MENTORS IN ORTHOPEDICS

MECHANICAL ALIGNMENT ALTERNATIVES: FROM ANATOMICAL TO KINEMATIC ALIGNMENT IN TOTAL KNEE ARTHROPLASTY

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SUMMARY

Background: Mechanical alignment (MA) has served as the standard of care in total knee arthroplasty (TKA) for four decades, aiming for a neutral mechanical axis to theoretically optimize implant longevity. Despite technical refinements and the integration of robotic assistance, approximately 20% of patients remain dissatisfied with functional outcomes, prompting an investigation into alternative alignment philosophies that prioritize individual constitutional anatomy.

Objective: This review evaluates the methodology, clinical rationale, and current evidence surrounding five distinct alignment strategies: mechanical, anatomical, adjusted mechanical, kinematic, and restricted kinematic alignment.

Key Points: Traditional MA utilizes systematic bone cuts perpendicular to the mechanical axis, often necessitating soft tissue releases. Anatomical alignment (AA) modifies this by targeting a 3° varus joint line while maintaining a neutral limb axis. Adjusted mechanical alignment (aMA) allows for residual constitutional varus up to 5°. Kinematic alignment (KA) aims to restore pre-arthritic joint surface orientation and laxity without soft tissue release, though concerns persist regarding long-term component fixation in cases of severe tibial varus. Restricted kinematic alignment (rKA) proposes a hybrid approach, utilizing KA principles within a defined "safe zone" (coronal alignment ≤3° and tibial obliquity ≤5°) to avoid extreme outliers.

Conclusion: While MA remains the conventional benchmark, alternative strategies like KA and rKA offer potential improvements in physiological kinematics and patient satisfaction. However, long-term survivorship data for these patient-specific approaches remain limited, and the optimal indications for each philosophy continue to be a subject of clinical debate.

KEYWORDS

Arthroplasty, Replacement, Knee; Bone Malalignment; Knee Joint; Osteoarthritis, Knee; Range of Motion, Articular

INTRODUCTION

Traditionally for the last 4 decades, the best outcome for a total knee arthroplasty (TKA) was seen with the mechanical alignment (MA) concept aiming for a neutral leg axis (180° mechanical femorotibial angle). At the same time, the MA technique aligns the femoral and tibial component frontally in 90° to the mechanical axis in order to create a femorotibial joint line perpendicular to the neutral mechanical axis. In the axial plane the femur component is aligned parallel to the transepicondylar axis, which is thought to be the best compromise for the flexion/extension axis of the native knee. For the axial alignment of the tibia component most surgeons used the tibia tubercle as the functional landmark to realign the MA TKA to the extensor mechanism.

The concept of MA was based on the assumption, that correcting all knees to neutral mechanical alignment, reduces the knee adduction moment and the forces on the implant, distributing them more evenly between the medial and lateral femorotibial compartments and thereby minimising the potential for accelerated polyethylene wear or early loosening. The MA concept systematically creates a knee implant that is supposedly 'biomechanically advantageous' but does not allow the surgeon to address the patient's specific constitutional alignment. This concept entails a systematic approach to knee replacements identically for each patient, irrespective of the native anatomy (1,2).

However, the disappointing outcome with up to 20 % unsatisfied patients after MA TKA and a better understanding of knee biomechanics have prompted discussion into alternative alignment concepts that give more respect to the patient's constitutional anatomy. There is an ongoing controversy, which alignment concept is the best for our TKA patients. At least five different "philosophies" are currently under debate (Figure 1) (1). So far there is no evidence that one of them might be in favour for a better functional outcome, can reduce the 20% unsatisfied patients or achieve better long-term survival. This article presents the various schools of thought and their potential advantages and disadvantages.

