MENTORS IN ORTHOPEDICS

LIGAMENT BALANCING AND ALIGNMENT

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SUMMARY

Background: Mechanical alignment (MA) has long been the standard in total knee arthroplasty (TKA), prioritizing long-term implant survival through neutral coronal cuts and ligament releases. Despite achieving high survivorship, 10% to 20% of patients remain dissatisfied due to residual symptoms and unnatural joint perception. This discrepancy has led to the development of personalized alignment philosophies, such as kinematic and functional alignment, which aim to restore native anatomy and kinematics.

Objective: This review aims to redefine the terminology regarding ligament tension and balancing while discussing the clinical implications of prioritizing ligamentous stability over strict bone alignment.

Key Points: Effective TKA implantation requires a distinction between limb alignment (HKA angle) and ligament tension, which involves distraction forces typically ranging from 60 N to 120 N. Native knee kinematics exhibit differential laxity, with the lateral compartment being more compliant than the medial side, particularly in flexion. Research indicates that achieving isometric, rectangular gaps may not replicate physiological motion; instead, maintaining a stable medial pivot with slight lateral laxity (1.5–2.0 mm) in flexion is associated with superior patient-reported outcomes. While personalized techniques like kinematic alignment aim to restore native joint line obliquity, they must remain within safe boundaries (e.g., HKA 174°–183°) to avoid increased risks of aseptic loosening or patellofemoral complications.

Conclusion: Shifting from an alignment-focused to a balance-focused philosophy, facilitated by robotic or navigational tools, allows for precise, patient-specific ligament tensioning. Restoring the pre-arthritic joint line while maintaining controlled ligamentous balance throughout the range of motion is essential for optimizing functional outcomes.

KEYWORDS

Arthroplasty, Replacement, Knee; Knee Joint; Ligaments, Articular; Biomechanical Phenomena; Robotic Surgical Procedures

INTRODUCTION

In retrospect, early total knee arthroplasty (TKA) implantations lacked precision, and technical errors were common. This was because surgeons were primarily focused on implant survival, with less emphasis on restoring the "native" anatomy and "normal" function of the knee [1]. To ensure satisfactory prosthetic survival, the mechanical alignment (MA-TKA) technique was promoted by Insall et al. in the 1980s. This involved neutral femoral and tibial frontal cuts (i.e., perpendicular to the mechanical axis), adjusted femoral rotation, and ligament release procedures to create equal flexion and extension gaps. The objective was to limit excessive stresses on the implants and, particularly, at the implant-bone interfaces [2]. This strategy, long considered dogmatic, proved successful in achieving satisfactory long-term implant survival, approaching 95% in national registries [3],[4],[5].

However, "survival" does not equate to "patient satisfaction." Indeed, after MA-TKA, many patients describe the sensation of an "unnatural" joint [6],[7], 10% to 20% of patients remain dissatisfied [8], 33% to 54% experience residual symptoms [9], and one in four patients would not wish to undergo the same surgical procedure again [10]. This finding correlates with functional restoration and mobility outcomes that are not always achieved. In fact, a number of operated patients walk with a reduced total knee range of motion, and significant kinematic discrepancies are present during gait analysis [11].

In 2010, the publication by Parratte et al. marked a turning point in the application of the mechanical alignment dogma by challenging its "protective against loosening" nature in a review of 398 cemented MA-TKAs at 15 years [13]. Over the past fifteen years, new, so-called personalised alignment philosophies have been described with the aim of improving patient outcomes and satisfaction by seeking to approximate the patient's pre-arthritic anatomy. Indeed, human knee anatomy is highly variable, and pathological changes further accentuate these constitutional deformities. Several studies have described different patient phenotypes and insist on respecting them during TKA implantation. Among these alignment techniques, we can cite kinematic alignment (KA), which aims to "resurface" the knee; restricted kinematic alignment (rKA), which limits the excesses of KA in extreme cases; inverse kinematic alignment (iKA), based on aligning the femur after performing the initial anatomical tibial cut; and finally, functional alignment (FA) [14]. Adjusted mechanical alignment (aMA) can also be mentioned.

Furthermore, the development of these techniques has occurred in parallel with the development of new implants (design), patient-specific instrumentation (cutting guides), navigation tools, robotics, and augmented reality.

