity had an apparent improved functional score and satisfaction for restricted inverse KA compared to adjusted MA. No complications or revisions were reported in either groups in the short term. However, these early results require further studies with increased patients and longer follow-up.

## RESTRICTED KINEMATIC ALIGNMENT

### Principles

KA without restriction remains controversial due to the increased stress on the implants as the knee deformity increases and alignment deviates from MA increasing the risk of aseptic loosening. Nakamura et al. with finite element analysis assessed the tibiofemoral contact force in relation to the limb alignment [34]. In varus knee models KA increases the contact stress on the tibial insert, bone resection surface and the medial tibial cortex. For moderate (10°) and severe (15°) varus knee models, the maximum stress in KA TKA increased by 24.8% and 32.2%, compared to MA TKA.

To account for the increasing stress, Vendittoli et al. recommended "safe zones" for TKA alignment and suggested the use of a restricted KA protocol [35]. Advanced osteoarthritic knee anatomy is very variable and to avoid reproducing extreme anatomy, the restricted KA is a hybrid option between MA and KA. The algorithm involves modifications of bony cuts within a "safe range" defined by the following criteria: independent tibial and femoral cuts must be within ± 5° of the mechanical axis and the HKA angle must fall within ± 3° of neutral. But the restricted KA technique follows the main technical principle of KA technique, which is to respect as much as possible the KA of the femoral component, and adjustment of the coronal limb alignment and joint line obliquity is first made by adjusting the tibial component cut.

### Surgical technique

The surgical planning is well described by Vendittoli (Figure 4). There are two situations: either the tibial and femoral mechanical axes are inferior or equal to 5°, or superior to 5°. In the first case with femoral and tibial axis inferior to 5°, if the femorotibial axis (HKA angle) is equal or inferior to 3°, the surgeon can perform the TKA with a KA technique. If the femorotibial axis is superior to 3° of varus, the tibial varus will be reduced until the HKA is equal to 3° of varus. If the femorotibial axis is superior to 3° of valgus, the tibial varus will be reduced until the HKA is equal to 3° of valgus.

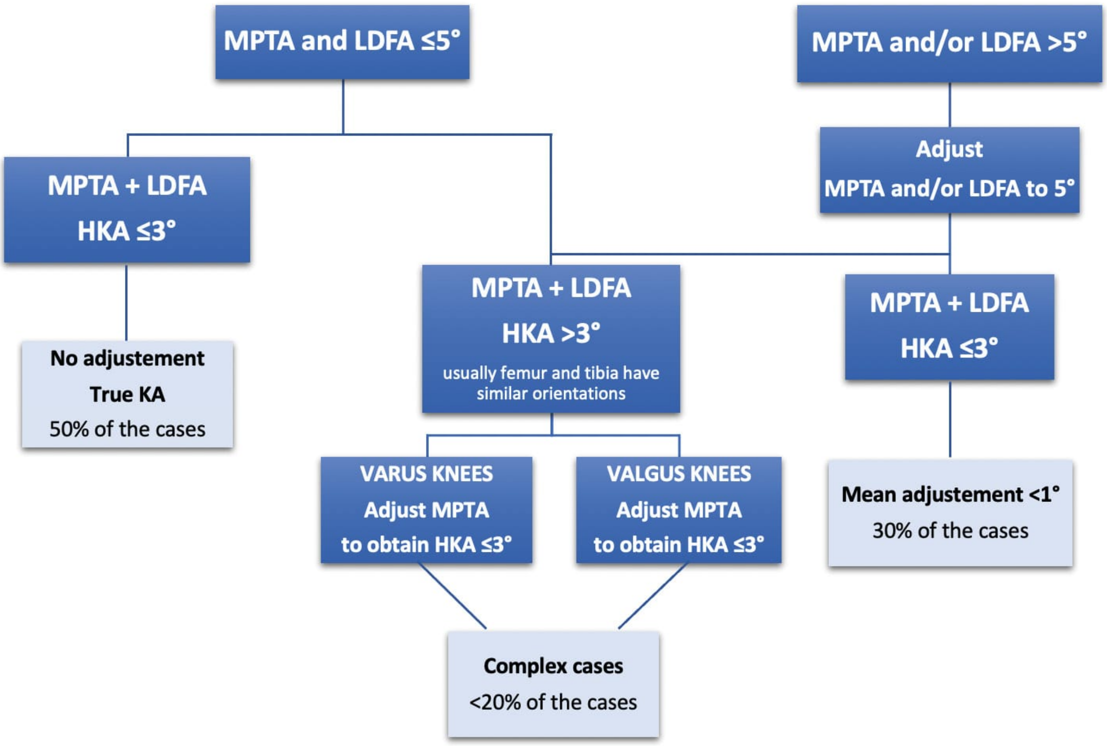


Figure 4: Restricted kinematic alignment protocol.