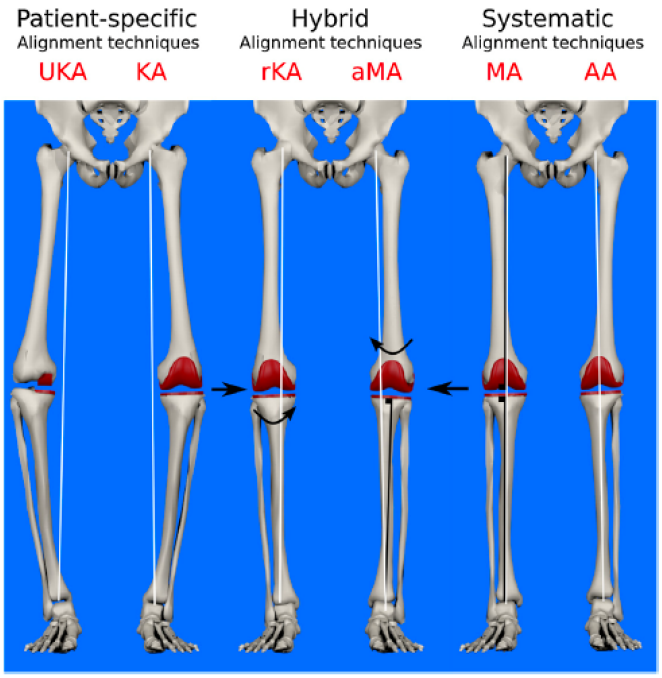

Figure 1: Five different realignment strategies

KA: Kinematic alignment, rKA: restricted kinematic alignment, aMA: adjusted mechanical alignment,

MA: mechanical alignment, AA: anatomic alignment.

PHYSIOLOGICAL ALIGNMENT

First, it is important to clarify that lower limb alignment is referenced against a vertical midline centred over the pubic symphysis. The anatomical axes are lines drawn along the length of the intramedullary canals of the femur and tibia. The mechanical limb axis is a line drawn from the centre of the head of femur to the centre of the talus and is referred to as Maquet's or Mikulicz's line. Provided there is no osteoarthritic degeneration of the knee, at the tibia the mechanical alignment usually matches the anatomical alignment, with a tibial mechanical-anatomical (TMA) angle of 0°, or neutral. In contrast the anatomical and mechanical axis of the femur are different and show a wide variation from 0 to 12° of valgus with an average femur mechanical-anatomical (FMA) angle of 6°. The distal femoral joint surface has an inclination of about 3° of valgus and the proximal tibia joint surface of about 3° of varus to the mechanical axis. This includes that the femorotibial joint line shows an inclination of 3° varus (Figure 2).

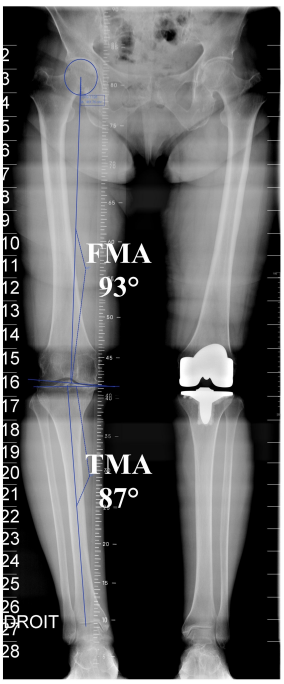

Figure 2: Femorotibial joint line inclination of 3° varus on long leg radiographs

Considering these definitions, overall alignment can be described in two ways, using either the anatomical femoral-tibial (AFT) angle or the mechanical femoral-tibial (MFT) angle. The AFT angle is simply the angle between the anatomical axis of the distal femur and the anatomical axis of the proximal tibia. In a normal knee the AFT should be about 6° of valgus (range 4 to 9°). The MFT represents the angle between the mechanical axis of the femur (centre femoral head and centre distal femur) and mechanical axis of the tibia (centre proximal tibia and centre ankle). In a normal knee the MFT should be neutral 0° (range 3° valgus to 3° varus). While the AFT angle can be estimated from standard (short-leg) radiographs, measurement of the MFT angle requires long-leg radiographs (Figure 3). The AFT does not represent the real lower limb alignment and allows pure guessing of the mechanical axis of the lower limb.