This multitude of technical and technological proposals, however, creates a degree of confusion for the surgeon in fully understanding the specificities and benefits of each. Moreover, the scientific literature is of somewhat limited help in decision-making. Whilst publications on the different alignment techniques have been numerous in recent years, none have shown the significant superiority of one type of alignment over another in terms of improving PROMs (Patient-Reported Outcome Measures) quality of life scores, despite encouraging functional outcomes. Thus, despite this desire to restore "ideal" and/or native alignment, patient satisfaction still remains unsatisfactory [12].

More recently, faced with "the relative inadequacy of replicating anatomy as a factor for improving patient satisfaction," research has increasingly focused on native knee kinematics as the ultimate goal of TKA. This notion of native knee kinematics, in addition to the question of "ideal" knee alignment, brings us back to the concept of optimal or optimised ligament balance. This hypothesis is not new; in the 1980s, Insall already considered that "Knee replacement surgery is soft tissue surgery" [15]. For all these reasons, ligament balancing has, for several years now, appeared to us to be the priority target in TKA implantation, beyond alignment and probably correlated with it – a fundamental point to master for a high-quality and durable implantation.

The objective of this review is, firstly, to clearly redefine the terminology necessary to understand the management of ligament tension and, secondly, to discuss the practical consequences in terms of tensioning objectives, its interplay with knee alignment, and the means to achieve them.

DEFINITIONS

The implantation of a TKA and the different implantation philosophies refer to three notions: alignment, ligament tension, and ligament balancing.

The notion of alignment is an arithmetical concept based on the measurement and restoration of axis values, angles, and/or bone resection measurements during TKA implantation. A distinction must be made between the measurements defining:

- “Knee alignment”, with the inclination angles in the frontal plane of the tibia (MPTA, Medial Proximal Tibial Angle) and femur (LDFA, Lateral Distal Femoral Angle), and in the sagittal plane with the tibial slope.
- and “Limb alignment”, described by the hip-knee-ankle (HKA) angle. This angle is affected by osteoarthritis. To “mitigate” this impact and effectively estimate the constitutional lower limb alignment as it was before the onset of osteoarthritis, the aHKA for “Arithmetic hip-knee-ankle angle” has recently been defined. The aHKA is calculated by subtracting the LDFA from the MPTA. This aHKA angle is independent of the loss of joint line height due to cartilage wear and of femorotibial subluxation in cases of severe osteoarthritis. It is also independent of intra-articular knee deformity (JLCA, Joint Line Convergence Angle) [16].

Recently, to facilitate research and computerised planning in this plane, a classification of knee alignment in the coronal plane (CPAK, Coronal Plane Alignment of the Knee) has been described [17]. However, coronal alignment is only one of the three dimensions that must be considered when implanting a TKA (axial, coronal, and sagittal). This classification proves to be primarily useful for scientific purposes for comparing different patient types rather than being an aid in clinical practice.

Ligament tension is a biomechanical concept that refers to the notion of forces. For TKA implantation, it corresponds to the distraction forces applied to the medial collateral ligament (MCL) and lateral collateral ligament (LCL) during trials and prosthetic implant placement. Several studies have analysed the mean pre-tensioning forces in the collateral ligaments of the knee during these arthroplasties. These forces average 72 N per compartment (i.e., 145 N in total for the knee) according to Walker et al. [18] and approximately 120 N according to Asano et al. [19]. Thus, the forces to be applied instrumentally with a ligament tensor, commonly accepted in the literature, range between 60 N and a maximum of 120 N, whilst 45 N is the minimum value considered to initiate ligament tension. Therefore, 90 N represents an average force for measuring femorotibial gap distances in extension and flexion without excessive or insufficient ligament tension. The objective here is to avoid inappropriate ligamentous constraints that could lead to laxity or secondary stiffness.

This ligament tension is therefore a key element to control during TKA implantation. This tension should not be confused with the concept of measuring femorotibial gaps, even though these elements are correlated. The distraction force is the applied force, the result of which, in terms of measurement, are the gaps. Ligaments are indeed elastic connective tissues, so the space in a compartment can increase if the distraction forces increase.

Any excessive stress imposed on the LCL or MCL during TKA implantation leads to an elongation of each collateral ligament of the order of 25-50 N/mm, translating to an imprecision of approximately 2-3 mm in practice in the assessment of the femorotibial gap in the absence of controlled applied tension.

