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A commentary by Per-Henrik Randsborg, MD, PhD, is linked to the online version of this article at jbjs.org.

The Impact of Surgeon Volume and Training Status on Implant Alignment in Total Knee Arthroplasty

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Background: Implant malalignment may predispose patients to prosthetic failure following total knee arthroplasty (TKA). A more thorough understanding of the surgeon-specific factors that contribute to implant malalignment following TKA may uncover actionable strategies for improving implant survival. The purpose of this study was to determine the impact of surgeon volume and training status on malalignment.

Methods: In this retrospective multicenter study, we performed a radiographic analysis of 1,570 primary TKAs performed at 4 private academic and state-funded centers in the U.S. and U.K. Surgeons were categorized as high-volume (≥50 TKAs/year) or low-volume (<50 TKAs/year), and as a trainee (fellow/resident under the supervision of an attending surgeon) or a non-trainee (attending surgeon). On the basis of these designations, 3 groups were defined: high-volume non-trainee, low-volume non-trainee, and trainee. The postoperative medial distal femoral angle (DFA), medial proximal tibial angle (PTA), and posterior tibial slope angle (PSA) were radiographically measured. Outlier measurements were defined as follows: DFA, outside of 5° ± 3° of valgus; PTA, >±3° deviation from the neutral axis; and PSA, <0° or >7° of flexion for cruciate-retaining or <0° or >5° of flexion for posterior-stabilized TKAs. "Far outliers" were defined as measurements falling >± 2° outside of these ranges. The proportions of outliers were compared between the groups using univariate and multivariate analyses.

Results: When comparing the high and low-volume non-trainee groups using univariate analysis, the proportions of knees with outlier measurements for the PTA (5.3% versus 17.4%) and PSA (17.4% versus 28.3%) and the proportion of total outliers (11.8% versus 20.7%) were significantly lower in the high-volume group (all p < 0.001). The proportions of DFA (1.9% versus 6.5%), PTA (1.8% versus 5.7%), PSA (5.5% versus 12.6%), and total far outliers (3.1% versus 8.3%) were also significantly lower in the high-volume non-trainee group (all p < 0.001). Compared with the trainee group, the high-volume non-trainee group had significantly lower proportions of DFA (12.6% versus 21.6%), PTA (5.3% versus 12.0%), PSA (17.4% versus 33.3%), and total outliers (11.8% versus 22.3%) (all p < 0.001) as well as DFA (1.9% versus 3.9%; p = 0.027), PSA (5.5% versus 12.6%; p < 0.001), and total far outliers (3.1% versus 6.4%; p = 0.004). No significant differences were identified when comparing the low-volume non-trainee group and the trainee group, with the exception of PTA outliers (17.4% versus 12.0%; p = 0.041) and PTA far outliers (5.7% versus 2.6%; p = 0.033). Findings from multivariate analysis accounting for the effects of patient age, body mass index, and individual surgeon demonstrated similar results.

Conclusions: Low surgical volume and trainee status were risk factors for outlier and far-outlier malalignment in primary TKA, even when accounting for differences in individual surgeon and patient characteristics. Trainee surgeons performed similarly, and certainly not inferiorly, to low-volume non-trainee surgeons. Even among high-volume non-trainees, the best-performing cohort in our study, the proportion of TKA alignment outliers was still high.

Level of Evidence: Therapeutic Level III. See Instructions for Authors for a complete description of levels of evidence.

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Primary total knee arthroplasty (TKA) is an effective treatment for end-stage osteoarthritis of the knee, with nearly all implant types attaining ≥95% survival 10 years postoperatively[1]. Long-term implant failure rates, however, have remained unchanged in recent years despite active research to improve prosthetic longevity. Although the persistence of suboptimal failure rates is partially driven by the existence of patient-specific risk factors (age, body mass index [BMI], comorbidities, bone quality), other factors that contribute to prosthetic failure are surgeon-specific[2-4]. These factors represent actionable opportunities for improvements in implant longevity.

One of the most impactful surgeon-specific factors affecting long-term implant survival is the accuracy of prosthetic implant alignment[5-12]. Implant malalignment has been identified as a risk factor for premature mechanical failure and poor clinical outcomes in numerous studies[3,4,7,8,13-16]. Ritter et al., for example, demonstrated that a medial distal femoral angle (DFA) measurement of <1.9° or >7.9° of valgus relative to the anatomic axis of the femur was associated with a 10.7-times higher rate of implant failure[7]. Similarly, Kim et al. identified a nearly 2.5-times greater incidence of implant failure with alignment outside of 5° ± 3° of valgus[16]. With respect to the medial proximal tibial angle (PTA), Ritter et al. found that alignment of ≤90° was associated with a 12.1-times greater risk of implant failure[7], and others have found similar susceptibility to premature failure with a PTA demonstrating a >±3° deviation from the neutral axis[17-19]. With respect to the posterior tibial slope angle (PSA), Kim et al. identified a greater incidence of implant failure when alignment was outside of 0° to 7° of flexion[16]. Importantly, the effect of "outliers" in implant alignment grows even stronger when multiple components are concomitantly malaligned. Knees placed in excessive femoral valgus and tibial varus, for example, were noted to have a 57.6-times higher risk of implant failure compared with well-aligned knees[7].

As a result of the link between implant alignment outliers and early implant failure, efforts have been made to optimize alignment with the use of robotic navigation and patient-specific instrumentation[19-32]. However, little work has been conducted to identify the primary surgeon-specific factors that drive these outliers in order to understand the optimal patient populations in which to utilize this expensive technology. Studies of total hip arthroplasty (THA) have demonstrated a strong relationship between surgeon volume and implant alignment in THA[33-35]. However, parallel studies have not been performed in the setting of TKA, to our knowledge. While ex vivo cadaveric studies have demonstrated improved implant alignment among experienced surgeons in a small cohort[36], the impact of surgeon experience and trainee status on implant alignment in vivo has not been studied.

TABLE I Surgeons and Knees per Group

Group	No. of Surgeons	No. of Knees
High-volume non-trainee (HVNT)	5	730
Low-volume non-trainee (LVNT)	4	230
Trainee	39	610

TABLE II Comparison of Preoperative Characteristics*

Characteristic	Group: HVNT	Group: LVNT	Group: Trainee	Overall
Age *(yr)*	68.4 (10.4)	65.9 (9.0)	69.6 (9.9)	67.5 (10)
BMI *(kg/m²)*	30.3 (5.7)	32.0 (6.0)	30.6 (4.9)	30.6 (5.5)

*The values are given as the mean, with the standard deviation in parentheses. HVNT = high-volume non-trainee, LVNT = low-volume non-trainee, and BMI = body mass index.

Given the divided nature of the existing literature, it is difficult to extrapolate the exact influence of surgeon volume and trainee status on the rate of malalignment in TKA. For example, results from studies assessing the impact of trainee surgeons and surgical experience on clinical outcomes following TKA and THA have demonstrated that neither experience nor trainee status significantly impacts outcomes[36-39]. However, similar studies assessing outcomes at U.S. Veterans Affairs (VA) training centers demonstrated mixed results[40,41]. A more thorough understanding of the surgeon-specific factors that contribute to implant alignment outliers following TKA may uncover actionable strategies for improving implant survival. Furthermore, understanding this relationship may have implications as to where to deploy expensive but potentially alignment-improving technologies, such as robotic navigation systems, in the future.