Figure 3: Measurement of AFT (short-leg radiographs) and MFT (long-leg radiographs)

A BRIEF HISTORY

Already more then 30 years ago D. Paley has introduced the concept of frontal deformity analysis on standardized long leg films for osteotomies. Since then it was clear, that in the normal population these numbers were just averages with a wide variation and a completely straight leg was uncommon (Paley, 1994) (Figure 4).

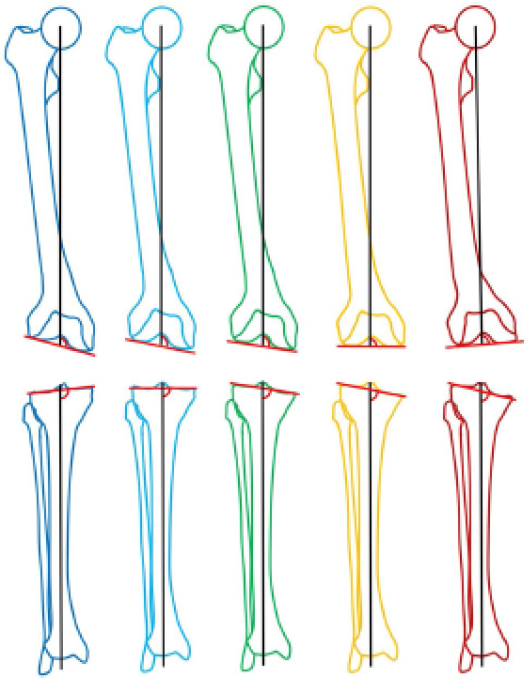

Figure 4: Wide variation of knee coronal alignment in a normal population

Unfortunately, this concept of deformity analysis has not been widely used until know for TKA procedures and most surgeons still plan on short radiographs only, which cannot represent the bony deformity of the lower limb

(Paley, 2016). Therefore, older studies, which support the use of a 'coronal safe zone' for TKA, are limited by the use of standard short radiographs only not representing the real lower limb alignment (NN).

It has long been suggested that restoring a neutral mechanical axis will increase the survivorship of TKA implants. Data from numerous clinical, simulator, finite element and retrieval studies have led to this belief. However, these studies merit closer analysis because many involve small numbers of patients, early designs of components and/or used short-leg radiographs only (3,4). In 1977, Lotke and Ecker showed that good clinical results were associated with a geometric TKR anatomically positioned between AFT 3° and 7° of valgus. Hood et al. and Hvid & Nielsen defined the ideal range of AFT as between 2° and 12° of valgus, whereas Moreland et al. recommended between 0° and 10°of AFT valgus. In a clinical and cadaveric study, Bargren et al. found that the Freeman–Swanson knee had a higher rate of failure when aligned in AFT varus. Insall believed that the mechanical axis should lie even lateral to the centre of the knee, producing valgus. In contrast, Townley thought that the mechanical axis should lie medial to the centre of the knee, in varus. However, all the studies mentioned above used older designs of components and short-leg radiographs, making it impossible to measure implant alignment reliably.

Jeffery et al. first-time popularised restoration of the mechanical axis to 0° (SD 3°) referenced from Maquet's line with the use of long-leg radiographs. While their study used a rather unique design of implant, many subsequent finite model analyses and laboratory investigations have supported this goal, including simulator studies and those in cadavers (NN).

WHY CONSIDER OTHER ALTERNATIVES?

Although MA TKA offers good long-term implant survival, the functional outcomes can sometimes be disappointing with 10–20% of dissatisfied patients (5,6). In fact, improvements in implant quality and surgical techniques did not change the overall patient dissatisfaction rate. Especially 'optimal MA' coronal positioning of the components and reducing outliers with computer assisted surgery (such as patient-specific instrumentation, navigation and robotics) did not improve patients' outcome. At the same time, several recent studies (7) showed that frontal alignment alone is not a good predictor of long-term survival for TKA and outliers in the frontal plane are showing no difference in the long-term survival. This highlights the importance of a better understanding of how to proper position our total knee replacements (5,6).