Ligament balancing is a dynamic and surgical biomechanical concept [20],[21] that is fundamental to understanding the review proposed here. It is the assessment of the balance between the ligament tension of the medial and lateral femorotibial gaps throughout the knee's range of motion, from extension to flexion. In knee arthroplasty, ligament balancing is therefore the concomitant management of ligament tension in the medial compartment/MCL and the lateral compartment/LCL. A knee or TKA has "balanced" ligaments when the MCL and LCL ligaments are tensioned identically (even if the medial and lateral flexion and extension gaps are not perfectly equal throughout the range of motion). The consequence of all this is that, during TKA implantation, the balancing of the femorotibial compartments in flexion and extension, or especially throughout the entire range of motion medially and laterally, necessarily, and in our view primarily, involves control of the applied and monitored ligament tension.

It is therefore fundamental not to confuse this notion of tensional ligament balancing with the concept of the gap after bone resection. For the same applied ligament tension, if the medial and lateral femorotibial gaps are equal, we speak of gap isometry. If these femorotibial gaps are different for the same tension applied in each compartment, we speak of anisometry. It is important, however, to specify that the main objective is not necessarily "gap isometry" but rather a well-balanced ligament system. Indeed, the flexion gap is natively anisometric (Figure 1).

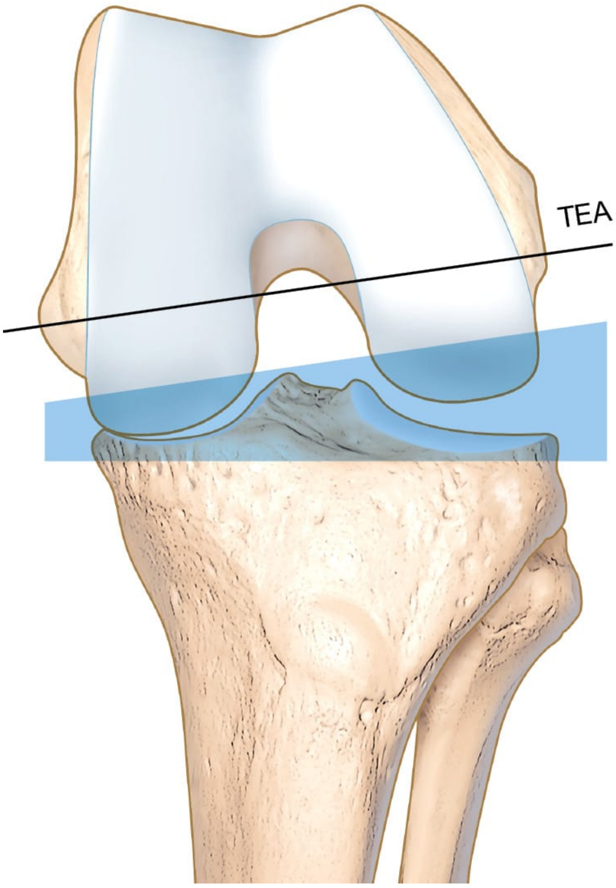
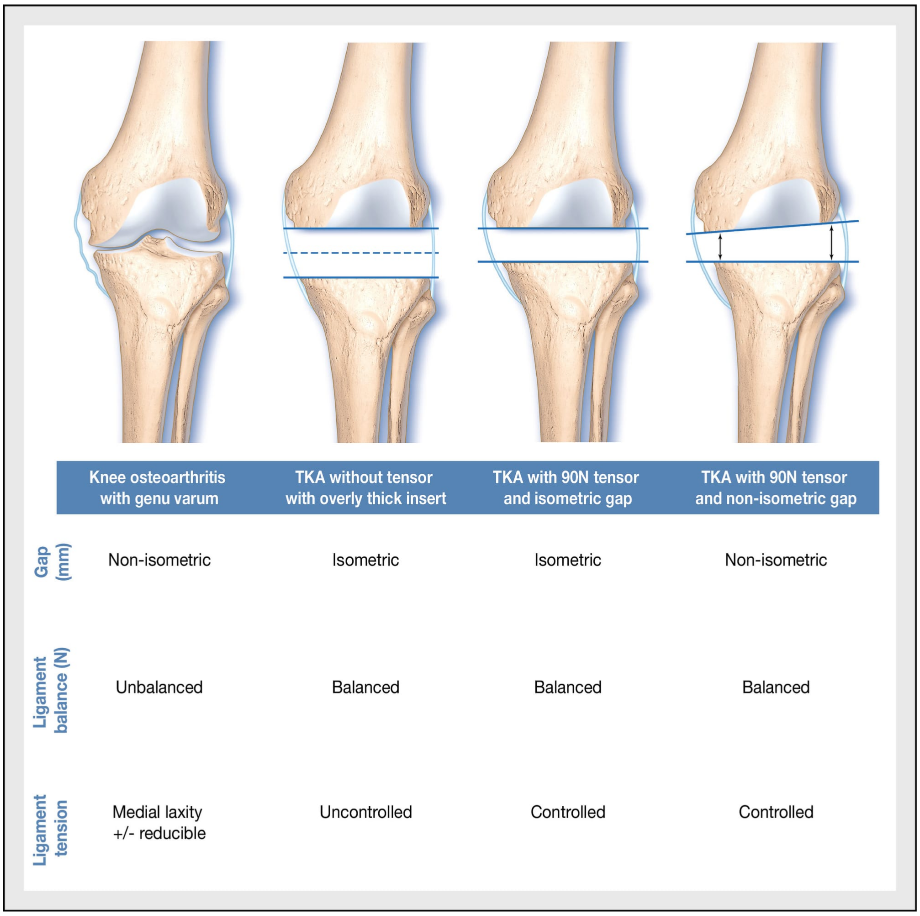