In cases where the femoral and tibial axis are superior to 5°, the surgeon will correct the tibial and/or the femoral bone cuts to fall within the 5° limit. This will then correct the overall HKA to within ±3° of neutral. If the patient maintains an HKA superior to 3°, the surgeon will further adjust the tibial cut as in the first situation (Figure 5).

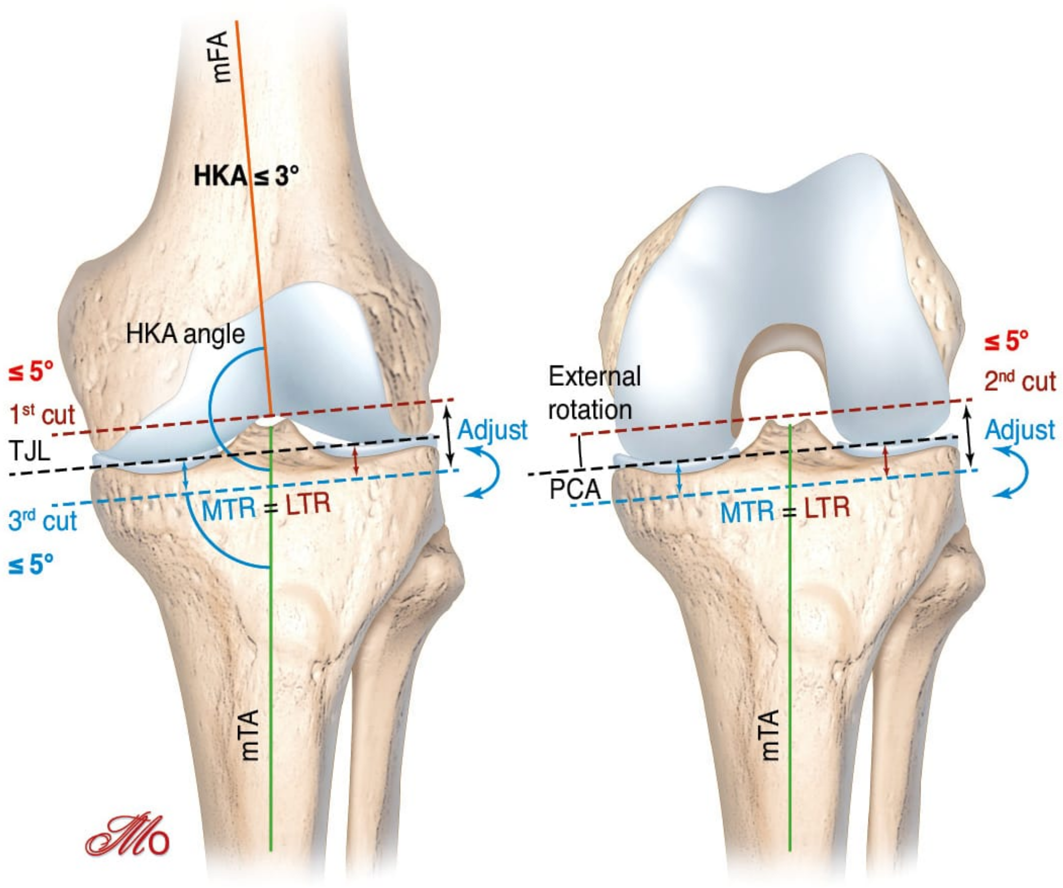


Figure 5: Restricted kinematic alignment cuts

We prefer to modify the tibia to preserve as much as possible the femoral anatomy and its flexion axis, as in KA technique. Ligamentous releases are usually not needed in cases with anatomic modifications of <3°. In larger corrections, minimal releases can be added (usually, to a much lesser degree compared to MA).

As with the unrestricted KA technique it is important to measure the bone resections after each cut. Computer navigation and robotic-assisted systems facilitate intraoperative operative adjustment in complex cases.

## Results

Of 2475 TKA cases Almaawi et al. reported 49% required restricted KA TKA and 51% unrestricted KA TKA[35]. Blakeney et al. simulated the extension and flexion gaps on 1000 lower limb CT scans according to the restricted KA or MA protocols. An "imbalance" was defined as a difference between medial and lateral gaps. In extension, there were significantly fewer cases having imbalance ≥3 mm with restricted KA (8.3%) versus MA (33%), and ≥ 5mm with restricted KA (1.5%) versus MA (11%). With restricted KA, the percentage of knees with space imbalances < 3mm in both extension and flexion was 92% versus 63% with MA with posterior condylar reference and 49% with MA with trans-epicondylar reference[36].