There is a consensus that TKA surgery needs proper bony cuts but remains a soft tissue procedure. It is surprising that after more than 40 years there is no evidence or consensus, which will be the proper bony cuts of the knee in all three dimensions. Performing the MA concept needs more or less soft tissue releases for the majority of TKA patients. Until now there is also no consensus, which type of soft tissue releases is in favour for a better outcome. It is therefore not surprising that some surgeons believe that more patient-specific bone cuts which require no soft tissue releases will improve the natural biomechanics and clinical outcome. Different concepts for this new approach had been proposed as an alternative to the classical MA and will be described in more detail.

ANATOMICAL ALIGNMENT (AA)

The anatomical alignment (AA) technique (Figure 5), first introduced in the 1980s by Hungerford et al., represents only a modification of the MA concept. The target is also a neutral mechanical axis for all knees but creating an oblique joint line (2°–3° of varus). Nevertheless, it represents also a 'systematic approach' like MA (i.e. identical for each patient irrespective of native anatomy).

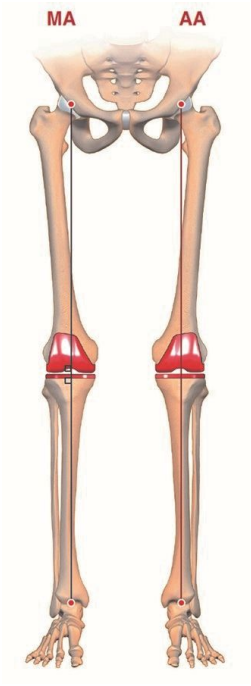

Figure 5: Systematic alignment with mechanical alignmnent (right leg) and anatomical alignment (left leg)

The technique is designed to reproduce the natural knee joint line obliquity with frontal bone cuts of femoral valgus 3° and a tibial varus 3° and to optimise patellar biomechanics by minimising any changes to the native distal femoral anatomy. However, this school of thought never took hold due to the technical difficulties in the 1980s of achieving accurate bone cuts. For most of the surgeons the risk of producing excessive (>3°) and presumably harmful varus of the tibial implant did not compensate the possible advantage of this more anatomical alignment concept. Nowadays, this lack of surgical precision has been overcome in two ways, namely the use of precision tools for implant positioning (navigation systems and robotics), and the development of TKA implants incorporating a 3° joint line obliquity in their design, which allows the surgeon to obtain an oblique femorotibial joint line using mechanical bone cuts ('AA-like technique'). Good mid to long-term results have been published with both techniques (AA and AA-like) (8,9) but in two recent RCT studies no difference could be identified in comparison to the MA technique.

ADJUSTED MECHANICAL ALIGNMENT (AMA)

The adjusted Mechanical Alignment (aMA) technique (Figure 6) creates a limb with a residual frontal deformity (varus or valgus). This concept was introduced by Bellemans as "constitutional alignment" (10) and is different to the classical MA and AA concept, which both aim for a neutral mechanical axis. The proposed benefit of aMA is based on the finding that the majority of knees are not neutrally aligned. Correcting them all to neutral will produce a none natural alignment and will need extra soft tissue releases. Adjustments to implant positioning are

made on the femoral side only and the tibial implant remains still mechanically aligned in 90° to the mechanical axis. The max residual deformity should not exceed 5°, otherwise the proponents believe that the clinical outcome will get worse and the long-term survival might be reduced. Good clinical outcomes have been reported for aMA-TKA (11,12) but conflicting results have been published by other groups (13,14). So far, no RCT study is available to prove the proposed benefits. Furthermore, the max allowed residual deformity is for debate and the jointline inclination is still not natural.

