How often do we alter constitutional limb alignment, joint line obliquity, and Coronal Plane Alignment of the Knee (CPAK) phenotype when performing mechanically aligned TKA?

A large single-institution retrospective radiological analysis

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Aims
While mechanical alignment (MA) is the traditional technique in total knee arthroplasty (TKA), its potential for altering constitutional alignment remains poorly understood. This study aimed to quantify unintentional changes to constitutional coronal alignment and joint line obliquity (JLO) resulting from MA.

Methods
A retrospective cohort study was undertaken of 700 primary MA TKAs (643 patients) performed between 2014 and 2017. Lateral distal femoral and medial proximal tibial angles were measured pre- and postoperatively to calculate the arithmetic hip-knee-ankle angle (aHKA), JLO, and Coronal Plane Alignment of the Knee (CPAK) phenotypes. The primary outcome was the magnitude and direction of aHKA, JLO, and CPAK alterations.

Results
The mean aHKA and JLO increased by 0.1° (SD 3.4°) and 5.8° (SD 3.5°), respectively, from pre- to postoperatively. The most common phenotypes shifted from 76.3% CPAK Types I, II, or III (apex distal JLO) preoperatively to 85.0% IV, V, or VI (apex horizontal JLO) postoperatively. The proportion of knees with apex proximal JLO increased from 0.7% preoperatively to 11.1% postoperatively. Among all MA TKAs, 60.0% (420 knees) were changed from their constitutional alignments into CPAK Type V, while 40.0% (280 knees) either remained in constitutional Type V (5.0%, 35 knees) or were unintentionally aligned into other CPAK types (35.0%; 245 knees).

Conclusion
Fixed MA targets in TKA lead to substantial changes from constitutional alignment, primarily a significant increase in JLO. These findings enhance our understanding of alignment alterations resulting from both unintended changes to knee phenotypes and surgical resection imprecision.

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Take home message

- Unintentional changes to Coronal Plane Alignment of the Knee phenotypes commonly occur with a fixed mechanical alignment approach in total knee arthroplasty surgery.
- Most of this change is caused by joint line alteration, resulting in a significant proportion of patients with a postoperative apex proximal joint line.

Introduction

Mechanical alignment (MA) in total knee arthroplasty (TKA) aims for neutral coronal alignment and horizontal joint line obliquity (JLO) to achieve a balanced load distribution.[1] Unintentional alterations to patients' constitutional alignment often result, because MA is a fixed alignment target, aiming to give all patients the same neutral JLO. Additionally, errors in surgical resection precision may occur.[2,3]

The Coronal Plane Alignment of the Knee (CPAK) classification categorizes knee alignment into nine phenotypes based on constitutional coronal alignment and JLO.[4] Regardless of the patient's constitutional knee phenotype, CPAK Type V is the alignment target for MA, resulting in neutral coronal alignment and horizontal JLO. Sappey-Marinier et al[5] retrospectively analyzed 1,078 knees, and found that 42% of MA TKAs did not achieve neutral mechanical alignment, and only 18% were restored to their CPAK type. However, little is known regarding the magnitude, direction, and implications of the constitutional alignment changes that result from MA. Categorization of each patient's unique pre-arthritic anatomy and final alignment angles may assist in more accurately defining the alignment alterations caused by these changes. Furthermore, understanding the resulting biomechanical and clinical impact is essential for refining surgical techniques in the era of personalized surgery, with its potential for optimizing patient outcomes.

We therefore conducted a radiological analysis of the magnitude and direction of alignment alterations from constitutional alignment in order to assess the proportion of alignment changes in patients undergoing MA TKA. Our primary hypothesis was that in patients undergoing primary MA TKA there would be significant alterations from constitutional alignment, JLO, and CPAK type. This study aims to advance our knowledge of these changes in constitutional alignment that occur with MA, providing valuable insights for surgeons and researchers aiming to improve TKA outcomes.

Methods

Study group

This retrospective cohort study included consecutive patients who underwent primary MA TKA between 8 January 2014 and 14 December 2017. The surgeries were performed by two experienced knee surgeons (SJM, DBC) at two centres in Sydney, Australia. Exclusion criteria were: need for increased prosthetic constraint beyond posterior-stabilized inserts; post-traumatic knee deformities; missing or low-quality imaging (e.g. patella significantly rotated relative to the distal femoral cortices, suggesting rotational imaging errors); and patients who did not provide written consent. The study obtained ethics approval from the Hunter New England Local Health District (#EX202011-01).

