Arthroplasty Today 15 (2022) 202–209

Contents lists available at ScienceDirect

Arthroplasty Today

journal homepage: http://www.arthroplastytoday.org/

Original research

Does Resident Participation Influence Surgical Time and Clinical Outcomes? An Analysis on Primary Bilateral Single-Staged Sequential Total Knee Arthroplasty

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ARTICLE INFO

Article history:
Received 17 September 2021
Received in revised form
8 February 2022
Accepted 26 February 2022
Available online 8 April 2022

Keywords:
Residency training
Resident education
Total knee arthroplasty
Single-staged bilateral
Postoperative outcomes
Orthopaedic surgery

ABSTRACT

Background: Although several studies have indirectly compared teaching and nonteaching hospitals, results are conflicting, and evaluation of the direct impact of trainee involvement is lacking. We investigated the direct impact of resident participation in primary total knee arthroplasties (TKAs).
Material and methods: Fifty patients undergoing single-staged sequential bilateral primary TKAs were evaluated. The more symptomatic side was performed by the attending surgeon first, followed by the contralateral side performed by a chief resident under direct supervision and assistance of the same attending surgeon. Surgery was subdivided into 8 critical steps on both sides. The overall time and critical stepwise surgical time and short-term clinical outcomes were then compared between the 2 sides.
Results: The attending surgeon completed the surgery (skin incision to dressing) significantly faster than the resident (70.2 vs 96.9 minutes) by a mean of 26.7 minutes ($P < .05$) and was also faster in all steps. The most significant differences in time were in “exposure” (9.5 vs 16.5 minutes) and “closure” steps (13.2 vs 24.9 minites), all $P < .001$. Adverse events occurred in 7 patients; 5 of these resolved uneventfully. There were no significant differences in surgical complications, objective outcome scores, or patient satisfaction scores between both sides.
Conclusion: Resident participation in TKA increased operative time without jeopardizing short-term patient clinical outcomes, satisfaction, and complications. This may alleviate concerns from patients and policymakers about TKA in an academic setting. Surgical “exposure” and “closure” were the most prolonged steps for the residents, and they may benefit with more focus and/or simulation studies during training.

Introduction

Nearly half of all surgical and one-third of orthopaedic procedures in the United States are performed at teaching hospitals [1]. However, concerns that resident participation may compromise patient care and potentiate adverse events and costs persist [1,2]. These concerns have become more relevant with bundled payment system introduction [3,4], resident duty-hour restrictions, and inexperience [5,6], as well as increased focus on quality-driven reimbursement metrics [5-8]. Since resident education is crucial in producing highly skilled and well-trained future health-care providers, residency programs must optimize patient safety and surgical outcomes, while also providing direct “hands-on” resident training efficiently. Several studies in various surgical specialties [9-12], including orthopaedics [1,2,13-20], have compared cost, outcomes, and adverse effects between teaching and nonteaching hospitals but present conflicting data [1,2,14,15,18-20]. Most of these studies utilized the American College of Surgeons National Surgical Quality Improvement Program database [21], which lacks

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https://doi.org/10.1016/j.artd.2022.02.029

specific details and consistency pertaining to residents' experience and degree of participation in procedures [12,16,17,22]. These conclusions may also be confounded by a bias toward a greater prevalence of relatively more complex cases in teaching hospitals [13,18,20].

Total knee arthroplasty (TKA) is among the most commonly performed and standardized orthopaedic surgical procedures worldwide [23]. A National Inpatient Sample study reported 680,150 TKAs were performed in 2014, with an expected annual projection of 1.3 million cases by 2030 [24]. The Accreditation Council for Graduate Medical Education (ACGME) now requires residents to complete at least 30 TKAs prior to graduation [25]. Because of the competency required for orthopaedic surgery residents, a routine procedure with fairly standardized and predictable steps, such as TKA, has been widely used as a surrogate for guidelines and policies [4,26] and can serve as an effective tool to investigate the impact of resident involvement on outcomes. Few studies have investigated the impact of resident involvement in TKA. All but 1 study [13] showed increased operative time (and thus direct/indirect costs), but outcomes and complications data have been conflicting [1,13,20]. Moreover, no previous studies have investigated details of operative time via subanalyses by surgical steps, and all share the same limitations as studies in other specialties, providing no direct comparison [9-11,27-30].

Single-staged sequential bilateral primary TKA performed during the same anesthesia provides a unique opportunity for the most direct comparison between the 2 sides, while controlling for potential confounders. We sought to evaluate the impact of resident participation on operative time, identify the most time-consuming step(s) that may warrant additional focus during training, and characterize differences in patient outcomes.

Material and methods

Study design and patient selection

This was a retrospective analysis of an institutional review board-approved prospectively maintained database of an adult reconstruction fellowship-trained attending orthopaedic surgeon (A.V.M.) from November 2013 to October 2020 at a single ACGME-accredited orthopaedic surgery residency program. All single-stage sequential primary bilateral TKAs under 1 type of anesthesia were included in this study. Patients with relatively controlled medical comorbidities and clinically significant knee deformities (≥15° in coronal and/or sagittal plane, and limb-length discrepancy that would potentially interfere with postoperative rehabilitation [31-33]) were offered a single-staged bilateral surgery after detailed discussion with patients, families, and their other health-care providers. All participants provided informed consent understanding that as a teaching institution, components of their procedure, including critical components, would be performed by an orthopaedic resident under full, direct supervision by the scrubbed attending at all times; however, subjects were blinded to which side and surgical steps would be performed by the attending or resident. The procedure was subdivided into 8 critical steps (Table 1) to compare timing, which was recorded by the same independent nonscrubbed observer for all cases.