Figure 1: Importance of lateral space over medial space

Following this reasoning, constantly aiming for isometric mediolateral gaps in flexion/extension without considering ligament balance could explain, at least in part, the mixed functional outcomes reported in meta-analyses.

In practice, we can define different situations based on the concepts of isometric or non-isometric gaps, controlled or uncontrolled tension, and ligament balancing (Table 1).



	Knee osteoarthritis with genu varum	TKA without tensor with overly thick insert	TKA with 90N tensor and isometric gap	TKA with 90N tensor and non-isometric gap
Gap (mm)	Non-isometric	Isometric	Isometric	Non-isometric
Ligament balance (N)	Unbalanced	Balanced	Balanced	Balanced
Ligament tension	Medial laxity +/- reducible	Uncontrolled	Controlled	Controlled

Table 1

WHAT IS THE DEFINITION OF OPTIMISED LIGAMENT BALANCING?

Ensuring balanced ligaments is a guarantor of satisfactory clinical outcomes in total knee arthroplasty (TKA) [22]. By prioritising this objective, it must be accepted as a corollary that bone resections may be asymmetrical (or not) and gaps anisometric (or not). Similarly, mediolateral and/or flexion/extension laxity differences may exist without being detrimental to the TKA outcome. These notions of ligament laxity and gap isometry fuel discussions [30]. Several elements are to be discussed:

Variability of native and prosthetic ligament laxity

In the native anatomy of the knee, physiologically, the medial compartment is more isometric than the lateral compartment (LCL). There is a differential ligament laxity for both the MCL and LCL depending on the zones of the range of motion arc, as they are tighter in extension than in flexion. This differential laxity is also found between the two collateral ligaments; the native knee appears laxer laterally than medially, a situation amplified in flexion [31] for the same ligament tension.

In an MRI study on live knees in 90 degrees of flexion, the lateral joint space opening was measured at 6.7±1.9 mm, whereas the medial joint space opened on average only 2.1±1.1 mm (0.2 to 4.2). These discrepancies indicate that the normal tibiofemoral flexion gap is not rectangular and that the lateral joint space is significantly looser. Furthermore, ligament laxity is greater in women than in men, and interindividual variation is significant. This wide variability of laxity in the population indicates that MA or any other technique whose sole objective is to create equal medial and lateral femorotibial gaps without controlling the ligament tension in each compartment would not perfectly restore correct knee kinematics [25],[26],[27]. Moreover, the most relevant ligament tension analysis appears to need to be performed throughout the entire range of motion, because even if the knee is stable at 0° and 90°, mid-flexion laxity may exist [28],[29]. Finally, human knee anatomy is highly variable and is aggravated by pathological changes. In addition, during TKA implantation, resection of the menisci and cruciate ligaments modifies native knee laxity. Sectioning the LCA (anterior cruciate ligament) increases the lateral extension gap by approximately 2 mm, and sectioning the LCP (posterior cruciate ligament) increases the flexion gap by 3 mm at constant tension.

