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RESEARCH

Evolving techniques in active robotic arm-assisted total knee arthroplasty: a retrospective study of pin placement strategies

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Abstract
Robotic-assisted total knee arthroplasty (RA-TKA) significantly improves surgical precision, implant alignment, and functional outcomes, but extra-incisional pin placement can lead to complications like infections, fractures, and quadriceps tethering. This study evaluates the outcomes of intra-incisional pin placement compared to traditional extra-incisional pin placement in RA-TKA using the fully active robotic system. A retrospective analysis was conducted including 1106 patients who underwent cruciate-retaining RA-TKA. Both the groups were operated by single surgeon with sub-vastus approach without tourniquet. Patients were categorized into two groups: intra-incisional pin placement (Group 1, $n=547$) and extra-incisional pin placement (Group 2, $n=559$). Outcomes were evaluated using the Oxford Knee Score (OKS) and Forgotten Joint Score (FJS), and complications, such as pin-site infections, fractures, stiffness, and wound issues, were compared between groups. Postoperative OKS and FJS showed comparable functional recovery between the groups, with Group 1 demonstrating slightly better patient-reported outcomes (OKS: 42.16 ± 14.78 vs. 41.78 ± 14.32; $p=0.66$; 95% CI −2.09 to 1.34; FJS: 87.34 ± 17.66 vs. 84.67 ± 15.88; $p<0.008$; 95% CI −4.65 to −0.69). The overall complication rate was significantly lower in Group 1 (2.01%) compared to Group 2 (14.31%, $p<0.001$), with no pin-site infections or fractures in the intra-incisional group. Pin-site pain, a major concern in Group 2, was absent in Group 1 (9.12% vs. 0%, $p<0.001$). Active RA-TKA can be effectively performed using intra-incisional pin placement, offering a safer alternative to extra-incisional approaches. This technique bars additional incisions, potentially lowering the risk of infection and fractures while preserving functional outcomes. Further research is needed to confirm these benefits across diverse patient populations.

Keywords Robotic-assisted total knee arthroplasty · Intra-incisional pin placement · Extra-incisional pin placement · Knee prosthesis · Surgical outcomes · Oxford knee score · Forgotten joint score

Introduction

Total knee arthroplasty (TKA) is an established treatment option for individuals with symptomatic osteoarthritis in at least 2 of the 3 compartments of the knee and unsuccessful conservative treatment, aimed at alleviating pain and restoring function [1]. There has been an exponential rise in the number of TKA surgeries during recent years in India, from 1019 in 2006 to 27,000 in 2019 [2]. In recent years, robotic-assisted TKA (RA-TKA) has emerged as a notable advancement, offering enhanced precision in bone cuts, optimized implant positioning, and superior alignment. These factors are critical for the longevity and functionality of the knee prosthesis, potentially leading to improved patient outcomes compared to conventional TKA techniques [3]. The integration of robotic systems in orthopedic surgery continues to evolve, with an increasing emphasis on refining intraoperative techniques to minimize complications and maximize surgical success [4].

One of the critical considerations in RA-TKA is the placement of bone array tracker pins, which are essential for intraoperative navigation and real-time tracking of bone resection and implant positioning. Traditionally, these pins have been placed outside the operative field through separate incisions (extra-incisional placement), which, although effective, may

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introduce complications, such as pin-site fractures, infections, delayed wound healing, and quadriceps tethering, potentially leading to stiffness and compromised function [5]. While the literature has extensively documented the benefits of robotic precision in TKA, there remains a paucity of research examining the impact of different pin placement strategies on patient outcomes globally [5–7].

From the observations of our previous experiences with RA-TKA surgeries, the need for modifications in pin placement became evident to mitigate complications and enhance patient recovery. During the initial phases of using the fully active CUVIS robotic system, we encountered technical challenges wherein the trajectory of extra-incisional pins occasionally conflicted with the robotic arm's predefined cutting path. This interference necessitated intraoperative adjustments, potentially affecting workflow efficiency and precision. Consequently, we explored various pin positioning techniques and ultimately adopted an intra-incisional placement approach for both femoral and tibial pins. The rationale behind this shift was to reduce additional incisions, minimize soft-tissue trauma, and potentially lower the incidence of pin-related complications [8].