Perioperative protocol and surgical technique

All patients underwent standardized perioperative surgical protocols (Supplementary Material 1) [34-43]. Both lower extremities were prepped and draped simultaneously. A uniform surgical technique via a standard midline incision and medial parapatellar approach was utilized. The tibia was cut first, followed by the distal femur cut and extension balancing by soft-tissue releases. This was followed by rest of the femur cuts, tibial preparation, and then patella preparation sequentially. The gap-balancing method with parallel-to-tibia cuts technique was utilized and cross-checked with epicondylar axis [34]. All cases were performed with a posteriorly stabilized implant system. A tourniquet was only utilized during cementing in the first 39 cases. The remaining cases were done without tourniquet as change in surgeon's preference. Bone cement was used in all but 1 patient.

The attending performed the overall more symptomatic, more clinically advanced (per degree of deformity and stiffness), and more radiographically severe (although all knees were of Kellgren Lawrence grade IV [44]) side first. Once the first side was complete, a chief resident (postgraduate year 5) operated on the contralateral knee under direct attending supervision, who was scrubbed, supervised, and assisted for the entirety of the procedure. However, the patellar preparation and the cementing steps were done by the attending surgeon bilaterally, as they were deemed as the most critical steps with less room for error and subsequent correction.

Table 1
The 8 critical steps for the total knee arthroplasty procedure along with the intraoperative comparative timing data for the attending and the resident.

Step number	Step name and definition	Attending mean ± SD (range)	Resident mean ± SD (range)	*P* value
1	Exposure (skin incision to placement of tibial jig)	9.5 ± 1.9 (7 to 15)	16.5 ± 4.2 (9 to 27)	**<.001**
2	Tibial jig placement and tibial cuts to the distal femur cut and extension balancing (including soft-tissue balancing in extension)	9.8 ± 3.4 (5 to 20)	13.2 ± 3.7 (7 to 21)	**<.001**
3	Extension balancing to the preparation of femur and femoral trial placement	12.0 ± 3.7 (8 to 27)	14.4 ± 3.1 (9 to 20)	**.004**
4	Femoral trial placement to the preparation and placement of tibial trial	3.7 ± 1.9 (1 to 12)	4.3 ± 2.5 (2 to 15)	.287
5[a]	Tibial trial placement to the preparation and placement of patellar trial with evaluation of patellar tracking	3.3 ± 0.9 (2 to 6)	4.2 ± 1.2 (2 to 8)	**.002**
6[a]	Patellar trialing to the start of mixing of cement	2.6 ± 1.7 (1 to 10)	2.7 ± 1.3 (1 to 6)	.776
7[a]	Cement mixing to the placement of final polyethylene insert (including removal of excessive cement after curing)	16.1 ± 3.5 (5 to 24)	16.7 ± 3.9 (6 to 24)	.447
8	Closure (final insert placement to skin closure and dressing application)	13.2 ± 2.3 (10 to 18)	24.9 ± 4.9 (14 to 32)	**<.001**
Total time (min)		70.2 ± 12.0 (52 to 108)	96.9 ± 14.7 (68 to 132)	**<.001**
EBL (mL)		228.1 ± 62.8 (100 to 400)	293.8 ± 54.1 (100 to 350)	**.002**
Tourniquet[a]		8.2 ± 1.2 (7 to 10)	7.8 ± 0.9 (7 to 10)	.259

EBL, estimated blood loss.
The freehand preparation of the patella and subsequent cementing of the final components until the insertion of the final polyethylene insert (*steps 5-7a*) were exclusively performed by the attending surgeon bilaterally as they were deemed the most critical steps for the procedure. A mean of 5.9 mins (range, 4-10 mins) were required between placement of the dressing on the first side and incision on the second side.
Bold values indicate statistical significance, P < .05.
[a] Tourniquet was used bilaterally only on first 39 patients and was inflated only for cementing part. The remaining cases were done without tourniquet as change in surgeon's preference.

Table 2
Demographics of included patients undergoing total knee arthroplasties.

Parameter	Mean ± SD (range)
Age (y)	65.5 ± 1.4 (49-78)
BMI (kg/m^2)	31.7 ± 1.6 (20.9-43.8)
Gender	
Male	11 (22.0%)
Female	39 (78.0%)
Diagnosis	
Primary osteoarthritis	46 (92.0%)
Inflammatory arthritis	4 (8.0%)
Deformity	
Bilateral varus	41 (82.0%)
Bilateral valgus	5 (10.0%)
Windswept	4 (8.0%)
Baseline preoperative Knee Society Score (KSS)	
Attending side	25.1
Resident side	29.2 (*P* = .249)
ASA grade	
1	1 (2.0%)
2	36 (72.0%)
3	13 (26.0%)
Anesthesia type	
Regional/Combined spinal-epidural	44 (88.0%)
General	6 (12.0%)
Implant used	
PFC Sigma PS, cemented (DePuy Synthes, Warsaw, IN)	29 (58.0%)
ATTUNE PS, cemented (DePuy Synthes, Warsaw, IN)[a]	19 (38.0%)
Triathlon, cementless (Stryker Corporation, Mahwah, NJ)	1 (2.0%)
Zimmer Persona, cementless (ZimmerBiomet, Warsaw, IN)	1 (2.0%)

ASA, American Society of Anesthesiologists; BMI, body mass index.
[a] Two were rotating platform.

The attending surgeon corrected the residents' errors before happening and guided them appropriately as much as possible.

