Addressing sagittal plane imbalance in primary total knee arthroplasty

functional alignment outperforms kinematic and mechanical alignment techniques

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Aims
Sagittal plane imbalance (SPI), or asymmetry between extension and flexion gaps, is an important issue in total knee arthroplasty (TKA). The purpose of this study was to compare SPI between kinematic alignment (KA), mechanical alignment (MA), and functional alignment (FA) strategies.

Methods
In 137 robotic-assisted TKAs, extension and flexion stressed gap laxities and bone resections were measured. The primary outcome was the proportion and magnitude of medial and lateral SPI (gap differential > 2.0 mm) for KA, MA, and FA. Secondary outcomes were the proportion of knees with severe (> 4.0 mm) SPI, and resection thicknesses for each technique, with KA as reference.

Results
FA showed significantly lower rates of medial and lateral SPI (2.9% and 2.2%) compared to KA (45.3%; p < 0.001, and 25.5%; p < 0.001) and compared to MA (52.6%; p < 0.001 and 29.9%; p < 0.001). There was no difference in medial and lateral SPI between KA and MA (p = 0.228 and p = 0.417, respectively). FA showed significantly lower rates of severe medial and lateral SPI (0 and 0%) compared to KA (8.0%; p < 0.001 and 7.3%; p = 0.001) and compared to MA (10.2%; p < 0.001 and 4.4%; p = 0.013). There was no difference in severe medial and lateral SPI between KA and MA (p = 0.527 and p = 0.307, respectively). MA resulted in thinner resections than KA in medial extension (mean difference (MD) 1.4 mm, SD 1.9; p < 0.001), medial flexion (MD 1.5 mm, SD 1.8; p < 0.001), and lateral extension (MD 1.1 mm, SD 1.9; p < 0.001). FA resulted in thinner resections than KA in medial extension (MD 1.6 mm, SD 1.4; p < 0.001) and lateral extension (MD 2.0 mm, SD 1.6; p < 0.001), but in thicker medial flexion resections (MD 0.8 mm, SD 1.4; p < 0.001).

Conclusion
Mechanical and kinematic alignment (measured resection techniques) result in high rates of SPI. Pre-resection angular and translational adjustments with functional alignment, with typically smaller distal than posterior femoral resection, address this issue.

Take home message
- Functional alignment technique in total knee arthroplasty has significantly lower rates of sagittal plane imbalance compared to other contemporary techniques.

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- The study's findings challenge the paradigm of "putting back in what has been resected" by demonstrating the limitations of measured resection techniques in achieving sagittal plane balance.

Introduction

Aiming for uniform tension in the periarticular soft-tissues through creation of equal flexion and extension gap heights is considered an important goal in total knee arthroplasty (TKA).[1] A balanced TKA has been associated with improved postoperative outcomes,[2-4] with coronal (or frontal) plane balance being the most extensively studied.[5-12] Balance in the sagittal plane, when viewing the knee from the side, is defined by the relative heights of extension and flexion gaps. Despite receiving comparatively less attention, sagittal plane imbalance (SPI) has been reported to result in stiffness, instability, and abnormal loading conditions on prosthetic implants and bone.[13-17]

Differences in tibial slope, posterior condylar offset, and distal and posterior condyle resection thickness have all been associated with SPI.[4] Most of these studies have been performed in the context of mechanical alignment (MA). In this fixed alignment strategy, a measured resection technique guides osseous resections with the aim of achieving a neutral mechanical axis and joint line.[18] A more recent alignment technique is kinematic alignment (KA), which replicates constitutional alignment, but once again with measured but equal osseous resections.[19,20] These measured alignment techniques do not account for individual variations, such as in posterior condylar offset,[21] asymmetrical cartilage loss, and soft-tissue laxities,[22] and therefore risk an extension-flexion gap mismatch, or SPI.[2,4,23]

Functional alignment (FA), a gap-balancing technique, does not adhere to strict measured resection but employs pre-resection adjustments of implant position based on constitutional laxities to deliver balanced coronal and sagittal gaps.[24-26] Although FA has been shown to improve coronal gap balance and decrease bone resection thicknesses compared to other alignment strategies,[27-29] research on how different alignment strategies produce SPI is lacking.

Therefore, this study aimed to determine the proportion and magnitude of SPI for KA, MA, and FA. The primary hypothesis was that in patients undergoing robotic-assisted TKA, SPI would be greatest in MA and least in FA. Secondary hypotheses were that FA would have the smallest proportion of severe SPI, and that FA would result in correction of SPI by reduced resections. The results will aim to enhance our understanding of how different alignment strategies affect SPI in TKA.

