Introduction

The causes of dissatisfaction following total knee arthroplasty (TKA) are likely to be multifactorial, with surgical factors such as instability, malalignment, patellofemoral maltracking, and stiffness reported to be significant contributors.\(^1-4\) Such dissatisfaction has led some surgeons to question the focus on creating the theoretically ideal mechanically aligned environment for the implant,\(^5-8\) suggesting instead ways to accurately recreate the constitutional (or pre-arthritic) alignment of the knee\(^9\) with a goal of improving patient satisfaction.\(^10-12\)

The kinematic alignment (KA) method\(^13\) aims to restore the constitutional knee joint by creating bone resections parallel to the pre-disease surface of distal femur, posterior femur, and proximal tibia, as opposed to cuts oriented perpendicular to the long axis of each bone. The rationale is that a knee aligned to the patient’s native anatomy will be better balanced and therefore will require little, if any, adjustment of the soft-tissue envelope to more closely approximate normal knee kinematics.\(^16\) It remains unclear whether such kinematic techniques improve quantitatively measured knee balance when compared with mechanical

Aims

It is unknown whether kinematic alignment (KA) objectively improves knee balance in total knee arthroplasty (TKA), despite this being the biomechanical rationale for its use. This study aimed to determine whether restoring the constitutional alignment using a restrictive KA protocol resulted in better quantitative knee balance than mechanical alignment (MA).

Methods

We conducted a randomized superiority trial comparing patients undergoing TKA assigned to KA within a restrictive safe zone or MA. Optimal knee balance was defined as an intercompartmental pressure difference (ICPD) of 15 psi or less using a pressure sensor. The primary endpoint was the mean intraoperative ICPD at 10° of flexion prior to knee balancing. Secondary outcomes included balance at 45° and 90°, requirements for balancing procedures, and presence of tibiofemoral lift-off.

Results

A total of 63 patients (70 knees) were randomized to KA and 62 patients (68 knees) to MA. Mean ICPD at 10° flexion in the KA group was 11.7 psi (SD 13.1) compared with 32.0 psi in the MA group (SD 28.9), with a mean difference in ICPD between KA and MA of 20.3 psi (\(p < 0.001\)). Mean ICPD in the KA group was significantly lower than in the MA group at 45° and 90°, respectively (25.2 psi MA vs 14.8 psi KA, \(p = 0.004\); 19.1 psi MA vs 11.7 psi KA, \(p < 0.002\), respectively). Overall, participants in the KA group were more likely to achieve optimal knee balance (80% vs 35%; \(p < 0.001\)). Bone recuts to achieve knee balance were more likely to be required in the MA group (49% vs 9%; \(p < 0.001\)). More participants in the MA group had tibiofemoral lift-off (43% vs 13%; \(p < 0.001\)).

Conclusion

This study provides persuasive evidence that restoring the constitutional alignment with KA in TKA results in a statistically significant improvement in quantitative knee balance, and further supports this technique as a viable alternative to MA.

Cite this article: Bone Joint J. 2020;102-B(1):117–124.
alignment (MA), despite evidence that this technique may contribute to improved patient outcomes.13-17

The aim of this study was to assess whether restoring the patient’s constitutional alignment during TKA using a restrictive KA protocol results in better quantitative soft-tissue balance when compared with the conventional method of MA. The null hypothesis was that there would be no difference in mean intercompartamental pressure difference (ICPD) at 10° of knee flexion in patients who underwent TKA performed with a restrictive safe zone KA protocol when compared with those having surgery using MA. Additionally, we wished to test null hypotheses that a restrictive KA protocol would result in no difference in mean ICPDs at higher degrees of knee flexion, on the proportion of balanced knees, number of balancing procedures, and number of cases of tibiofemoral lift-off when compared with MA.

Methods
Study design. We conducted a randomized, controlled, parallel-group superiority trial comparing intraoperative soft-tissue balance in TKAs implanted using kinematic versus MA with a 1:1 ratio. Participants, assessors and statisticians were blinded in order to enable unbiased collection and analysis of patient-reported and functional outcomes. Allocation was performed via sequentially numbered, sealed opaque envelopes. Randomization was undertaken using computer-generated permuted blocks of four, with surgeons unaware of block size. Bilateral procedures were included and randomized once, with both sides being assigned to the same group. The study protocol was approved by Bellberry Ethics Committee (#2017-12-911) and was prospectively registered with the Australian New Zealand Clinical Trials Registry (#ACTRN12617001627347).