Variables and outcomes

Data and outcome measures included patient demographics (age, sex, body mass index [kg/m^2], and American Society of Anesthesiologists class), time required to complete each step, total operative time (incision to dressing placement), and intraoperative estimated blood loss. Blood loss was calculated separately for each side by calculating blood in the suction canister and quantified from the number of laparotomy sponges utilized [45,46]. Outcomes included 90-day readmission, medical complications including but not limited to deep vein thrombosis, pulmonary embolism, urinary tract infection, cardiopulmonary and gastrointestinal complications, complex regional pain syndrome, and 1-year surgical complications including revision, infections, manipulation under anesthesia, patellar clunk syndrome, and wound issues. Functional outcomes included 1-year patient-reported satisfaction and postoperative preference for side and the Knee Society Score (KSS) [47].

Statistical analysis

A descriptive analysis was performed to evaluate patient and surgeon demographics related to TKA case volume. Overall mean operative time and surgical step durations were compared between the attending and residents via student's t-tests. Appropriate parametric and nonparametric tests were utilized to assess residents' performance in terms of total operative duration, duration of stages, and overall timing between their first and last operations compared with the attending. Postoperative patient satisfaction and side preference, KSS, and complications were compared between both groups through 1 year. All analyses were performed by a blinded researcher with SPSS version 25.0 (IBM Corp., Armonk, NY), using a *P* value <.05 as the threshold for statistical significance.

Results

A total of 54 patients (108 TKAs) were included in this study. Four patients (8 TKAs) underwent single-staged bilateral TKAs, with both sides performed by an attending periodically to serve as an internal control. There was no difference in total operative time between sides (mean ± standard deviation: 67.8 ± 4.7 vs 66.8 ± 3.3 minutes, *P* = .660); no difference was also identified in any of the 8 steps or outcomes. There were no complications.

Thus, the comparative analysis with residents was done on 50 patients (100 TKAs). Patient and surgeon demographics are listed in Tables 2 and 3, respectively.

Timing

The attending completed his portion of the procedure significantly faster than residents in all 50 cases, with a mean of 70.2 ± 12.0 minutes (range, 52 to 108) vs 96.9 ± 14.7 minutes (range, 68 to 132) (*P* < .001) and a mean difference of 26.7 ± 9.1 minutes between the attending and surgeon from incision to closure of their respective sides. This difference was present in all steps and statistically significant in most steps, particularly in the "*exposure*" and "*closure*" steps (Table 1).

Table 3
Total knee arthroplasty (TKA) experience of the orthopaedic residents at our institute.[a]

Number	Chief residents involved in this study (n = 27)	All chief residents that graduated from the program during the study period
Total Number	30	35
Mean TKA numbers as junior residents (PGY1-4)	101 (68-145)	96 (56-145)
Mean TKA numbers as chief residents (PGY 5)	29 (17-41)	26 (14-41)
Mean TKA numbers in entire residency (PGY1-5)	128 (87-180)	122 (78-180)
Mean months as PGY5 before their index study case	6 (1-11)	N/A
Mean TKA cases as a PGY5 before the index study case	19 (1-27)	N/A

PGY, postgraduate year.
Mean numbers for national resident performance obtained from the ACGME [48]. During their entire residency (60 mo), all residents rotated with the same attending surgeon (A.V.M.) for 8 mo (4 as a junior resident [PGY-1 and PGY-3] and 4 as a chief resident [PGY-5] in 4 different 2-month slots). This study was conducted during their third slot, and thus all residents have had some prior experience with the procedure and the attending surgeon's technique. A total of 30 chief residents participated in this study, and 11 of them were involved with multiple cases (1 case, n = 18; 2 cases, n = 7; 3 cases, n = 3; 4 cases, n = 1; 5 cases, n = 1). The graduating residents, as well as residents included in this study, had comparable primary TKA experience to residents nationally [48] during the study period (*P* > .842). A total of 5 (16.7%) chief residents matched into adult reconstruction fellowship prior to their study participation period. In comparison, the attending surgeon had performed 64 primary TKAs before the index study case and additional 891 (127 per year) during the study period.
[a] National Resident Average of TKAs performed, 2013-2019: 117.1 ± 9.1.

Table 4
Complications in the study patients.

Complication	Number (n)	In-hospital vs after discharge	Outcome	Laterality (attending vs resident)	Readmission	Return to operating room
Aspiration pneumonitis after general anesthesia	1	In-hospital	Treated with initiation of antibiotics, pulmonary hygiene, and incentive spirometry, resolved uneventfully.	NA	No	No
Isolated peroneal deep vein thrombosis (DVT)	1	In-hospital	The patient was maintained on aspirin [49,50] and monitored by serial clinical examination and ultrasound Doppler, and the clot resolved at 8 wks uneventfully.	Resident	No	No
Mortality	1	After discharge	The patient was reported as deceased at 6 wks postoperatively at another hospital emergency room after an initial uneventful course. This patient had a BMI of 30 kg/m^2, with hypertension, and was still on aspirin for venous thromboembolism prophylaxis. No postmortem analysis or PE studies were performed, but a cardiopulmonary cause was suspected per emergency room notes.	NA	Patient returned to emergency room of another hospital	No
Complex regional pain syndrome (CRPS)	1	Both in-hospital and after discharge	Being treated conservatively by pain management, still active.	Both sides	No	No
Patellar clunk	1	After discharge at 1 y	Surgical excision at 15 mo, resolved uneventfully	Attending	Ambulatory surgery	Yes
Stiffness	2	After discharge	Manipulation under anesthesia: 1 patient × 3 mo; second patient × 6 wks[a]	Both sides	Ambulatory surgery	Yes

BMI, body mass index; NA, not applicable; PE, pulmonary embolism.
[a] This patient also had a suture granuloma on the attending side along with stiffness bilaterally. Thus, she was returned to the operating room at 6 wks for excision of suture granuloma with primary closure and manipulation under anesthesia relatively earlier than usual.