Table I. Baseline characteristics.

Variable	Value
Mean age, yrs (SD)	68.2 (7.9)
Mean BMI, kg/m² (SD)	29.7 (5.7)
Sex, female % (n)	61.4 (395)
Laterality, left, % (n)	48.6 (340)
Surgical technique, % (n)	
Instrumented	85.6 (599)
CAS	14.4 (101)
Fixation, % (n)	
Fully cemented	98.5 (689)
Cementless femur and tibia	0.1 (1)
Cementless femur, cemented tibia	1.4 (10)
Insert type, % (n)	
Posterior-stablized	89.9 (629)
Cruciate-sacrificing	10.0 (70)
Cruciate-retaining	0.1 (1)

CAS, computer-assisted surgery; SD, standard deviation.

Surgical technique – mechanical alignment

All patients underwent spinal anaesthesia (with or without general anaesthesia) and a medial parapatellar surgical approach was used. Total knee prosthesis systems included Legion (Smith & Nephew, USA); Score Rotating Platform (Amplitude Surgical SAS, France); Anatomic Posterior-Stabilized (Amplitude Surgical SAS); and Evolution Medial Pivot (MicroPort Orthopedics, USA). The patella was resurfaced in all cases, and either conventional instrumentation or computer-assisted navigation was used. Fixation was per surgeon preference. Soft-tissue releases were performed if imbalance existed after implant trialling. All TKAs were aligned according to the following MA targets: coronal alignment (neutral to the mechanical axes for both the proximal tibia and distal femur); femoral rotation (3° external rotation relative to the posterior condylar axis, or neutral relative to the surgical transepicondylar axis); tibial rotation (parallel to Insall's Line);[6] femoral flexion (3° to 5°); and tibial slope (3°).

Recorded measurements

Participants underwent preoperative standing long leg radiographs (LLRs) in the "stand-at-attention" position, with both patellae facing forward.[7] A single observer (LC) measured the lateral distal femoral angle (LDFA) and the medial proximal tibial angle (MPTA). The joint line of the proximal tibia was determined by identifying the most distal contours on the medial and lateral tibial plateaus. Likewise, the joint line of the distal femur was determined by locating the most distal points on the medial and lateral femoral condyles. These measurements were used to calculate the arithmetic hip-knee-ankle angle (aHKA, calculated as MPTA – LDFA), JLO (calculated as MPTA + LDFA), and CPAK types. Postoperatively, a CT scan was performed at a single imaging centre following a standardized Perth Protocol.[8] Two trained CT radiographers