Isometric or anisometric gaps?

There is some disagreement regarding the importance of aiming for perfect rectangular gaps during total knee arthroplasty (TKA). Conversely, blindly reproducing patients' identical anatomy, if it is at least partly responsible for the osteoarthritis, may seem risky today, potentially negatively impacting TKA biomechanics and degrading its outcome more rapidly [23],[24], even if replication of native knee kinematics remains the ultimate goal of TKA implantation.

Whilst most surgeons target a rectangular flexion gap in TKA, unlike in the native knee, some, prioritising ligament balancing, have accepted asymmetrical bone resections. Meneghini et al. evaluated the effect of in vivo flexion gap asymmetry on patient-reported outcome measures (PROMs) in contemporary TKAs. The results of this study suggest that patients with either a balanced and isometric flexion gap or lateral flexion laxity have superior PROMs. This study shows the clinical advantage of facilitating posterolateral femoral rollback in flexion, which mimics native knee kinematics [32],[33]. Thus, achieving symmetrical and rectangular gaps in flexion and extension would not correspond to the native knee's kinematic profile. A perfectly isometric gap in extension and in flexion therefore does not seem suited to native knee kinetics and supports the idea of tolerating a larger lateral than medial flexion gap (Figure 1). This seems to be explained by the fact that residual lateral laxity might be necessary for the normal knee's medial pivot movement. A question arises: what average tolerance can we then apply to mediolateral and flexion-extension gap differences? Indeed, varus-valgus laxity is negligible in extension and increases with flexion, being more significant at 90°, especially in varus.

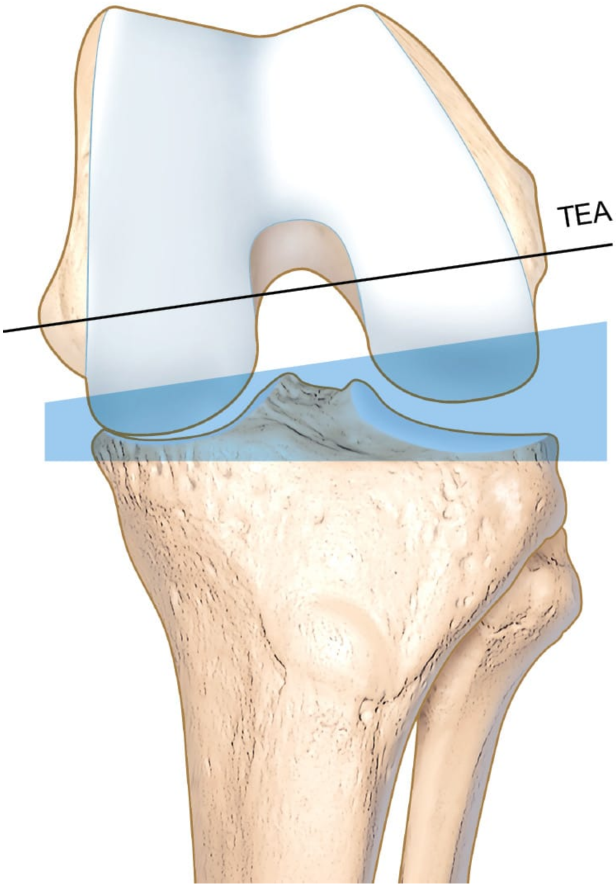


Figure 1: Importance of lateral space over medial space

To improve ligament balance, the surgeon can thus decide to modify the native knee's bone anatomy with reference to either the medial, lateral, or bilaterally balanced compartment, thus defining 3 different pivot points for performing the cuts: medial, central, or lateral. The medial compartment is the stability compartment: it should be considered the reference, as the MCL is the most isometric. The lateral compartment is the mobility compartment, with greater tolerable laxity, especially in flexion, of the order of 1-2 mm in extension and 1-3 mm in flexion at 90°, for the same tension in both compartments. A medial pivot point will therefore allow restoration of the most isometric medial compartment gap in extension and flexion, with a resection thickness equal to that of the implant, and will modify the resection gap on the lateral side. This concept of a medial pivot is also still debated. Although patient-specific laxities in TKA remain to be determined, the trend is to restore a rectangular extension gap and a slight lateral opening in flexion, of approximately 1.5-2 mm **[34],[35]**.