The residents' overall timing did improve with increasing experience. To objectively assess the role of procedural experience on timing, data on residents who performed ≥3 cases were subanalyzed (range, 3-5). There was significant improvement of mean timing (17.2 minutes) between residents' first (103.0 ± 11.5 minutes [range, 83 to 112]) and last (85.8 ± 14.2 minutes [range, 68 to 106]) cases ($P = .023$). When compared with the attending timing for the same cases, the difference improved from 29.6 ± 13.9 minutes (range, 11 to 44) for their first case to 17.6 ± 3.9 minutes for their last case (range, 14 to 24).

As a subanalysis, timing differences were evaluated between residents who matched into adult reconstruction fellowship (n = 5) and those who matched into other orthopaedic subspecialty fellowships (n = 25). Total operative time for residents who matched into adult reconstruction trended better but were not statistically different than that for residents who matched into other fellowships (92.0 vs 97.9 minutes, $P = .437$). Similar findings were observed for "*exposure*" (15.4 vs 17.0 minutes, $P = .264$) and "*closure*" (22.6 vs 24.7 minutes, $P = .131$) steps. Consistently, total operative time difference between the attending and both groups was also similar for overall cases (adult reconstruction fellowship-matched, 22.1 minutes; other fellowship-matched, 26.5 minutes; $P = .513$).

Complications

There were no intraoperative complications. Blood loss was significantly higher on the resident side, and this may be due to increased operative time (293.8 vs 228.1 ml; Table 1). Adverse events occurred in 7 patients, and 5 of these resolved uneventfully (Table 4). There was no significant difference in complications between the attending and resident sides.

Patient-based outcomes

Outcome measures were available on 49 patients at 1 year postoperatively, as there was 1 mortality at 6 weeks. All but 1 patient (with complex regional pain syndrome) were satisfied with the outcomes and indicated that they would undergo their bilateral procedure again if given the chance. Thirty-seven patients (75.5%) indicated no specific laterality preference at 1-year follow-up, exhibiting equal satisfaction with both sides. Among those who indicated a preference, no difference was observed between patients' preference for the side performed by the attending or resident (14.2% [n = 7] vs 10.2% [n = 5], respectively; $P = .393$). At 90 days postoperatively, KSS were comparable between the attending's and the resident's sides (95.6 vs 94.1, $P = .414$).

Discussion

Resident training is an integral part of medical education, but resident participation also raises concerns about compromised patient care and potential increases in adverse events and health-care costs [1,2]. Due to recent paradigm shifts in health-care policies at multiple fronts, concerns have been raised about residents' overall experience and readiness when they start in practices [3-8]. Thus, resident participation and its implications on value, safety, and cost are being heavily scrutinized. Numerous studies in medical specialties, including orthopaedics (Supplementary Table 2), have investigated the impact of resident participation via comparison of teaching vs nonteaching hospitals or presence/absence of resident during surgeries. Although each had their own intrinsic methodological limitations, most studies have found increased operative time and direct/indirect cost but show conflicting data on patients' postoperative outcomes and complications [1,19,20,49-56]. Moreover, neither details of drivers of these differences have been elaborated nor suggestions for improvement have been recommended by any previous study.

We chose TKA, as it is one of the most common standardized procedures and is projected to grow exponentially in the future [24]. Moreover, it is a part of the core competency "case minimum" required by the ACGME. Although the exact number of minimum TKAs required in training to develop a skilled independent surgeon varies widely [57], it is imperative to maximize residents' surgical experience with minimal complications to patients and health care in this limited timeframe. Also, as the supply of fellowship-trained arthroplasty surgeons may not meet the demand for increasing TKA

Table 5
Summary of published studies investigating the impact of resident involvement in knee arthroplasty procedures.

