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Original Research

Laxity, Balance, and Alignment of a Simulated Kinematic Alignment Total Knee Arthroplasty

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ABSTRACT

Background: Kinematic alignment (KA) and related personalized alignment strategies in total knee arthroplasty (TKA) target restoration of native joint line obliquity and alignment. In practice, deviations from exact restoration of the prearthritic joint surface are tolerated for either the femur or tibia to achieve ligamentous balance. It remains unknown what laxity, balance, and alignment would result if a pure resurfacing of both femur and tibia were performed in a KA TKA technique.
Methods: We used data from 382 robot-assisted TKA performed with a digital joint tensioner to simulate TKA with a pure resurfacing KA technique for both femur and tibia. All knees had the posterior cruciate ligament retained. Knees were subdivided into 4 groups based on preoperative coronal alignment: valgus, neutral, varus, and high varus. Medial and lateral laxity in extension and flexion, balance in extension and flexion, and coronal plane alignment were compared between groups using analysis of variance testing.
Results: In simulated pure resurfacing KA TKA across a range of preoperative coronal plane deformities, only 11%-31% of knees would have mediolateral extension ligament balance within ±1 mm, and 20%-41% would have a medial flexion gap that is looser than the lateral flexion gap. Over 45% of knees would have coronal hip-knee-ankle angle >3 degrees from mechanical neutral.
Conclusions: In simulations of pure resurfacing KA TKA, there was wide variability in the resulting laxity and alignment outcomes. Most knees had alignment and balance outcomes outside of normally accepted ranges. Techniques that deviate from pure resurfacing in order to achieve balance appear favorable.

Introduction

Total knee arthroplasty (TKA) has a long legacy of success in relieving pain and restoring function for patients with end-stage degenerative joint disease of the knee. However, up to 20% of patients report dissatisfaction and chronic pain following surgery [1–4]. While a systematic review reported that the rate of satisfaction is higher over the past decade [5], current registry data reports a satisfaction rate of only 83.7% [6], despite advances in surgical techniques, implant designs, and perioperative protocols [7–10]. Even with the advent of computer-assisted surgery and robotic technologies that enable precise component positioning, high-quality studies do not show meaningful improvements in outcomes compared to non-computer-assisted surgery techniques when traditional alignment targets are utilized [11–15].

Prior research has identified patient demographic, comorbidity, and expectation factors that are associated with dissatisfaction [10]. The majority of these patient factors, including age, race, education level, and comorbidity burden, are nonmodifiable. Emerging literature has suggested that surgical factors including component alignment, soft tissue balance, and kinematics may play a role in patient satisfaction and that modifications to alignment may result in better function than performing soft tissue releases [16–18]. Personalized alignment strategies have been proposed that aim to more closely recreate native knee morphology and kinematics. Popularized by Howell, kinematic alignment (KA) describes a technique that aims to restore the prearthritic joint surfaces and alignment of the femur and tibia by removing the bone and

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cartilage thickness that will be replaced by the implant, taking into account cartilage wear [19]. KA can therefore be conceptualized as a resurfacing procedure, wherein native joint surfaces are replaced by prosthetic surfaces but the position and alignment of the joint surfaces are not changed. The rationale for the KA approach is that restoration of the patient's native alignment and joint line will provide optimal kinematics and function without the need for soft tissue releases. This contrasts with mechanical alignment, in which implants are positioned perpendicular to the mechanical axes of the femur and tibia in a manner independent of the prearthritic joint surfaces, and soft tissue releases are performed to bring limb alignment into mechanical neutral.

In practice, the surgeon performing a KA TKA may face a tradeoff between performing a pure resurfacing and achieving desired ligament balance [20–22]. In traditional KA, the surgical technique describes a pure resurfacing of the femur first, and then the tibial cut is modified as needed in order to balance the extension gap [23]. In a related technique called inverse KA, the tibia is purely resurfaced, then the femoral cuts are modified as needed to balance the extension and flexion gaps [24]. Deviations from exact restoration of the native anatomy are therefore tolerated for either the femur or tibia in order to achieve ligament balance. It remains unknown what alignment and laxity profiles would result if a pure resurfacing of both femur and tibia were to be performed across a range of alignments. This study aims to determine the resulting alignment and balance achieved when performing a pure resurfacing KA TKA in a posterior cruciate ligament (PCL)-retaining cohort.