The TKA design must also be considered. Thus, there is a genuine debate on how to define a "balanced" TKA and on the most effective way to achieve optimal balance, which is likely prosthesis-specific. For posterior-stabilised (PS) TKAs, the dogma is balancing with isometric gaps in full extension and at 90° of flexion; however, this does not account for the consequences of cruciate ligament section throughout the range of motion, particularly in mid-flexion and flexion beyond 100°, where stability is provided by the posterior capsule and no longer by the collateral ligaments. In cruciate-retaining (CR) TKAs, optimal balance may be a stable medial compartment and a looser lateral joint which, together, facilitate posterior migration of the articular contact point as flexion increases **[38]**.

Current findings also challenge the recent concept that reproducing constitutional knee alignment in its extreme variants is the main driver of near-normal knee kinematics and joint proprioception: whilst reproduction of joint line obliquity by planned bone cuts plays a major role in the alignment of the knee joint's coronal and transverse planes [36], restoration of the "static" pre-arthritic joint line is not sufficient to recover the joint's true pre-arthritic kinematics, which are "dynamic" by definition. In summary, patients with a slight increase in lateral laxity, in both extension and flexion, exhibited knee kinematics closer to normal. These elements tend to show the limitations of an "all-alignment" reasoning as a guarantee of TKA outcome.

Of course, excessive lateral laxity can be detrimental [37].

Wakelin EA et al. [39] showed that TKA implantation with intraoperative control of ligament balance was associated with better outcomes and less pain. Also, Lee GC et al. [40] showed that a robotically balanced knee with a 1 mm difference between the medial and lateral sides in flexion and extension was correlated with better outcomes and less pain at 1 year. Keggi et al. [41] report that the use of robotic predictive balancing improved TKA outcomes, with better results seen in balanced knees. Limiting medial and lateral flexion laxity to less than 1.5 mm resulted in an increased likelihood of achieving less pain at 12 months.

Vigdorchik et al. [42] note that adding soft tissue release procedures after bone cuts is associated with worse KOOS scores for up to 2 years, but with a bias, which is a higher frequency in the most deformed knees, hence the most difficult to balance. According to him, only a robotic tool can effectively control ligament tension. We consider more broadly that only navigation allows real-time determination of ligament tensions and thus the achievement of optimised ligament balancing.

What are the limitations of prioritising ligament balancing?

The prioritisation of ligament balance management cannot be entirely independent of alignment parameter management.

Indeed, current survival series of prostheses that underwent kinematic alignment seem to show a higher risk of loosening. Sappey Marinier et al. report significantly higher survival at approximately 4-5 years of follow-up in the MA-TKA group compared to the reverse KA-TKA group (97% vs 84%; $p<0.001$), with the endpoint being revision for aseptic loosening. An increased risk of tibial implant loosening was observed with rKA compared to MA using a posterior-stabilised TKA in the short term [43].

Acceptable alignment boundaries must therefore be respected in all cases, as defined in functional alignment by Lustig et al. [44]:

- Tibia: mMPTA from 6° varus to 2° valgus
- LDFA: 6° valgus to 3° varus
- HKA= 174° to 183°, corresponding to 93% of the Caucasian population [60]
- External Rotation (ER) > 0°

However, coronal plane alignment and ligament balance management should not overlook the "3rd compartment" of the TKA, the patellofemoral joint, a common cause of TKA failure or dissatisfaction. Indeed, after pure kinematic alignment, an increase in patellar complications has been described [45],[46],[47]. The distal femoral valgus angle relative to the mechanical axis can exceed 10°, displacing the prosthetic trochlea medially, which can impair patellar tracking, leading to patellar subluxation or lateral patellar facet conflict in some patients. Even with a medial pivot TKA without patellar resurfacing, Øhrn et al. [48] reported a higher rate of revisions for instability, malalignment, and patellar erosion.

