

WHY DOES INDIVIDUALIZED TKA FACILITATE THE RESTORATION OF NATIVE ALIGNMENT?

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SUMMARY

Background: Traditional total knee arthroplasty (TKA) frequently utilizes systematic mechanical alignment and off-the-shelf (OTS) implants, which may not accommodate individual phenotypic variations. Recent shifts toward personalized alignment strategies highlight limitations in OTS designs, specifically regarding prosthetic overhang, ligamentous balancing, and the "trochlea dilemma," where patellofemoral tracking is compromised by fixed prosthetic geometry during kinematic alignment.

Objective: This article evaluates the technical rationale and clinical application of fully individualized TKA, focusing on the integration of 3D computed tomography (CT) planning and parametric implant design to restore patient-specific pre-arthritis anatomy.

Key Points: The manufacturing process utilizes 3D CT data of the hip, knee, and ankle to differentiate between native alignment and arthritic bone loss. A parametric model allows independent customization of femoral and tibial zones, facilitating the decoupling of patellofemoral and tibiofemoral kinematics. This approach addresses the mismatch between the prosthetic trochlear angle and the quadriceps line of force often observed in OTS implants. Surgical execution is guided by additive-manufactured patient-specific instruments. While the strategy aims to restore constitutional alignment, a "safe zone" is maintained, restricting tibial and femoral angles to 85°–95° and the hip-knee-ankle angle to 185°–193°. By replicating native joint surface radii and orientation, the requirement for intraoperative ligamentous release is minimized, potentially standardizing surgical technique through high-level personalization.

Conclusion: Individualized TKA components, designed through 3D modeling, allow for the restoration of pre-arthritis phenotypes while optimizing patellofemoral tracking. This comprehensive approach addresses the geometric limitations of conventional implants and supports the transition toward functional alignment strategies.

KEYWORDS

Arthroplasty, Replacement, Knee; Prosthesis Design; Imaging, Three-Dimensional; Patient-Specific Modeling; Knee Joint

As we reach the 50th anniversary of ‘modern TKA’, new technologies and new industrial processes render the production of fully individualized implants feasible [21],[27]. Their main goals are to: (i) optimize bone-implant fit and avoid prosthetic overhang, (ii) facilitate the restoration of the native pre-arthritis limb alignment, (iii) improve ligament balancing by avoiding iatrogenic laxity due to asymmetric bone cuts and by restoring the native radii of curvature and (iv) improve patellofemoral tracking by decoupling the patellofemoral joint from the tibiofemoral joint.

This article is based on our experience with the Origin® individualized TKA (Symbios, Yverdon-les-Bains, Switzerland). The manufacturing is based on a classic process of Chromium-Cobalt casting, followed by machining and polishing. Eight different areas are defined on the femur and the tibia, with predefined ranges of variations (width, contours, radii, thickness...) in a parametric model, each being fully customized and designed independently from one another (Figure 1).

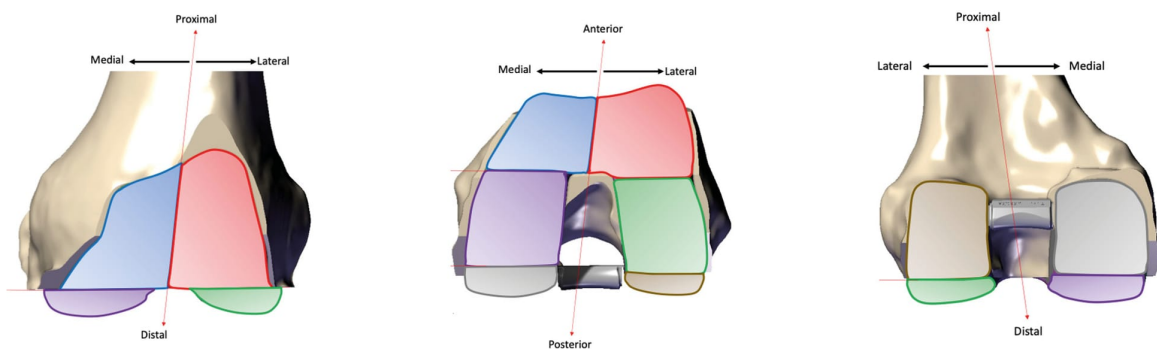


Figure 1: Six different areas are individualized in the femoral component in which the range of possible variations is defined and validated. Each area is designed independently from the others, allowing great versatility.