The objective of the current study was to determine the impact of surgical volume and institution type on the frequency of DFA, PTA, and PSA outliers following TKA. We hypothesized that low surgeon volume and trainee surgeons would be associated with an increased frequency of alignment outliers.

Materials and Methods

Study Design

This retrospective multicenter study involved radiographic analysis of 1,570 primary TKAs without complications performed by 9 non-trainee surgeons and 39 trainee surgeons at 4 private academic and state-funded centers in the U.S. and U.K. Data were collected from Barnes-Jewish Hospital (St. Louis, Missouri), John Cochran Veterans Hospital–VA St. Louis Health Care System (St. Louis, Missouri), The Princess Grace Hospital (London, U.K.), and University College London Hospitals (London, U.K.). Institutional review board approval was attained prior to the initiation of this study.

In order to determine the influence of surgeon volume and training status on implant alignment, surgeons were individually categorized according to volume in accordance

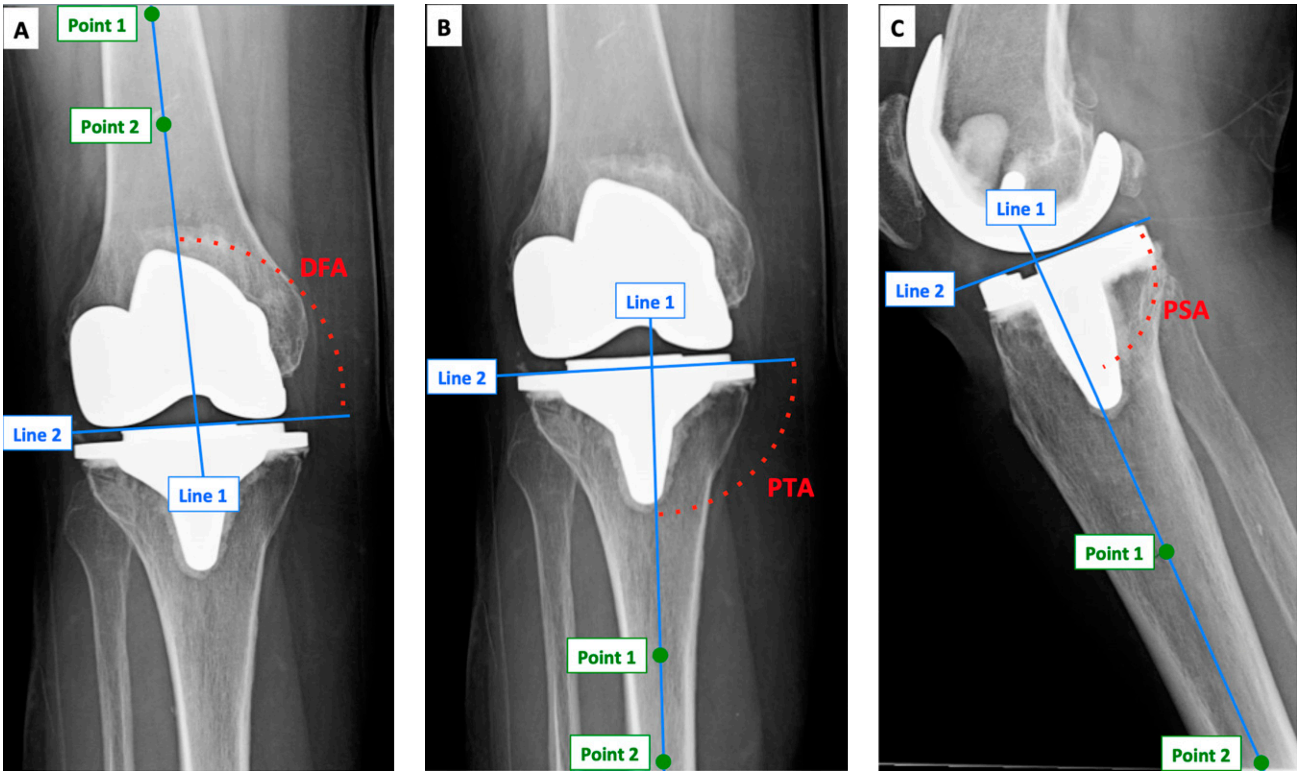

Fig. 1-A Fig. 1-B Fig. 1-C

Figs. 1-A, 1-B, and 1-C Radiographic measurements of the distal femoral angle, the proximal tibial angle, and the posterior slope angle. **Fig. 1-A** The distal femoral angle (DFA) was measured on anteroposterior radiographs and was defined as the medial angle (red) between (1) the anatomic axis of the femur (proximal-to-distal line in the medullary canal bisecting the femoral shaft) and (2) a line drawn parallel to the distal aspect of the femoral component (parallel to the medial and lateral condyles of the femoral component)[7]. Line 1 (blue) was defined by 2 points (green): (1) the proximal-most point of the radiograph at the center of the femoral shaft and (2) 10 cm superior to the knee joint, equidistant from the medial and lateral medullary cortices of the femur[42]. **Fig. 1-B** The proximal tibial angle (PTA) was measured on anteroposterior radiographs and was defined as the medial angle (red) between (1) the anatomic axis of the tibia and (2) the line parallel to the superior aspect of the tibial plate[7]. Line 1 (blue) was defined by 2 points (green): (1) 10 cm inferior to the knee joint, equidistant from the medial and lateral medullary cortices of the tibia[42] and (2) the distal-most point of the radiograph at the center of the tibial shaft. **Fig. 1-C** The posterior slope angle (PSA) was measured on lateral radiographs and was defined as the posterior angle (red) between (1) the tibial anatomic axis and (2) the tibial plate plateau[2]. Line 1 (blue) was drawn according to the methods described for Line 1 of the PTA measurement in Fig. 1-B, except using the lateral radiographs and the anterior and posterior medullary cortices of the tibia.

with methods previously described for hip arthroplasty by Barrack et al.[34]. Surgeons were categorized as “high-volume” if they performed ≥50 TKAs/year and as “low-volume” if they performed <50 TKAs/year. Surgeons were also classified as a “trainee” (a fellow/resident under the supervision of an attending surgeon) or as a “non-trainee” (an attending surgeon). On the basis of these categorical assignments, 3 distinct groups were created: high-volume non-trainees (HVNTs), low-volume non-trainees (LVNTs), and trainees. A breakdown of the number of surgeons and the number of knees within each group is shown in Table I.

Study Population

Included in the analysis were male and female patients ≥18 years of age who underwent TKA at 1 of the aforementioned institutions during the period of 2012 to 2017 and who had available postoperative radiographs. Patients were excluded if they underwent revision TKA or primary TKA with complicating factors, or if nonconventional TKA (robotic, custom instrumentation) was performed. Preoperative patient characteristics (age and BMI) by group are shown in Table II.