Study	Study design	Procedure	Outcomes/Differences
Lavernia et al., 2000 [60]	• Retrospective analysis • Institutional data	• Primary TKA	• Teaching hospitals were associated with significantly higher hospital costs and operative time, with a trend toward higher morbidity in patients undergoing primary TKA
Woolson and Kang, 2007 [61]	• Retrospective cohort • Institutional data	• Primary THA/TKA	• Aside from longer operative times with resident involvement, postsurgical complication rates did not differ between attendings and trainees
Gandhi et al., 2009 [62]	• Retrospective cohort • Institutional data	• Primary THA/TKA	• No significant difference in functional outcomes or patient satisfaction following TJA between academic and community hospitals up to 1 y postoperatively
Perfetti et al., 2017 [20]	• Retrospective cohort • NYS SPARCS	• Primary TKA	• TKA patients in teaching hospitals had longer lengths of stay, higher hospital costs, and 90-d readmissions, but similar discharge disposition status compared with nonteaching institutions
Bao et al., 2018 [64]	• Retrospective cohort • Institutional data	• Primary TKA	• Resident participation did not increase the risk of postoperative hospital length of stay, facility discharge, or worse patient-reported functional outcomes, despite longer operative times in all except senior (PGY5) residents
Weber et al., 2018 [13]	• Retrospective cohort • Institutional data	• Primary TKA	• Operative times were similar among residents and attendings for navigated TKA, but longer in the former group for conventional TKA • Patient-reported functional outcomes and complications rates were similar between residents and attendings after 1-y follow-up
Storey et al., 2018 [65]	• Retrospective review • New Zealand Joint Registry	• Primary TKA/UKA	• Despite lengthier operative times with resident involvement, revision rates and patient-reported functional outcomes did not differ between senior residents and attendings but were higher in attendings than in junior and unsupervised residents performing a TKA
Theelen et al., 2018 [66]	• Retrospective analysis from Netherland • Institutional data	• Primary TKA	• Operative time was significantly higher with resident involvement, but no statistical differences were detected in the complication and revision rates, as well as radiographic alignment and patient-reported functional outcomes between attendings and residents
Kazarian et al., 2019 [67]	• Retrospective multicenter cohort • Institutional data	• Primary TKA	• Residents were at higher risk for radiographic outlier and far-outlier malalignment than high-volume attending surgeons
Khanuja et al., 2019 [68]	• Retrospective multicenter cohort • Institutional data	• Primary TKA (6003 TKA by 41 surgeons) • 4024: no trainee (with 40 surgeons) • 1979: resident and/or fellow (with 18 surgeons)	• No difference in operative time (102 ± 20 vs 115 ± 30 min, $P = .069$)
Madanipour et al., 2021 [69]	• Systematic review and meta-analysis	• Primary TKA	• Included 9 studies of 92,309 arthroplasties, 80,655 were performed by consultants, 11,654 by trainees. • No significant difference between the 2 groups' rate of revision ($P = .07$). • Trainees were associated with a lower rate of infection ($P = .03$). • No difference in the rate of neurological deficit, transfusion rate, or thrombosis. • No difference in operation time ($P = .35$). • The trainee group had less favorable functional outcome scores ($P < .01$). However, this difference was not clinically significant.
Hoerlesberger et al., 2021 [70]	• Retrospective single-center radiographic cohort study • Institutional data	• Primary TKA (206 by 2 surgeons, 1:1 matched between attending and PGY-3 resident)	• Learning curve showed decrease across time, with differences in deviation points for first, second, and fourth quintiles of cases • Incision-to-closure time decreased across quintiles for residents (79.5 to 65.17 mins, respectively), with only the first and second quintile of cases significantly differing from the attending (mean, 66.0 mins; $P < .05$).
Current study	• Prospective cohort • Institutional data	• Single-staged bilateral primary TKA	• Resident participation increased operative time significantly, with exposure and closure as the most time-consuming steps. • Resident participation increased total TKA procedure time by 26.7 mins, reflecting an opportunity cost of 1 additional TKA for the attending surgeon for every 3 TKAs performed with active resident participation • No difference in patient-reported function, preference, or complications was noted between residents' and the attending's operative sides

THA, total hip arthroplasty; TJA, total joint arthroplasty; PGY, postgraduate year; UKA, unicompartmental knee arthroplasty; NYS SPARCS, New York State Statewide Planning and Research Cooperative System.

in the future [58], many young surgeons may have to rely on their experiences during residency to perform a technically sound TKA. A study on orthopaedic surgeons who took the American Board of Orthopaedic Surgery Part II examination from 2003 to 2013 found that non–fellowship-trained surgeons performed 45% of primary TKA procedures [59]. Thus, training of primary TKA becomes more important in an orthopaedic residency program, and ways to improve residents' experience need to be explored.

There are several studies that have investigated the impact of residents specifically related to TKA (Table 5), yet all still share the same intrinsic methodological limitations and have shown conflicting data [1,13,20,70]. None of these studies have clarified the exact degree of resident and attending participation. Additionally, none of them have quantified operative time in a detailed, stepwise fashion. While two recent studies have evaluated resident participation in a bilateral single-stage TKA model [71,72], a unique model which provides for the most direct comparison with controlling of confounders and limitations as much as possible, these studies have not reported attending and resident participation with the degree of granularity as is presented in this study.

An important finding of our study was that, on average, the active resident participation increased total TKA procedure time by 26.7 minutes. Our finding is consistent with the literature, as all but 1 study [13] have reported longer operative time with resident participation. However, the novel finding we report is the quantification of the time difference as it relates not only to cost savings but also to resident education. Considering a mean of approximately 70 minutes required by the attending (26.7 minutes less than the resident), this represents a potential opportunity cost for approximately an additional case for every 3 cases ($26.7 \times 3 = 80.1$ minutes $\approx$ 72 minutes $\approx$ one TKA) [12,17,22]. However, this needs to be interpreted with caution. This represents a best-case scenario in our setting, as the attending was scrubbed and actively supervising throughout the procedure and did the 3 most critical steps himself on both sides (Table 1). Less involved participation of the attending may have increased the operative time further. We analyzed "skin-to-skin" timing for each side, and the turnover time was not included in bilateral cases, as both sides were prepped and draped together, but this would need to be taken to account for unilateral cases. Moreover, this opportunity cost must be considered in light of the time that residents save by participating in several other aspects of patient care and documentation that may otherwise burden the attending. We do emphasize that "hands-on" resident training is a necessary investment to create a future skilled workforce and should not be compromised.

Equally informative were the durations of individual TKA steps, with "*exposure*" and "*closure*" identified as the most time-consuming steps. This has often been anecdotally discussed among surgeons without substantiating evidence. The attending was expectedly faster with almost all steps. Operative timing has been observed to improve with experience and interest, as was shown in our study and others [51]. Our data suggest that orthopaedic residency programs could specifically benefit by providing focused training programs in "*exposure*" and "*closure*" for residents, either through cadaveric or virtual simulations, thus improving the total timing to surgeons and teaching hospitals. As a subanalysis of our data by ultimate fellowship choice, residents pursuing adult reconstruction performed their cases comparably to their counterparts pursuing other orthopaedic fellowships, and no significant difference was observed in the individual "*exposure*" and "*closure*" steps as well as total operative time between both groups and the attending surgeon, highlighting a uniformity of training under constant attending supervision.