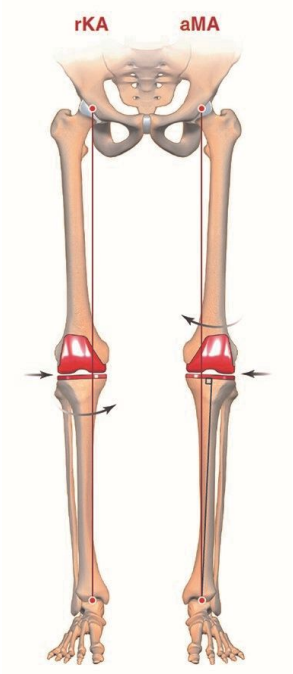

Figure 6: Hybrid alignment with adjusted mechanical alignment (left leg)

KINEMATIC ALIGNMENT (KA)

The kinematic alignment (KA) technique was described and popularised by the work of Stephen Howell and his group (15,16) (Figure 7 and 8).

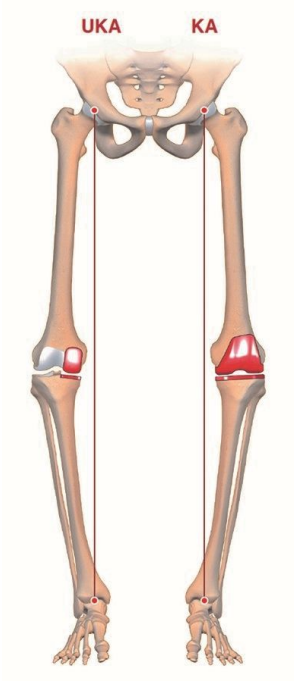

Figure 7: Patient-specific and physiological positioning with kinematic alignment (left leg)

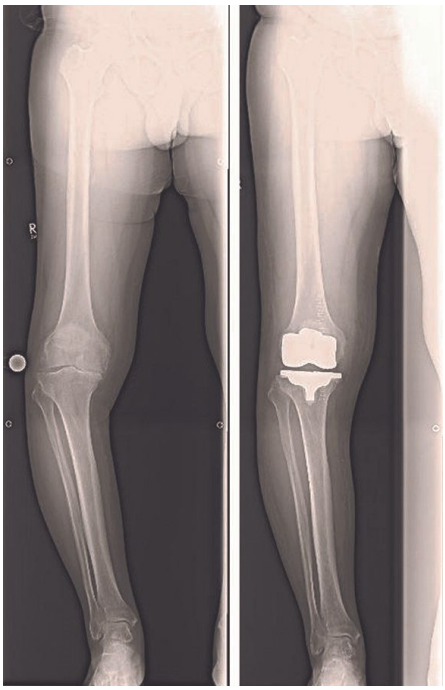

Figure 8: Total knee arthroplasty with kinematic alignment

The aim is to achieve true 'resurfacing' of the femorotibial joint by placing the TKA components in all three dimensions to restore the pre-arthritic deformity. The KA is a pure bone procedure which leaves the capsuloligamentous structure intact and requires no soft tissue releases. This keeps the natural oblique femorotibial joint line and the native soft tissue laxity of the knee. This technique applies the principles developed by Philippe Cartier (17) which has been used successfully for more than 4 decades for partial knee replacements. For TKA KA represents a new surgical technique using new anatomical markers to position the TKA implants. The differences to the classical MA technique are described in Table 1.(1)

KA concept claims to produce more natural knee biomechanics, better natural gait (18,19) and dynamic more physiological alignment of the limb during knee flexion. This will be reached by restoration of the pre-arthritic

state, more natural joint line orientation, no soft tissue releases and creating a stable prosthetic knee with no relevant lateral lift-off (20). The proponents believe that KA will reduce the 20% unsatisfied patients without compromising the long-term survival of the components.

To date, eleven research teams (19,21–30) have compared KA and MA implants and all without exception reported in the short term either equal or superior functional outcomes for KA patients. It seems to be logical that without performing soft tissue releases the short-term clinical outcome should be better (31), but in many papers this benefit will not be clinically relevant anymore after 1 to 2 years. So far long-term results are published by Howell only. He claims no limitations in patient selection, used several different surgical tools, performed no medial-lateral soft tissue release, reported no intraoperative complications, acceptable postoperative alignment, no problems with patella maltracking and clinical scores and survival comparable to other classical papers.