Radiographic Analysis

DFA, PTA, and PSA measurements were made on anteroposterior and lateral short-leg radiographs by 2 authors (G.S.K., M.J.D.) using digital measurement tools. Readers were blinded to surgeon. The methodology was similar to measurement methods used in prior studies and is detailed in Figures 1-A, 1-B, and 1-C[2,7,42].

In order to validate these measurements, interreader reliability was assessed for a subset of 50 radiographs by an additional author (T.N.B.). Although the use of short-leg radiographs in the assessment of TKA has been debated, evidence suggests that this method is an acceptable substitute for long-leg radiographs in the

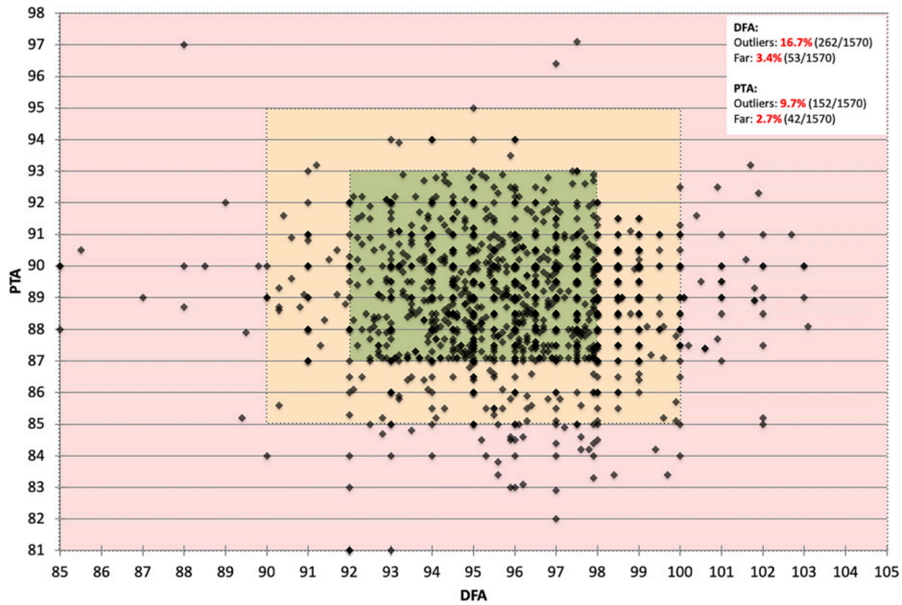

Fig. 2-A

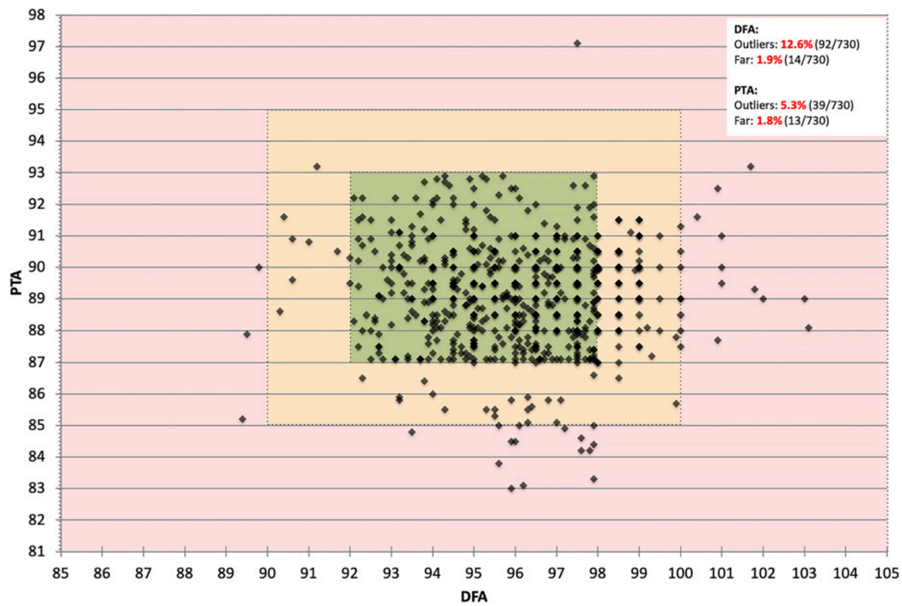

Fig. 2-B

Figs. 2-A through 2-D Scatterplot of distal femoral angle (DFA) and proximal tibial angle (PTA) measurements for all total knee arthroplasties (**Fig. 2-A**), the high-volume non-trainees (HVNTs) (**Fig. 2-B**), low-volume non-trainees (LVNTs) (**Fig. 2-C**), and trainees (**Fig. 2-D**). Green shading indicates optimal alignment, within 5° ± 3° of valgus for the DFA and within ±3° deviation from the neutral axis for the PTA. Yellow shading indicates outliers that remain within ±2° of the optimal alignment ranges. Red shading indicates "far" outliers, which are an additional >±2° outside of the outlier range.

assessment of TKA alignment[42-46]. In order to internally validate this methodology, we separately assessed 200 TKAs with available short-leg and long-leg radiographs and compared the findings to determine whether the rate of implant alignment outliers was similar between these methods.

Defining Postoperative Radiographic Outliers

Prior studies have described the relationship between the accuracy of implant alignment and the subsequent risk of postoperative mechanical failure. While the definition of "outlier" varies drastically between studies, our measurement ranges are based on previous research identifying clinically relevant "safe zones," outside of which increased failure rates were noted. On the basis of Ritter et al., we defined DFA outlier status as alignment outside of 5° ± 3° of valgus, and on the basis of Kim et al. and Ritter et al., we defined PTA outlier status as a >±3° deviation from the neutral axis[7,16-19]. On the basis of Kim et al.[16], optimal PSA