The design and manufacturing process of the Origin TKA takes five to six weeks and requires cooperation between surgeons and engineers. The design is based on 3D CT analysis of bony anatomy, arthritic deformities, and limb alignment, based on a specific radiographic protocol, including the knee, hip, and ankle joints. The DICOM files are collected and sent electronically to the engineering team through a secured ‘Symbios box’. A 3D analysis is performed with the Knee-Plan® software (Symbios, Yverdon-les-Bains, Switzerland). This process integrates 3D planning and the manufacturing of implants adapted to a specific alignment. A set of patient-specific instruments (PSI) manufactured with additive technology provides accurate adjustment of the bone cuts (Figure 2).

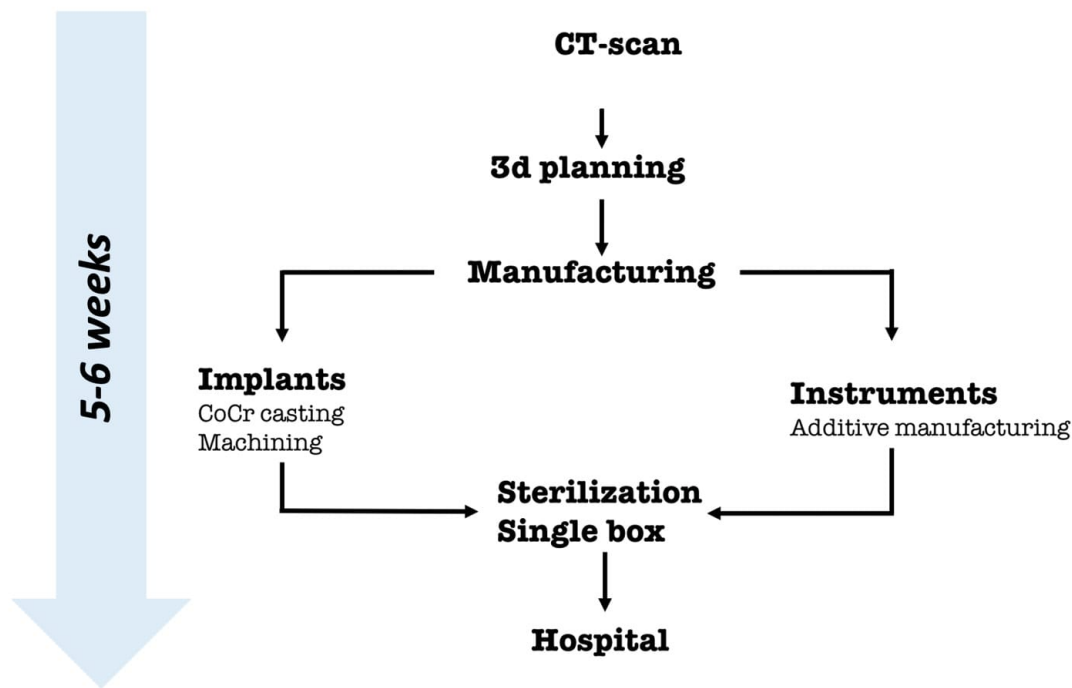


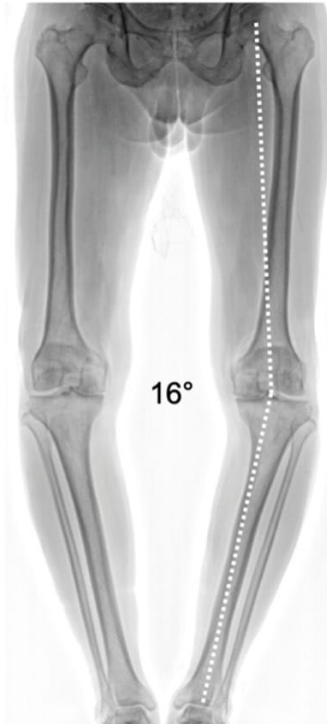
Figure 2: Implants and instruments are designed from a CT-scan. Manufacturing of the definitive implants use ‘pre-shapes’, previously manufactured with classic chromium-cobalt casting technology for the femur and Titanium (Ta6V) for the tibial baseplate. Final customization is done using automated quick milling. The custom guides are made with additive manufacturing using polyamide. Implants and instruments are then assembled into a single box and sent directly to the hospital.