Material and methods

Data collection

To determine the alignment and laxity that would result from a pure resurfacing KA technique, we used data on alignment, joint morphology, wear, and laxity acquired from robotic-assisted TKAs using a digital tensioning device to perform simulations (Corin, UK). The digital joint tensioner consists of 2 independent actuators (medial and lateral) that apply a digitally controlled force to the joint through a tibial baseplate placed on the tibial resection surface and 2 paddles that distract the medial and lateral femoral condyles. Intraoperative data obtained from 382 robot-assisted TKAs using the digital tensioning device (OMNIBotics and BalanceBot, Corin, UK) was extracted from the CorinRegistry (Corin, UK) (institutional review board approval: WCG Independent Review Board: 120190312). Inclusion criteria were: TKA cases in which the joint tensioner was used in conjunction with the robot-assisted platform; complete intraoperative dataset; and only surgeons with PCL-retaining workflow. Exclusion criteria were: Cases with incomplete data capture; robotically assisted cases that did not use a digital joint tensioner; PCL sacrificing workflow. All cases were performed as a tibia-first gap-balancing workflow. Femur and tibia landmarks and coronal deformity in extension were extracted from the robotics system. Tibial resections were validated, and the tibial resection thickness was recorded. Osteophytes were removed, but no releases were performed. The digital joint tensioning device was inserted into the joint, and a force of 80 N was applied. The medial and lateral gaps between the tibial resection plane and distal and posterior femurs were recorded at 10° and 90°, respectively. Demographics of the cohort were 59.7% female, 66.9 ± 8.9 years, and a preoperative coronal deformity of 4.4 ± 5.0° varus.

Analysis

Knees were subdivided into varus (≥0°) (n = 326) and valgus (<0°) (n = 56) subgroups to account for cartilage wear. The lateral distal femoral angle and medial proximal tibial angle were calculated from the navigated landmarks. Standard wear values of 2 mm for the medial (varus knees) and lateral (valgus knees) distal femur and proximal tibia, as well as the posterior lateral femur (valgus knees only) were estimated based on previous literature estimates and wear measurements [25–28]. Specifically, Nam et al (2014) measured the amount of bone and cartilage wear in 154 varus and 54 valgus TKAs (208 in total) using narrow-slice magnetic resonance imaging and reported that distal femoral cartilage wear averaged 1.7 ± 0.5 mm medially in varus knees and 1.3 ± 0.6 mm laterally in valgus knees, with posterior femoral cartilage wear averaging 1.1 ± 0.7 mm laterally in valgus knees [25]. Similarly, average cartilage thicknesses of approximately 2 mm have been reported on the tibia [29,30], and authors have recommended using wear corrections of 2 mm intraoperatively in TKA to anatomically resurface both the tibia [27,31] and the femur [32] in varus and valgus deformities. Moreover, other studies simulating resurfacing TKA have applied similar wear assumptions of 2 mm on the distal femur and proximal tibia [28,33]. Alignment criteria for applying wear corrections are shown in Table 1.

Knees were then subdivided, as has been previously described [33] based on navigated hip-knee-ankle (HKA) angle for simulation of joint balance and component alignment. The mean HKA deformity for the whole cohort was 4.4° ± 5.0° varus; see distribution of HKA angles in Figure 1. The distribution of TKA cases and mean angles across these groups is shown in Table 2.

Expected postoperative joint gaps and component angles were calculated following a simulated pure resurfacing KA TKA with the femoral component aligned to the lateral distal femoral angle and lateral posterior femoral angle at 0 and 90 degrees flexion, respectively, and the tibial component aligned to the medial proximal tibial angle, adjusting for cartilage wear as described above. Joint laxity is calculated as the distance between the tibial and femoral joint lines on the medial and lateral sides in extension and flexion, after adjusting for wear. Joint balance is defined as the medial laxity minus the lateral laxity (such that a positive value indicates relative medial laxity). Laxity, balance, and component alignment are compared between knee coronal categories using a one-way analysis of variance test in which a critical P value of .05 was used. Significance is indicated throughout as follows: *$P < .05$, **$P < .01$, ***$P < .001$. Data are presented as boxplots with medians as centerlines, lower and upper boxes as first and third quartiles (25th and 75th percentiles), and lower and upper whiskers extending to the smallest and largest values within a 1.5× interquartile range (or distance between the first and third quartiles). Datapoints beyond the whiskers are plotted individually as outlying points.

Results

Laxity and balance

Medial and lateral laxity as well as joint balance was impacted by HKA angle when pure resurfacing KA resections were performed. In extension, medial laxity was greatest in the valgus group

Table 1
Cartilage wear assumptions for distal femur and proximal tibia.