The use of a tensor in "ligament balancing" procedures allows for more personalised determination of femoral rotation. In our experience with navigation, variations in femoral rotation distribution range from 0° to 11°, with 33% of patients not exhibiting rotation greater than 3°. Applying a ligament balancing procedure with a tensor therefore allows for fine-tuning of the patellofemoral engagement setting. It also allows for choosing, in real-time, the best compromise between balance and joint line height, which helps to correct a patella baja or alta whilst “keeping control” over the optimal balance we wish to achieve. These compromises are only possible during a ligament balancing procedure conducted with computer-assisted surgery, whether robotic or not. Recently, Shatrov et al. described an adaptation of their robotic navigation to allow patellar tracking monitoring, thereby redefining the concept of patellofemoral balancing thanks to the additional information provided to better understand patellofemoral biomechanics and their relevance to clinical outcomes after total knee arthroplasty. Intraoperative assessment of patellar tracking in TKA remains vague, both in terms of patellofemoral centering and the thickness of the anterior patellofemoral space (understuffing and overstuffing). Respect for the ligament balance of the “3rd compartment” therefore also seems predominant, although still difficult.

Genestoux et al. recently published a series of patients operated on using the inverse kinematic alignment technique and showed that performing a personalised alignment respecting tibial anatomy with an initial iKA tibial cut allowed for better control of femoral implant rotation and better functional scores [59].

Towards which solutions during TKA implantation?

TKA implantation seems to require a compromise between optimised ligament balancing, a lower limb axis close to native anatomical variation within acceptable limits, and respected extensor mechanism function through restored or corrected patellofemoral adjustment. This latter aspect, which is not central to this article, is nonetheless fundamental; this part of the implantation procedure is facilitated by navigated ligament balancing, as we have mentioned.

Navigation and robotics provide us with precise real-time information to plan our choices and very good precision in cuts to restore knee and limb alignment. A navigated ligament balancing procedure, in our experience, offers added value for the reasons discussed in this article.

The limitation lies in the routine use of mechanical tensors, which only allow balance acquisition at 90° flexion and in extension.

Determining ligament balance throughout the entire range of motion requires the use of controlled ligament tensors, applying independent controlled tension to the medial and lateral compartments, and operating with the patella in situ (reduced) to avoid any valgus constraint in the event of patellar eversion via a medial parapatellar approach. Whilst checking flexion-extension gaps is easy in conventional surgery, finding the right tension throughout the full range of motion is more difficult. Indeed, Shady SS et al. [49] showed in a cadaveric study that subjective soft tissue assessment led to a 1 to 2 mm variation in insert thickness choice. Consequently, the development of tools to standardise soft tissue assessment in TKA to control the force applied by the surgeon, in order to better control variations in insert selection, is necessary.

The surgeon will need to prioritise and define their objectives:

- Balance = primary objective with a knee with balanced ligaments under a controlled tension of 90N, throughout the entire range of motion (flexion, extension, and mid-flexion), with slightly greater lateral laxity in flexion.
- Alignment = secondary objective with a knee aligned within safe boundaries.

The “all-alignment” logic does not prevail. For us, it is a secondary objective, even if it remains fundamental.

Alignment strategies based solely on bone anatomy seem to lead to unacceptable laxity variability. In a study on 382 robot-assisted TKAs performed with a digital tensor, simulations of TKA with pure kinematic alignment showed great variability in the resulting laxity and alignment outcomes. Most knees exhibited alignment and balance results outside normally accepted ranges. Only 11% to 31% of knees would have mediolateral extension ligament balance within ±1 mm, and 20% to 41% would have a medial flexion gap looser than the lateral flexion gap. More than 45% of knees would have an HKA angle greater than 3 degrees from mechanical neutral. Techniques that deviate from pure kinematic alignment to achieve balance therefore seem favourable [50].

This is all the more true as the alignment technique contributes more to laxity and balance variability than implant design. Implant geometry has limited effect on mediolateral balance variability. Laxity variability due to alignment technique was similar to the variability measured in the arthritic knee population. Greater attention should be paid to the alignment technique rather than implant geometry when achieving balance in TKA [51].

Considering the numerous morphological variations, ligament balancing is the most informative and adaptive procedure during navigated surgery.

Techniques based on navigated ligament balancing seem to yield good results in the literature. In a comparative study, mechanical alignment resulted in tighter joints, with mediolateral gap imbalances > 3 mm in 30% of knees. Ligament balancing planning improved mediolateral balance throughout flexion [52]. Compared to restricted kinematic alignment, both techniques reported greater lateral laxity in flexion, but the digital ligament balancing technique better improved mediolateral balance in flexion from 10° to 45° [53].