This sequence facilitates the restoration of the native pre-arthritic alignment in different ways: (i) 3D analysis enables assessment of native alignment from the preoperative CT scans (ii) decoupling the patellofemoral joint from the tibiofemoral joint solves the ‘trochlea dilemma’ of kinematic alignment and (iii) the definition of clear targets is easier thanks to the versatility of the process.

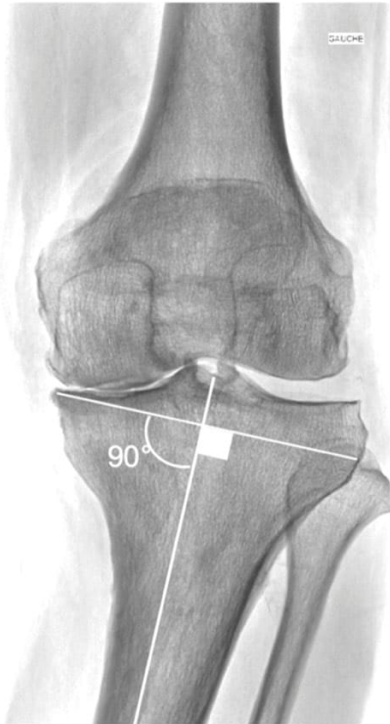
FROM PRE-OPERATIVE TO PRE-ARTHRITIC ALIGNMENT: PREDICTING THE PAST

One of the main paradigm shifts of knee arthroplasty in the last decades has been the switch from systematic alignment (mechanical or anatomic) to individualized alignment (kinematic, restricted, inverse kinematic, or functional alignment...) [2],[24],[27]. Many surgeons have abandoned the concept of ‘90° cuts for all’ and now try to restore, at least partially, the native phenotype (femoral and tibial angles as well as joint line orientation) [2],[3],[4],[15],[16],[18],[22],[24]. However, most surgeons plan their procedures on plain radiographs showing only the global deformity of the limb, which is a combination of native alignment, arthritic remodelling (bone wear and laxity), and radiologic errors due to fixed flexion deformity and/or malrotation[5]. It is therefore unrealistic to deduce the true native alignment of a given patient from their preoperative radiograph. This is a main limitation because: (i) in daily life we only have an approximate knowledge of a patient’s phenotype and (ii) the literature never differentiates native and arthritic deformities and fails to define the appropriate targets (Figure 3).

Constitutional varus



Orthogonal cut



Varus cut

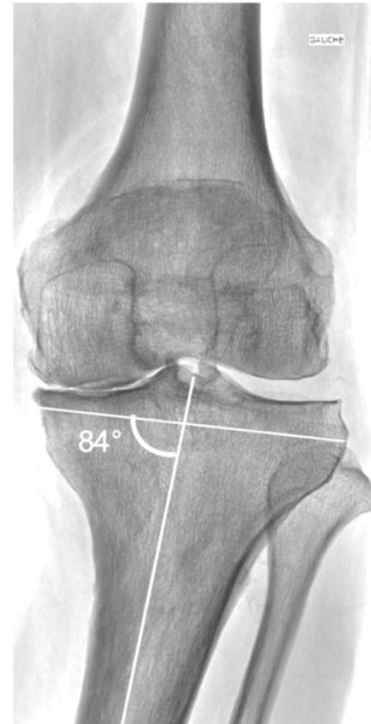


Figure 3A: This patient has a medial OA with 16° deformity on both knees. The varus is mainly due to a constitutional varus. In this patient a 90° cut on the tibia would create a very asymmetric resection, with difficult ligament balancing due to the 'resection induced laxity'. A cut in varus will decrease the risk of laxity and the bone cut will remain close to the subchondral plate.