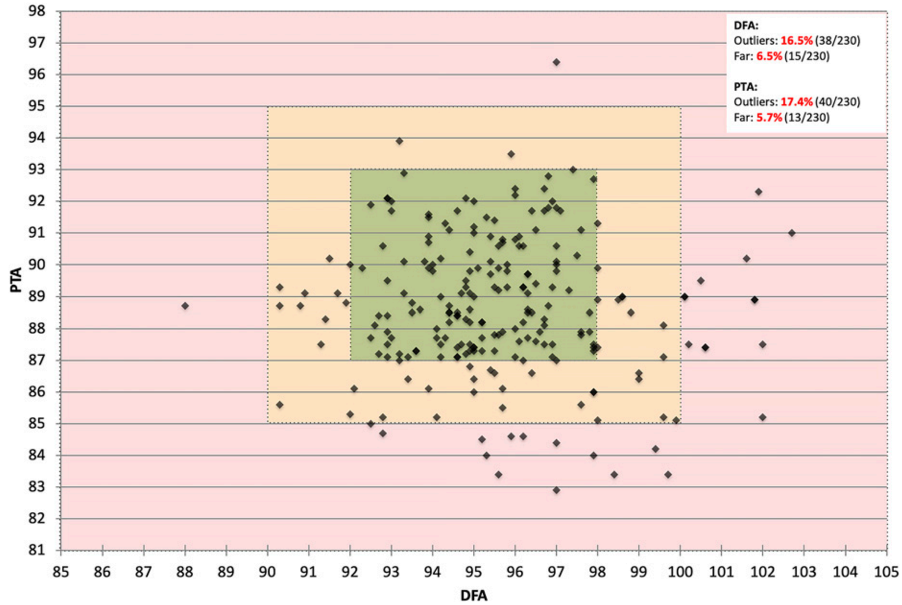

Fig. 2-C

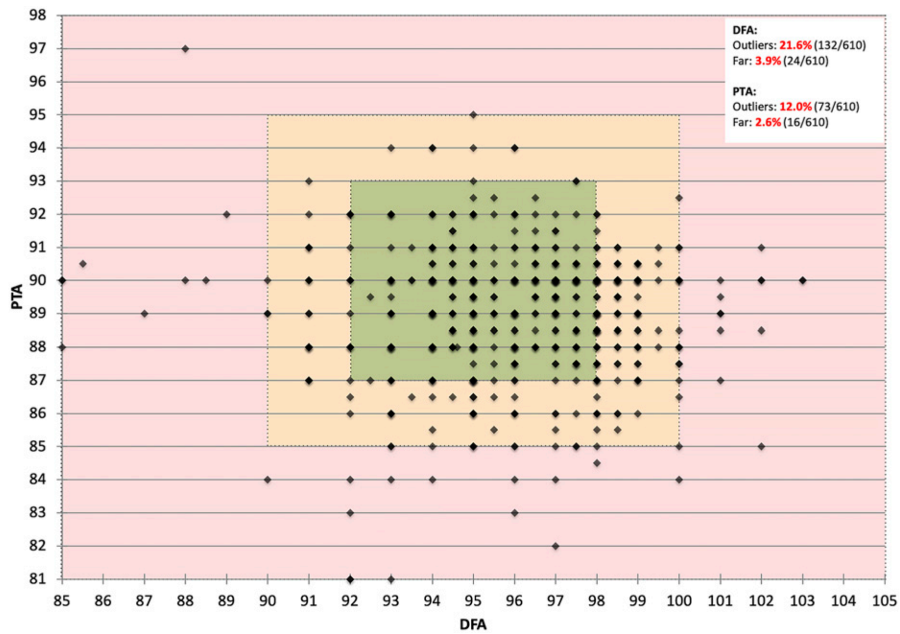

Fig. 2-D

alignment was defined as 0° to 7° of flexion in knees that underwent cruciate-retaining TKA, and on the basis of our own senior surgeons' experience, optimal alignment for posterior-stabilized knees was defined as 0° to 5° of flexion. A "far outlier" was defined as any measurement that fell >±2° outside of the aforementioned outlier ranges. "Highest-risk" outliers were defined as outliers that concomitantly had a DFA of ≥8° and a PTA of ≤90°[7].

Statistical Analysis

Descriptive statistics were calculated for continuous variables and categorical data. Continuous variables were compared using Student t tests and described using means and standard deviations. Categorical variables were compared using 2-proportion Z tests. The threshold for significance was established at $p < 0.05$.

Using SAS (version 9.4, PROC GLIMMIX; SAS Institute), we also performed multivariate analyses with a multilevel random-intercepts logistic regression. Two separate models were assessed: the first, a fixed-effects multivariable model, did not include random effects for variation in individual surgeons; the second, a random-effects mixed model, integrated the covariates of patient age and BMI and random effects for individual surgeon in

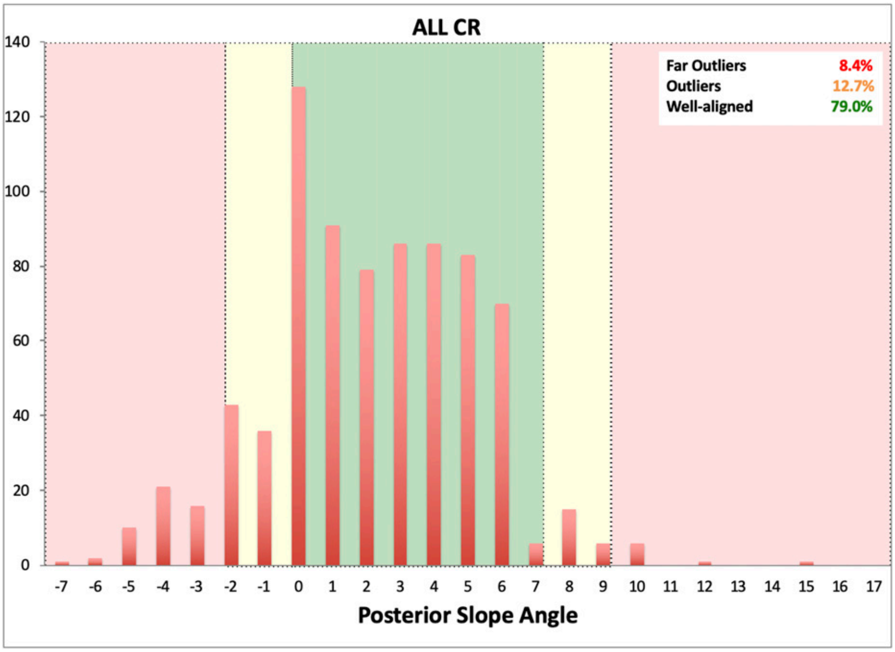

Fig. 3
Bar chart of the posterior slope angle for all cruciate-retaining (CR) total knee arthroplasties. Green shading indicates optimal alignment (0° to 7° of flexion). Yellow shading indicates outliers that remain within ±2° of the optimal alignment ranges. Red shading indicates "far" outliers, which are an additional >±2° outside of the outlier range.

order to assess whether individual surgeons and patient characteristics had an impact on alignment outcomes. The output for this assessment was odds ratios (ORs) and p values.

Results

Overall Alignment

For the 1,570 knees included in this study, the mean postoperative measurements were as follows: DFA, 96.0° (95%

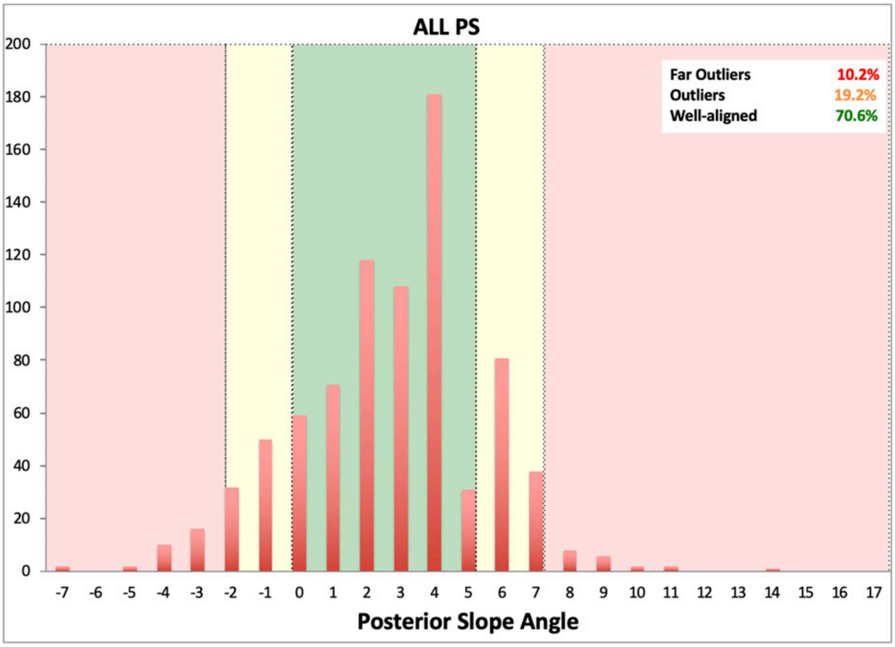

Fig. 4
Bar chart of the posterior slope angle (PSA) for all posterior-stabilized (PS) total knee arthroplasties. Green shading indicates optimal alignment (0° to 5° of flexion). Yellow shading indicates outliers that remain within ±2° of the optimal alignment ranges. Red shading indicates "far" outliers, which are an additional >±2° outside of the outlier range.