This retrospective analysis aims to compare intra-incisional and extra-incisional pin placement techniques in RA-TKA using the fully active robotic system. As pin placement plays a critical role in procedural efficiency and post-operative recovery, evaluating its impact can provide valuable insights for refining surgical techniques. This study seeks to contribute to the growing body of RA-TKA literature by assessing the safety profile, complication rates, and functional recovery associated with intra-incisional versus extra-incisional pin placement.

Methods

Study design and setting

This retrospective study was conducted between January 2022 and January 2024. The study included patients who underwent cruciate-retaining total knee arthroplasty (TKA) using the fully active (CUVIS-CUREXO made, and MISSO-MERIL made) robotic system during this period.

Study population

All patients who underwent robotic-assisted TKA using the robot were included in this retrospective analysis. However, patients with a history of osteosynthesis or osteotomy around the knee were excluded. A total of 1106 cruciate-retaining TKA procedures were performed during the study period, as identified from the records. Of these, 547 cases were performed using intra-incisional pin placement (Group 1), while 559 cases were performed using extra-incisional pin placement (Group 2).

Surgical procedure and pin placement

All surgeries were performed by a single surgeon under subarachnoid block anesthesia, using a midline incision and sub-vastus approach without tourniquet. Initially, conventional extra-incisional pin placement was used. However, due to associated complications, intra-incisional pin placement was adopted from February 2023 onward.

Pin placement in group 1 (intra-incisional pins)

The proximal tibial pin (diameter 4 mm; standard Schanz pin, 150 mm length, 4.5 mm width, 2.7 mm pitch) was placed 3–4 cm from the medial joint line, and the distal tibial pin was positioned 6–7 cm from the medial joint line, with 3 cm spacing between the two. Pins were inserted using a power drill from the anteromedial tibial surface, directed laterally toward the opposite cortex. Initially, an insertion angle of approximately 60° was used with pins directed toward the joint line; following complications, the angle was adjusted to 30–35° and later to 10–15°, directing pins toward the opposite cortex (Fig. 1).

For femoral pin placement, the proximal pin (standard Schanz pin, 150 mm length, 4.5 mm width, 2.7 mm pitch) was inserted 3–4 cm from the medial joint line, and the distal pin 6–7 cm from the medial joint line. Both were inserted from the anteromedial surface, directed toward the opposite cortex at 30–35° from the coronal plane, and placed unicortically into cortical bone to ensure stability and minimize bone trauma.

Pin placement in group 2 (extra-incisional pins)

Two 4 mm femoral pins and tibial pins, spaced 3 cm apart, were placed through separate stab incisions in the femoral and tibial shaft. Femoral pins were inserted through the quadriceps muscle, 9–12 cm from the joint line in the sagittal plane. Tibial pins were inserted in the coronal plane, in the tibial shaft 7–9 cm from the joint line through separate incisions. All 4 mm pins were inserted unicortically using a T-handle after pre-drilling the cortices with a 3.2 mm drill bit (Fig. 2).

Outcome measures

The primary outcome measures included functional outcomes assessed using the Knee Society Score (KSS) and evaluation of pin-site-related complications such as infection (superficial and deep), pin-site or peri-prosthetic fractures, wound-healing issues, knee stiffness

Fig. 1 Pin position and placement of intra-incisional pins

due to quadriceps tethering from scarring, neurovascular complications, and perioperative ligament injuries. Patients' records were reviewed to assess their follow-ups at 6 months and 1 year postoperatively to assess functional recovery. Functional outcomes were further evaluated using the Oxford Knee Score (OKS) and Forgotten Joint Score (FJS).

Statistical analysis

Descriptive statistics were used to summarize the data. Continuous variables, including age, height, weight, BMI, OKS, and FJS, were presented as mean values. Categorical variables, such as gender distribution and complication rates, were presented as counts and percentages. Comparisons using p values and 95% confidence intervals were performed for all relevant parameters.

Ethical considerations

The study was conducted in accordance with the Declaration of Helsinki and was approved by the institutional ethics committee. Informed consent was waived due to retrospective nature of the study.