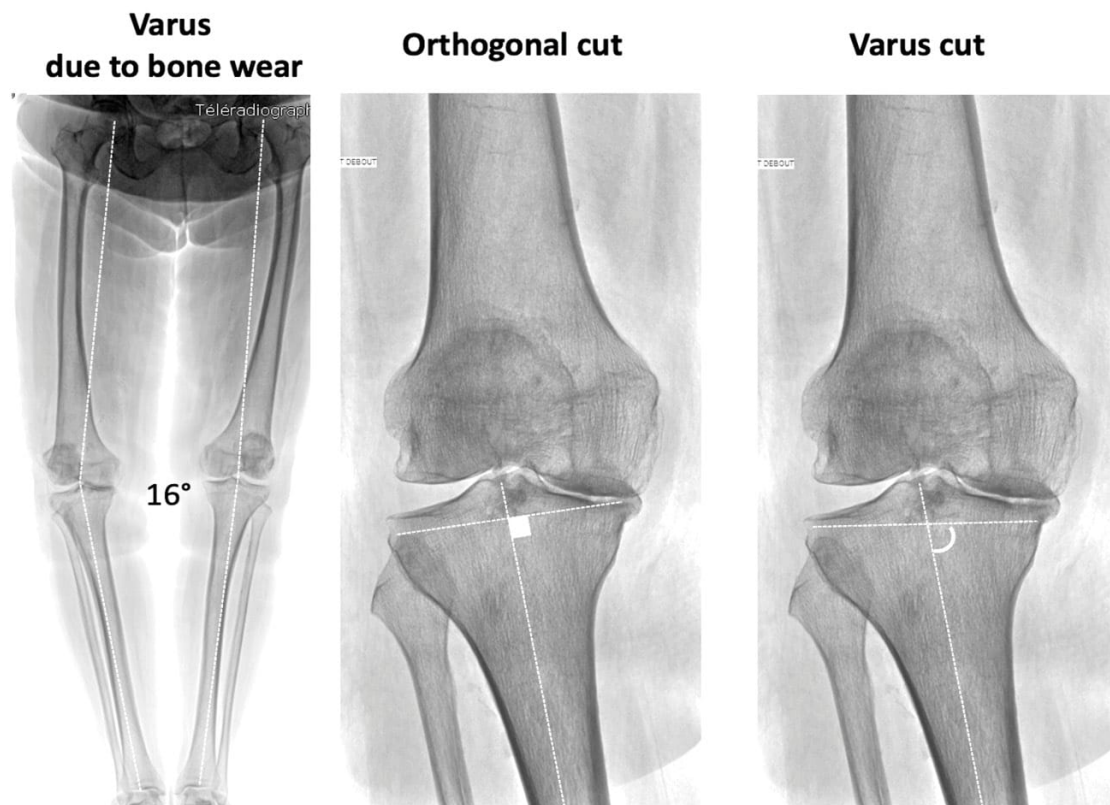


Figure 3B: This patient has also a medial OA with 16° deformity on the right knee. Here, the varus is asymmetric and is mainly due to the bone wear on the medial plateau. Before the arthritis, this tibia was well aligned. In this patient a 90° cut on the tibia will correct the bone loss with the prosthesis and recreate the pre-arthritis anatomy.

An important advantage of 3D CT planning is that it enables direct visualization of the bone defects, which generally involve only a limited area of the tibial plateau (or more rarely the condyle), and to deduce the native shape of the articular surface by referring to non-damaged areas (Figure 4) [7]. While the femur and tibia are analyzed separately, it is possible to calculate the native femoral and tibial angles, the arithmetic HKA, and to know the precise native phenotype of the patient. All technologies based on preoperative CT analysis provide this advantage, and the success of image-based robotics is due to, among other reasons, this possibility to plan in 3D and to facilitate the kinematic alignment technique [1],[14],[19].