Participants. Between February and August 2018, consecutive patients listed at our knee clinic to undergo primary TKA were screened for eligibility resulting in 125 participants and 138 knees being assigned to the same group. The study protocol was approved by Bellberry Ethics Committee (#2017-12-911) and was prospectively registered with the Australian New Zealand Clinical Trials Registry (#ACTRN12617001627347). All TKAs were implanted using computer-assisted navigation (OrthoMap Precision Navigation; Stryker, Kalamazoo, Michigan, USA) to improve accuracy as well as to ensure consistency between surgeons. Additional surgical techniques, and utilizing the sensor as per Gustke et al.21

The absolute mean ICPD of the two readings constituted the primary endpoint.

ICPD assessments and balance. The pressure sensor insert (VERASENSE; OrthoSensor, Dania Beach, Florida, USA) recorded initial knee ICPDs at 10°, 45°, and 90°, confirmed with computer-assisted navigation. Compartment pressures were recorded by the operating surgeon and surgical assistant. The absolute mean ICPD of the two readings constituted the primary endpoint.

The surgeon then undertook final balancing by standard surgical techniques, and utilizing the sensor as per Gustke et al. All knees were considered balanced if they achieved an ICPD of 15 psi or less at all three flexion angles. Improved one-year functional and satisfaction scores have been reported in patients with ICPDs less than 15 psi. Further bony resection was performed if the absolute pressure in one compartment was greater than 60 psi, or an ICPD was greater than 40 psi. If the ICPD was between 16 psi and 40 psi, a soft-tissue release was
performed. The aim was to achieve a final ICPD of 15 psi or less, with a single compartmental pressure of 40 psi or less at the three flexion angles.

**Endpoints at surgery and postoperative outcomes.** The primary endpoint with respect to improved knee balance was the difference of the mean ICPD at 10° of flexion between groups. This was recorded with trial implants in situ and prior to balancing procedures. A flexion of 10° was chosen as the primary endpoint as this is the position in which weight acceptance occurs during the gait cycle and walking on level ground is the most common activity after TKA. Additionally, the planning for KA was performed in the coronal plane to give distal femoral and proximal tibial resections and resultant extension gap, as opposed to a posterior femoral resection determining flexion gap balance. A primary endpoint measured at 10° (near extension) would therefore better reflect the different surgical technique in the KA cohort.

Secondary endpoints of mean ICPDs at 45° and 90° corresponded to mid- and high-flexion activities such as stair-climbing and rising from a seated position. We recorded the need for subsequent balancing procedures (further bony resection or soft-tissue releases) once pressures were recorded. We determined the proportions in each group that were balanced and recorded tibiofemoral ‘lift-off’ (no contact in one compartment with at least 20 psi of pressure in the contralateral compartment, agreed by both observers) as an indicator of significant imbalance. The requirement for a 20 psi minimum pressure of the contralateral side was to ensure that the zero reading was not due to an overall reduced joint tension, and instead reflected significant tightness of the collateral ligament on the contralateral side of the lift-off. Total operative time in minutes from skin incision to wound closure was recorded.

Radiological assessment of postoperative alignment was undertaken with CT using the Perth protocol. We analyzed the final postoperative CT alignment in both groups with respect to neutral MA and final target alignments (± 2° and ± 3°) for HKA, LDFA, and MPTA.

Finally, we recorded preoperative and one-year postoperative patient-reported outcome scores using the Knee Injury and Osteoarthritis Outcome Score 4 (KOOS4), the aggregated mean score of the subscales that are most specific to TKA recovery: pain, symptoms, function in daily living, and knee-related quality of life along with all five subscales of KOOS. In addition, we recorded the Forgotten Joint Score-12 (FJS-12), which focuses on patients’ awareness of their knees in everyday life, and the EuroQol five-dimension five-level questionnaire (EQ-5D-5L) as a standard measure of overall health status.33,34

**Sample size.** We analyzed the ICPDs of 280 consecutive mechanically aligned TKAs and found a mean initial 10° ICPD of 30 psi (SD 30) prior to knee balancing. Given the...
**Table I.** Patient demographics and radiological characteristics for each group.

| Characteristic                  | MA      | KA      | p-value |
|--------------------------------|---------|---------|---------|
| Patients, n                    | 62      | 63      | N/A     |
| Total knee arthroplasty cases, n| 68      | 70      | N/A     |
| Bilateral cases, n             | 6       | 7       | N/A     |
| Mean age, yrs (range)          | 65.0 (56 to 86) | 67.4 (36 to 89) | 0.322* |
| Sex ratio, male:female, n      | 28:34   | 23:40   | 0.225†  |
| Side, left:right, n            | 26:42   | 34:36   | 0.221†  |
| Body mass index, kg/m²         | 30.1    | 30.2    | 0.883*  |
| Mean preoperative HKA angle, ° (range) | -3.7 (-17.6 to +14.7) | -2.8 (-16.0 to +19.9) | 0.505* |
| Mean preoperative LDFA, ° (range) | 87.6 (81.6 to 95.4) | 87.5 (80.0 to 92.2) | 0.886* |
| Mean preoperative MPTA, ° (range) | 87.3 (81.6 to 91.5) | 87.5 (80.1 to 94.2) | 0.259* |

*Independent samples t-test.
†Chi-squared test.