Location	HKA ≥0° (mm)	HKA <0° (mm)
Femur		
Dist. medial	2.0	-
Dist. lateral	-	2.0
Postlateral	-	2.0
Tibia		
Medial	2.0	-
Lateral	-	2.0

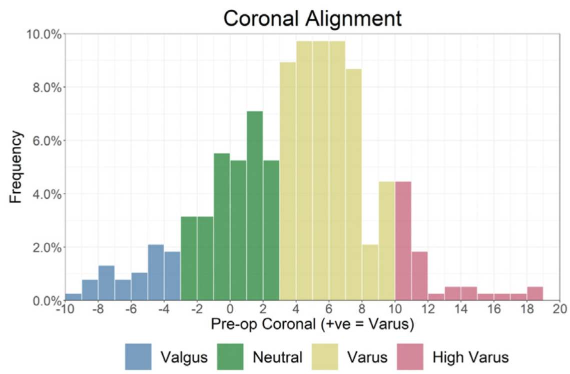

Figure 1. Distribution of hip-knee-ankle (HKA) angle across cohort. Knees are subdivided into 4 cohorts shown in different colors.

(2.2 ± 3.1 mm) and lowest in the neutral group (−0.5 ± 2.7 mm) before increasing in the varus (−0.4 ± 2.5 mm) and high varus (1.0 ± 3.4 mm) groups (Fig. 2a). In contrast, lateral laxity was lowest in the valgus and neutral groups (2.0 ± 3.0 mm and 1.9 ± 3.1 mm respectively) and highest in the high varus group (3.6 ± 2.8 mm) (Fig. 2b). Extension joint balance was similar in neutral, varus, and high varus groups, reporting between (2.4-2.6) ± (2.5-3.6) mm of relative lateral laxity, whereas valgus knees reported 0.2 ± 2.5 mm of relative medial laxity (Fig 3a). A low proportion of knees report balance within ±1 mm, from a maximum of 31% in the valgus group to a minimum of 11% in the high varus group (Table 3). When balance windows are widened, the proportion of knees within the window increases. For a window of ±3 mm, valgus knees report the highest proportion of 81%. Valgus knees also report the highest proportion of knees with medial laxity greater than lateral laxity (56%).

Flexion laxity and balance showed similar trends to extension. Medial laxity was highest in valgus knees (3.2 ± 2.2 mm) and lowest in neutral knees (1.5 ± 2.2 mm) before increasing for high varus knees again (2.6 ± 2.8 mm) (Fig. 2c). Lateral laxity increased with increasing varus angle from a minimum of 2.3 ± 4.4 in the valgus group to 5.8 ± 3.1 in the high varus group (Fig. 2d). Joint balance showed increasing relative lateral laxity with increased varus angle from low relative medial laxity in the valgus group (0.9 ± 4.2 mm) to high relative lateral laxity in the high varus group (3.2 ± 3.7 mm) (Fig. 3b). A low proportion of knees report flexion balance within ±1 mm, with valgus knees reporting the highest proportion (29%) (Table 4). Valgus knees also report the greatest proportion of knees with medial laxity greater than lateral laxity (41%), while up to 63% of knees in the high varus cohort report balance outside of ±3 mm.

Alignment

Postoperative HKA was more neutral than preoperative deformity (−0.6° ± 5.0° vs 4.4° ± 5.0°, $P < .001$), in which the femoral component was placed in 3° valgus and the tibial component in 2.3° varus on average (Fig. 4). Femoral coronal angle was impacted by coronal alignment, in which more varus knees reported less valgus component alignment (Table 5). A similar trend was observed for tibial alignment, in which a more varus deformity

Table 2
Distribution of knees across coronal categories.

	Valgus (<-3°)	Neutral (±3°)	Varus (>3°)	High varus (>10°)
n	32 (8%)	112 (29%)	203 (53%)	35 (9%)
HKA angle (°)	−5.5 ± 2.6	0.9 ± 1.6	6.4 ± 1.8	13.1 ± 3.3

Table 3
Breakdown of coronal balance distribution in extension according to preoperative coronal deformity.

Balance (M-L)	Valgus (<−3°)	Neutral (±3°)	Varus (>3°)	High varus (>10°)
± 1 mm	31%	13%	19%	11%
± 2 mm	63%	30%	43%	31%
± 3 mm	81%	43%	57%	51%
M > L	56%	21%	13%	17%

resulted in a higher varus tibial component alignment. Finally, postoperative HKA increased varus angle with increasing preoperative varus HKA deformity, with mean differences of up to 6.5° between groups.