The other equally important and assuring finding of our study was that resident participation did not jeopardize patient safety or satisfaction, with no significant differences in postoperative complications, functional scores, or laterality preference between patients operated on by the attending or a resident. Again, this could be attributed to active supervision of the attending throughout the procedure, which may minimize intraoperative variability and complications. However, there are conflicting data in the literature on the participation of residents and patient outcomes and complications across all specialties. This should be interpreted with caution, as there are many confounding factors in these studies, and there may be a bias toward more complex cases in teaching hospitals [2,51,55,60,63]. Lévy et al. [73] recently described early major and minor complication rates of single-staged bilateral TKA during the first 90 days postoperatively, reporting rates within the range of our cohort with respect to mortality (0%), major complications (4.3%), and minor complications (11%). Mortality rates (0.3%), minor (22.8%) and major complications (4.3%), and patient satisfaction (willingness to undergo single-staged bilateral TKA: 73% definitely yes, 22% probably yes; 98.0% yes in our cohort) reported by Putnis et al. [74] were also within range of our findings. A recent systematic review and meta-analysis included 9 studies of 92,309 TKAs (80,655 by consultants and 11,654 by trainees), concluding that the trainee group had similar timing, less infection, similar other complications, and less favorable but clinically insignificant functional outcome scores [69].

Our study does have several limitations to consider when interpreting the results. A major downside of having the same patient as the control in a bilateral TKA study is the inability to compare variables such as total cost, length of stay, systemic complications, survival, and readmissions. The geographically localized sample size in our study was relatively small and may be underpowered for some variables due to relatively low complication rates for TKA in general [73,74]. Increasing experience of the attending during the extended study period may also potentially influence differences observed with residents. We only studied the impact of chief residents, as this level of postgraduate education is presumed to be most experienced. We acknowledge that everyone teaches and learns at their own pace; thus, our study design may fail to account for the proficiency of all attending surgeons or the differences between senior and junior residents. Moreover, some chief residents may differ from their peers, as they may have already matched in their specialty of interest for fellowships and may have variable interest in TKA operations. Additionally, residents always operated on the second, and presumably less difficult, side and were potentially aware of the tips and tricks learned from the first side, minimizing the actual time difference. The free-hand patella resurfacing and cementing steps were performed by the attending bilaterally, as these were considered the most critical and least correctable steps of the procedure, and any intraoperative complications here could have been detrimental for the patient. The attending was scrubbed and actively supervised the resident throughout the case, not just for the mandated critical/key steps, and would bail out the residents in a timely fashion before any potential major error/complication, as needed. He also influenced the decision-making for "balancing" the knee. This may have mitigated further increases in duration and potential complications. An area for future study would be recording instances of attending intervention, to potentially identify other areas of improvement for residents. Thus, despite our study representing the best-case scenario, which may not necessarily represent typical teaching conditions, the difference in all parameters would likely be more pronounced in general settings. Despite these limitations, the greatest strength of our study is the degree of granularity of data reported on in the "single-stage bilateral" methodology that has only recently been utilized in limited studies [71,72], providing new insights into the topic.

Conclusions

Active resident participation in TKA significantly increased operative time without jeopardizing functional outcomes, patient satisfaction, and complications. The 2 most significant time-consuming steps of operation that needed more focus during training were "*exposure*" and "*closure*". The results of the present study also provide objectivity and should help alleviate concerns of patients and policymakers about TKA procedures performed with residents. Larger studies, especially evaluating such differences observed in fellowship tracks, are warranted to validate our results and provide more insight.

Conflicts of interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: No financial support was received for this article. No direct or indirect conflicts of interest exist in relation to this manuscript nor did they impact any aspect of this work. The following authors report no financial disclosures: A.V.M., C.G., T.H.C., V.S., and N.V.S. A.V.M. is a board or committee member of the Musculoskeletal Tumor Society, and an editorial or governing board member of the World Journal of Orthopaedics, outside the submitted work.

For full disclosure statements refer to https://doi.org/10.1016/j.artd.2022.02.029.

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Appendix

Supplementary Material 1. Perioperative protocol, Surgical Technique and Steps

All patients underwent a standardized peri-operative surgical protocols [1]. Both lower extremities were prepped and draped simultaneously. An identical surgical technique utilizing a standard midline incision and a medial parapatellar approach was used for both sides. The tibia was cut first, followed by the distal femur cut and extension balancing by soft tissue releases. This was followed by rest of the femur cuts, tibial preparation and then patella preparation sequentially. Gap-balancing method with parallel-to-tibia cuts technique was utilized and cross checked with epicondylar axis [2]. All cases were performed with a posteriorly-stabilized (PS) implant system. A tourniquet was only utilized during cementing in the first 39 cases. The remaining cases were done without tourniquet as change in surgeon's preference. Bone cement was used in all but one patient.

Step 1. Exposure (skin incision to placement of tibial jig)

A standard midline anterior incision was used with the knee in flexion. In cases of multiple incisions, the most lateral one was preferred. Deep flaps prepared with sharp dissection to expose the rectus/vastus medialis oblique (VMO) interval. A medial parapatellar arthrotomy was created, followed by partial release of the posteromedial structures to subluxate the tibia anterolaterally. Subsequently, partial excision of the patellar fat pad and lateral patella-femoral ligament as well as synovectomy in the gutters and suprapatellar pouch were performed [3]. Three retractors were placed: A sharp Hohman retractor laterally, one blunt Hohman retractor medially and one blunt Hohman retractor posteriorly. The tibia was then dislocated anteriorly in flexion and external rotation (the RanSall maneuver) [4]. Meniscectomy was then completed and all bleeders coagulated. Once the proximal tibia was exposed, the tibial jig was placed and medialized.