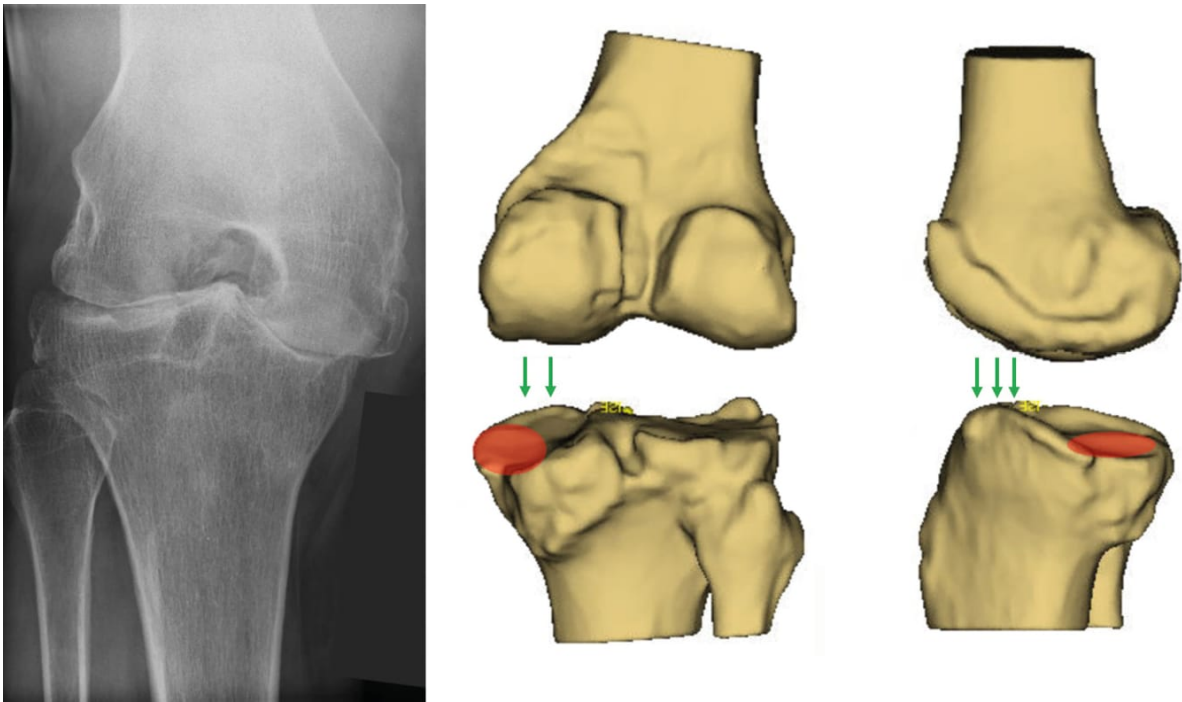


Figure 4: In this patient, with a severe bone wear of the medial tibial plateau, it is difficult with the XR evaluate the pre-arthritic tibial angle. The CT-scan allows 3D reconstructions where we can distinguish areas with bone wear (red areas) and intact areas (green arrows).

THE LINK BETWEEN ALIGNMENT AND DESIGN: THE TROCHLEAR DILEMMA

Recent anatomic studies have demonstrated that in healthy knees, phenotypes are highly variable, particularly the joint line orientation [9],[10],[11],[12]. The trochlear angle, between the distal condylar line and the trochlear axis, is also variable so that the trochlea remains aligned with the quadriceps line of force in the coronal plane whatever the joint line obliquity [13],[25],[28],[29]. With kinematic alignment, or any kind of individualized alignment, surgeons aim to restore the native phenotype and align the implants with the joint line: they prioritize coronal limb alignment, sometimes to the detriment of trochlear orientation, to an extent that the patellofemoral joint becomes a mere subordinate of the tibiofemoral joint. In most off-the-shelf (OTS) TKA, the orientation of the prosthetic trochlea is set at 6° to 7° valgus from the prosthetic distal condylar line (Prosthetic Trochlear Angle) [6], [20],[25],[26]. Consequently, when using such an implant with kinematic alignment, the trochlear orientation becomes variable and can deviate medially or laterally from the quadriceps line of force (Figure 5) [28],[29].