HKA, hip-knee-ankle angle; KA, kinematic alignment; LDFA, lateral distal femoral angle; MA, mechanical alignment; MPTA, medial proximal tibial angle; N/A, not applicable.

### Results

A total of 131 consecutive patients were eligible for inclusion. Two patients refused to participate, one patient did not meet the inclusion criteria, and three patients were excluded from final analysis due to inability to assess the primary endpoint. There were 62 patients (68 knees) in the MA group and 63 patients (70 knees) in the KA group who received the allocated intervention and were included in statistical analysis (Figure 1). There were no significant preoperative differences between groups (Table I).

**Intercompartmental sensor pressure agreement between observers.** Intraclass correlation coefficients for ICPD measures showed excellent agreement between the two observers. Mean ICCs were 0.970 (95% CI, 0.958 to 0.979), 0.962 (95% CI, 0.947 to 0.973), and 0.923 (95% CI, 0.892 to 0.945), at 10°, 45°, and 90°, respectively (p < 0.001 at all angles).

**Primary outcome – mean intercompartmental pressure difference at 10°.** The mean ICPD at 10° in the MA group was 32.0 psi (SD 28.9; 0 to 138), which was nearly three times more than the KA group ICPD of 11.7 psi (SD 13.1; 0 to 63; p < 0.001, independent samples t-test).

**Intercompartmental pressure difference at all knee flexion angles.** The mean ICPD in the MA group was almost twice that of patients undergoing the KA protocol at 45° and 90° of flexion of the knee (Table II).

**Proportion of balanced knees between groups.** The proportion of knees that were unbalanced in each group was determined in order to calculate absolute risk, absolute risk reduction, and relative risk reduction. More than twice as many knees were balanced in the KA group at 10° (80%; 56/70 knees) when compared with the MA group (35%; 24/68 knees; p < 0.001, chi-squared test). The absolute and relative risks of having an unbalanced knee at each flexion angle are presented in Table III. In patients undergoing TKA with KA, there was a relative risk reduction of knee imbalance of 69%, 27%, and 48% at 10°, 45°, and 90°, respectively, when compared with MA group of patients. There was a significant relative risk reduction by undertaking a KA procedure at 10° and 90° of knee flexion compared with MA.
Table III. The absolute and relative risks of an unbalanced knee when comparing mechanical alignment (MA) and kinematic alignment (KA) techniques in total knee arthroplasty.

| Knee angle, ° | MA absolute risk of being unbalanced, % (n) | KA absolute risk of being unbalanced, % (n) | Absolute risk reduction, % | Relative risk reduction, % | p-value* |
|--------------|--------------------------------------------|---------------------------------------------|-----------------------------|----------------------------|----------|
| 10°          | (65) 44                                    | (20) 14                                     | 45                          | 69                         | < 0.001† |
| 45°          | (54) 37                                    | (40) 28                                     | 14                          | 27                         | 0.090    |
| 90°          | (47) 32                                    | (24) 17                                     | 23                          | 48                         | 0.005†   |

*Chi-squared test.
†Statistically significant.
KA, kinematic alignment; MA, mechanical alignment.

Table IV. Difference in requirements for knee balancing procedures during total knee arthroplasty using either mechanical alignment (MA) or kinematic alignment techniques.

| Knee balancing intervention | MA, n (%); n = 68 | KA, n (%); n = 70 | p-value |
|-----------------------------|-------------------|------------------|---------|
| Type of knee balancing intervention |                    |                  |         |
| Patients requiring soft-tissue releases only | 11 (16) | 16 (23) | 0.439† |
| Patients requiring bone recuts only | 18 (26) | 1 (1) | < 0.001‡† |
| Patients requiring both bone recuts and soft-tissue releases | 15 (22) | 5 (7) | 0.013‡† |
| Proportion of bone recuts |                    |                  |         |
| Patients requiring any bone cuts | 33 (49) | 6 (9) | < 0.001‡† |
| Tibial recuts only | 24 (35) | 4 (6) | < 0.001‡† |
| Femoral recuts only | 5 (7) | 2 (3) | 0.271‡† |
| Both tibial and femoral recuts | 4 (6) | 0 (0) | 0.056‡† |

*Statistically significant.
†Chi-squared test.
‡Fisher’s exact test.
KA, kinematic alignment; MA, mechanical alignment.