Discussion

With the increasing popularity of personalized alignment in TKA, there is a growing need to understand how deviations from traditional techniques affect alignment and balance. Currently employed KA techniques and their derivatives prioritize ligament balance over exact restoration of prearthritic anatomy. We sought to determine the alignment and balance that would result from a strict resurfacing KA TKA. In a study of simulated pure resurfacing KA technique for a cohort of patients undergoing robotic TKA with a digitized ligament tensor, we find substantial variability in the resulting laxity and alignment outcomes. Depending on preoperative alignment, we find that only 11%-31% of patients would have mediolateral extension ligament balance within ±1 mm, and 13%-56% would have a medial flexion gap that is looser than the lateral flexion gap. Furthermore, >45% of knees would have a postoperative HKA angle outside of ±3 degrees from mechanical neutral.

Prior studies have shown that approximately one-third of the healthy population without knee osteoarthritis has an HKA angle outside of 3 degrees from mechanical neutral, with most of these outliers in varus alignment [34,35]. In a report of >200 patients treated with KA TKA, Howell described 7% of patients with postoperative HKA angle >3 degrees varus and 20% of patients with postoperative HKA angle >3 degrees valgus [36]. Our data indicates that in a pure resurfacing technique that does not include tibial recuts and soft tissue release to balance, close to 50% of knees across all alignment types fall outside of ±3 degrees from a neutral HKA angle. Our data, together with Howell's, suggest that the subset of patients that require TKA may include different proportions of alignment outliers than the general population. Studies that investigate the alignment ramifications of KA technique may be more suitable for cohorts of arthritic knees instead of nonarthritic controls [37].

Our results are comparable to those of Bouche et al, who reported that with KA resurfacing on the tibia and femur, a balanced knee could be achieved in only 12% of cases using a 3-point balance score that considers balance in extension and flexion [28]. Moreover, when adjusting the distal femoral and proximal tibial resections of up to 2 mm (ie, 4 mm total) on the worn side to correct for imbalance, balanced gaps could be achieved in 71% of cases in extension and 41% of cases in flexion [28]. This is in the range that we report for imbalance within ±3 mm in extension (43%-81%) and flexion (37%-72%) across alignments.

There is controversy regarding whether deviations from mechanical neutral alignment impact long-term implant survivorship in TKA. A study of almost 7000 TKA reported up to a 6.9× higher revision rate when HKA angle was greater than ~3 degrees from mechanical neutral [38]; this study, however, utilized anteroposterior knee radiographs to determine alignment instead of hip-to-ankle radiographs. In contrast, several studies have shown

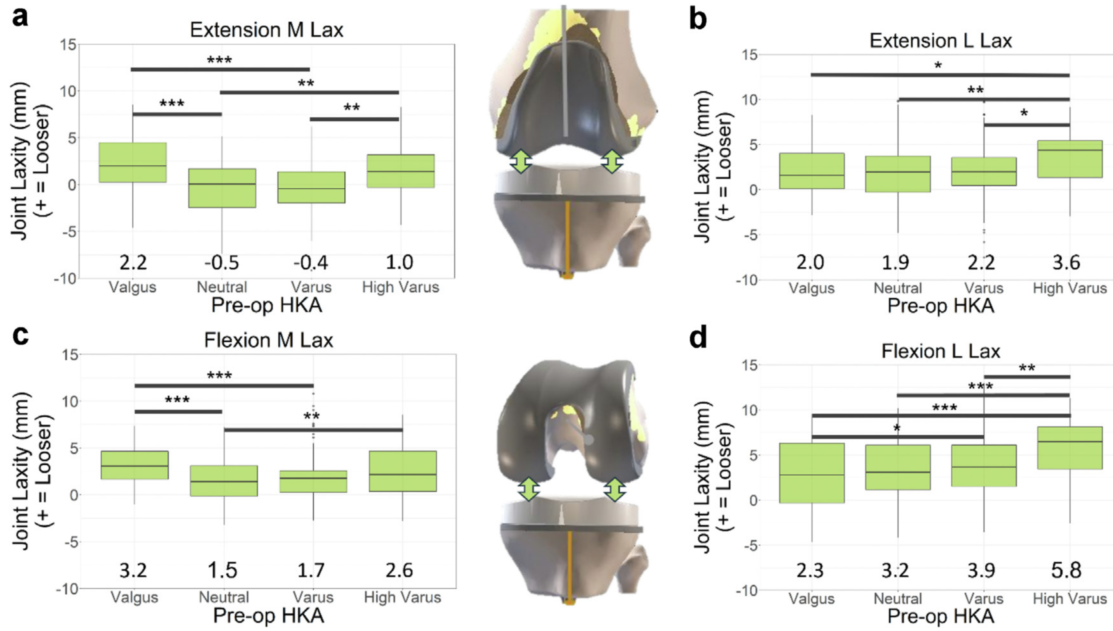

Figure 2. Comparison of (a) medial and (b) lateral extension laxity and (c) medial and (d) lateral flexion laxity across HKA groups. Data labels indicate mean values.