TABLE III Comparison of the Proportion of Outliers in the HVNT, LVNT, and Trainee Groups*

	Group				P Value		
	HVNT (N = 730)	LVNT (N = 230)	Trainee (N = 610)	Overall (N = 1,570)	HVNT vs. LVNT	HVNT vs. Trainee	LVNT vs. Trainee
DFA outlier	12.6%	16.5%	21.6%	16.7%	0.130	<0.001	0.101
PTA outlier	5.3%	17.4%	12.0%	9.7%	<0.001	<0.001	0.041
PSA outlier	17.4%	28.3%	33.3%	25.2%	<0.001	<0.001	0.165
Total outliers	11.8%	20.7%	22.3%	17.2%	<0.001	<0.001	0.624
DFA far outlier	1.9%	6.5%	3.9%	3.4%	<0.001	0.027	0.113
PTA far outlier	1.8%	5.7%	2.6%	2.7%	<0.001	0.292	0.033
PSA far outlier	5.5%	12.6%	12.6%	9.3%	<0.001	<0.001	0.996
Total far outliers	3.1%	8.3%	6.4%	5.1%	<0.001	0.004	0.342
0 outliers	69.0%	49.6%	44.8%	56.8%	<0.001	<0.001	0.214
1 outlier	26.7%	38.7%	44.1%	35.2%	<0.001	<0.001	0.159
2 outliers	4.1%	11.7%	10.7%	7.8%	<0.001	<0.001	0.654
3 outliers	0.1%	0.0%	0.5%	0.3%	0.575	0.236	0.288
Highest risk	8.6%	11.7%	16.1%	12.0%	0.159	<0.001	0.118

*The proportion of outliers was compared using 2-proportion Z tests. "Far outliers" were defined as any measurement that fell >±2° outside of established outlier ranges. HVNT = high-volume non-trainee, LVNT = low-volume non-trainee, DFA = distal femoral angle, PTA = proximal tibial angle, and PSA = posterior slope angle.

confidence interval [CI], 95.9° to 96.1°); PTA, 89.0° (95% CI, 88.9° to 89.1°); and PSA, 85.8° (95% CI, 85.7° to 85.9°) (Figs. 2-A through 4). The overall frequency of outliers was 16.7%, 9.7%, and 25.2% for the DFA, PTA, and PSA, respectively. Overall, 17.2% of all measurements represented outliers. The overall frequency of far outliers was 3.4%, 2.7%, and 9.3% for the DFA, PTA, and PSA, respectively. Overall, 5.1% of all measurements represented far outliers. A total of 12.0% of all measurements fell into the highest-risk category (Table III).

HVNT Compared with LVNT Group

The high-volume non-trainee (HVNT) group outperformed the low-volume non-trainee (LVNT) group on nearly all measures. A significantly greater proportion of knees in the LVNT compared with the HVNT group had outlier measurements for the PTA (17.4% compared with 5.3% of the cases), the PSA (28.3% compared with 17.4%), and overall (total outliers, 20.7% for LVNT compared with 11.8% for HVNT) (all $p < 0.001$). In addition, a significantly greater proportion of knees in the LVNT compared with the HVNT group demonstrated far outliers for the DFA (6.5% compared with 1.9%), the PTA (5.7% compared with 1.8%), the PSA (12.6% compared with 5.5%), and overall (total far outliers, 8.3% for LVNT compared with 3.1% for HVNT) (all $p < 0.001$) (Table III). The proportion of knees with 0 outliers was significantly higher in the HVNT group (69.0% for HVNT compared with 49.6% for LVNT), and the number of knees with 1 (26.7% for HVNT compared with 38.7% for LVNT) and 2 (4.1% for HVNT compared with 11.7% for LVNT) outliers was significantly lower in the HVNT group (all $p < 0.001$).

HVNT Compared with Trainee Group

The HVNT group outperformed the trainee group on nearly all measures. A significantly greater proportion of knees in the trainee compared with the HVNT group had outlier measurements for the DFA (21.6% compared with 12.6%), the PTA (12.0% compared with 5.3%), the PSA (33.3% compared with 17.4%), and overall (total outliers, 22.3% for trainee compared with 11.8% for HVNT) (all $p < 0.001$). In addition, a significantly greater proportion of knees in the trainee group demonstrated far outliers for the DFA (3.9% compared with 1.9%; $p = 0.027$), the PSA (12.6% compared with 5.5%; $p < 0.001$), and overall (total far outliers, 6.4% for trainee compared with 3.1% for HVNT; $p = 0.004$) (Table III). The proportion of knees with 0 outliers was significantly higher in the HVNT group (69.0% for HVNT compared with 44.8% for trainee), and the number of knees with 1 (26.7% for HVNT compared with 44.1% for trainee) and 2 (4.1% for HVNT compared with 10.7% for trainee) outliers was significantly lower in the HVNT group (all $p < 0.001$). The proportion of knees that fell into the highest-risk category was significantly greater in the trainee group (16.1% compared with 8.6%; $p < 0.001$).

LVNT Compared with Trainee Group

The LVNT and trainee groups performed similarly across nearly all measures. A significantly greater proportion of knees in the LVNT compared with the trainee group had outlier measurements for the PTA (17.4% compared with 12.0%; $p = 0.041$) and far outliers for the PTA (5.7% compared with 2.6%; $p = 0.033$), but the percentages for total outliers (20.7% compared with 22.3%; $p = 0.624$) and total far outliers (8.3% compared with

TABLE IV Findings from Multivariate Analysis, Including a Mixed Model with Fixed Effects and a Mixed Model with Random Effects for Individual Surgeon and Covariates of Patient Age and BMI*