MacDessi et al. have reported encouraging results after TKA with restricted kinematic alignment in a randomized controlled trial [37]. They found that the mean intraoperative intercompartmental pressure difference at 10° of flexion in the KA group was significantly lower than in the MA group, using an interoperative pressure sensor. Overall, participants in the KA group were more likely to achieve optimal knee balance (80% vs 35%).

Currently no study has assessed the mid- or long-term clinical outcomes after restricted KA TKA.

# FUNCTIONAL POSITIONING

## Principles

Functional positioning has similar aims and was developed for similar reasons as KA [38]. It constitutes an evolution and increased precision of the KA concept. Patient-specific implants and three-dimensional printed cutting blocks have been used pre-operatively to achieve KA in TKA. Functional positioning is obtained by manipulating alignment, bone resections, fine-tuning implant positioning and/or soft tissue releases at the surgeon's discretion intraoperatively with robotic assisted systems to achieve balanced flexion–extension gaps and soft tissue tension while maintaining the patient's native limb alignment. These new and constantly improving technologies enable quantifiable measurement and precision adjustment of femoral and tibial cuts, implant positioning or tissue release in three planes, of one or two degrees, to obtain optimal functional positioning, including patella tracking. The precision offered by robotic assistance may make achieving non-neutral limb alignment targets more reproducible [39], reducing the risk of missing the target and producing significant alignment outliers. Theoretically, functional TKA reduces the need for intraoperative periarticular soft tissue releases if not desired by the surgeon while restoring the patient's native pre-arthritic knee kinematics

## Surgical technique

Robotic-assisted systems are constantly evolving both in hardware and software platforms and algorithms. Planning may initially begin preoperatively on a 3D and be completed during the surgery prior to bone cuts. Once the bone cuts have been made and the trial is in place the robotic system, soft tissue sensor or surgeon may discover a soft tissue imbalance. Adjustments can then be assessed with software 3D manipulation virtually and then recut guidance or releases performed with the robotic-assisted system if indicated.

In the coronal plane, femoral implant positioning is modified from a starting point of 0° to the mechanical axis to balance the extension gap. In the sagittal plane, femoral component is positioned to optimize the component sizing and to avoid femoral notch by flexing up to 10°. In the axial plane, the femoral component is aligned to the surgical trans-epicondylar axis with 3° of freedom to balance the flexion gap. The size of the femoral implant is selected using posterior referencing with the smallest size that does not overhang the femur, notch the anterior femur, or overhang mediolateral bone edges, and avoids overstuffing the patellofemoral joint. The femoral implant is positioned at the center of the mediolateral cortical bone edges, with a small lateral position if necessary. In the coronal plane, tibial implant position is aligned to the tibial mechanical axis and then modified to balance flexion and extension gaps by up to 6° of varus. Valgus tibial position should be avoided. In the sagittal plane, tibial implant position is set to match the patient's native posterior tibial slope, modified to balance the flexion gap if necessary. In the axial plane, the tibial implant is positioned using Akagi's line.