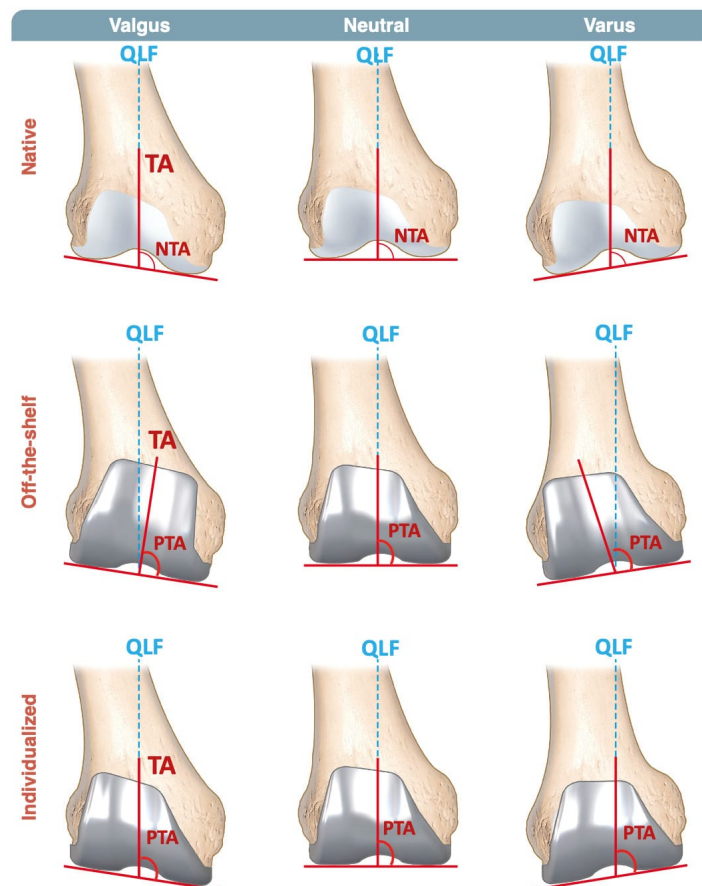


Figure 5: Coronal plane. In healthy knees (first row), the Native Trochlear Angle (NTA), between the distal condylar line and the trochlear axis is variable. The Trochlear axis is aligned with the Quadriceps Line of Force (QLF), whatever the obliquity of the joint line. When an off-the-shelf prosthesis is implanted with kinematic alignment (second row), the components are aligned with the native joint line, but the Prosthetic Trochlear Angle (PTA) is fixed in the design (6° or 7°), and as a result the trochlear line can diverge from the QLF. In individualized prosthesis (third row), the PTA is adapted so that, whatever the joint line obliquity, the trochlear axis remains aligned with the QLF.

Lower Forgotten Joint Scores were observed when the angle of the prosthetic trochlea is medial to the quadriceps line of force in kinematically aligned OTS implants [13]. Moreover, Wang et al. [31] showed that the undercoverage of the trochlear resection surface in kinematic alignment OTS TKA is mainly correlated with the degree of valgus of the distal femoral joint line. The authors suggested that this correlation should be considered in the development of prostheses specifically for kinematic alignment, or ideally a fully individualized component. Similarly, in the axial plane, the femoral component is aligned with the posterior condylar line, which can result in trochlear misorientation with OTS symmetric components [30].

With individualized implants, all areas are designed independently, and the trochlear groove can be oriented to optimize patellofemoral kinematics independently from the femoral condyles, which should be aligned to optimize tibiofemoral kinematics [17],[20],[23],[24]. This decoupling of the patellofemoral and tibiofemoral joints solves the trochlear dilemma of kinematic alignment with off-the-shelf implants [27] (Figure 6).