Step 2. Tibial jig placement to distal femur cut and extension balancing (including soft tissue balancing in extension)

An appropriate tibial cut was then made perpendicular to the anatomical axis of the tibia, cutting approximately 6-10 mm from the higher noninvolved side, depending on the deformities. Valgus knees had relatively thinner tibial cuts, and knees with significant flexion contractures had additional bony cuts. The cut was confirmed, and extra soft tissues were released as necessary to expose the tibia. The lateral cortex of tibia was marked with a marking pen, and sizing was done. Reduction osteotomy was often performed on the medial side to lateralize the component and down-size the component to eliminate defects in the medial and postero-medial tibia in the varus knees [5]. The tibia was then reduced back and the medial retractor was adjusted to protect the medial collateral ligament (MCL) on the femoral side. The femoral drill was then used to open the femoral canal. The distal femoral cutting jig was then applied (most often with 5° of valgus cut for a varus knee and 3° for a valgus knee). In cases of severe deformities/extra-articular deformities/prior implants, either a computed tomography (CT) scanogram and/or imageless navigation (OrthAlign sensor [OrthAlign, Inc., Aliso Viejo, California, USA] [6,7]) was used to match the patient's mechanical axis. The cut was then completed perpendicular to the mechanical axis of the femur, approximately 10 mm from the more prominent medial side (and occasionally an extra 2-4 mm side in cases of valgus knee with hypoplastic femoral lateral condyle and/ or with significant flexion contractures). The jig was then removed and a balanced rectangular symmetric extension gap was achieved, with nearly 2 mm of opening on each side with a spacer block. Appropriate medial or lateral soft tissue releases were performed to achieve this. In cases of valgus knees, a pie-crusting technique with an inside-out manner was utilized [2].

Step 3. Extension balancing to preparation of femur and femoral trial placement

We then used a gap-balancing technique using the parallel to the tibial cut method for rotations and flexion gap balancing [8]. A customized jig was used to create a flexion gap similar to the extension gap for this particular implant design. An appropriate custom block corresponding to the extension gap was used for preparation of the femur and the anterior cut (based on the tibial cut and posterior femoral condyles). The block was confirmed with the epicondylar axis (especially in valgus knees) and adjusted accordingly and pinned in, and the anterior cut was subsequently made. The four-in-one jig was then placed on this anterior cut, and the posterior and chamfer cuts were made, followed by a box cut. Excessive osteophytes were removed from the posterior femur. A trial implant was placed and adequacy checked.

Step 4. Femoral trial to preparation and placement of tibial trial

The tibia was then again dislocated anteriorly and a tibial jig was applied for drill and punch. The tibial component was lateralized and rotations were adjusted in reference to the medial third of tibial tuberosity [9]. Trial tibial implants and inserts were placed and stability and balancing were checked.

Step 5. Tibial trial to preparation and placement of patellar trial with evaluation of patellar tracking

The patellar thickness was then measured, with a goal of reproducing similar thickness with the implant. The patella was prepared with a free-hand technique, cutting at the level of the lateral facet. Drill holes were made and the patellar trial was placed. Excessive osteophytes were removed and synovectomy was performed in the suprapatellar region to minimize the chances of patellar crepitus/ clunk. Patellar tracking was evaluated. In all, no cases required a lateral release and all cases were resurfaced. The trial implants were then removed. Drill holes were made in the sclerotic bone for better cement penetration.

Step 6. Patellar trial to start of cement mixing

Thorough lavage followed, and the tourniquet was then inflated. The operating team changed gloves. In the meantime, cement mixing was initiated in the back table by the surgical technician and the senior resident prepared the back table with all required instruments and retractors.

Step 7. Cement mix to placement of final insert (including removal of excessive cement after curing)

Only one packet of antibiotic-laden bone cement (1 gram tobramycin sulfate; Simplex P with Tobramycin, Stryker Corporation, Kalamazoo, Michigan, USA) for all cases in this series [10]. Once the cement reached an appropriate consistency, the cement was applied to the backside of all three implants. Cement was then applied to the femoral bone surface and the femoral component was cemented first followed by removal of excessive cement. The tibia was then dislocated anteriorly and cement was applied on the proximal surface followed by placement of the tibial component. Excessive cement was then removed. Similarly, the patellar component was then also placed and pressurized with the provided clamp. The tourniquet was then deflated. The knee was then held in extension with axial and posterior pressure. As the cement cured, a pain cocktail was then injected in the surrounding soft tissues [1]. Once the cement was cured, the joint was again exposed and excessive cement was removed. The trial insert was removed and a final insert was then placed and locked.

Step 8. Closure (final insert placement to skin closure and dressing application)

The knee was then placed in about 30° of flexion. Wound lavage was done. A Jackson-Pratt (cardinal health, Dublin, OH) drains was used only until 2016. The arthrotomy was closed using interrupted 3-4 #1 Ethibond (Johnson & Johnson, New Brunswick, New Jersey, USA) sutures followed by a continuous barbed bi-directional double-armed suture (#2 Quill [B. Braun, Melsungen, Germany]). The subcutaneous tissue was closed using #0 Quill and the skin was closed using 3-0 Monocryl (Johnson & Johnson, New Brunswick, New Jersey, USA) and staples, followed by an Aquacel dressing (ConvaTec. Reading, Berkshire, UK). If the patient had significant subcutaneous tissue, then an additional 1-2 layers of #1 pop-off Vicryl (Johnson & Johnson, New Brunswick, New Jersey, USA) sutures were used.