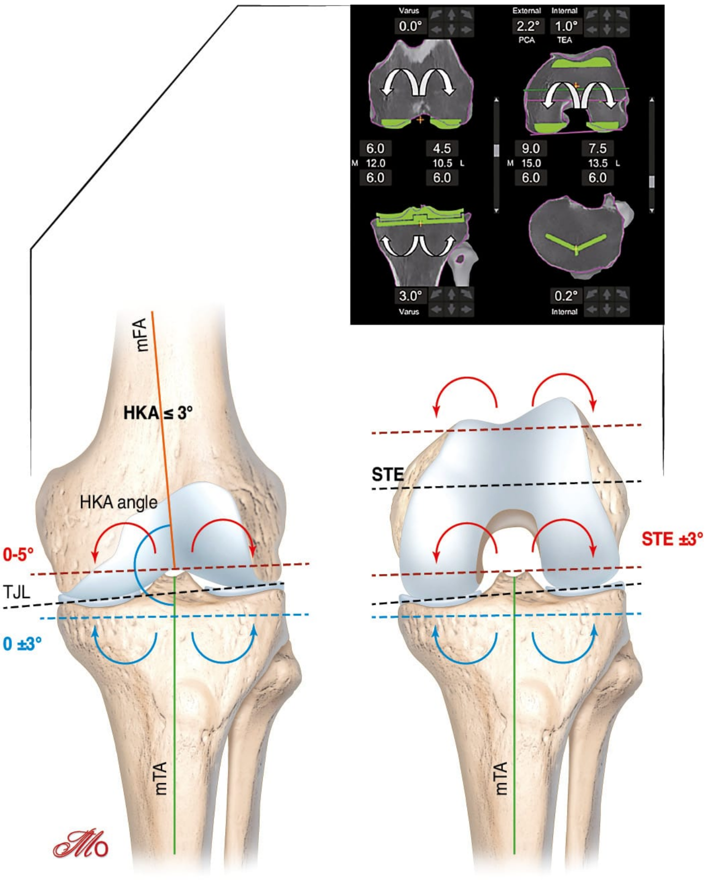


Figure 6: Functional positioning

The goal of functional alignment is to position the components in the position that least compromises the soft tissue envelope of the knee in 3D and hence to restore the plane and obliquity of the joint to that which the soft tissues dictate, restoring also optimal patella femoral tracking by restoring trochlea anatomy. If there are fixed deformities, ligament release may be required to balance the gaps, although the extent and frequency of such releases is smaller when compared with the standard MA technique.

### Results

Several studies assessed the accuracy and the reproducibility of the robotic assisted surgery [40],[44]. Sires et al. performed postoperative CT scans to assess the accuracy of the CT-based robotic-assisted TKA and reported that 93% of the intraoperative measurements were ≤3 degrees of the postoperative CT measurements [44]. The use of preoperative CT scanning and the planning accuracy of robotic-assisted TKA resulted in well-balanced knees [45]. Recent studies have assessed the functional and clinical outcomes of this alignment technique, showing some promising outcome at short term [46].

## CONCLUSION

Several concepts and evolving surgical techniques continue to develop personalized alignment in total knee arthroplasty. Personalized alignment aims to restore native knee alignment and improve functional outcomes after TKA. New technologies have increased the ability to restore native knee kinematics with TKA (Table 1). A long-term follow-up is crucial to determine clinical outcomes and implant survivorship of these current alignment concepts.

| | | Mechanical Alignment | Kinematic Alignment | Inverse Kinematic Alignment | Restricted Alignment | Functional Positioning |
|---|---|---|---|---|---|---|
| FEMORAL COMPONENT | Flexion | Follows distal femoral bowing Target: 0 to 5° of flexion | Follows distal femoral bowing Target: 2 ± 3° | Follows distal femoral bowing Target: 2 ± 3° | Follows distal femoral bowing Target: 2 ± 3° | Follows distal femoral bowing. Target: 0 to 10° of flexion |
| | Distal cut | Systematic and perpendicular to the femoral mechanical axis Target: 0° | Parallel to the distal femoral joint line (considering wear) | Parallel to the distal femoral joint line (considering wear) | Correct to <5°, then Parallel to the distal femoral joint line (considering wear) Target: <5° | Parallel to the distal femoral joint line (considering wear) Target: 0 to 5° |
| | Posterior cut | External or neutral rotation relative to posterior condylar line. Measured resection or gap-balancing techniques Posterior or anterior referencing techniques | Parallel to the posterior condylar line | Parallel to the posterior condylar line | Parallel to the posterior condylar line | Surgical trans epicondylar axis ± 3° |
| | Trochlea | N/A | N/A | N/A | N/A | Restore native anatomy |
| | Mediolateral | Slightly lateralised | Centred on the notch | Centred on the notch | Centred on the notch | Centred on the distal femur |
| TIBIAL COMPONENT | Coronal cut | Systematic and perpendicular to the tibial mechanical axis Target: 0° | Parallel to proximal tibial joint line (considering wear) Target: -6° to 9° | Parallel to proximal tibial joint line (considering wear) within safe zone of 84° to 92° Target: -6° to 2° | Correct to <5°, then Parallel to proximal tibial joint line (considering wear) Target: <5° | Perpendicular to the tibial mechanical axis Target: -6° to 2° |
| | Slope | Systematic and varies between 2° and 7° relative to the sagittal tibia mechanical axis | Parallel to the medial plateau slope | Parallel to the medial plateau slope | Parallel to the medial plateau slope | Parallel to the medial plateau slope Target: 0° to 3° |
| | Rotation | Towards the medial third of the tibial tuberosity | Parallel to lateral plateau long-axis | Parallel to lateral plateau long-axis | Parallel to lateral plateau long-axis | 0–5° of external rotation to Akagi's line |
| KNEE BALANCING | | Soft tissues | Tibial cut | Femoral cut (distal and/or posterior) | Tibial cut + Soft tissues | Femoral and tibial positioning + Soft tissues |
| SOFT TISSUE RELEASE | Femorotibial joint | Frequent | None | None | Sometimes | Rarely |
| | Lateral retinaculum | Sometimes | Rarely | Rarely | Rarely | Rarely |

Table 1: Surgical parameters for each kind of alignment

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