Requirements for subsequent knee balancing procedures. Additional bony resection to alter the final alignment of the knee were more likely to be required in the MA group to achieve optimal knee balance (49% MA group, 9% KA group; p < 0.001, chi-squared test). The majority of such resections were made on the tibia (Table IV). A higher proportion of resections required additional soft tissue balancing in the MA group.

Presence of lift-off. Prior to knee balancing, there was a significantly higher proportion of patients with lift-off in the MA group in at least one position (43% MA, 13% KA; p < 0.001, chi-squared test). The majority of these phenomena were noted in the lateral compartment (23/29 cases in MA group, 1/9 cases in KA group). When comparing two or more positions with lift-off, 27% had lift-off in the MA group compared with 4% in the KA group (p < 0.001, chi-squared test).

Operative time. The mean total operative time was 78 minutes in the MA group (SD 12.3; 58 to 120) and 79 minutes in the KA group (SD 17.0; 58 to 160; p = 0.907; independent samples t-test).

Alignment. The postoperative alignment was within 3° of the surgically recorded computer-assisted navigation resections in 94% of cases for both groups (Table V). The LDFA in the KA group had a greater mean valgus angulation (KA 89.2° (SD 1.8°; 85° to 93°), MA 90.6° (SD 1.5°; 86° to 93°); p < 0.001, independent samples t-test). By contrast, the MPTA in the KA group had a greater mean varus angulation (KA 88.9° (SD 1.8°; 84° to 95°), MA 90.0° (SD 1.9°; 85° to 94°; p = 0.003, independent samples t-test). There was no significant difference in the mean hip-knee-ankle (HKA) or the percentage of cases within ± 2° and ± 3° of neutral MA when comparing KA with MA with secondary balancing (including bone recuts).

Clinical outcomes. Table VI presents a summary of patient-reported outcome scores. There were no statistically significant differences between groups when comparing baseline with one-year postoperative scores. It should be noted that a significant proportion of participants assigned to MA and KA groups underwent subsequent alignment changes and soft-tissue balancing procedures based on sensor pressures if required, hence these outcomes do not represent a direct comparison of MA and KA.

Discussion
This randomized controlled trial confirmed that recreating the constitutional alignment of the knee within a restrictive safe zone via kinematic alignment results in a lower mean ICPD at 10° of flexion compared with mechanical alignment. Significantly lower ICPDs were also seen at higher knee flexion angles in the KA group. At all knee positions, knees were found to have more equal mediolateral compartmental loads when KA was used, compared with MA. The ICPD decreased slightly between groups with increasing knee flexion. This may have been as a result of the coronal nature of the radiological planning of kinematic bone resections, leading to more pronounced differences near full extension than when in flexion.

The high rate of knee balancing noted in the current study is most likely multifactorial. The sensor may overestimate the requirement to undertake knee balancing because an optimal ICPD that correlates with patient outcomes has not been demonstrated by high-quality studies. Additionally,
lateral condylar lift-off as a cause of impaction wear. Although there is a concern regarding increased alignment outliers with KA,\(^\ddagger\) it is possible that the technique may actually reduce polyethylene wear through reduced incidence of lift-off. Our study did not find an increase in outliers with KA when compared with MA, despite KA significantly reducing lift-off.

The current study has several limitations. First, the one-year clinical results do not represent a true comparison of the two methods as both groups underwent balancing if indicated, due to the ethical conflict inherent in failing to address a knee concern. Nearly half of all mechanically aligned knees subsequently underwent further bony resections that likely aligned them closer to their constitutional alignment. The results do indicate that both alignment strategies with subsequent knee balancing using sensor technology may produce similar early clinical outcomes. Kinematic alignment may, however, provide a potential surgical efficiency advantage in the absence of sensor technology as initial balance was achieved more readily and required significantly fewer balancing procedures. We used only one type of knee prosthesis with a posterior-stabilized design. As such, the results of this study may not be applicable to other implant designs, especially those with differing levels of stability or more anatomical articulations, as it is known that flexion laxities are altered with resection of the posterior cruciate ligament.\(^{44-47}\)

Although patient blinding was undertaken, the surgeon was not blinded when sensor measures were recorded, and hence we cannot exclude measurement or treatment bias. For this reason, a second observer was used and intraclass correlations showed the theory of lateral condylar lift-off as a cause of impact wear. Although there is a concern regarding increased alignment outliers with KA,\(^\ddagger\) it is possible that the technique may actually reduce polyethylene wear through reduced incidence of lift-off. Our study did not find an increase in outliers with KA when compared with MA, despite KA significantly reducing lift-off.