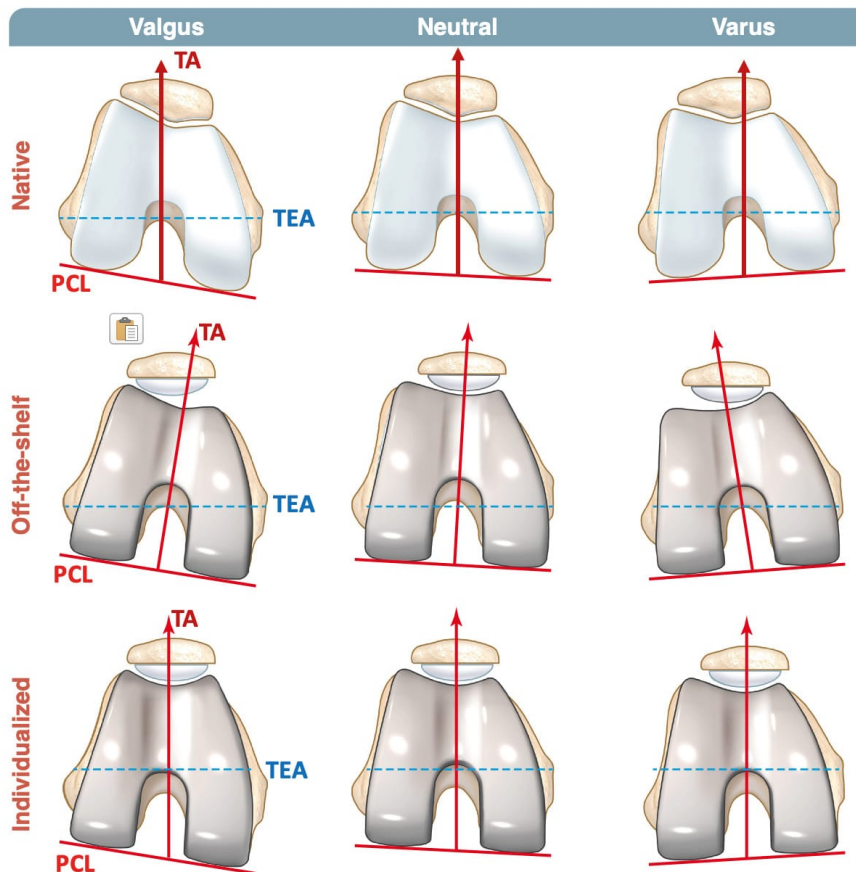


Figure 6: Axial plane. In healthy knees (first row), the Transepicondylar axis (TEA) and the Trochlear axis (TA) are not always aligned with the Posterior Condylar Line (PCL). When an off-the-shelf prosthesis is implanted with kinematic alignment (second row), the components are aligned with the native PCL but the TA is fixed in the design, and as a result the trochlear axis has a variable orientation, with possible maltracking. In individualized prosthesis (third row), the TA is independent from the PCL and adapted to optimize patellar tracking.

DEFINING THE TARGET: HOW MUCH VARUS IS TOO MUCH? ---

When switching from a mechanical to an individualized alignment strategy, surgeons are faced with three main challenges: How to plan the surgery? How to match the planning with the operating field? How to define the limits? The process of individualized TKA fixes these three aspects [5]:

WHAT ABOUT THE LIGAMENTS? ---

One criticism of individualized implants planned on a CT scan might be that they ignore the soft tissue envelope, and cannot integrate laxities in the planning [21]. This critique is valid in severe deformities with ligament distensions or ruptures, which are exclusion criteria for individualized implants.

The basic concept behind individualized implants is that most ligament problems encountered in TKA are iatrogenic, due to asymmetric resections or poor anatomic restoration, and that conversely, restoration of the native alignment and native shape of the knee largely prevents ligament problems. Pioneers of modern knee arthroplasty who stated that “TKA is a soft-tissue procedure” meant precisely that intra-operative adaptations of the soft tissues were necessary because of the non-anatomic restoration. Individualization of TKA reverses the paradigm through the restoration of the native anatomy and alignment and reduces the need for intra-operative adaptations and ligament releases [8]. The better the tools we have for personalization, the more we can standardize our surgical techniques. And while total elimination of intra-operative adaptations may seem an over-ambitious asymptote, custom implants enable a considerable leap towards that goal. The ‘custom implant paradox’ is that ‘the more we personalize TKA implants, the less we need intra-operative adaptations and the more we standardize the surgical techniques’ [27].

