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Mechanical alignment technique for TKA: Are there intrinsic technical limitations?

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ABSTRACT

Background: Mechanically aligned (MA) total knee arthroplasty (TKA) is affected by disappointing functional outcomes in spite of the recent improvements in surgical precision and implant designs. This might suggest the existence of intrinsic technical limitations. Our study aims to compare the prosthetic and native trochlear articular surfaces and to estimate the extent of collateral ligament imbalance, which is technically uncorrectable by collateral ligament release when TKA implants are mechanically aligned.

Study hypothesis: Conventional MA technique generates a high rate of prosthetic overstuffing of the distal groove, distal lateral trochlear facet and distal lateral femoral condyle (Hypothesis 1), and technically uncorrectable collateral ligament imbalance (hypothesis 2)? Disregarding the distal femoral joint line obliquity (DFJLO) when performing femoral cuts explains distal lateral femoral prosthetic Stuffing and uncorrectable imbalance (hypothesis 3)?

Methods: Twenty patients underwent a conventional MA TKA. Pre-operative MRI-based 3D knee models were generated and MA TKA was simulated. Native and prosthetic trochlear articular surfaces were compared using in-house analysis software. Following the automatic determination by the planning software of the size of the extension and flexion gaps, an algorithm was applied to balance the gaps and the frequency and amplitude of technically uncorrectable knee imbalance were estimated.

Results: The conventional MA technique generates a significant slight distal lateral femoral prosthetic overstuffing (mean 0.6 mm, 0.8 mm, 1.25 mm for the most distal lateral facet point, groove, and at the most distal point of lateral femoral condyle, respectively) and a high rate of type 1 and 2 uncorrectable knee imbalance (30% and 40%, respectively). The incidence of distal lateral prosthetic overstuffing (trochlea and condyle) and uncorrectable knee imbalance were strongly to very strongly correlated with the DFJLO (r = 0.53 to 0.89).

Conclusion: Conventional MA technique for TKA generates frequent lateral distal femoral prosthetic overstuffing and technically uncorrectable knee imbalance secondary to disregarding the DFJLO when adjusting the femoral component frontal and axial rotations, respectively.

Level of evidence: level 4.

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1. Introduction

For decades, a stable knee with a neutral mechanical axis lower limb alignment has been one of the primary goals of mechanically aligned (MA) total knee arthroplasty (TKA) because it was believed to be important for successful clinical outcomes and implant survivorship [1–3]. The joint line is made perpendicular to the neutral mechanical axis of the limb and the femoral component is expected to be frontally and axially aligned with the trans-epicondylar axis (TEA), which then becomes the flexion-extension axis of the knee [4]. The aim is not to restore the constitutional knee anatomy but rather to obtain a “biomechanically friendly prosthetic knee”, which aims at reducing the adduction moment and at distributing the load more evenly on the tibial compartments in order to prevent instability, accelerated polyethylene wear and early implant loosening. Moreover, the extensor mechanism is frontally aligned in order to prevent patella instability [5]. MA TKAs with modern implant designs are barely affected by loosening and wear [2,6], but remain functionally disappointing with are portedly high rate of residual symptoms (50% – pain, instability, stiffness, swelling, etc.)

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and patient dissatisfaction (10 to 20%) [7]. Interestingly, neither “precise cutting tools” improving implant positioning (computer assisted surgery, CAS and robotic technologies), nor the constant improvement of implant designs have solved this issue [8–11], suggesting that this is likely to be a consequence of the poor restoration of patient-specific knee kinematics [12].