The current study has several limitations. First, the one-year clinical results do not represent a true comparison of the two methods as both groups underwent balancing if indicated, due to the ethical conflict inherent in failing to address a knee concern. Nearly half of all mechanically aligned knees subsequently underwent further bony resections that likely aligned them closer to their constitutional alignment. The results do indicate that both alignment strategies with subsequent knee balancing using sensor technology may produce similar early clinical outcomes. Kinematic alignment may, however, provide a potential surgical efficiency advantage in the absence of sensor technology as initial balance was achieved more readily and required significantly fewer balancing procedures. We used only one type of knee prosthesis with a posterior-stabilized design. As such, the results of this study may not be applicable to other implant designs, especially those with differing levels of stability or more anatomical articulations, as it is known that flexion laxities are altered with resection of the posterior cruciate ligament.\(^{44-47}\)

Although patient blinding was undertaken, the surgeon was not blinded when sensor measures were recorded, and hence we cannot exclude measurement or treatment bias. For this reason, a second observer was used and intraclass correlations showed the theory of lateral condylar lift-off as a cause of impact wear. Although there is a concern regarding increased alignment outliers with KA,\(^\ddagger\) it is possible that the technique may actually reduce polyethylene wear through reduced incidence of lift-off. Our study did not find an increase in outliers with KA when compared with MA, despite KA significantly reducing lift-off.

The current study has several limitations. First, the one-year clinical results do not represent a true comparison of the two methods as both groups underwent balancing if indicated, due to the ethical conflict inherent in failing to address a knee concern. Nearly half of all mechanically aligned knees subsequently underwent further bony resections that likely aligned them closer to their constitutional alignment. The results do indicate that both alignment strategies with subsequent knee balancing using sensor technology may produce similar early clinical outcomes. Kinematic alignment may, however, provide a potential surgical efficiency advantage in the absence of sensor technology as initial balance was achieved more readily and required significantly fewer balancing procedures. We used only one type of knee prosthesis with a posterior-stabilized design. As such, the results of this study may not be applicable to other implant designs, especially those with differing levels of stability or more anatomical articulations, as it is known that flexion laxities are altered with resection of the posterior cruciate ligament.\(^{44-47}\)

Although patient blinding was undertaken, the surgeon was not blinded when sensor measures were recorded, and hence we cannot exclude measurement or treatment bias. For this reason, a second observer was used and intraclass correlations showed high levels of agreement between measures, thereby reducing the risk of measurement bias. Knee balancing procedures were
Table VI. Patient-reported outcome scores for mechanical alignment and kinematic alignment groups comparing preoperative and one-year postoperative scores.