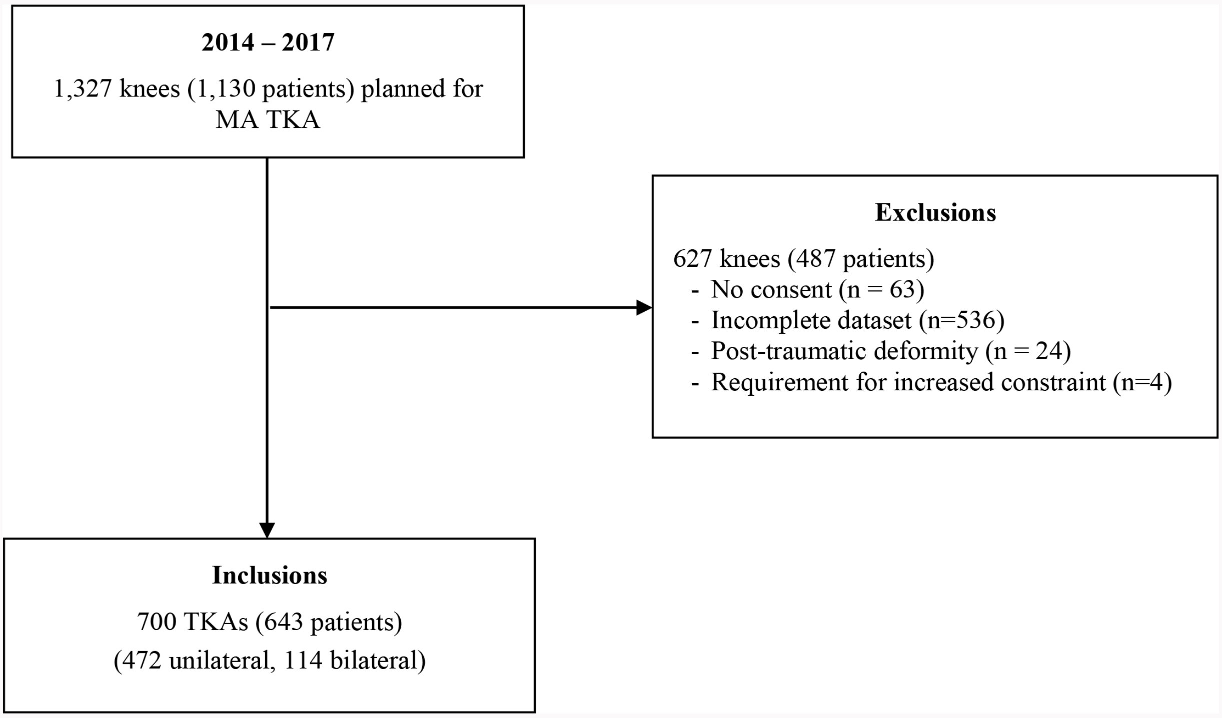

Fig. 1

Study flowchart. MA, mechanical alignment; TKA, total knee arthroplasty.

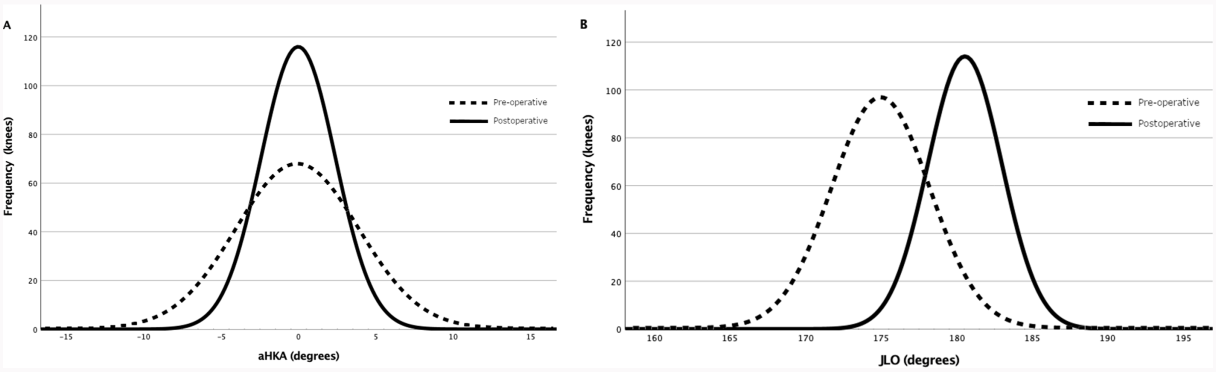

Fig. 2

a) Comparison of pre- vs postoperative arithmetic hip-knee-ankle angle (aHKA) distribution. Mean preoperative aHKA = -0.1° (standard deviation (SD) 4.0°); mean postoperative aHKA = 0.0° (SD 2.4°).The predefined 2° coronal alignment boundary and 3° joint line obliquity (JLO) boundary yielded neutral target alignment in 60.0% of knees. However, expanding the coronal alignment boundary to 3° would have resulted in neutral target alignment in 73.4% of knees. b) Comparison of pre- vs postoperative JLO distribution. Mean preoperative JLO = 174.7° (SD 3.3°); mean postoperative JLO = 180.5° (SD 2.4°).

(see Acknowledgements) measured the MPTA and LDFA, as described by Solayar et al,[9] and these values were used to calculate the postoperative aHKA, JLO, and CPAK type. The Perth CT protocol demonstrates good-to-excellent intra- and interobserver reliability for these measurements.[10]

Outcomes

The primary outcome was the magnitude and direction of alteration of MPTA, LDFA, aHKA, and JLO in patients undergoing MA TKA, with the following subgroups: 1) constitutional coronal alignment (varus, < -2°; neutral, -2° to 2° inclusive; valgus, > 2°); 2) JLO (apex distal, < 177°; apex neutral, 177° to 183° inclusive; apex proximal, > 183°); and 3) CPAK Types I to IX. The secondary outcome was the proportion of alignments changed in patients undergoing MA TKA. This was analyzed for the same subgroups as specified above, categorized to: 1) achievement of MA alignment target (neutral aHKA with 2° alignment boundary and horizontal JLO with 3° alignment boundary, resulting in CPAK Type V); 2) unintentional restoration of constitutional alignment; or 3) unintentional change to all other alignments.