The inability to significantly improve functional outcomes after MA-TKA might highlight the existence of potential intrinsic limitations in disregarding patient-specific knee anatomy and the potential to generate frequent collateral ligament imbalance that are technically uncorrectable by collateral ligament release [13], which could prevent good functional outcomes. To illustrate, it is well known that patellofemoral complications after MA TKA are largely dominated by anterior knee pain, which has generally been attributed to abnormal patellar mechanics [14–17]. Also, we know that the patella follows a circular path mainly determined by the trochlea's geometry [18–20] (by the circular trochlear groove proximally and by the inner part of medial and lateral condyles distally) and the lateral soft tissue restraint (lateral retinacular ligament) [21], which is a complex multi-layered structure linking the patella to the ilio-tibial band (ITB) (superficial ITB-patellar fibres) and the lateral femoral condyle (deep lateral patellofemoral ligament, LPFL) [21]. Therefore, as the distal femoral cut with MA technique is performed disregarding the frequently valgus oriented DFJLO, it is probable that this frequently generates distal lateral prosthetic overstuffing (trochlear facet and femoral condyle) which likely causes stretching of the lateral retinaculum during knee flexion thereby affecting patients’ functional outcomes.

Our study therefore aims to compare the prosthetic and native trochlear articular surfaces and to estimate the frequency of collateral ligament imbalance that is technically uncorrectable by collateral ligament release when TKA implants are mechanically aligned. We therefore tested the following hypotheses: does the positioning of TKA implants following a conventional MA technique generate a high rate of prosthetic overstuffing of the distal groove, distal lateral trochlear facet and distal lateral femoral condyle (Hypothesis 1), and technically uncorrectable collateral ligament imbalance (hypothesis 2)?

Does disregarding the distal femoral joint line obliquity (DFJLO) when performing femoral cuts explain distal lateral femoral prosthetic stuffing and uncorrectable imbalance (hypothesis 3)?

2. Methods

2.1. Population

A total of 20 patients, (9 females and 11 males, mean age 71 years [61–81], mean BMI 27.4 (20.3–36), primary medial tibio-femoral bone on bone osteoarthritis Ahlbäck ≤ 3). Mean pre-operative frontal limb alignment was 175° including fourteen patients with more than three degrees of varus angulation, four with more than three degrees of valgus angulation and two neutrally aligned. Patients had knee Magnetic Resonance Imaging (MRI) before they underwent a MA-TKA. Patients were already enrolled in a previously published randomized controlled trial [22] for which they gave informed consent. Because images and clinical data from this previous study [22] were all anonymised, our current retrospective study was not subject to further approval by our institutional review board.

2.2. Generation of a 3D knee model

Patients’ MRIs were segmented using Mimics® software (Materialize, Belgium) which included slices through the “hip-knee-ankle”. Twenty 3D bone models (cartilage not segmented) of the lower extremity, including the femoral head, knee and distal tibial plafond, were created.

2.3. Simulation of mechanical implant positioning (Fig. 1)

A set of Persona® TKA implants (Zimmer, Warsaw, USA) were laser scanned (C-track 780 3D laser scanner, Creaform, Québec, Canada) to create 3D implant models, which were then mechanically aligned on the bone models using in-house planning software (Fig. 2). The mounting protocol aimed a MA technique with measured resection and posterior referencing techniques. The distal and posterior condyles (medial and lateral) of the Persona® femoral component were 9 mm thick, and the minimal tibial component thickness was 10 mm. In order to match implant thickness, femoral and tibial components were perpendicularly aligned to their frontal mechanical axes (femur and tibia, respectively) and 9 mm and 10 mm of bone was removed on the distal part of the medial femoral condyle and on the medial tibial plateau, respectively. Taking into account that cartilage thickness on the posterior part of femoral condyle is 2 mm and usually remains in medial tibio-femoral osteoarthritis [23], the simulated posterior medial condyle cut aimed at removing 7 mm of bone. Sizing of the femoral implant was done to achieve an anterior femoral cut flush with the anterior femoral cortex. The tibial posterior slope and the femoral flexion were set systematically at 3 degrees relative to the sagittal/tibial and femoral mechanical axes, respectively. The axial femoral component rotation was adjusted about the centre of the implant and systematically set at 3° external rotations relative to the posterior condylar line (PCL, conventional technique, Fig. 3). In order to answer the third hypothesis, a different femoral implant rotation, a patient-specific rotation equalising the amount of DFJLO, was simulated (alternative Ω-angle technique, Fig. 4).