Methods

Study group

A prospective cohort study of consecutive patients undergoing Mako robotic arm-assisted primary TKA with a cruciate-retaining (CR) Triathlon knee system (Stryker, USA) was performed. Two knee surgeons (SJM, DBC) performed the operations at a single centre (St George Private Hospital, Kogarah, Australia) between July and December 2020. Exclusions were requirements for increased prosthetic constraint more than CR stability. The study group comprised 137 knees in 116 patients who had a mean age of 66.6 years (SD 8.3) and a mean BMI of 29.5 kg/m^2 (SD 4.9). In the cohort, 51.1% (n = 70) were female and 46.0% (n = 63) of TKAs were performed on the left knee. A total of 40 knees (37 patients) were excluded because a different implant was used (n = 27), there was a data recording error (n = 11), a higher constraint insert was used (n = 8), or no consent was obtained (n = 5). Ethics approval was granted by Ramsay Health Care Research Ethics and Governance (#2023/ETH/0029).

Surgical technique

CT imaging with rendering and segmentation was obtained preoperatively to develop a 3D bone model for each patient, allowing for determination of implant sizes, implant alignments, and bone resection depths. All procedures were performed via a medial parapatellar approach. The anterior cruciate ligament (ACL) and anterior portion of the lateral meniscus were excised to gain access to the knee. CT-based validation was then completed with optical motion-capture tracking by registration of osseous landmarks. Osteophytes were removed and the joint capsule temporarily closed prior to the gap measurements.

Implants were then virtually positioned according to three alignment philosophies. For all 137 TKAs, the three alignment strategies were applied consecutively. The first was MA with measured resections off the intact medial side of the femur and lateral side of the tibia. Next, the knee was aligned as per KA with measured and matched resections of the femur and tibia. Finally, we then assessed balance with pre-resection FA using a restricted KA start plan. In the FA group, final coronal, axial, and sagittal virtual adjustments were performed to achieve symmetrical medial and lateral laxities. The femoral and tibial implants in the FA group were then virtually translated in the proximal-distal and anterior-posterior planes to create equal sagittal gap heights in flexion and extension, while avoiding anterior cortical notching and optimizing trochlear fit. The boundary conditions are provided in Table I. Initial posterior referencing was used in all three alignment scenarios. The patella was maintained in a reduced position during all gap measurements to improve accuracy.[30] Final insert thickness was determined by the surgeon's assessment of optimal laxity and range of motion (ROM).

Laxity measurements

Stressed gap laxity measurements were recorded for all three strategies by applying maximal varus and valgus stress in near-extension (10° of knee flexion to de-tension the posterior capsule and minimize the effect of posterior osteophytes),[24,32,33] and at 90°. For MA and KA, these were pre-resection laxity measurements. For the FA group, these were post-resection measurements with the trial implants in situ.

From the four gap laxities recorded, the following were determined: 1) medial sagittal gap differential: the difference between medial extension and medial flexion laxities; and 2) lateral sagittal gap differential: the difference between lateral extension and lateral flexion laxities.

Outcomes

The primary outcome was the proportion and magnitude of SPI, defined as a gap differential > 2.0 mm,[34] for KA, MA, and FA. These were independently measured for medial and lateral sagittal gap differentials. Secondary outcomes were: 1)

Table I. Alignment strategies.

Parameters	MA protocol*	Unrestricted KA protocol†	FA protocol‡
Coronal	Neutral to mechanical axes: • 8.0 mm from most distal and posterior points of MFC • 7.0 mm from highest point of tibia	Constitutional, symmetrical measured resections: • 6.5 mm from most distal and posterior MFC and LFC • 7.0 mm from medial and lateral tibial plateau	Constitutional adjusted to laxities, boundaries for coronal alignments: • HKA angle: 6.0° varus to 3.0° valgus • Tibial coronal alignment: 6.0° varus to 3.0° valgus • Femoral coronal alignment: 6.0° valgus to 3.0° varus
Femoral rotation	Parallel to sTEA	Parallel to PCA	6.0° internal to 6.0° external rotation from the sTEA
Tibial rotation	Akagi's line[1]	Akagi's line[1]	Akagi's line[1]
Femoral flexion	0.0 to 6.0° to optimize sizing	0.0 to 6.0° to optimize sizing	0.0 to 6.0° to optimize sizing
Tibial slope	0.0 to 6.0° to match LTP slope	0.0 to 6.0° to match LTP slope	0.0 to 6.0° to match LTP slope
Combined component flexion	Not to exceed 10.0°	Not to exceed 10.0°	Not to exceed 10.0°