Statistical analysis

Continuous data were presented as means and standard deviations (SDs), while discrete data were presented as frequencies with percentages. Normality of data distribution was assessed with histograms, Q-Q plots, and the Shapiro-Wilk test for group sizes < 50 and Kolgomorov-Smirnov test for

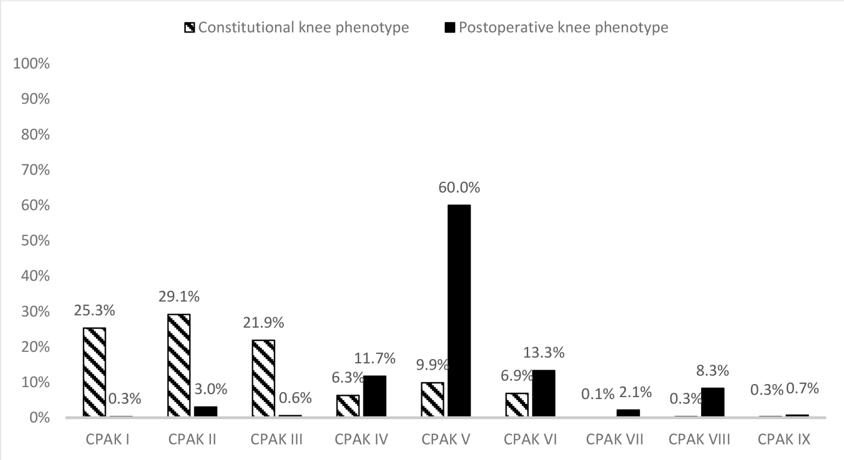

Fig. 3
Constitutional and postoperative knee alignment according to Coronal Plane Alignment of the Knee (CPAK) types.

Table II. Preoperative and postoperative alignment characteristics.

Variable	Mean preop* MPTA° (SD)	Mean postop† MPTA° (SD)	Mean preop* LDFA° (SD)	Mean postop† LDFA° (SD)	Mean preop* aHKA° (SD)	Mean postop† aHKA° (SD)	Mean preop* JLO° (SD)	Mean postop† JLO° (SD)
Total	87.3 (2.8)	90.3 (1.6)	87.4 (4.0)	90.3 (1.6)	-0.1 (4.0)	0.0 (2.4)	174.7 (3.3)	180.5 (2.4)
aHKA								
Varus (n = 222)	84.7 (2.3)	89.7 (1.6)	89.3 (1.9)	91.2 (1.8)	-4.6 (2.2)	-1.5 (2.3)	174.0 (3.6)	180.9 (2.6)
Neutral (n = 275)	87.5 (1.7)	90.2 (1.5)	87.4 (1.6)	90.2 (1.6)	0.0 (1.1)	0.1 (2.1)	174.9 (3.1)	180.4 (2.4)
Valgus (n = 203)	89.8 (1.8)	90.9 (1.4)	85.2 (1.9)	89.4 (1.7)	4.6 (2.0)	1.5 (2.0)	175.0 (3.1)	180.3 (2.4)
JLO								
Apex distal (n = 534)	86.5 (2.6)	90.2 (1.6)	86.8 (2.2)	90.0 (1.8)	-0.2 (4.1)	0.1 (2.4)	173.3 (2.4)	180.2 (2.3)
Apex horizontal (n = 161)	89.5 (1.9)	90.5 (1.6)	89.3 (1.9)	91.1 (1.8)	0.2 (3.6)	-0.6 (2.4)	178.9 (1.4)	181.7 (2.5)
Apex proximal (n = 5)	93.3 (2.0)	90.6 (2.1)	91.1 (3.0)	90.0 (1.4)	2.2 (5.0)	0.6 (3.0)	184.4 (1.2)	180.6 (1.9)
CPAK type								
I (n = 177)	84.0 (2.0)	89.6 (1.5)	88.7 (1.5)	90.9 (1.8)	-4.7 (2.3)	-1.3 (2.3)	172.7 (2.7)	180.5 (2.4)
II (n = 204)	86.8 (1.2)	90.2 (1.5)	86.8 (1.2)	89.9 (1.5)	0.0 (1.1)	0.2 (2.0)	173.5 (2.1)	180.1 (2.3)
III (n = 153)	89.2 (1.5)	90.8 (1.4)	84.5 (1.5)	89.1 (1.7)	4.7 (2.0)	1.7 (1.9)	173.7 (2.2)	180.0 (2.4)
IV (n = 44)	87.5 (1.3)	90.2 (1.8)	91.6 (1.3)	92.4 (1.6)	-4.2 (2.0)	-2.2 (2.3)	179.1 (1.6)	182.5 (2.5)
V (n = 69)	89.4 (0.9)	90.5 (1.5)	89.3 (0.8)	90.9 (1.7)	0.1 (1.0)	-0.4 (2.1)	178.7 (1.3)	181.4 (2.4)
VI (n = 48)	91.6 (1.3)	91.0 (1.5)	87.3 (1.0)	90.4 (1.5)	4.3 (1.9)	0.6 (1.9)	178.9 (1.3)	181.3 (2.3)
VII (n = 1)	91.1 (N/A)	87.0 (N/A)	95.3 (N/A)	91.0 (N/A)	-4.2 (N/A)	-4.0 (N/A)	186.4 (N/A)	178.0 (N/A)
VIII (n = 2)	92.4 (0.5)	91.0 (0.0)	91.7 (0.9)	90.0 (1.4)	0.7 (1.4)	1.0 (1.4)	184.0 (0.4)	181.0 (1.4)
IX (n = 2)	95.3(1.0)	92.0 (0.0)	88.4 (1.4)	89.5 (2.1)	7.0 (2.4)	2.5 (2.1)	183.7 (0.3)	181.5 (2.1)