Results

Out of the total population, the number of female patients was higher in both groups (68% and 72%). The mean age in Group 1 was 58.65 and 55.84 in group 2. Demographic variables, including gender distribution, height, weight, and BMI, were comparable between the two groups, except for age, which was significantly higher in Group 1 ($p = 0.002$) (Table 1).

Fig. 2 Image showing incisions required for extra-incisional pin placement

Table 1 Demographic details of patients in both groups

Demographic details	Group 1	Group 2	*P* value
Male *n* (%)	175 (32%)	156 (28%)	0.13
Female *n* (%)	372 (68%)	403 (72%)	0.13
Age (mean, years)	58.65 ± 14.56	55.84 ± 14.96	0.002
Height (mean, cm)	161.54 ± 11.08	162.11 ± 11.87	0.41
Weight (mean, kg)	83.67 ± 15.88	82.88 ± 14.66	0.39
BMI (mean, kg/m^2)	32.1 ± 9.84	31.5 ± 8.98	0.29

The preoperative OKS was comparable at baseline between both groups. At a minimum follow-up of 6 months, both groups showed significant improvement. Group 1 demonstrated a mean post-operative FJS of 87.34 ± 17.66 compared to 84.67 ± 15.88 in Group 2 ($p < 0.008$; 95% CI −4.65 to −0.69), indicating toward an improved patient-reported outcomes in the intra-incisional pin placement group (Fig. 3).

The overall complication rate was significantly higher in Group 2 compared to Group 1 (14.49% vs. 2.01%; $p < 0.001$). Pin-site pain (9.12%), stiffness (3.39%), and delayed wound healing (1.07%) occurred exclusively in Group 2. Conversely, pin interference with robotic arm movement (1.46%) and proximal tibia pin exposure (0.55%) were observed only in Group 1. Pin-site infections (0.53%) and fractures (0.35%) were rare and occurred only in Group 2 (Table 2) (Fig. 4).

Discussion

The findings from this retrospective analysis highlight the importance of precise pin placement in active robotic arm-assisted TKA. Postoperative functional recovery, as assessed by OKS and FJS, was comparable between the groups, with Group 1 demonstrating slightly better patient-reported outcomes (OKS: 42.16 ± 14.78 vs. 41.78 ± 14.32; $p = 0.66$; FJS: 87.34 ± 17.66 vs. 84.67 ± 15.88; $p < 0.008$). The mean age of patients in Group 1 was slightly higher, closely matched BMI values (32.1 ± 9.84 vs. 31.5 ± 8.98, $p = 0.29$). This indicates that obesity, a known risk factor for post-operative complications in TKA, was evenly present in both cohorts [9]. During the initial procedures, surgical approach involved placing femoral pins 9–12 cm proximal to the joint line. In this study, two cases of peri-prosthetic femoral fractures occurred due to eccentric pin placement, leading to abnormal stress distribution along the femoral shaft. Both the cases were successfully managed with closed reduction and interlocking intramedullary nailing, ensuring stable fixation and fracture healing (Fig. 4). This highlights the importance of precise pin placement and guided insertion to prevent stress-related fractures.

A study by Desai et al. (2023) comparing site complication rates in small and large pin diameters in RA-TKA patients observed that large pin diameter group exhibited a 5.6% complication rate, while the small pin diameter group had a 2.6% rate. Although the difference was not statistically significant, there was a trend suggesting higher complications with larger pins. Moreover, the most frequent complication was infection or persistent drainage, occurring in 1.9% of patients. Intraoperative fractures of the second cortex were observed in 1.4% of cases. Notably, there was one post-operative pin-site fracture in the large pin diameter group that required surgical intervention [10].