*MA protocol: simulation of measured resection technique for MA TKA.
†KA protocol: simulation of measured and matched-resection technique for KA TKA.
‡FA protocol: based on restricted KA boundaries capturing 85.4% of native alignment types.[31] Implant positioning after laxity measurements: balanced gaps between medial and lateral compartments (defined as implant alignment within restricted boundaries and compartment gap differential ≤ 2.0 mm in extension and flexion).[30]
MA, mechanical alignment; KA, kinematic alignment; FA, functional alignment; MFC, medial femoral condyle; LTP, lateral tibia plateau; LFC, lateral femoral condyle; HKA, hip-knee-ankle angle; sTEA, surgical trans-epicondylar axis; PCA, posterior condylar axis.

the proportion of knees with severe SPI, defined as a gap differential > 4.0 mm for KA, MA, and FA; and 2) resection thicknesses for the different alignment strategies. As KA is a measured and matched resection technique resulting in equal medial and lateral extension and flexion resections (13.5 mm), KA was used as reference for comparison to the other strategies' thicknesses.

Statistical analysis

Continuous data were presented as means and SDs, and discrete data as frequencies with percentages. The distribution of data was evaluated with histograms, Q-Q plots, and the Shapiro-Wilk test for group sizes < 50 and the Kolgomorov-Smirnov test for group sizes ≥ 50. Differences between groups for categorical data were analyzed with chi-squared tests. Differences between groups for normally distributed continuous data were analyzed with independent-samples *t*-test, and for non-parametric continuous data with Mann-Whitney U tests. Level of statistical significance was set at p ≤ 0.05. Statistical analyses were performed using SPSS Statistics v. 27 (IBM, USA).

Results

Primary outcome

For medial SPI, FA had significantly lower rates of imbalance (2.9%) compared to KA (45.3%; p < 0.001) and MA (52.6%; p < 0.001), but there was no statistically significant difference between KA and MA (45.3 vs 52.6%; p = 0.228). For lateral SPI, FA had significantly lower rates of imbalance (2.2%) compared to KA (25.5%; p < 0.001) and MA (29.9%; p < 0.001), but there was no statistically significant difference between KA and MA (25.5 vs 29.9%; p = 0.417, all chi-squared test).

Medial gaps were on average 2.4 mm (SD 1.5), 2.4 mm (SD 1.8), and 0.7 mm (SD 0.9) larger in extension than flexion for KA, MA, and FA, respectively. Lateral gaps were on average 1.2 mm (SD 2.3), 0.4 mm (2.4), and 0.1 mm (SD 1.1) larger in extension than flexion for KA, MA, and FA, respectively.

Secondary outcomes

For severe medial SPI, FA had significantly lower rates of imbalance (0%) compared to KA (8.0%; p < 0.001) and MA (10.2%; p < 0.001), but there was no statistically significant difference between KA and MA (8.0% vs 10.2%; p = 0.527). For severe lateral SPI, FA had significantly lower rates of imbalance (0%) compared to KA (7.3%; p = 0.001) and MA (4.4%; p = 0.013), but there was no statistically significant difference between KA and MA (7.3 vs 4.4%; p = 0.307, all chi-squared test).

MA resulted in thinner resections than KA in medial extension (mean difference (MD) 1.4 mm thinner, SD 1.9; p < 0.001), medial flexion (MD 1.5 mm thinner, SD 1.8; p < 0.001), and lateral extension (MD 1.1 mm thinner, SD 1.9; p < 0.001), but similar lateral flexion resections (MD 0.1 mm thinner, SD 1.5; p = 0.306, all independent-samples *t*-test).

FA resulted in thinner resections than KA in medial extension (MD 1.6 mm thinner, SD 1.4; p < 0.001) and lateral extension (MD 2.0 mm thinner, SD 1.6; p < 0.001) in similar lateral flexion resections (MD 0.1 mm thinner, SD 1.3; p = 0.265), but in thicker medial flexion resections (MD 0.8 mm thicker, SD 1.4; p < 0.001, all independent-samples *t*-test). Overall resection thicknesses are presented in Figure 1. The absolute overall, femoral, and tibial resections for the different alignment strategies are presented in Table II.