*Preoperative (radiograph-derived)
†Postoperative (CT-derived)
aHKA, arithmetic hip-knee-ankle angle; CPAK, Coronal Plane Alignment of the Knee; JLO, joint line obliquity; LDFA, lateral distal femoral angle; MPTA, medial proximal tibial angle; N/A, not applicable; SD, standard deviation.

group sizes ≥ 50. Paired-samples *t*-tests were used to compare the means between pre- and postoperative alignment results. Intra- and interobserver agreement of preoperative radiological measures were determined using intraclass correlation coefficients (ICCs) on a subset of 25 patients between two authors (LEC, SJM), with measurements taken one week apart. Intra- and interobserver agreement measurements showed ICCs of 0.98 and 0.99, respectively, indicating high consistency. Level of statistical significance was set at $p < 0.05$. Excel v.16 (Microsoft, USA) and SPSS Statistics 29 (IBM, USA) were used for statistical analyses.

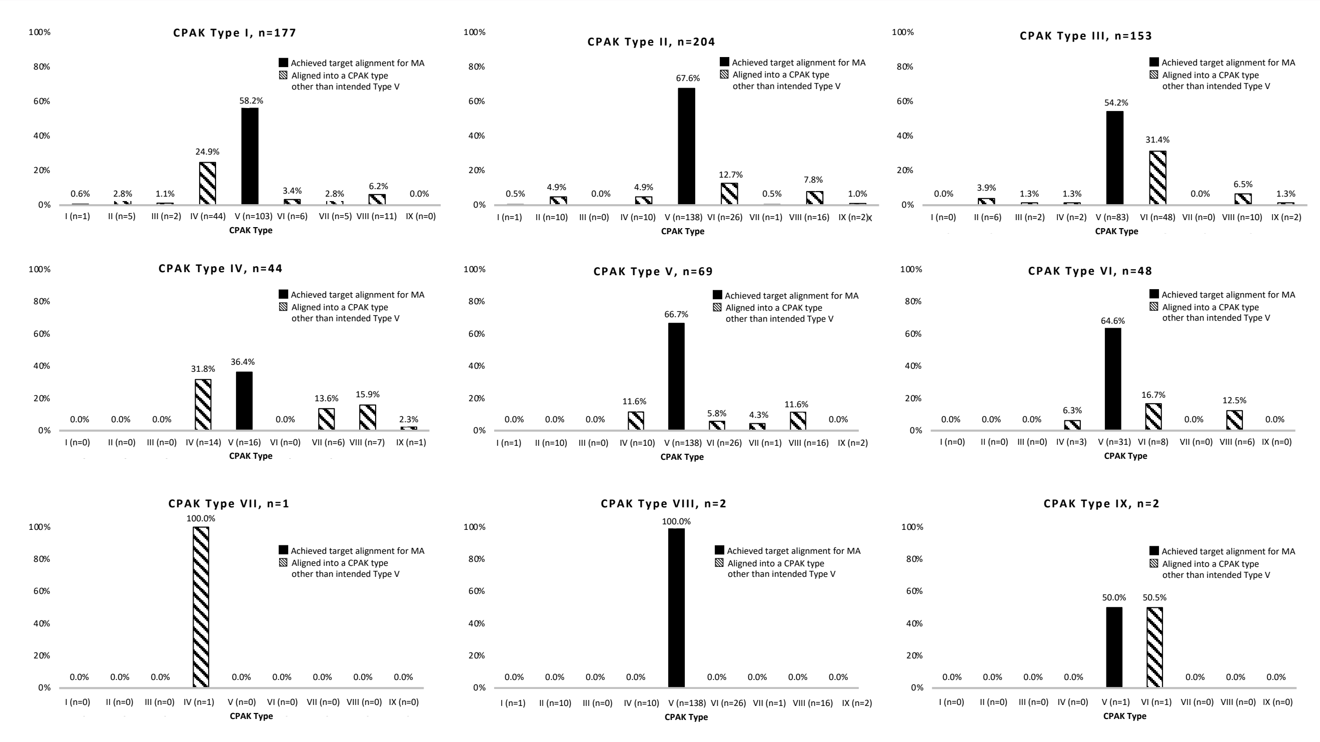

Fig. 4

Postoperative distribution of knee phenotypes in mechanically aligned (MA) total knee arthroplasty (TKA) for each of the constitutional Coronal Plane Alignment of the Knee (CPAK) types.

Results

Study group

A total of 700 TKAs performed in 643 patients met the inclusion criteria and were subsequently included in this analysis (Figure 1). Table I presents the baseline characteristics of the participants.

Primary outcome