Compared to inverse kinematic alignment techniques, the navigated ligament balancing technique yielded similar results in terms of ligament balance, laxity, and aHKA, but inverse kinematic alignment techniques better restored native JLO (Joint Line Obliquity) and CPAK phenotypes [54]. Indeed, this strategy has shown its effectiveness in best restoring the pre-arthritic morphotype of the majority of patients. Strauch et al. [56] reported a series of 367 patients who underwent navigated TKA using a patient-specific alignment technique with an initial tibial cut and ligament balancing aimed at achieving balanced gaps and simultaneously reconstructing the individual bone phenotype. Resection limits for the medial proximal tibial angle (MPTA) of 86° to 92°, the mechanical lateral distal femoral angle (mLDFA) of 86° to 92°, and the hip-knee-ankle (HKA) angle of 175° to 185° were defined. This technique achieved balanced gaps in extension, flexion, and mid-flexion in over 90% of cases. Similarly, Graichen et al. [57], using the same restricted patient-specific alignment technique, focused on tibia-first and secondary femoral ligament balancing to restore bone morphology and phenotypes in 367 patients, found restoration of bone phenotypes and joint line obliquity in the majority of neutral and varus knees, and most valgus and extreme varus knees were normalised.

Finally, improvements in balance were observed in mid-flexion instability and balance variability throughout flexion when a tibia-first approach in combination with a digital balancing tool was used. The combination of a digital balancing tool and a tibia-first approach achieved a target joint balance with more precision compared to a sensorless augmented or femur-first approach [55].

The technique should, as Einstein said, "...be made as simple as possible, but not simpler."

A reliable and reproducible technique is also necessary, called: "restricted and functional anatomical patient-specific implantation technique by kinematic ligament balancing."

- Systematic patellar resurfacing to avoid any patellofemoral overpressure and poor patellar tracking.

- Planning and control of cuts by robot or navigation.

- Respect for the patient’s pre-arthritic tibial anatomy by respecting joint line orientation (JLO) and performing an initial tibial cut according to the patient’s MPTA, and aiming for a limb axis (aHKA) close to the pre-arthritic anatomy.

  - JLO = MPTA+ LDFA
  - aHKA = MPTA - LDFA

- Kinematically aligned and balanced, the femur positioned with a standardised ligament tensor at 90 N, throughout the entire range of motion, to achieve ligament balance independent of the medial and lateral compartments, with constant ligament tension with the patella in situ. Anisometry will be possible with a slightly laxer lateral compartment in flexion.

Aberrant anatomies (e.g., extreme varus/valgus and/or significant patellar maltracking) will warrant adjustments.

This philosophy can be defined as a technique for personalised implant positioning through kinematic ligament balancing and restricted, functional anatomical alignment for TKA implantation.

The implant type should also be considered in this balancing and alignment strategy.

CONCLUSION

Surgeons have long focused on TKA survival at the expense of functional outcomes, which remain unsatisfactory. They have used increasingly robust conventional instruments to ensure procedural reproducibility and have improved TKA designs, implanting them according to mechanical alignment principles and based on their intuition and experience. However, digital measurement tools have provided multiple pieces of information allowing for personalised TKA implantation, thereby multiplying surgical philosophy choices and the definition of targets and limits.

Today, the data that seem most important are:

- The orientation and height of the joint line, to be restored by accurately reproducing the pre-arthritic tibial anatomy and using the femur to balance the knee, all within well-described limits.
- The management of ligament tension in each compartment throughout the range of motion (equal medial and lateral gap in extension, and medial gap in flexion, with slight lateral laxity in flexion).

The definition of boundaries in terms of alignment and laxity remains a crucial challenge to secure the surgeon’s procedure and the patient’s outcome. Thus, without abandoning alignment concepts, shifting from an “alignment-focused” philosophy to a “balance-focused” philosophy could be a path to improving our results. However, it will be crucial not to forget the patella in this analysis, including its height, patellar fill/profile, and centering.

The main strengths of a good implantation assistance system, whether robotic or navigation-based, will therefore be:

- to allow 3D analysis of native anatomy
- to facilitate patient-specific alignment
- to help “balance” the knee
- to offer accurate reproducibility and precision of bone resections

- to validate the “planned” versus the “executed”
- and to capture data allowing for the improvement of our knowledge, particularly via AI tools enabling predictive surgery.

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