		Multivariable Model with Fixed Effects		Multivariable Model with Random Effects	
	Comparison	OR (95% CI)	P Value	OR (95% CI)	P Value
DFA outlier	HVNT vs. LVNT	0.729 (0.483-1.099)	0.131	0.641 (0.264-1.556)	0.325
	HVNT vs. trainee	0.522 (0.390-0.699)	<0.001	0.656 (0.458-0.939)	0.021
	LVNT vs. trainee	0.717 (0.481-1.067)	0.101	1.023 (0.406-2.580)	0.962
PTA outlier	HVNT vs. LVNT	0.268 (0.168-0.429)	<0.001	0.252 (0.062-1.021)	0.054†
	HVNT vs. trainee	0.415 (0.277-0.623)	<0.001	0.118 (0.033-0.423)	<0.001
	LVNT vs. trainee	1.549 (1.018-2.357)	0.041	0.469 (0.090-2.447)	0.369†
PSA outlier	HVNT vs. LVNT	0.535 (0.379-0.755)	<0.001	0.541 (0.376-0.777)	<0.001
	HVNT vs. trainee	0.422 (0.327-0.545)	<0.001	0.403 (0.303-0.537)	<0.001
	LVNT vs. trainee	0.790 (0.566-1.102)	0.165	0.746 (0.517-1.077)	0.118
DFA far outlier	HVNT vs. LVNT	0.280 (0.133-0.590)	<0.001	0.304 (0.126-0.735)	0.008
	HVNT vs. trainee	0.477 (0.245-0.932)	0.030	0.393 (0.179-0.863)	0.020
	LVNT vs. trainee	1.704 (0.877-3.310)	0.116	1.291 (0.568-2.934)	0.542
PTA far outlier	HVNT vs. LVNT	0.303 (0.138-0.663)	0.003	0.303 (0.078-1.176)	0.084†
	HVNT vs. trainee	0.673 (0.321-1.411)	0.295	0.664 (0.108-4.075)	0.658
	LVNT vs. trainee	2.224 (1.052-4.703)	0.036	2.191 (0.303-15.844)	0.437†
PSA far outlier	HVNT vs. LVNT	0.402 (0.243-0.665)	<0.001	0.396 (0.235-0.666)	<0.001
	HVNT vs. trainee	0.401 (0.269-0.598)	<0.001	0.346 (0.223-0.536)	<0.001
	LVNT vs. trainee	0.999 (0.632-1.578)	0.996	0.874 (0.535-1.431)	0.593
Highest risk	HVNT vs. LVNT	0.710 (0.440-1.145)	0.160	0.829 (0.069-10.271)	0.884
	HVNT vs. trainee	0.494 (0.352-0.691)	<0.001	0.633 (0.434-0.922)	0.017
	LVNT vs. trainee	0.695 (0.440-1.097)	0.118	0.764 (0.061-9.606)	0.835

*BMI = body mass index, OR = odds ratio, CI = confidence interval, DFA = distal femoral angle, HVNT = high-volume non-trainee, LVNT = low-volume non-trainee, PTA = proximal tibial angle, and PSA = posterior slope angle. †Indicates that the statistical significance varies between the univariate analysis shown in Table III and multivariate analysis. No differences in statistical significance were identified between the univariate analysis and the fixed-effects model.

6.4%; p = 0.342) were similar between the 2 groups. No significant differences were identified for any of the other measures in this study when comparing these 2 groups (Table III).

Multivariate Analysis

Our multivariate analysis with fixed effects demonstrated trends identical to those of the univariate analysis with respect to significant differences in outliers, far outliers, and high-risk malalignment when comparing the HVNT, LVNT, and trainee groups (Table IV). The mixed model with random effects demonstrated similar overall trends, with the exception of the analysis of PTA outliers. While the univariate analysis identified significant differences in terms of PTA outliers and far PTA outliers when comparing the HVNT and LVNT groups and when comparing the LVNT and trainee groups, the random-effects model did not (Table IV).

A subset of 200 TKAs with available long and short-leg radiographs was assessed to determine if the proportion of outliers was significantly different when assessed by short-leg radiographs. No significant differences were found, as shown in Table V. The interreader reliability was 98% in categorizing measurements as "aligned," "malaligned," or "far outliers."

TABLE V Comparison of the Proportion of Outliers When Assessed by Short and Long-Leg Radiographs*

	DFA Outliers	PTA Outliers	PSA Outliers
Short-leg	17.5%	9.4%	24.2%
Long-leg	16.2%	11.1%	22.2%
Kappa	0.93	0.90	0.92
P value	0.726	0.575	0.638

*No significant differences were identified. DFA = distal femoral angle, PTA = posterior tibial angle, and PSA = posterior slope angle.

Discussion

In the current study, we assessed the relationship between surgeon volume, trainee status, and implant alignment outliers in TKA in the hopes of uncovering potential surgeon-specific,

and hence modifiable, factors that contribute to alignment outliers. Similar to the findings of prior studies[7,8,16,47], we identified a moderately high frequency of implant alignment outliers in our overall cohort, including DFA, PTA, and PSA alignment outliers. Furthermore, a surprisingly low proportion of knees (only 56.8%) demonstrated alignment within the target range for all measures, and a surprisingly high proportion of all outlier measurements (5.1%) represented far outliers.

When these results were analyzed according to surgeon volume and training status, the high-volume non-trainee (HVNT) group tended to outperform the low-volume non-trainee (LVNT) group and the trainee group on nearly all measurements assessed in this study, while the LVNT and trainee groups performed similarly. The general findings from the multivariable analysis confirmed that these effects were being driven by differences in surgeon volume and training status, and not individual surgeon performance or patient demographics. However, these factors may contribute to differences detected in PTA outliers and far PTA outliers when comparing the HVNT and LVNT groups and the LVNT and trainee groups. Despite clear advantages with respect to increasing surgeon volume, trainee surgeons interestingly performed similarly to the LVNTs. While implant alignment is not a perfect proxy for clinical outcomes, this may demonstrate that trainees perform similarly to LVNTs, who perform the majority of TKAs. This finding partially validates current surgical training practices.

Despite the establishment of well-defined "safe zones" for implant alignment, even the most accurate cohort in our study (HVNTs) placed only 69.0% of knees in optimal alignment for all 3 measurements. Perhaps most importantly, the proportion of knees that were alignment outliers for multiple components was exceedingly high. Among HVNTs, 4.2% of knees had alignment outliers for ≥2 components, and this number increased to 11.7% and 11.2%, respectively, among LVNTs and trainees. In light of findings from Ritter et al.[7], which demonstrated that compound malalignment vastly increases the rate of failure, these results are concerning. Moreover, because the assessment by Ritter et al.[7] did not address the possibility of additional risk increase associated with concomitant PSA alignment outliers, these findings may be even more concerning than anticipated.

Whether improved alignment translates to better outcomes and survival has yet to be definitively demonstrated. Although multiple studies have identified implant malalignment as a predictor of premature mechanical failure and poor clinical outcomes[3,4,7,8,13-16], studies such as that of Parratte et al.[48] demonstrated minimal impact of TKA malalignment on postoperative survival. That study, however, only assessed results from a single surgeon and did not separately assess the impact of far outliers. It is possible that, due to the small sample size of the study, an insufficient number of far outliers were captured in order to detect their contribution to the overall failure rate. Furthermore, the study did not assess the impact of PSA outliers, the most common type of outlier, and far outlier, in our cohort.