Despite the excellent short- and mid-term clinical outcomes with KA, there are still several questions open to allow to generally introduce KA in the daily practice. Until now the evidence for better clinical outcome is still limited, since the published RCT studies reported conflicting results (32). The only RCT study using bilateral simultaneous procedures did not find any clinically relevant benefit for KA after 2 years FU (28). There remains concern that especially severe tibia vara might compromise the long-term survival (33,34). Current implants were designed for mechanical alignment and do not allow the surgeon to reproduce the native trochlear anatomy specific to each patient (35,36). Nevertheless, several studies confirm the safety of kinematic alignment using contemporary implants and particularly no increase in the patellar complication rate (15,19,21–29,37). The design of the implant might play also a role. Recently a single surgeon serious reported better outcome for Medial Pivot vs CR knees with KA technique (27). Last but not least the ideal indications for KA are not yet properly well-defined and many surgeons do believe to some patient selection restrictions (38,39).

RESTRICTED KINEMATIC ALIGNMENT (RKA)

It is highly likely that not all patients are suitable for classical KA. The native anatomy in patients coming for TKA can be biomechanical inferior in terms of severe patho-anatomy in all three dimensions (40–42). This may contribute to primary deterioration and results in complications if the bony pathology is not corrected. Severe constitutional deformity of the limb stretched out ligaments on the convex side (thrust), significant knee joint line obliquity or patellar instability enhanced by an unsuitable knee/limb morphotype are examples for these limitations.

Therefore, some authors have opted for a compromise when performing a TKA on patients with substantial limb deformity. Using computer assisted tools they assess limb frontal alignment and proximal tibial joint surface obliquity during the procedure. They then perform the arthroplasty using the KA technique if constitutional frontal limb deformity ≤ 3° and proximal tibial joint obliquity ≤ 5° obliquity (safe alignment zone) (39). Otherwise, in approximately 40% of cases, the authors adjust the bone cut (tibial and/or femoral) to bring the patient into their safe alignment zone. Otherwise the rKA technique (Figure 9) follows the same principles as the classical KA technique.

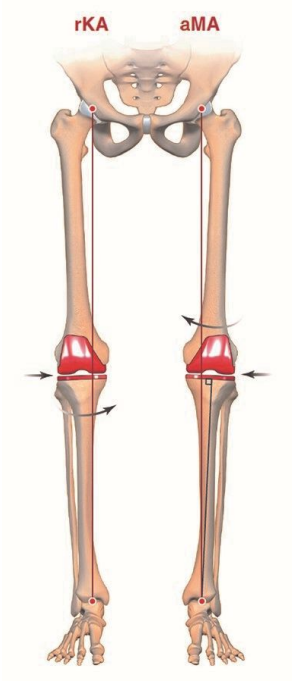

Figure 9: Hybrid alignment with restricted kinematic alignment

CONCLUSION

Mechanical alignment technique remains still the “golden standard” for most of the knee surgeons. Despite improvements in implant design and surgical tools designed for more accurate and reproducible surgical techniques the high rate of unsatisfactory functional outcomes did not change during the last decade. This is why an increasing number of surgeons believe that another alignment concept might be helpful to further improve the outcome in TKA. The anatomical alignment concept is not new but failed to prove any clinical benefit but has the risk of severe varus malalignment for the tibia component, that’s why it had not been adapted by most surgeons during the last 30 years. Adjusted MA or constitutional alignment has recently been introduced as modified technique which keeps the knee in some residual deformity to follow more the natural alignment and reduce the need for soft tissue less releases. The clinical benefit of aMA is not proven yet and the maximum limit of undercorrection remains still unclear. Kinematical alignment represents a complete new surgical technique for TKA and has been used for UKA for more than 40 years. KA performs a pure cartilage resurfacing procedure without correction of any bony deformity which makes no soft tissue releases necessary. The short to mid-term outcome has been reported in several studies to improve the patient functional outcomes, but conflicting results are published in RCT studies. KA has become a more “religious approach” with strong promotors and many surgeons who don’t see the clinical benefit and are afraid of possible compromises for the long-term survival.

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