Second Side

After the first side was complete, we discussed with the anesthesiologist whether the patient was stable enough to proceed with the contralateral side (no case was excluded for the second side in this series at this stage). The first side was then placed in a sterile sheet and was wrapped gently with Coban self-adherent wrap (3M, Saint Paul, Minnesota, USA). This was followed by covering the initial surgical side with a split-sheet and subsequent exposure of the second side. The instruments were cleaned on the back table and the jigs were adjusted accordingly based on the operating side. Everyone changed surgical gloves before the incision on the second side. All surgical steps were followed like the first side. Following completion of the second side, postoperative radiographs were obtained, and the patient was then transferred to the postoperative recovery room.

Postoperative Protocol

All patients underwent standardized pre- and post-surgical protocols, consisting of a multimodal regimen including preemptive analgesia, local intra articular injections, oral multimodal regimen and a femoral/adductor canal block [11]. All patients started physical therapy on postoperative day 1, as all of them were the last case for the day. They were weight bearing as tolerated. All patients received aspirin 325 mg once daily with sequential compressive devices (SCDs) for DVT prophylaxis while admitted, and were discharged on a total of 6 weeks of aspirin 325 mg once daily. Discharge disposition was either home, subacute or acute rehabilitation department depending on how each patient progressed with physical therapy, home situation, and their insurances.

Supplementary Table 2
Summary of published literature on the impact of resident involvement in orthopedic procedures.

Study	Study design	Procedure	Outcomes
Farnworth et al. 2001 [1]	• Retrospective Cohort • Institutional Data	• Arthroscopic ACL reconstruction	• Anesthesia time, case time, and costs, were significantly higher in cases with resident involvement than with resident absence
Silber et al. 2009 [2]	• Retrospective review • Medicare Claims Data	• Lumbar/lumbosacral or cervical fusions • Revision of hip or knee replacement • Spinal canal exploration • Excision of intervertebral disc • Primary THA/TKA • Hip hemiarthroplasty • ORIF humerus/tibia/femur/radius/ulna • Shoulder arthroplasty • Rotator cuff repair • Femur internal fixation • Closed reduction-internal fixation femur/radius/ulna Femoral implant device removal • Toe amputation	• Survival was higher at teaching hospitals as a result of lower mortality, despite lengthier operative times
Schoenfeld et al. 2013 [3]	• Retrospective Cohort • ACS NSQIP	• Primary THA/TKA • Lumbar discectomy • Anterior cervical arthrodesis • Below/above knee amputation • Anterior cruciate ligament reconstruction • High tibial osteotomy • Distal biceps tenodesis • Major peripheral nerve neuroplasty • Flexor tendon repair • Extensor tendon repair	• Significant association between resident involvement and the risk of developing ≥1 postoperative or major systemic complications in patients undergoing primary TKA and THA but not with other orthopedic procedures
Pugely et al. 2014 [4]	• Retrospective Cohort • ACS NSQIP	• Primary/revision THA/TKA • Basic/advanced arthroscopy • Lower extremity trauma • Spinal fusion	• Resident involvement correlated with higher morbidity in TJAs, lower extremity trauma, and fusions, but not with increased mortality • Operative time was greater with resident involvement in all procedural domains, but longer hospital length of stay and higher 30-day reoperations were only detected in residents involved in lower extremity trauma and fusions
Edelstein et al. 2014 [5]	• Retrospective Cohort • ACS NSQIP	• Primary THA/TKA • Arthroscopic medial and/or lateral meniscectomy • Arthroscopic rotator cuff repair • Arthroscopic subacromial decompression • Open treatment of femoral neck fracture • Arthroscopic ACL reconstruction • Intramedullary implant for intertrochanteric, pertrochanteric, or subtrochanteric femoral fracture • Total shoulder arthroplasty	• Resident involvement was associated with increased rates of overall and medical complications, reoperations, as well as increased operative time, relative value units, and hospital length of stay on univariate analysis • Resident involvement decreased the odds of overall and medical complications, and did not predict wound complications, reoperations, or readmissions on multivariate analysis
Haughom et al. 2014 [6]	• Retrospective Cohort • ACS NSQIP	• Primary THA	• Resident participation did not increase the odds of developing 30-day complications in patients undergoing primary THA but a longer operative time was required
Weber et al. 2017 [7]	• Retrospective cohort • Institutional Data	• Primary THA	• While patient-reported functional outcomes and complications rates were similar between residents and attendings, operative times were longer in the former group
Basques et al. 2018 [8]	• Retrospective Cohort • ACS NSQIP	• Shoulder arthroscopy	• Resident involvement did not correlate neither with increased odds of 30-day postoperative complications and readmissions, nor increased operative time
Lebedeva et al. 2019 [9]	• Retrospective Cohort • ACS NSQIP	• ACL reconstruction	• Despite longer operative time, resident participation did not increase the risk of 30-day postoperative overall complications rates compared to attendings
Zhu et al. 2019 [10]	• Retrospective Cohort • ACS NSQIP	• Hand surgery	• Operative time and relative value units were significantly higher with resident involvement, which is associated with an opportunity cost to the attending surgeons • 30-day complications were not statistically significant between resident involvement and attending only groups
Beletsky et al. 2020 [11]	• Retrospective Cohort • ACS NSQIP	• Acute/chronic open rotator cuff repair • Arthroscopic rotator cuff repair • Biceps tenodesis • Bankart repair, open shoulder stabilization • Bicompartmental/unicompartmental arthroscopic partial meniscectomy • ACL repair	• Operative time and relative units were significantly higher with resident involvement, which is associated with an opportunity cost to the attending surgeons

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