Discussion

This study found that when CR TKA is performed with KA or MA, medial SPI occurs in approximately half of all knees, and lateral SPI in one-quarter of knees. The rate of severe

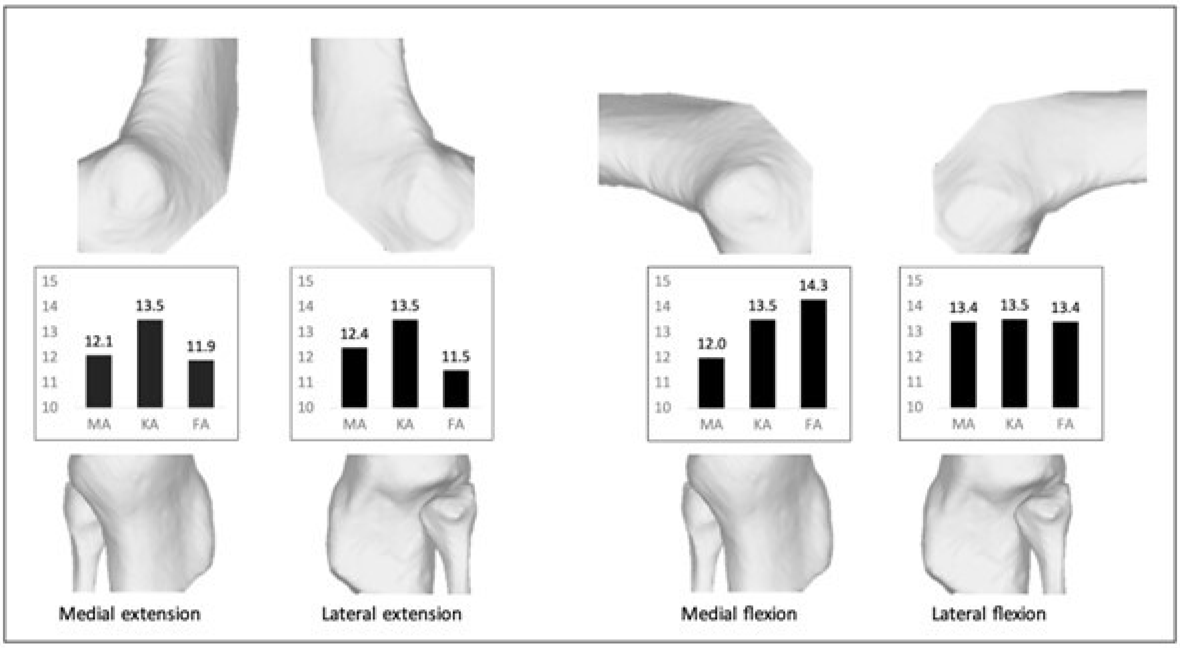

Fig. 1
Overall mean resection depths in mm for the different alignment strategies. FA, functional alignment; KA, kinematic alignment; MA, mechanical alignment.

Table II. Absolute resections in mm for the different alignment strategies. All values are presented as means and SDs.

Variable	MA				KA				FA			
	Distal medial	**Distal lateral**	**Posterior medial**	**Posterior lateral**	**Distal medial**	**Distal lateral**	**Posterior medial**	**Posterior lateral**	**Distal medial**	**Distal lateral**	**Posterior medial**	**Posterior lateral**
Overall resection	12.1 (1.9)	12.4 (1.9)	12.0 (1.8)	13.4 (1.5)	13.5 (0.0)	13.5 (0.0)	13.5 (0.0)	13.5 (0.0)	11.9 (1.4)	11.5 (1.6)	14.3 (1.4)	13.4 (1.3)
• Femur	7.9 (0.4)	5.6 (1.7)	7.9 (0.3)	6.5 (1.3)	6.5 (0.0)	6.5 (0.0)	6.5 (0)	6.5 (0.0)	5.8 (1.2)	4.9 (1.4)	8.3 (1.2)	6.7 (1.0)
• Tibia	4.2 (1.8)	6.8 (0.7)	4.2 (1.8)	6.8 (0.7)	7.0 (0.0)	7.0 (0.0)	7.0 (0.0	7.0 (0.0)	6.0 (1.0)	6.6 (1.0)	6.0 (1.0)	6.6 (1.0)

FA, functional alignment; JLO, joint line obliquity; KA, kinematic alignment; MA, mechanical alignment.

SPI (gap differential more than 4 mm) was up to 8% in KA knees, and up to 10% in MA knees. The mean medial gap in extension was 2.4 mm larger than the medial flexion gap with both MA and KA. Comparatively, FA nearly eliminated SPI by employing pre-resection component adjustments that balanced sagittal plane gaps. Although there were fewer distal femoral resections with FA, greater posterior femoral resections were required to avoid SPI, partly rejecting our secondary hypothesis. Combined, the results question the validity of the 'measured resection' technique, whether performed with MA or KA, due to the high incidence of medial SPI.