2.4. Method to assess the generation of collateral ligament knee imbalance

The in-house planning software used to simulate implant positioning also did an automated measure of the native DFJLO relative to the frontal femoral mechanical axis and enabled an automated determination of the maximum thickness of the bone cuts regarding the medial and the lateral tibio-femoral compartments. The need and magnitude for collateral ligament release required to correct the tight collateral ligament(s) and create balanced rect-angular flexion and extension gaps and the determination of the prosthetic knee balance status (presence and magnitude of technically uncorrectable imbalance) were defined by applying the following algorithm. We first balanced the extension gap and determined the amount of lengthening of the collateral ligament needed, then we considered this ligament lengthening to have the same impact on the flexion gap. We therefore defined the quality of balance based on the flexion gap, considering the gap to be imbalanced if there was ≥ 2 mm of difference between medial and lateral compartments. This threshold of 2 mm was considered relevant because surgeons intra-operatively exchange tibial liners that differ by increments of 1 or 2 mm in thickness in order to fine-tune stability. This imbalance was considered as uncorrectable by collateral ligament release as any attempt to balance the flexion gap would affect the balance of the extension gap. The balance status of the prosthetic knee was defined with two different philosophies (goals) of knee balance: firstly, obtaining rectangular and symmetrical extension and flexion gaps (goal 1: imbalance type 1) and secondly, the preservation of patient-specific physiologic lateral laxity in flexion which is on average 1.5 mm higher than the medial tibio-femoral physiologic laxity [24] and is likely to

2.5. Method for comparing native and prosthetic trochlear articular surfaces (Fig. 1)

Analysis software written specifically for this study was used to measure stuffing between native and prosthetic articular surfaces (Fig. 5). A reference axis, named the “patellar axis”, was generated as a line passing through the centre of the circle best fitting the native trochlear groove, and being parallel to the cylindrical (or trans-condylar) axis. Cutting planes were rotated about the patellar flexion axis in 1° increments along the trochlea. To account for the difference in angular sweep between trochleae, degrees of rotation were converted to a percentage rotation, where 0% and 100% were defined as the most proximal and distal points on the native groove, respectively. No measurement was done proximally to the native trochlea. We also measured the difference in stuffing between native and prosthetic surfaces at the most distal point of the lateral distal condyle, which was manually defined in the sagittal plane relative to the sagittal femoral mechanical axis, and approximated 110% of the revolving process. The difference in stuffing between native and prosthetic articular surfaces was the parameter of interest and was automatically calculated by the analysis software (Fig. 5). As we didn’t segment cartilage and therefore created pure bone models, 2 mm

Fig. 1. The four steps to enable comparison of prosthetic and native articular surfaces.

Fig. 2. Planning software with simulation of bone cuts (distal femoral [A] and tibial [B]) and automated calculation of their thickness.
were added to each measure of the native articular surfaces, corresponding to the average physiological cartilage thickness in the knee [23,26].

2.6. Statistical analysis

The reliability of measurements was tested by repeating measurements in 4 randomly selected knees by two observers (intra- and inter-observer reliability), using the intraclass correlation coefficient (ICC). The ICC was calculated as a one-way random effects model of single measures for each variable and resulting ICCs indicated good agreement (0.72 to 0.91). Paired t-tests were conducted to compare native and prosthetic articular surfaces (lateral and medial facets, and groove) at 10%, 30%, 50%, 70%, 90%, and 100% of the revolving process. Results are presented as mean (SD, min to max) and as proportion for continuous and categorical variables, respectively. A Bonferroni correction for multiple comparisons was performed with the significance level set at $P \leq 0.03$. All statistical analyses were performed in SPSS® 22.0 (IBM, Armonk, USA).