| Score     | Preoperative mean, psi (SD) | Postoperative mean, psi (SD) | Mean score change, psi (SD) | Mean difference (MA - KA), psi (95% CI) | p-value* |
|-----------|-----------------------------|-----------------------------|-----------------------------|----------------------------------------|----------|
| KOOS4     |                             |                             |                             | -1.2 (-8.5 to 6.0)                    | 0.735    |
| MA        | 40.0 (16.7)                 | 79.6 (14.7)                 | 39.6 (20.6)                 |                                        |          |
| KA        | 41.5 (13.5)                 | 82.2 (16.4)                 | 40.8 (21.2)                 |                                        |          |
| KOOS Symptoms |                     |                             |                             | -5.5 (13.6 to 2.6)                    | 0.180    |
| MA        | 45.9 (21.6)                 | 77.0 (14.6)                 | 31.2 (23.2)                 |                                        |          |
| KA        | 43.8 (16.2)                 | 80.5 (16.5)                 | 36.7 (23.1)                 |                                        |          |
| KOOS Pain |                             |                             |                             | 0.8 (-7.0 to 6.6)                     | 0.845    |
| MA        | 41.8 (19.6)                 | 85.4 (16.0)                 | 43.6 (22.9)                 |                                        |          |
| KA        | 43.9 (13.8)                 | 86.7 (16.1)                 | 42.8 (21.7)                 |                                        |          |
| KOOS ADL  |                             |                             |                             | 1.4 (6.6 to 9.4)                      | 0.736    |
| MA        | 46.9 (18.8)                 | 84.5 (16.4)                 | 37.6 (23.6)                 |                                        |          |
| KA        | 50.3 (16.9)                 | 86.5 (15.2)                 | 36.2 (22.2)                 |                                        |          |
| KOOS Sports |                             |                             |                             | -9.8 (-21.1 to 1.5)                   | 0.088    |
| MA        | 23.8 (27.4)                 | 57.4 (29.1)                 | 33.6 (36.7)                 |                                        |          |
| KA        | 18.9 (17.8)                 | 62.3 (25.4)                 | 43.4 (27.3)                 |                                        |          |
| KOOS QoL  |                             |                             |                             | -1.6 (-10.9 to 7.7)                   | 0.733    |
| MA        | 25.5 (16.1)                 | 71.5 (21.8)                 | 46.0 (26.1)                 |                                        |          |
| KA        | 27.5 (17.5)                 | 75.1 (22.6)                 | 47.6 (27.2)                 |                                        |          |
| FJS-12    |                             |                             |                             | -6.8 (-16.2 to 2.6)                   | 0.155    |
| MA        | 15.5 (16.4)                 | 56.8 (26.0)                 | 41.2 (28.1)                 |                                        |          |
| KA        | 15.9 (13.2)                 | 63.9 (26.6)                 | 48.0 (25.8)                 |                                        |          |
| EQ-5D-5L  |                             |                             |                             | -1.4 (-6.8 to 4.0)                    | 0.610    |
| MA        | 75.0 (14.5)                 | 82.4 (13.2)                 | 7.4 (16.8)                  |                                        |          |
| KA        | 75.3 (18.4)                 | 84.1 (15.2)                 | 8.8 (14.6)                  |                                        |          |

*Independent samples t-test.
ADL, function in activity of daily living subscale; CI, confidence interval; EQ-5D-5L, EuroQol five-dimension five-level questionnaire; FJS-12, Forgotten Joint Score-12; KA, kinematic alignment group with subsequent knee balancing; KOOS, Knee injury and Osteoarthritis Outcome Score; KOOS4, aggregated mean score of subscales of pain, symptoms, function in daily living, and knee-related quality of life; MA, mechanical alignment group with subsequent knee balancing; QoL, quality of life subscale.

performed based on the predefined sensor pressures, aiming to reduce the risk of treatment bias. The cost of the sensor technology used to determine and undertake knee balancing may prohibit widespread adoption. For the purposes of this study, however, the sensors provided an objective, quantifiable measure of knee balance.

The results of this study provide persuasive evidence that restoration of the patient’s constitutional alignment within a restrictive kinematic safe zone significantly improves knee balance, reduces knee balancing procedures, and may more closely restore native soft-tissue tension when compared with MA. Further high-quality randomized trials with long-term follow-up to evaluate efficacy, safety, and subsequent revision risk are needed to confirm the validity and efficacy of this approach.

Take home message
- Restoring the constitutional alignment of the knee using a restrictive kinematic protocol improves quantitative knee balance when compared to mechanical alignment.
- Twice as many patients undergoing kinematic alignment will have an optimally balanced knee when compared to mechanical alignment.
- Kinematic alignment significantly reduces the rate of tibiofemoral lift-off and the requirement for knee balancing procedures.