Despite this controversy, it seems clear that gross alignment outliers are likely to have an impact on knee function, kinematics, and wear characteristics, and efforts to diminish such outliers appear warranted. Given the impact of implant failure and revision TKA on costs and quality of life[49], countless efforts have been implemented in order to minimize the incidence of implant alignment outliers and subsequent failure. Patient-specific instrumentation, navigation, and robotic assistance, for example, have been introduced with varying levels of success. While custom cutting guides offer theoretical advantages, the majority of mid-to-long-term studies assessing their efficacy have demonstrated nonsuperiority[20-26]. Although the true value and cost-effectiveness of robotic technology have been debated, the use of robotic-arm assistance has demonstrated superiority to patient-specific instrumentation[27] and has shown the ability to improve TKA alignment in multiple studies[19,28-32]. The findings of the current study, especially if alignment outlier status is linked to increases in implant failure in follow-up studies, may justify the increased use of these technologies in the future.

Among the strengths of our study, it involved a large number of surgeons at various levels of training and experience, which lends to the external validity. In addition, it is the first study, to our knowledge, to assess surgeon volume and trainee status as risk factors for implant alignment outliers in TKA. Weaknesses of this study include the use of short-leg radiographs and the lack of follow-up regarding outcomes and survival. However, our short-leg measurements were largely similar to paired measurements made on a subset of long-leg radiographs.

Conclusions

Low surgical volume and trainee status were notable risk factors for outlier and far-outlier alignment, even when accounting for differences in individual surgeon and patient characteristics. These findings may suggest that increasing the proportion of TKAs performed at high-volume centers or employing technology to optimize alignment in higher-risk surgeon populations could improve outcomes. Even among HVNTs, the best-performing cohort in our study, the proportion of TKA alignment outliers was still high. Finally, trainee surgeons performed similarly to, and certainly not inferiorly to, low-volume surgeons. ■

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References

1. Graves S., Davidson D., de Steiger RN. Australian Orthopaedic Association National Joint Replacement Registry annual report. 2013. https://aoanjrr.sahmri.com/documents/10180/127202/Annual+Report+2013. Accessed 2019 Jun 6.

2. Gromov K, Korchi M, Thomsen MG, Husted H, Troelsen A. What is the optimal alignment of the tibial and femoral components in knee arthroplasty? Acta Orthop. 2014 Sep;85(5):480-7. Epub 2014 Jul 18.

3. Longstaff LM, Sloan K, Stamp N, Scaddan M, Beaver R. Good alignment after total knee arthroplasty leads to faster rehabilitation and better function. J Arthroplasty. 2009 Jun;24(4):570-8. Epub 2008 May 19.

4. Choong PF, Dowsey MM, Stoney JD. Does accurate anatomical alignment result in better function and quality of life? Comparing conventional and computer-assisted total knee arthroplasty. J Arthroplasty. 2009 Jun;24(4):560-9. Epub 2008 May 19.

5. Tew M, Waugh W. Tibiofemoral alignment and the results of knee replacement. J Bone Joint Surg Br. 1985 Aug;67(4):551-6.

6. Fang DM, Ritter MA, Davis KE. Coronal alignment in total knee arthroplasty: just how important is it? J Arthroplasty. 2009 Sep;24(6)(Suppl):39-43. Epub 2009 Jun 24.

7. Ritter MA, Davis KE, Meding JB, Pierson JL, Berend ME, Malinzak RA. The effect of alignment and BMI on failure of total knee replacement. J Bone Joint Surg Am. 2011 Sep 7;93(17):1588-96.

8. Ritter MA, Faris PM, Keating EM, Meding JB. Postoperative alignment of total knee replacement. Its effect on survival. Clin Orthop Relat Res. 1994 Feb;299:153-6.

9. Scuderi GR, Insall JN, Windsor RE, Moran MC. Survivorship of cemented knee replacements. J Bone Joint Surg Br. 1989 Nov;71(5):798-803.

10. Lotke PA, Ecker ML. Influence of positioning of prosthesis in total knee replacement. J Bone Joint Surg Am. 1977 Jan;59(1):77-9.

11. Weinstein JN, Andriacchi TP, Galante J. Factors influencing walking and stairclimbing following unicompartmental knee arthroplasty. J Arthroplasty. 1986;1(2):109-15.

12. Jonsson B, Aström J. Alignment and long-term clinical results of a semiconstrained knee prosthesis. Clin Orthop Relat Res. 1988 Jan;226:124-8.

13. Ritter MA, Herbst SA, Keating EM, Faris PM, Meding JB. Long-term survival analysis of a posterior cruciate-retaining total condylar total knee arthroplasty. Clin Orthop Relat Res. 1994 Dec;309:136-45.

14. Berend ME, Ritter MA, Meding JB, Faris PM, Keating EM, Redelman R, Faris GW, Davis KE. Tibial component failure mechanisms in total knee arthroplasty. Clin Orthop Relat Res. 2004 Nov;428:26-34.

15. Huang NF, Dowsey MM, Ee E, Stoney JD, Babazadeh S, Choong PF. Coronal alignment correlates with outcome after total knee arthroplasty: five-year follow-up of a randomized controlled trial. J Arthroplasty. 2012 Oct;27(9):1737-41. Epub 2012 Aug 3.

16. Kim YH, Park JW, Kim JS, Park SD. The relationship between the survival of total knee arthroplasty and postoperative coronal, sagittal and rotational alignment of knee prosthesis. Int Orthop. 2014 Feb;38(2):379-85. Epub 2013 Sep 10.

17. Abane L, Anract P, Boisgard S, Descamps S, Courpied JP, Hamadouche M. A comparison of patient-specific and conventional instrumentation for total knee arthroplasty: a multicentre randomised controlled trial. Bone Joint J. 2015 Jan;97-B(1):56-63.

18. Vandekerckhove PJ, Lanting B, Bellemans J, Victor J, MacDonald S. The current role of coronal plane alignment in total knee arthroplasty in a preoperative varus aligned population: an evidence based review. Acta Orthop Belg. 2016 Mar;82(1):129-42.

19. Mason JB, Fehring TK, Estok R, Banel D, Fahrbach K. Meta-analysis of alignment outcomes in computer-assisted total knee arthroplasty surgery. J Arthroplasty. 2007 Dec;22(8):1097-106.

20. Nam D, Park A, Stambough JB, Johnson SR, Nunley RM, Barrack RL. The Mark Coventry Award: custom cutting guides do not improve total knee arthroplasty clinical outcomes at 2 years followup. Clin Orthop Relat Res. 2016 Jan;474(1):40-6.

21. Camarda L, D'Arienzo A, Morello S, Peri G, Valentino B, D'Arienzo M. Patient-specific instrumentation for total knee arthroplasty: a literature review. Musculoskelet Surg. 2015 Apr;99(1):11-8. Epub 2014 Oct 11.

22. Voleti PB, Hamula MJ, Baldwin KD, Lee GC. Current data do not support routine use of patient-specific instrumentation in total knee arthroplasty. J Arthroplasty. 2014 Sep;29(9):1709-12. Epub 2014 May 27.

23. Conteduca F, Iorio R, Mazza D, Ferretti A. Patient-specific instruments in total knee arthroplasty. Int Orthop. 2014 Feb;38(2):259-65. Epub 2014 Jan 7.

24. Barrack RL, Ruh EL, Williams BM, Ford AD, Foreman K, Nunley RM. Patient specific cutting blocks are currently of no proven value. J Bone Joint Surg Br. 2012 Nov;94(11)(Suppl A):95-9.