3. Results

3.1. Hypothesis 1

Results for the amplitude of stuffing between prosthetic and native articular surfaces are illustrated in Fig. 6. Prosthetic and native heights were significantly different for every measurement except at 90% of the lateral facet. The prosthetic lateral facet and groove slightly overstuffed the native articular surfaces at 100% of the revolving process (the end of the trochlea) by 0.6 mm (SD 1.3 mm, min –1.6 mm–max 3.7 mm) and 0.8 mm (SD 1.4 mm, min –1.1 mm–max 3.2 mm), respectively. The MA femoral component generated a higher (mean of 1.25 mm, SD 1.24 mm, min –0.9 mm–max 4.2 mm) overstuff of the native articular surface at 110% of the revolving process (distal condyle). Out of the 20 patients, prosthetic overstuffing $\geq 2$ mm was present at 100% of the lateral facet for 3 patients (mean 2.7 mm, 2 to 3.7 mm), at 100% of the groove for 3 patients (mean 3 mm, 2.8 to 3.2 mm), and at the most distal point of the lateral femoral condyle for 4 patients.
Fig. 5. In-house analysis software. The cutting plane revolves around the patellar axis from the most proximal (0%) to the most distal (100%) point of the native groove. Prosthetic (blue line) and native (red line) heights were measured for lateral trochlea facet (B), groove (A), and medial facet (C).

(mean 2.85 mm, 2 to 4.2 mm). Figs. 7 and 8 illustrate the worst and the best-case scenarios regarding the stuffing of the lateral facet, respectively. The average DFJLO was 3.1° valgus (SD 2°, −1° varus to 7° valgus); the prosthetic stuffing at the distal part of the lateral facet (90% and 100%) and at the most distal point of the lateral condyle were very strongly correlated with the DFJLO ($r = 0.561$ to $r = 0.884$, $P < 0.0001$).

3.2. Hypothesis 2

The conventional MA technique generated 40% (8/20) and 30% (6/20) type 1 and 2 imbalance, respectively (Table 1).

3.3. Hypothesis 3

The incidence of “type 1 imbalance” was very strongly correlated ($r = 0.71, P < 0.001$) with the DFJLO, and the incidence of “type 2 imbalance” was very strongly correlated ($r = 0.78, P < 0.001$) with the adjusted DFJLO where a 3° valgus DFJLO (mean DFJLO in the current study) was considered as 0. The Ω-angle technique did not generate any uncorrectable type 1 or 2 imbalance. Measurements of distal lateral femoral prosthetic stuffing were strongly to very strongly correlated with the DFJLO ($r = 0.56, r = 0.74, r = 0.89$ at 90%, 100% and 110% of revolving process, respectively [$P < 0.01$]).

Fig. 6. Difference between native and prosthetic trochlea heights for lateral facet and groove.
Table 1
knee balance status for goal 1 and 2.

<table>
<thead>
<tr>
<th>Case</th>
<th>Distal femoral JLO (°)</th>
<th>Extension gap</th>
<th>Flexion gap</th>
<th>Flexion gap after having balanced the extension gap</th>
<th>Balance status for goal 1 (mm)</th>
<th>Balance status for goal 2 (mm)</th>
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<td></td>
<td>Medial (mm)</td>
<td>Lateral (mm)</td>
<td>Medial (mm)</td>
<td>Lateral (mm)</td>
<td>Release (mm) to balance extension gap (− for MCL, + for LCL)</td>
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<td>−3.3</td>
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Bold text indicates knee collateral ligaments status regarding goals 1 and 2.
4. Discussion

We found that the conventional MA technique for TKA often generates lateral distal prosthetic femoral overstuffing and uncorrectable collateral ligament imbalance as a result of not restoring the valgus obliquity of the DFJL.