that slight deviations from mechanical neutral do not portend increased revision risk. Howell's report of >200 knees at 10-year follow-up showed 97.4% survivorship free of revision [36]. In a study of 398 TKAs with 20-year follow-up, Abdel et al reported no increase in revision rate for the 27% of knees that had HKA angle >3 degrees from mechanical neutral [39]. Our data show that 19%-42% of knees in a strict resurfacing technique would have HKA angle greater than 5 degrees from neutral, an alignment that has been deemed beyond the 'safe zone' for practitioners of restricted KA technique [37].

Prior studies have shown improved patient-reported outcomes with an extension gap that is balanced or has a tighter medial side [21,22,40]. Wakelin et al found in a prospective study of 135 TKA patients that Knee Injury and Osteoarthritis Outcome Score scores were significantly better for knees with mediolateral extension balance within 0.5 mm or the medial side tighter [21]. Our data shows that in a purely resurfacing KA technique, 56% of valgus knees and 13%-21% of neutral or varus knees had a medial extension gap that was looser than the lateral extension gap. Over 69% of knees had mediolateral extension imbalance greater than 1 mm. The majority of varus knees would have required additional varus in order to achieve a balanced extension gap, and the majority of valgus knees would have required additional valgus.

In flexion, prior studies have found that a loose lateral flexion gap does not adversely affect outcome so long as the medial flexion gap is not loose [22,41,42]. A trapezoidal flexion space with the lateral side looser may be physiologic and is targeted in traditional KA techniques [19,43], with one study showing that a looser lateral flexion gap is associated with improved patient-reported outcomes [44]. Other data has shown that a balanced flexion gap is favorable [21]. Our data shows a pure resurfacing KA technique would result in a medial flexion space that is looser than the lateral side in >40% of valgus knees and in 20%-26% of neutral/varus knees. Over 60% of the high varus group had mediolateral flexion imbalance >3 mm. In order to achieve a balanced flexion space, neutral and varus knees would on average require additional femoral external rotation, whereas valgus knees would require femoral internal rotation in comparison to a pure resurfacing.

This study has several limitations. The biggest limitation is that our simulations incorporated assumptions about cartilage wear that may have been subject to error. These assumptions are population generic and not patient-specific; however, our assumptions are based on a number of prior studies that have found cartilage thickness on the distal and posterior femur and proximal tibia are approximately 2 mm. Furthermore, although we make assumptions about cartilage wear, the remainder of the data in the simulations was real-life data

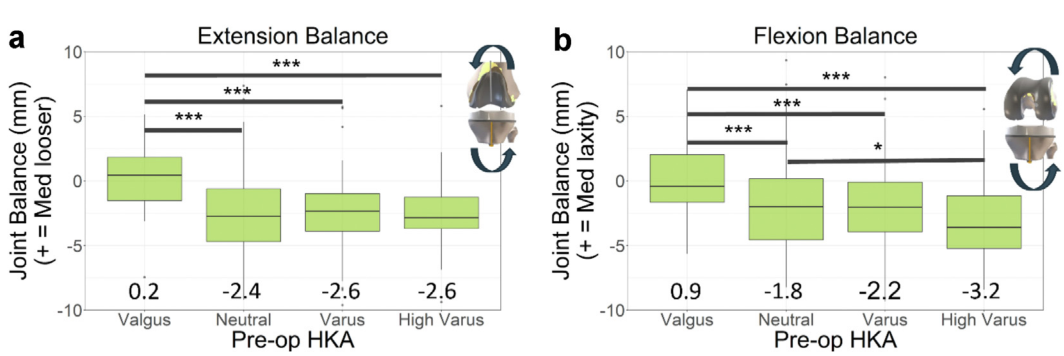

Figure 3. Comparison of extension balance in (a) extension and (b) flexion across HKA groups.