The mean MPTA and LDFA increased by a mean of 3.0° (SD 2.7°) and 2.9° (SD 2.1°) from pre- to postoperative, respectively. The mean aHKA increased by a mean of 0.1° (SD 3.4°), from –0.1° (SD 4.0°) preoperatively to 0.0° (SD 2.4°) postoperatively. The mean JLO increased by a mean of 5.8° (SD 3.5°), from 174.7° (SD 3.3°) preoperatively to 180.5° (SD 2.4°) postoperatively. Figure 2 illustrates the aHKA and JLO changes from pre- to postoperative.

CPAK Type I had the greatest increase in mean aHKA, from constitutional varus to neutral aHKA alignment (mean difference (MD) 3.4° (SD 2.8°), $p < 0.001$, paired *t*-test), followed by CPAK Type IV (MD 2.0° (SD 2.3°), $p < 0.001$, paired *t*-test), although the mean postoperative aHKA in this group was still in varus (-2.2° (SD 2.3°)).

CPAK Types III and VI had the greatest decrease in mean aHKA, from constitutional valgus to neutral aHKA alignment (MD –3.0° (SD 2.3°), $p < 0.001$; and MD –3.7° (SD 2.3°), $p < 0.001$, respectively). CPAK Types I, II, and III had the greatest increase in mean JLO (MD 7.8° (SD 2.9°), $p < 0.001$; MD 6.6° (SD 2.8°), $p < 0.001$; and MD 6.3° (SD 3.0°), $p < 0.001$, respectively), while patients with a constitutionally neutral JLO (CPAK Types IV, V, and VI) had the least increase in mean JLO (MD 3.5° (SD 2.6°), $p < 0.001$; MD 2.6° (SD 2.7°), $p < 0.001$; and MD 2.4° (SD 2.7°), $p < 0.001$, respectively all paired *t*-test).