4.1. Hypothesis 1

Our results correlate with that of Varadarajan et al. [27] who performed a similar computational study with the NexGen® femoral component. In contrast with our study, the authors’ software was based on revolving around the trans-epicondylar axis, which, compared to the patella axis used in our analysis software, makes for a less reliable assessment of the distal part of the trochlea and condyles where the patella articulates in deep flexion. This prosthetic overstuffing is the result of the non-restoration of the physiologic DFJLO, which is often valgus oriented. The surprisingly small amount of prosthetic overstuffing observed on the distal lateral facet and condyle is probably explained by the fact that our method of simulation did not aim at compensating for the worn...
cartilage on the distal part of the medial condyle, with the goal to replicate common surgical practice. When looking individually however, some patients have substantial prosthetic overstuffing in our study, reaching 3.7 mm, 3.2 mm, and 4.2 mm for the distal parts of the lateral facet and groove (100%), and the distal condyle (110%), respectively.

This distal lateral femoral overstuffing might be responsible for lateral retinacula stretching during knee flexion, potentially leading to anterior knee pain [15,28] and patella mal-tracking [29]. This would explain previous findings that showed a tendency for the patella to increasingly laterally shift and tilt as the prosthetic knee flexes [16], the increased contact force on the lateral patella facet after TKA, which is reduced by lateral retinacular release [30], the frequent need for lateral retinacular release when performing a MA TKA [31] and the fact that a randomised trial found that systematic lateral retinacular release during MA TKA significantly reduced the rate of anterior knee pain [32]. Pierson et al. [33] found no correlation between functional outcomes and trochlea stuffing, however they only assessed the proximal trochlea offset (flange area).

If distal lateral femoral overstuffing could affect clinical outcomes, surgical techniques like the kinematic [34,35] and the anatomic [36,37] alignment techniques and implant designs incorporating a 3° joint line obliquity in their design [38,39] aiming to reduce its frequency and amplitude could be clinically beneficial. To

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**Fig. 9.** Illustration of uncorrectable imbalance in a knee with 6.5° valgus angulation of the distal femoral joint line obliquity. After balancing the lateral tightness of the extension gap (black arrow, A) by releasing the lateral soft tissue envelope, the patient is likely to have excessive lateral flexion gap laxity. Extension gap (A), flexion gap (B).

**Fig. 10.** Illustration of uncorrectable imbalance in a knee with 1° varus angulation of the distal femoral joint line obliquity. While the extension gap is almost balanced after bone cuts, the flexion gap remains tight laterally (black arrow). Because there is a physiologic lateral knee laxity, this would result in a loss of this laxity (type 2 uncorrectable imbalance). Extension gap (A), flexion gap (B).
illustrate, Ghosh et al. [28,40,41] found the cadaveric implantation of the Genesis II® femoral component (Smith & Nephew, Memphis, TN, USA), which has a 3° valgus built-in oriented joint line, had no significant effect on the elongation of the lateral retinaculum during knee flexion, when compared to a native knee.

4.2. Hypothesis 2

Preserving the lateral tibio-femoral laxity [24] has been shown to be beneficial for tibio-femoral [42–45] and patella-femoral [46] biomechanics and for clinical outcomes, but often (40%) impossible to achieve with the conventional MA technique. Our results correlate with the one from Gu et al. [13] who found 42% of type 1 imbalance (goal 2 was not considered) by doing a similar study on 50 healthy knees. This might explain the frequent “balancing-related complications” after conventional MA TKA [2,24,47,48], in addition to the technical demand of the knee balancing technique and its resulting poor reproducibility and the fact that aiming to obtain symmetrical, rectangular, non-physiologic extension and flexion gaps might not be an optimal goal [24,42–46]. This might also explain why standing limb alignment has been shown to fairly accurately predict dynamic knee behaviour (dynamic alignment, adduction moment, and knee loading) of native knees during gait [49] but becomes of poor value after conventional MA TKA [50]. A few reports have found conventional MA TKA to frequently display substantial residual frontal laxity at 10° of knee flexion with no correlation with clinical outcomes [51,52]; those studies are however affected by multiple biases and further research is needed to better assess the clinical impact of those residual prosthetic knee laxities.