Considering these risk factors, our technique was modified to use 4 mm threaded Schanz pins, which are inserted unicortically into the metaphyseal cancellous bone under direct vision using a power drill. This approach ensured more secure fixation in cancellous bone, significantly reducing the risk of fractures that are more commonly seen when pins are placed in dense cortical bone, which is inherently less flexible and more prone to stress fractures at pin sites. The literature supports this observation, as biomechanical analyses have demonstrated higher rates of pin-site fractures in cortical bone compared to cancellous bone [11, 12]. By shifting femoral pin placement to the medial condyle intra-incisionally, fracture complications were effectively eliminated, demonstrating the critical role of pin positioning in

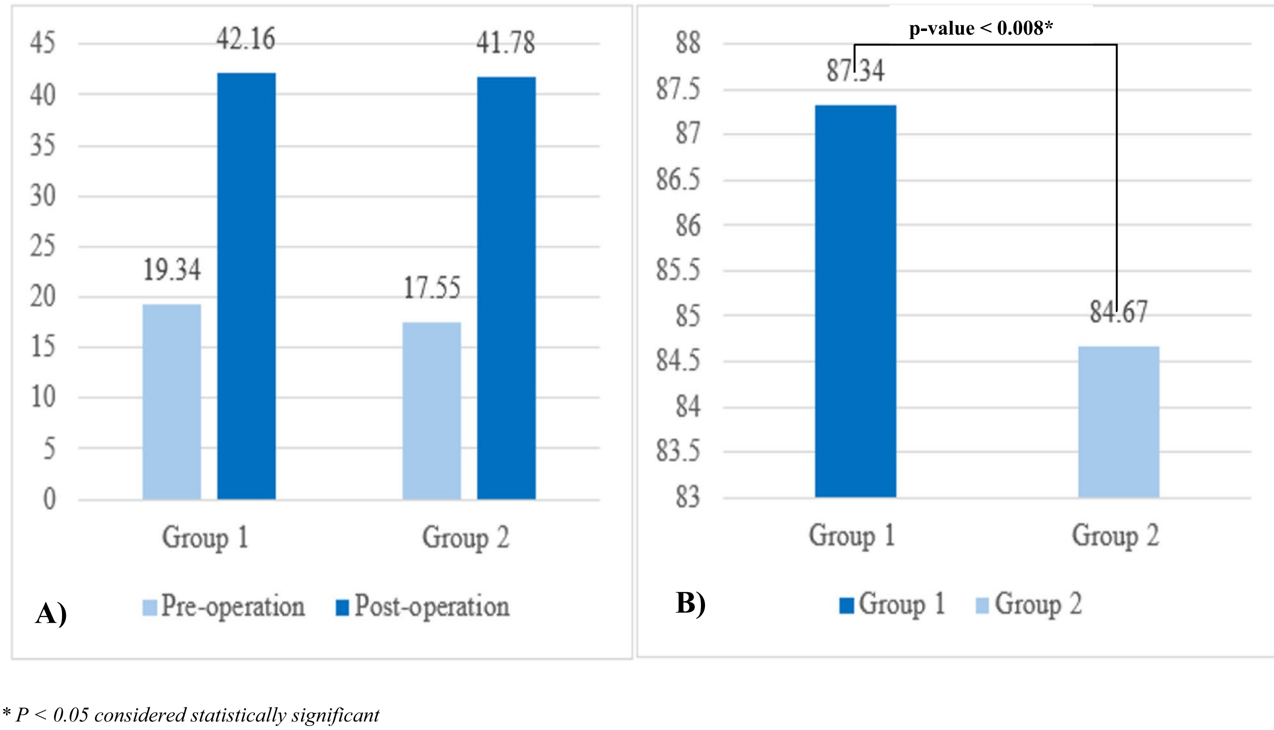

Fig. 3 **A** Comparison of Pre-op and Post-op OKS between groups. **B** Comparison of Post-op FJS score between groups. **P* < *0.05* considered statistically significant

Table 2 Comparison of post-operative complications between groups

Complications	Group 1	Group 2	*P* value
Total cases	547	559	
Pin-site infection, *n* (%)	0	3 (0.53)	0.249
Pin-site fracture, *n* (%)	0	2 (0.35)	0.499
Stiffness, *n* (%)	0	19 (3.39)	< 0.001
Delayed wound healing, *n* (%)	0	6 (1.07)	0.030
Pin interference with robotic arm movement, *n* (%)	8 (1.4)	0	0.003
Proximal tibia pin exposure during lateral tibia cut and conversion to manual, *n* (%)	3 (0.54)	0	0.121

ensuring patient safety. Additionally, pin insertion technique played a crucial role in reducing complications. Previously, we used tapering pins, which tended to bend during insertion with a T-handle, leading to mismatched force application and increased eccentric pin placement risks. The introduction of Schanz pins inserted with a power drill eliminated these issues, allowing for controlled and precise pin placement under direct visualization, at the same time, avoiding damage to the muscle.