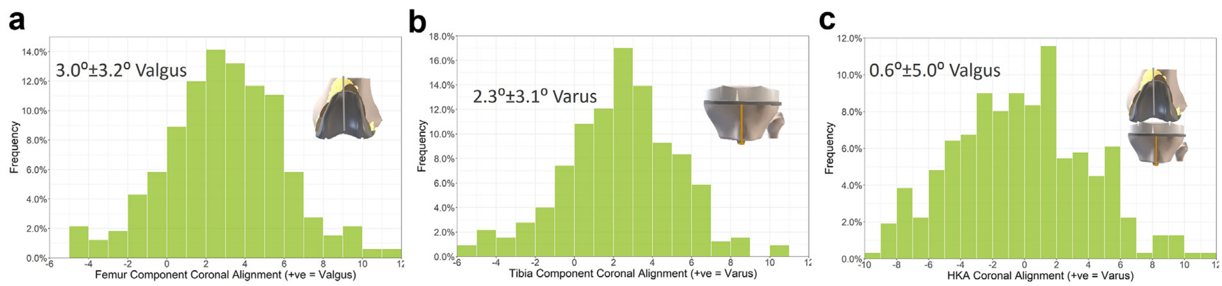

Figure 4. Resulting (a) femoral, (b) tibial, and (c) tibio-femoral coronal component alignment from a KA approach.

Table 4
Breakdown of flexion balance distribution according to preoperative coronal deformity.

Balance (M-L)	Valgus (<−3°)	Neutral (±3°)	Varus (>3°)	High varus (>10°)
± 1 mm	29%	15%	23%	9%
± 2 mm	47%	37%	42%	17%
± 3 mm	72%	53%	61%	37%
M > L	41%	26%	22%	20%

Table 5
Comparison of femoral, tibial, and tibio-femoral component angles in extension.

Preoperative HKA category	Femoral coronal alignment	Femur significant differences	Tibial coronal alignment	Tibia significant differences	Postoperative HKA alignment	Postoperative HKA significant differences
Valgus	4.1° ± 3.4° Valgus % within ± 3°: 31% within ±5°: 65	Var, high var	0.7° ± 3.3° Varus % within ±3°: 69% within ±5°: 85	High var	3.4° ± 5.6° Valgus % within ±3°: 38% within ±5°: 58	Var, high var
Neutral	3.7° ± 3.5° Valgus % within ±3°: 35% within ±5°: 59	Var, high var	0.8° ± 3.2° Varus % within ±3°: 65% within ±5°: 87	Var, high var	2.9° ± 5.5° Valgus % within ±3°: 40% within ±5°: 58	Var, high var
Varus	2.6° ± 2.8° Valgus % within ±3°: 54% within ±5°: 83	Val, neu	3.0° ± 2.5° Varus % within ±3°: 49% within ±5°: 79	Neu, high var	0.4° ± 4.0° Varus % within ±3°: 55% within ±5°: 81	All
High varus	1.8° ± 3.2° Valgus % within ±3°: 57% within ±5°: 89	Val, neu	4.9° ± 2.9° Varus % within ±3°: 29% within ±5°: 57	All	3.1° ± 4.2° Varus % within ±3°: 50% within ±5°: 64	All

collected from a representative sample of arthritic knees. Second, owing to the simulated nature of the study, we do not have data on how these knee replacements would have performed clinically. Given that a majority of simulated TKAs fell outside of usual boundaries for alignment and laxity, performing surgery in this fashion to collect actual clinical outcome data is not feasible. Third, the method of simulated knee reconstruction deviates substantially from how most surgeons would execute a knee replacement. Notwithstanding, the simulation provides a useful experimental platform for examining the consequences of a pure resurfacing KA TKA.

Conclusions

In a study of simulated pure resurfacing KA TKA technique, we found substantial variability in the resulting laxity and alignment outcomes. Most knees had alignment and balance outcomes that were outside of normally accepted ranges. Techniques that deviate from pure resurfacing in order to achieve balance appear favorable.

Conflicts of interest

A. Edelstein is a paid consultant for Corin and Depuy; an editorial board member of Arthroplasty Today; and committee member of the American Association of Hip and Knee Surgeons (AAHKS). E. Wakelin and C. Plaskos are employees of Corin Group with stocks. L. Suleiman is a paid consultant for Corin, Stryker, Depuy, and Total Joint Orthopedics and board/committee member of the Women in Arthroplasty Group (AAHKS) and the Ruth Jackson Society Board.

For full disclosure statements refer to 10.1016/j.artd.2023.101204.

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