Preoperatively, CPAK Types I to III (apex distal JLO) were the most common phenotypes, accounting for 25.3%, 29.1%, and 21.9%, respectively. Postoperatively, CPAK Types IV to VI (apex neutral JLO) were the most common phenotypes, accounting for 11.7%, 60.0%, and 13.3%, respectively. Whereas preoperatively only 0.7% had apex proximal JLO, the proportion of patients with an apex proximal JLO increased to 11.1% postoperatively. Table II presents the mean pre- and postoperative alignment parameters. An overview of the pre- and postoperative distribution of knee phenotypes is shown in Figure 3.

Secondary outcomes

Among all TKAs, 60.0% (420 knees) were realigned from their constitutional phenotype into CPAK Type V, which is the MA target. Another 35.0% (245 knees) were aligned into a phenotype other than the intended Type V. Only 5% (35 knees) maintained their original CPAK type.

Final neutral coronal alignment was achieved in 64.0% (142 of 222 knees) of constitutional varus, 80.0% (225 of 275 knees) of constitutional neutral, and 67.5% (137 of 203 knees) of constitutional valgus aHKA subgroups. Final horizontal JLO was achieved in 86.1% (460 of 534 knees) of constitutional apex distal, 80.7% (130 of 161 knees) of constitutional apex neutral, and 100% (five of five knees) of constitutional apex proximal JLO subgroups. Table III presents the final alignment changes per analyzed subgroup, and Figure 4 provides detail of final phenotype alignments for each constitutional knee phenotype.

Table III. Alignment changes per constitutional alignment subgroup.

Variable	Preop* % (n)	Postop† % (n)	Aligned to neutral % (n)	Restored to constitutional alignment % (n)	Changed to other alignment % (n)
Total	100 (700)	100 (700)	60.0 (420)	5.0 (35)	35.0 (245)
aHKA					
Varus	31.7 (222)	14.1 (99)	64.0 (142)	32.0 (71)	4.0 (9)
Neutral	39.3 (275)	71.3 (499)	80.0 (220)	N/A	20.0 (55)
Valgus	29.0 (203)	14.6 (102)	67.5 (137)	30.0 (61)	2.5 (5)
JLO					
Apex distal	76.3 (534)	3.9 (27)	86.1 (460)	5.1 (27)	8.8 (47)
Apex horizontal	23.0 (161)	85.0 (595)	80.7 (130)	N/A	19.3 (31)
Apex proximal	0.7 (5)	11.1 (78)	100 (5)	0 (0)	0 (0)
CPAK type					
I	25.3 (177)	0.3 (2)	58.2 (103)	0.6 (1)	41.4 (73)
II	29.1 (204)	3.0 (21)	67.6 (138)	4.9 (10)	27.5 (56)
III	21.9 (153)	0.6 (4)	54.2 (83)	1.3 (2)	44.4 (68)
IV	6.3 (44)	11.7 (82)	36.4 (16)	31.8 (14)	31.8 (14)
V	9.9 (69)	60.0 (420)	66.7 (46)	N/A	33.3 (23)
VI	6.9 (48)	13.3 (93)	64.6 (31)	16.7 (8)	18.8 (9)
VII	0.1 (1)	2.1 (15)	0 (0)	0 (0)	100 (1)
VIII	0.3 (2)	8.3 (58)	100 (2)	0 (0)	0 (0)
IX	0.3 (2)	0.7 (5)	50 (1)	0 (0)	50 (1)

*Preoperative (radiograph-derived)
†Postoperative (CT-derived)
aHKA, arithmetic hip-knee-ankle angle; CPAK, Coronal Plane Alignment of the Knee; JLO, joint line obliquity.

Discussion

The most important finding from this study is that with a fixed MA approach, even though the mean constitutional coronal knee alignment is not altered, the mean joint line angle is significantly increased. This is consistent with the MA philosophy of creating neutral coronal resections, altering the commonly apex distal JLO to neutral, and externally rotating the femoral component. These results highlight for the first time the unintentional changes to knee phenotypes that often occur with a fixed alignment approach to TKA surgery, not to mention any accompanying imprecision that may occur.

To our knowledge, this is the first comprehensive analysis of alterations to constitutional alignment parameters and knee phenotypes in MA TKA. Previous studies that focused on clinical outcomes of MA TKA found no difference when comparing postoperative coronal alignment outliers to cases that achieved neutral alignment.[11-16] However, none of these studies systematically assessed alignment changes based on aHKA, JLO, and CPAK Type. Without knowledge of the specific alignment changes, drawing conclusions on any approach's outcomes becomes difficult, if not impossible. Therefore, accurate assessment of magnitude and direction of alignment changes is essential for a comprehensive understanding of the effectiveness of different strategies in TKA.