In this study, both groups demonstrated improvement in functional outcomes following RA-TKA, as reflected by the OKS and FJS. Group 1 achieved a mean post-operative FJS of 87.34 ± 17.66, slightly higher than 84.67 ± 15.88 in Group 2 ($p < 0.008$; 95% CI −4.65 to −0.69), suggesting that patients in the intra-incisional group experienced better joint integration and reduced awareness of the prosthesis in daily activities. These findings reinforce that intra-incisional pin placement maintains functional outcomes comparable to extra-incisional placement while potentially offering advantages in terms of reduced complications and enhanced patient-reported satisfaction [6].

These findings also demonstrate that proper intra-incisional pin placement allows for safer and more inclusive patient selection. Initially, RA-TKA was limited to patients with good bone density (T-score > −1.0), due to the complications associated with extra-incisional pin placement [10]. However, with the intra-incisional technique, where pins are placed in cancellous bone using a power drill, we are now

Fig. 4 Two cases of peri-prosthetic pin-site fracture in extra-incisional group managed with closed reduction and interlocking intramedullary nailing

able to successfully perform TKA in patients with severe osteoporosis (T-score < -3.5) without increased complication risks. Despite the clear benefits of intra-incisional pin placement, certain challenges remain. For posterior-stabilized knee replacements, femoral pins may become loose due to the box cut, requiring adjustments in pin insertion direction to prevent interference. If femoral pins are directed distally toward the joint, they may interfere with the box cut, necessitating careful planning and possible modifications in placement techniques. As observed by Baek et al. (2022) in a prospective study to determine the placement of a pin tracker in distal femur in RA-TKA. The patients reported no peri-historic fracture, or any minor or major complications [13].

The initial strategy for tibial pin placement involved positioning the pins 7–9 cm distal to the medial joint line in both cortices of cortical bone using separate stab incisions. This approach led to superficial infections and delayed wound healing in three patients, necessitating further refinement. During early intra-incisional tibial pin placements, the proximal tibial pin interfered with the movement of the robotic arm, particularly during the lateral tibia cut. In 3 cases, protruding tip of tibia pins interfered with movement of robotic arm, the robotic procedure had to be abandoned. To resolve this issue, we initially converted certain cuts to manual execution using a femoral jig. However, further refinements led to a modification in tibial pin placement at least 3 cm away from the medial joint line at an optimized angle of 30–35 degrees from the coronal plane, ensuring adequate bone purchase without impeding robotic arm movement. This refinement proved successful in resolving infection and healing issues while optimizing robotic workflow efficiency.

The intra-incisional technique offers several advantages, particularly in reducing external contamination risks and minimizing stress at pin sites, which is especially beneficial for patients with osteoporosis. Additionally, the elimination of extra stab incisions reduces cosmetic concerns among female patients, addressing one of the most frequently cited patient concerns in the extra-incisional pin placement group [8]. These findings suggest that with careful consideration and strategic adjustments, the benefits of RA-TKA can be fully realized, leading to improved patient outcomes. Further studies are warranted to validate these findings across broader patient demographics and different robotic systems. Additionally, long-term follow-up studies are necessary to assess the durability of these outcomes and ensure the continued success of modified pin placement techniques.

Conclusion

Active RA-TKA can be effectively performed using intra-incisional pin placement, providing a viable alternative to conventional extra-incisional techniques. This approach minimizes additional incisions, potentially reducing the risk of wound-healing delays, pin tract infections, and pin-site fractures, while maintaining comparable or improved functional outcomes. By optimizing pin stability and reducing contamination risks, intra-incisional placement enhances surgical efficiency and patient safety. Further research is warranted to assess its long-term benefits and applicability across diverse patient populations.

Author contributions All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Dr. Sujoy Kumar Bhattacharjee, Dr. Malay Kumar, and Dr. Neelavjyoti Deka. The first draft of the manuscript was written by Dr. Malay Kumar and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability No datasets were generated or analyzed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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