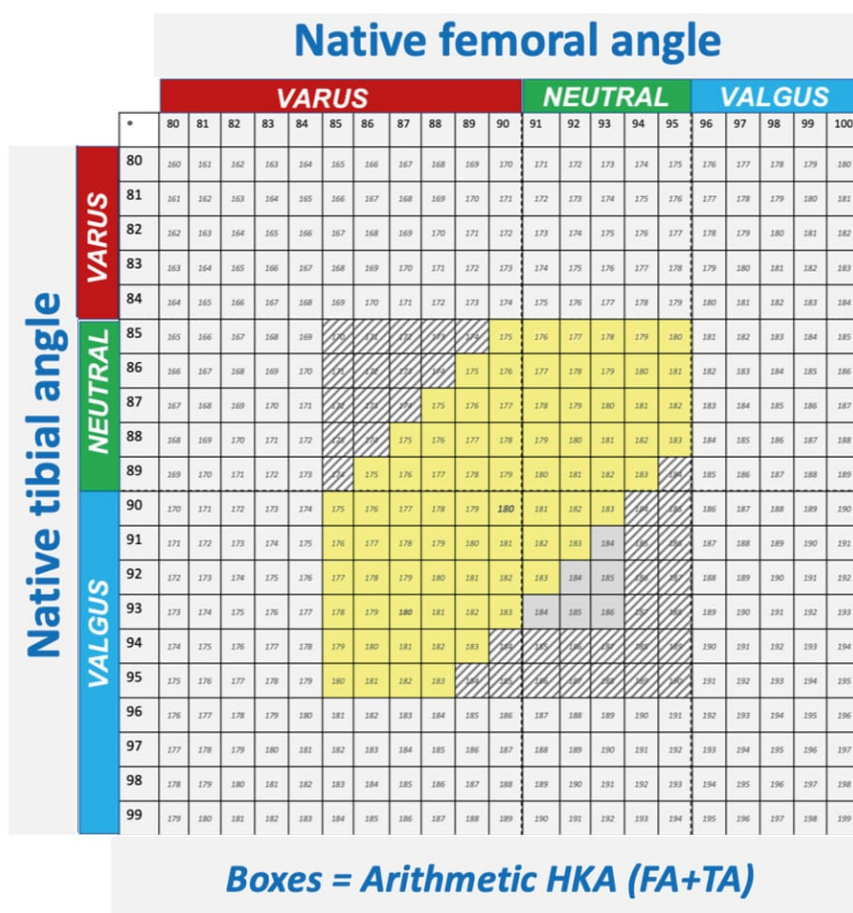


Figure 7: The safe zone is represented in yellow on this planification matrix, based on the native angle measured from the CT scan. This safe zone corresponds to Tibial and Femoral angles limited to the range [85° to 95°] and an HKA angle to the range [185° to 193°].

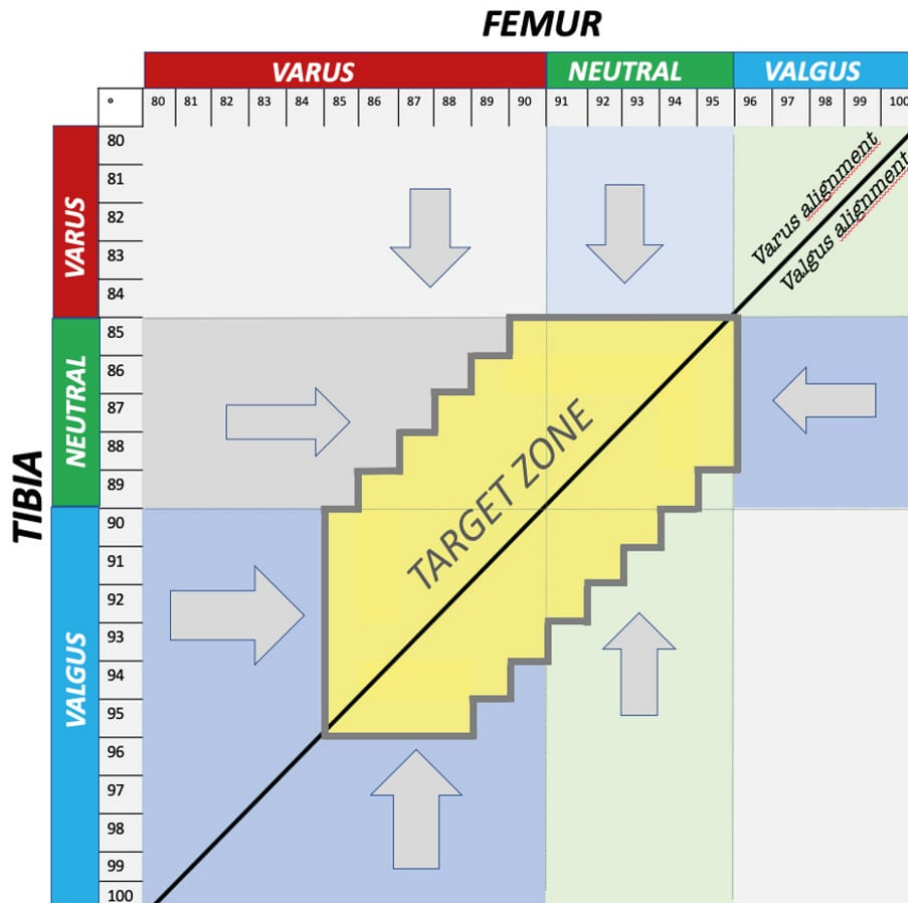


Figure 8: From the patient's CT scan, the native Tibial and Femoral angle are measured, the corresponding arithmetic HKA is calculated, and the patient is positioned on the planification matrix. When the native angles are inside the safe zone, the planning reproduce it precisely. When native angles are outside the safe zone, some corrections are included to reposition the patient inside the safe zone. This correction respects the native phenotype of the patient.

CONCLUSION

The concept of lower limb alignment during TKA is complex as it is entangled with implant design and preoperative imaging and planning techniques. Each strategy, derived from conventional technologies, has its limitations and inaccuracies, resulting in a lack of consensus. Only a comprehensive approach integrating all these aspects and using new technologies will lead to personalized and reasoned alignment.

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