Sappey-Marinier et al[5] reported that after MA TKA, only 18% of knees were restored to their CPAK type. This finding was higher than the 5% we found in our study. In that study, the authors described that the highest proportion of restored phenotypes was found for CPAK Type IV knees,[5] a result consistent with our findings. Additionally, our study revealed that CPAK Type IV knees were the least likely to have to neutral coronal alignment restored, as indicated by the mean postoperative aHKA of −2.2° (SD 2.3°).

Although restoration of constitutional alignment is not the aim of MA, when neutral alignment is not achieved, it is imperative to prevent undesirable alignment changes. Our results show that a significant portion of patients (35.0%, n = 245) were moved into a phenotype different than either the target (CPAK Type V) or their constitutional alignment. Strikingly, with the MA approach, one in three knees with constitutional neutral alignment (preoperative CPAK Type V) were altered away from that to a different CPAK type. This unintentional alignment change was predominantly caused by an increase in JLO, resulting in a substantial proportion of patients (11.1%, n = 78) with a postoperative apex proximal JLO (CPAK Types VII to IX), which are extremely rare phenotypes.

Clark et al[17] compared the outcomes of functional alignment with a MA starting plan versus a kinematic alignment (KA) starting plan. The authors found that a MA plan increased the JLO but did not significantly alter coronal alignment. They also reported that changing JLO in CPAK Type I phenotypes negatively affects clinical outcomes in TKA.[17] These results suggest that alignment alteration with MA, or more specifically JLO change, could negatively affect the outcomes of MA TKA surgery. Our radiological findings align with these results, as we observed that the primary contributing factor to alignment change was an increase in JLO. We also found an increase in the rare constitutional CPAK Types VII to IX, from 0.7% preoperatively, which is consistent with the literature,[4,18,19] to 11.1% postoperatively. As these phenotypes are not yet fully understood, surgeons should be mindful to avoid an excessive increase in JLO that may risk potential complications or inferior outcomes.

Our study used the CPAK classification to categorize pre- and postoperative alignment change.[4] The use of different coronal alignment boundaries in other studies (3° vs 2°) explains the higher proportion of patients considered neutral after MA TKA.[20-24] Future research should investigate how these differences in boundaries affect MA outcomes.

This study has inherent limitations. First, its retrospective nature without a control group limits the generalizability of the findings. Second, different radiological methods were used preoperatively (long-leg radiographs) versus postoperatively (CT scans). However, postoperative CT scans improved accuracy of the final alignment measurements,[25] which was our primary objective. Third, the group sizes for knees with apex proximal JLO (CPAK Types VII to IX) and the individual CPAK type numbers were small, and though this relative distribution is consistent with findings in the literature,[4,18,19] cautious interpretation of subgroup analyses is warranted. Finally, racial differences were not accounted for in this study, though this important variable has been shown to affect alignment,[26] and should be included in future investigations.

Prior research on MA TKA has focused on the precision of the technique itself, that is, how reproducible the alignment methods were at achieving neutral coronal alignment.[2,3] However, in the era of personalized TKA surgery, no studies have delved into how constitutional knee alignment is altered with a fixed mechanical alignment target considering both coronal alignment and JLO. Future studies on alignment strategies should incorporate postoperative phenotypes to improve outcomes reporting. The CPAK classification is an easy and reproducible method that can be used for this.

The clinical and biomechanical impact of constitutional alignment alteration requires further research, and should include imprecisions that may unintentionally change patients into rare apex proximal joint line phenotypes. While not the remit of this paper, it is notable that there was a more than two-fold increase in the proportion of patients ending up with an apex proximal JLO when comparing manual surgery (12.2%) to computer-assisted surgery (5.0%); this suggests that a significant portion of alignment alterations may stem from instrument imprecision. This premise is consistent with existing evidence supporting the precision of computer-assisted surgery to mitigate the risk of surgical outliers.[2,3]

In conclusion, a fixed MA target in TKA results in substantial changes to a patient's constitutional alignment, with a significant increase in JLO and shift in CPAK type. These findings enhance our understanding of alignment alterations that occur from both unintended changes to knee phenotype parameters and surgical resection imprecision in MA TKA.

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Data sharing

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