25. Nunley RM, Ellison BS, Ruh EL, Williams BM, Foreman K, Ford AD, Barrack RL. Are patient-specific cutting blocks cost-effective for total knee arthroplasty? Clin Orthop Relat Res. 2012 Mar;470(3):889-94. Epub 2011 Dec 20.

26. Huijbregts HJ, Khan RJ, Sorensen E, Fick DP, Haebich S. Patient-specific instrumentation does not improve radiographic alignment or clinical outcomes after total knee arthroplasty. Acta Orthop. 2016 Aug;87(4):386-94. Epub 2016 Jun 1.

27. Steinhaus ME, McLawhorn AS, Richardson SS, Maher P, Mayman DJ. Handheld navigation device and patient-specific cutting guides result in similar coronal alignment for primary total knee arthroplasty: a retrospective matched cohort study. HSS J. 2016 Oct;12(3):224-34. Epub 2016 Feb 29.

28. Suero EM, Lueke U, Stuebig T, Hawi N, Krettek C, Liodakis E. Computer navigation for total knee arthroplasty achieves better postoperative alignment compared to conventional and patient-specific instrumentation in a low-volume setting. Orthop Traumatol Surg Res. 2018 Nov;104(7):971-5. Epub 2018 Apr 25.

29. Martín-Hernández C, Sanz-Sainz M, Revenga-Giertych C, Hernández-Vaquero D, Fernández-Carreira JM, Albareda-Albareda J, Castillo-Palacios A, Ranera-Garcia M. Navigated versus conventional total knee arthroplasty: a prospective study at three years follow-up. Rev Esp Cir Ortop Traumatol. 2018 Mar 28:S1888-4415(18)30007-9. Epub 2018 Mar 28. Spanish.

30. Kayani B, Konan S, Huq SS, Tahmassebi J, Haddad FS. Robotic-arm assisted total knee arthroplasty has a learning curve of seven cases for integration into the surgical workflow but no learning curve effect for accuracy of implant positioning. Knee Surg Sports Traumatol Arthrosc. 2019 Apr;27(4):1132-41. Epub 2018 Sep 17.

31. Kayani B, Konan S, Tahmassebi J, Pietrzak JRT, Haddad FS. Robotic-arm assisted total knee arthroplasty is associated with improved early functional recovery and reduced time to hospital discharge compared with conventional jig-based total knee arthroplasty: a prospective cohort study. Bone Joint J. 2018 Jul;100-B(7):930-7.

32. Pietrzak JRT, Rowan FE, Kayani B, Donaldson MJ, Huq SS, Haddad FS. Preoperative CT-based three-dimensional templating in robot-assisted total knee arthroplasty more accurately predicts implant sizes than two-dimensional templating. J Knee Surg. 2018 Aug 1. Epub 2018 Aug 1.

33. Bosker BH, Verheyen CC, Horstmann WG, Tulp NJ. Poor accuracy of freehand cup positioning during total hip arthroplasty. Arch Orthop Trauma Surg. 2007 Jul;127(5):375-9. Epub 2007 Feb 13.

34. Barrack RL, Krempec JA, Clohisy JC, McDonald DJ, Ricci WM, Ruh EL, Nunley RM. Accuracy of acetabular component position in hip arthroplasty. J Bone Joint Surg Am. 2013 Oct 2;95(19):1760-8.

35. Callanan MC, Jarrett B, Bragdon CR, Zurakowski D, Rubash HE, Freiberg AA, Malchau H. The John Charnley Award: risk factors for cup malpositioning: quality improvement through a joint registry at a tertiary hospital. Clin Orthop Relat Res. 2011 Feb;469(2):319-29.

36. Amanatullah DF, Pallante GD, Ollivier MP, Hooke AW, Abdel MP, Taunton MJ. Experience influences the agreement and reliability of tibial component positioning in total knee arthroplasty. J Arthroplasty. 2018 Apr;33(4):1231-4. Epub 2017 Nov 13.

37. Beattie N, Maempel JF, Roberts S, Waterson HB, Brown G, Brenkel IJ, Walmsley PJ. Surgery performed by supervised registrars does not adversely affect medium-term functional outcomes after total knee replacement. Ann R Coll Surg Engl. 2018 Jan;100(1):57-62. Epub 2017 Sep 15.

38. Reidy MJ, Faulkner A, Shitole B, Clift B. Do trainee surgeons have an adverse effect on the outcome after total hip arthroplasty?: a ten-year review. Bone Joint J. 2016 Mar;98-B(3):301-6.

39. Wilson MD, Dowsey MM, Spelman T, Choong PF. Impact of surgical experience on outcomes in total joint arthroplasties. ANZ J Surg. 2016 Dec;86(12):967-72. Epub 2016 Sep 6.

40. Bowman RR, Guyer WD, Bos GD. Total knee arthroplasty at a Veterans Administration Medical Center. Clin Orthop Relat Res. 1991 Aug;269:51-7.

41. Heck DA, Maar DC, Lowdermilk GA, Kalasinski LA, Mesko JW. Comparative analysis of total knee arthroplasty in two health care delivery systems. J Arthroplasty. 1992 Mar;7(1):93-100.

42. Petersen TL, Engh GA. Radiographic assessment of knee alignment after total knee arthroplasty. J Arthroplasty. 1988;3(1):67-72.

43. Skyttä ET, Lohman M, Tallroth K, Remes V. Comparison of standard anteroposterior knee and hip-to-ankle radiographs in determining the lower limb and implant alignment after total knee arthroplasty. Scand J Surg. 2009;98(4):250-3.

44. Fang D, Sueyoshi T, Davis KE, Ritter MA. Short leg film is sufficient for postoperative follow-up in total knee arthroplasty. Open J Orthop. 2015;5(7):175-8.

45. McGrory JE, Trousdale RT, Pagnano MW, Nigbur M. Preoperative hip to ankle radiographs in total knee arthroplasty. Clin Orthop Relat Res. 2002 Nov;404: 196-202.

46. Tammachote N, Kriengburapha N, Chaiwuttisak A, Kanitnate S, Boontanapibul K. Is regular knee radiograph reliable enough to assess the knee prosthesis position? J Arthroplasty. 2018 Sep;33(9):3038-42. Epub 2018 May 30.

47. Brin YS, Nikolaou VS, Joseph L, Zukor DJ, Antoniou J. Imageless computer assisted versus conventional total knee replacement. A Bayesian meta-analysis of 23 comparative studies. Int Orthop. 2011 Mar;35(3):331-9. Epub 2010 Apr 8.

48. Parratte S, Pagnano MW, Trousdale RT, Berry DJ. Effect of postoperative mechanical axis alignment on the fifteen-year survival of modern, cemented total knee replacements. J Bone Joint Surg Am. 2010 Sep 15;92(12):2143-9.

49. Kazarian GS, Lonner JH, Maltenfort MG, Ghomrawi HMK, Chen AF. Cost-effectiveness of surgical and nonsurgical treatments for unicompartmental knee arthritis: a Markov model. J Bone Joint Surg Am. 2018 Oct 3;100(19):1653-60.