4.3. Hypothesis 3

Performing the distal and the posterior femoral cuts via independent and unrelated techniques (perpendicular to the femoral mechanical axis and 3° systematic external rotation relative to the posterior condylar line, respectively), both disregarding the amount of DFJLO, seems to explain the generation of a high rate of uncorrectable imbalance with the conventional MA technique for TKA. While every patient ended up with an almost similar posterior femoral cut, their distal femoral cut is highly variable in thickness secondary to the high inter-individual variability in the DFJLO [53–56] (Fig. 3). This creates a mismatch between flexion and extension gaps, which is often technically uncorrectable. Figs. 9 and 10 illustrate knees with atypical DFJLO (6.5° valgus and 1° varus), which theoretically generates an uncorrectable imbalance. Fig. 11 illustrates a typical 3° DFJLO, which generates a correctable imbalance.

The alternative Ω-angle technique seems to be successful in preventing uncorrectable imbalance for either goal (1 or 2) (Figs. 3 and 4). This finding was anticipated as the technique is likely to generate almost similar distal and posterior cuts for every tibio-femoral compartment. This further confirms that the generation of uncorrectable knee imbalance is related to disregarding the DFJLO when setting femoral implant rotation. However, while this Ω-angle technique could be an interesting way to solve the issue of uncorrectable imbalance, the femoral rotation would range in our cohort from −1° internal rotation to 7° external rotation. Such variability in femoral component axial rotation might have a clinical impact on the patellofemoral joint making this technique probably not appropriate for every patient. Its value remains to be assessed.

A few limitations should be discussed that might affect the generalisation of the findings. Firstly, results for prosthetic stiffing (hypothesis 1) are implant-specific and only apply to the Persona® femoral component. However, we believe we would find a similar high rate of distal lateral femoral prosthetic overstiffing (trochlea, condyle) with other femoral component designs as this overstiffing is mainly the consequence of the MA positioning of the femoral component which does not respect the valgus obliquity of the DFJL. Secondly, we might have underestimated the extent of distal lateral prosthetic overstiffening as we systematically used the distal part of the medial condyle as a reference to adjust the cranio-caudal positioning of the femoral implant. However, secondary to a worn medial tibio-femoral compartment (all patients had a varus arthritic knee) it is probable that a few patients would have had their healthy distal lateral condyle more distal and therefore intra-operatively referenced. Thirdly, it is difficult to precisely estimate the real knee balance status (hypothesis 2) as it is impossible to predict the true effect of releasing the soft tissue envelope for mainly
three reasons. Firstly, we assumed that the release of a collateral ligament (the primary restraint for frontal stability) would have the same effect in extension and flexion, but we know it is theoretically possible to fine-tune the balance of either the extension or flexion gap by releasing the anterior or posterior portion of the MCL [4]. Secondly, we did not take into account the release of secondary soft tissue restraints which we acknowledge can help to fine-tune knee balance [4]. Thirdly, every knee has its own unique soft tissue envelope physiologic laxity [24], which makes it difficult to estimate how much soft tissue release would be needed after mechanical bone cuts to obtain symmetrical and rectangular flexion and extension gaps (goal 1). However, because the physiologic knee soft tissue envelope.

5. Conclusion

Conventional mechanically aligned positioning of TKA components generates frequent prosthetic overstuffing at the distal lateral femur (troclea and condyle) and technically uncorrectable collateral ligament imbalance as a result of disregarding the DFJLO. Their clinical impact remains to be defined. The kinematic alignment technique for TKA might be an attractive option to prevent those limitations to happen.

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Disclosure of interest

The authors declare that they have no competing interest. Outside the current study, Charles Rivière declares having been a consultant for Depuy, Sébastien Parratte declares being a consultant for Zimmer-Biomet, Arthrex, Grafys, and Adler Orthodox, and to receiving royalties from Euros, and Justin Cobb declares being a consultant for Zimmer-Biomet, MatOrtho, and to receiving a fee from MicroPort.

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