References
1. Dalury DF, Pomeroy DL, Gorab RS, Adams MJ. Why are total knee arthroplasties being revised? J Arthroplasty. 2013;28(8 Suppl):120–121.
2. Lombardi AV Jr, Berend KR, Adams JB. Why knee replacements fail in 2013: patient, surgeon, or implant? Bone Joint J. 2014;96-B Suppl A:101–104.
3. Schroer WC, Berend KR, Lombardi AV, et al. Why are total knees failing today? Etiology of total knee revision in 2010 and 2011. J Arthroplasty. 2013;28(8 Suppl):116–119.
4. Sharkey PF, Lichstein PM, Shen C, Tokarski AT, Parvizi J. Why are total knee arthroplasties failing today—has anything changed after 10 years? J Arthroplasty. 2014;29(9):1774–1778.
5. Aglietti P, Buzzi R. Posterolateral stabilised total-condylar knee replacement. Three to eight years’ follow-up of 85 knees. J Bone Joint Surg Br. 1988;70-B(2):211–216.
6. Berend ME, Ritter MA, Meding JB, et al. Tibial component failure mechanisms in total knee arthroplasty. Clin Orthop Relat Res. 2004;428:26–34.
7. Fang DM, Ritter MA, Davis KE. Coronal alignment in total knee arthroplasty: just how important is it? J Arthroplasty. 2009;24(6 Suppl):28–33.
8. Ritter MA, Fairis PM, Keating EM, Meding JB. Postoperative alignment of total knee replacement. Its effect on survival. Clin Orthop Relat Res. 1994;299:153–156.
9. Bellamans J, Colyn W, Vandenneucker H, Victor J. The Chitranjan Ranawat award: is neutral mechanical alignment normal for all patients? The concept of constitutional varus. Clin Orthop Relat Res. 2012;470(1):45–53.
10. Howell SM, Howell SJ, Kuznik KT, Cohen J, Hull ML. Does a kinematically aligned total knee arthroplasty restore function without failure regardless of alignment category? Clin Orthop Relat Res. 2013;471(3):1000–1007.
11. Matsumoto T, Takayama K, Ishida K, Hayashi S, Hashimoto S, Kuroda R. Tibial component failure mechanisms in total knee arthroplasty. Bone Joint J. 2017;99-B(5):640–646.
12. McEwen P, Balandra G, Domka M. Medial and lateral gap laxity differential in computer-assisted kinematic total knee arthroplasty. Bone Joint J. 2019;101-B(3):331–339.
13. Howell SM, Kuznik K, Hull ML, Siston RA. Results of an initial experience with custom-fit positioning total knee arthroplasty in a series of 48 patients. Orthopedics. 2008;31(9):857–863.
14. Delport H, Labey L, Innocenti B, De Corte R, Vander Sloten J, Bellemans J. Restoration of constitutional alignment in TKA leads to more physiological strains in the collateral ligaments. Knee Surg Sports Traumatol Arthrosc. 2015;23(8):2159–2169.

15. Dossett HG, Swartz GJ, Estrada NA, LeFever GW, Kvasman BG. Kinematically versus mechanically aligned total knee arthroplasty. Orthopedics. 2012;35(2):e160–e169.

16. Howell SM, Papadopoulos S, Kuznik KT, Hull ML. Accurate alignment and high function after kinematically aligned TKA performed with generic instruments. Knee Surg Sports Traumatol Arthrosc. 2013;21(10):2271–2280.

17. Hutt J, Maase V, Lavigne M, Vendettoli PA. Functional joint line obliquity after kinematic total knee arthroplasty. Int Orthop. 2016;40(1):29–34.

18. Paley D. Principles of Deformity Correction. Heidelberg: Springer-Verlag. 2003.

19. Bargren JH, Blaha JD, Freeman MA. Alignment in total knee arthroplasty. Correlated biomechanical and clinical observations. Clin Orthop Relat Res. 1983;173:178–183.

20. Parratte S, Pagnano MW, Trousdale RT, Berry DJ. Effect of postoperative mechanical axis alignment on the fifteen-year survival of modular, cemented total knee replacements. J Bone Joint Surg Am. 2010;92-A(12):2143–2149.

21. Schnaser E, Lee YY, Boettner F, Gonzalez Della Valle A. The Position of the Patella and Extensor Mechanism Affects Intraoperative Compartamental Loads During Total Knee Arthroplasty: A Pilot Study Using Intraoperative Sensing to Guide Soft Tissue Balance. J Arthroplasty. 2015;30(8):1348–1353.e3.

22. Gustke KA, Golladay GJ, Roche MW, Elson LC, Anderson CR. A Targeted Approach to Ligament Balancing Using Kinetic Sensors. J Arthroplasty. 2017;32(7):2127–2132.

23. Chow J, Wang K, Elson L, Anderson C, Roche M. Effects of Cementing on Ligament Balance During Total Knee Arthroplasty. Orthopadek. 2017;40(3):e495-e499.

24. Gustke KA, Golladay GJ, Roche MW, Elson LC, Anderson CR. A new method for defining balance: promising short-term clinical outcomes of sensor-guided TKA. J Arthroplasty. 2015;29(10):1855–1860.

25. Gustke KA, Golladay GJ, Roche MW, Jerry GJ, Elson LC, Anderson CR. Increased satisfaction after total knee replacement using sensor-guided technology. Bone Joint J. 2014;96-B(10):1333–1338.

26. Dennis DA, Komistek RD, Walker SA, Cheal EJ, Stiehl JB. Femoral condylar lift-off in vivo in total knee arthroplasty. J Bone Joint Surg Br. 2001;83-B(1):33–39.

27. Insall JN, Scuderi GR, Komistek RD, Math K, Dennis DA, Anderson DT. Correlation between condylar lift-off and femoral component alignment. Clin Orthop Relat Res. 2002;402:143–152.