In recent years, much research in TKA has focused on different alignment strategies targeting recreation of patients' constitutional coronal anatomy,[25] yet the sagittal plane remains underexplored. Studies that measured gaps with an intact ACL and in full extension reported a larger flexion than extension gap, and an increasing gap in initial flexion.[35,36] In the present study, in which the extension gaps were larger than the flexion gaps, gaps were measured after ACL resection. ACL resection predominantly increases the medial extension gap.[37] While ACL resection thus changes the native sagittal laxity,[37] most modern TKA designs require resection of the ACL. Therefore, our findings replicate the prosthetic condition, which we believe is more clinically relevant. Additionally, gaps in the present study were measured in 10° of knee flexion, thereby de-tensioning the posterior capsule and mitigating the influence of posterior osteophytes, resulting in larger gaps than when measured in full extension.[38]

In the native knee, there are variations in medial and lateral coronal laxities. While medial laxities remain relatively constant throughout the ROM, lateral laxities typically increase with greater flexion.[38-40] This facilitates a medial pivot motion and lateral femoral rollback.[41] Therefore, achieving sagittal medial stability is crucial for replicating a physiological medial pivot motion and ensuring stable movement throughout the ROM.[41-43] However, it is crucial to recognize the differences in soft-tissue balance of a native knee compared to a prosthetic knee. KA implant position, by definition, reflects constitutional balance after resection of ACL, menisci, and osteophytes and assuming no bone loss has occurred. Hence, the SPI results for KA represent the constitutional SPI present in the prosthetic state. Both measured and matched resections techniques, by design, do not correct for pre-existing medial and/or lateral imbalances, as was confirmed by this study.

SPI can result from overtight gaps, resulting in stiffness and a reduced ROM; loose gaps, leading to instability or asymmetrical gaps; or asymmetrical gaps, resulting in implant issues such as asymmetrical poly wear and delamination from paradoxical sliding motion. SPI may negatively affect kinematics, patient-reported outcomes, and implant durability,[2,44-50] highlighting the importance of achieving balance in the sagittal plane during TKA. It is imperative to optimize bone resection, because both over-zealous and insufficient resection have been associated with SPI.[4] Manual measured resection techniques, however, only rely on post-resection measures to address SPI. This risks altering the patient's anatomy and kinematics, and should be performed cautiously, especially when undertaken with manual instrumentation.[27] FA enables pre-resection adjustments and optimization of balance, thereby eliminating unnecessary bone resections.[27-29,51] While our results demonstrate limitations of MA or KA in achieving sagittal plane balance, further research is needed to determine the impact of these proportions of SPI on patient-reported outcomes and overall patient satisfaction in TKA.

This study has several limitations. First, SPI is not only determined by extension and flexion laxities. Other factors, including sagittal implant orientation and tibial slope, contribute to SPI.[52-56] Unique to this study, however, is that we replicated the patient's native tibial slope for each patient. Hence, it is likely that SPI is worse with a fixed alignment approach where all patients have the same tibial slope. Second, laxity was manually measured without quantifying the applied stress, utilizing navigation-based measurements. Nevertheless, previous studies have demonstrated a high degree of concordance between stressed laxities and sensor-derived compartmental loads, confirming the reliability of this technique.[57] Third, the present study only looked at CR implants and may not be generalizable to other constraint implants. Although the flexion gap is increased in a posterior-stabilizing design, this is at the cost of higher constraint.[53,58] Fourth, constitutional soft-tissue laxities are highly variable and there is no universally accepted gold standard for their normative values nor for optimal targets. Fifth, this study employed pre-resection or simulated laxity measurements for MA and KA strategies, compared to post-resection laxity measurements for the FA strategy. While acknowledging that differences can exist between pre-resection and final gaps, the decision to obtain multiple measurements from different strategies within each individual was deliberate, aiming to capture their unique laxity profiles.

This study highlights the significance of also viewing the knee from the side in the pursuit of achieving a balanced TKA. It provides insights into the prevalence of SPI both with MA and KA, and ultimately challenges the paradigm of putting back in what has been resected. Furthermore, it demonstrates that FA with pre-resection balance assessment and implant position adjustments most effectively achieves sagittal balance. Hence, if sagittal balance is a primary objective, FA appears superior to MA and KA. Nonetheless, future research should identify precise targets for balance, accounting for constitutional laxity and implant design.

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Data sharing

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