28. Chauhan SK, Clark GW, Lloyd S, Scott RG, Breidahl W, Sikorsky JK. Computer-assisted total knee replacement. A controlled cadaver study using a multi-parametre quantitative CT assessment of alignment (the Perth CT Protocol). J Bone Joint Surg Br. 2004;86-B(8):818–823.

29. Sikorsky JK. Alignment in total knee replacement. J Bone Joint Surg Br. 2008;90-B(9):1121–1127.

30. No authors listed. The 2012 User’s Guide to: Knee injury and Osteoarthritis Outcome Score KOOS. 2012. http://www.koos.nu/index.html (date last accessed 18 October 2019).

31. Roos EM, Lohmander LS. The Knee injury and Osteoarthritis Outcome Score (KOOS): from joint injury to osteoarthritis. Health Qual Life Outcomes. 2003;1:164.

32. Hamilton DF, Loth FL, Giesinger JM, et al. Validation of the English language Forgotten Joint Score-12 as an outcome measure for total hip and knee arthroplasty in a British population. Bone Joint J. 2017;99-B(2):218–224.

33. EuroQol Group. EuroQol—a new facility for the measurement of health-related quality of life. Health Policy. 1990;16(3):199–208.

34. Herdman M, Gudex C, Lloyd A, et al. Development and preliminary testing of the five-level version of EQ-5D (EQ-5D-5L). Qual Life Res. 2011;20(10):1727–1736.

35. Chow JC, Breslauer L. The Use of Intrasurgical Sensors Significantly Increases Accuracy of Intraoperative Ligament Balancing Using Kinetic Sensors. J Bone Joint Surg Am. 2017;99-B(2):218–224.

36. Meneghini RM, Ziemia-Davis MM, Lovro LR, Ireland PH, Damer BM. Can Intraoperative Sensors Determine the “Target” Ligament Balance? Early Outcomes in Total Knee Arthroplasty. J Arthroplasty. 2016;31(10):2181–2187.

37. MacDessi SJ, Gharabiha MA, Harris IA. How Accurately Can Soft Tissue Balance Be Determined in Total Knee Arthroplasty? J Arthroplasty. 2019;34(2):290–294.e1.

38. Kim SH, Lee HH, Jung HJ, Lee JS, Kim KS. Less femoral lift-off and better femoral alignment in TKA using computer-assisted surgery. Knee Surg Sports Traumatol Arthrosc. 2013;21(10):2255–2262.

39. Schmidt R, Komistek RD, Blaha JD, Penenberg BL, Maloney WJ. Fluorescopic analyses of cruciate-retaining and medial pivot knee implants. Clin Orthop Relat Res. 2003;410:139–147.

40. Freeman MA, Pinkerova V. The movement of the normal tibio-femoral joint. J Biomech. 2005;38(2):197–208.

41. Vandekerckhove PTK, Teeter MG, Naudie ODR, Howard JL, MacDonald SJ, Lanting BA. The Impact of Coronal Plane Alignment on Polyethylene Wear and Damage in Total Knee Arthroplasty: A Retrieval Study. J Arthroplasty. 2017;32(6):2012–2016.

42. Li Z, Esposito CI, Koch CN, Lee YY, Padgett DE, Wright TM. Polyethylene Damage Increases With Varus Implant Alignment in Posterior-stabilized and Constrained Condylar Knee Arthroplasty. Clin Orthop Relat Res. 2017;475(12):2981–2981.

43. Nakamura S, Itoh M, Saito Y, Yano T, Oka M. The effects of kinematically aligned total knee arthroplasty on stress at the medial tibia: A case study for varus knee. Bone Joint Res. 2017;6(1):43–51.

44. Chaiyakun P, Meknarin S, Hongku N. Effects of posterior cruciate ligament resection in total knee arthroplasty using computer assisted surgery. J Med Assoc Thai. 2009;92(Suppil 6):S80–S84.

45. Matsueda M, Gengerke TR, Murphy M, Lew WD, Gustilo RB. Soft tissue release in total knee arthroplasty. Cadaver study using knees without deformities. Clin Orthop Relat Res. 1999;365:264–273.

46. Matziolis G, Mehlhorn S, Schattatt N, et al. How much of the PCL is really preserved during the tibial cut? Knee Surg Sports Traumatol Arthrosc. 2012;20(6):1083–1086.

47. Park SJ, Seon JK, Park JK, Song EK. Effect of PCL on flexion-extension gaps and femoral component decision in TKA. Orthopedics. 2009;32(10 Suppl):22–25.