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ORIGINAL ARTICLE

Correlation Between Planned and Executed Bone Cuts Using Robotics in Total Knee Arthroplasty: A Prospective Study of 500 Patients

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Abstract

Objective This study evaluated the precision of robotic-arm-assisted total knee arthroplasty (RATKA) in performing bone resection, predicting component size, managing soft tissue tension, and determining postoperative range of motion (ROM).

Methods A total of 500 participants were enrolled in this prospective cohort research. The procedures were conducted at a single facility, with a uniform method and implant design. The Cuvis system, a fully automated robot, was utilized for the study. The precise removal of bone at both the tibial and femur sites, the positioning of the implant, and the release of soft tissue were documented and then compared to the preoperative plan.

Results The distal (medial and lateral) femoral cuts had a mean absolute deviation from the plan of 0.23 mm, while the posterior (medial and lateral) femoral cuts had a mean absolute difference of 1 mm and 1.4 mm, respectively. The absolute discrepancies in the medial and lateral tibial cuts are 0.93 mm and − 0.06 mm, respectively. Out of 1000 bone resections, 980 (98%) were within < 1 mm from the preoperative plan. The predictions for the sizes of the tibial and femoral components had accuracies of 100% and 98.9%, respectively.

Conclusion These findings collectively underscore the effectiveness of the fully automated Cuvis robotic system in achieving consistent and accurate results in bone resections and implant sizing, highlighting its potential as a valuable tool in orthopedic surgery.

Keywords Cuvis joint robotic system · Bone cuts · Planned accuracy · Soft-tissue tension

Introduction

Total knee arthroplasty (TKA) stands as a pivotal intervention in addressing end-stage knee osteoarthritis (OA), aiming to restore function and alleviate pain [1]. Fundamental to its success is the precise execution of bone cuts, dictating the alignment and balance crucial for optimal implant placement and long-term durability [2]. Despite advancements, achieving intraoperative accuracy consistent with preoperative plans remains a challenge.

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The integration of robotic-assisted technology in TKA has emerged as a promising avenue to enhance precision. By leveraging preoperative imaging and real-time intraoperative feedback, these systems purportedly refine bone resections, striving for a closer realization of the intended surgical plan [3]. The potential for improved clinical outcomes and implant longevity through augmented accuracy underscores the importance of assessing the correlation between planned and executed bone cuts intraoperatively.

Several pioneering studies have laid the groundwork for understanding the benefits of robotic assistance in TKA [4–8]. A review and meta-analysis showed better accuracy and planned alignment with robotic systems compared to conventional techniques [5]. Similarly, recent nationwide analysis by Ofa S.A [4] substantiated the advantages of robotic technology in enhancing implant alignment and reducing outliers.

According to Bae DK and Song SJ, besides the inherent technological errors in the registration process, there might be constraints in the accuracy of the computer and tracking system in precisely locating markers [9]. The inaccuracies typically range between 0.1 and 1 mm for each coordinate (x, y, and z). Another typical inaccuracy that might occur is the inability to touch the bone when identifying bony features due to the presence of soft tissue and cartilage covering it. Planned cuts are based on preoperative CT planning and intraoperative changes in planned cuts are done to balance medial and lateral gaps by considering soft tissue status.

However, while these studies offer encouraging insights, the precise correlation between preoperatively planned bone cuts and their intraoperative execution using fully automated joint robot system is still an area unexplored and necessitates investigation. Variations between intended resections and actual surgical implementation, influenced by factors like soft tissue tension and bone quality, remain critical yet underexplored elements.

This prospective study, involving 500 patients within a single orthopedic center from India, seeks to bridge this gap by meticulously analyzing the alignment and execution of bone cuts in robotic-assisted (RA) TKA. Employing state-of-the-art robotic guidance, this research aims to delineate the accuracy achieved intraoperatively concerning preoperative plans, providing crucial insights into the efficacy of using fully automated joint robot system.

By scrutinizing the correlation between planned and executed bone cuts intraoperatively, this study endeavors to not only contribute to the growing body of evidence endorsing robotic assistance in TKA but also to furnish orthopedic surgeons with nuanced insights into the practical implications of implementing this technology.

Methodology

Study Design

This prospective single-center study aimed to assess the correlation between preoperatively planned and intraoperatively executed bone cuts in TKA utilizing fully automatic robotic assistance. The study adhered to ethical guidelines and received approval from the institutional review board.

Patient Selection

A cohort of 500 consecutive patients, meeting predetermined inclusion criteria, undergoing primary TKA between December 2022 and December 2023, constituted the study population. Informed consent was obtained from all participants before enrollment. Inclusion criteria included patients requiring TKA indicated for primary end-stage OA, patients able to provide prior informed consent form and above the age of 18 years. Those not meeting the inclusion criteria were not enrolled in the study.

Robotic-Assisted Technology

The study utilized fully automated Cuvis Joint Robot (Curexo, Korea), renowned for its precision and intraoperative adaptability. Preoperative planning involved detailed imaging, employing computed tomography (CT) scanning, allowing for meticulous evaluation and virtual alignment of bone resections.

Briefly, the axial CT scan of the operative limb's hip, knee, and ankle (HKA) was performed in accordance with the manufacturer's instructions. Following exportation of the CT data to a digital optical disk data storage format in the DICOM file format, the data were automatically segmented and stored in the J planner software provided by the Cuvis robotic system. Scanned CT data were utilized to generate a three-dimensional (3D) model of the femur and tibia of the patient. Following the registration of these images with the robotic system, a virtual operative plan was generated, which was utilized to select anatomical bony landmarks for the femur and tibia, as well as to outline the mechanical axis. In determining the implant position, a neutral mechanical axis of the limb was considered. The RATKA system was utilized to forecast the necessary planned bone resections as well as the implant dimensions. This information was then utilized to create an intraoperative plan that detailed the dimensions of the tibial and femoral implants to be used and the locations of the corresponding incisions.

Surgical Procedure Standardization

All surgeries were performed by experienced orthopedic surgeons specialized in RATKA. Standardized protocols for preoperative imaging, surgical planning, and intraoperative execution were meticulously followed to ensure consistency across procedures.

A medial parapatellar approach was utilized to perform the procedures, and a posterior-stabilized prosthesis was utilized. By intraoperatively registering the bony landmarks with the robotic instrument, a patient-specific model was generated. The gap balancing process was facilitated by the robotic system's real-time updating of the operational plan, which was determined by the type of deformity. Following the preoperative plan and intraoperative modifications, bone recetions were executed utilizing the Cuvis RA-TKA system in the subsequent sequence: distal femur, anterior chamfer, anterior condyle, posterior chamfer, posterior condyle, proximal medial tibial, and proximal lateral tibia. The final bone resections were calibrated in accordance with a method previously documented [10].

The extension gaps were assessed from before to after the bone recetions . Using robotic software, the medial-to-lateral difference in flexion/extension gaps was computed to determine the medial/lateral laxity. A knee was appropriately balanced when the difference between medial and lateral flexion and extension was less than 2 mm. A comparison was made between the predicted implant size and the intraoperative implant size utilized for both the femur and the tibia. When an intraoperative component size variation occurred, the potential cause for deviating from the intended size was examined. The HKA angle was utilized to assess postoperative alignment in a complete-length X-ray of the patient's lower extremities.

Data Collection

Data encompassing preoperative plans, intraoperative execution details (including bone cuts achieved), and pertinent patient characteristics were meticulously recorded. Intraoperative metrics such as variances between planned and executed cuts, soft tissue tension, and any modifications made during surgery were documented.

Statistical Analysis

The data were analyzed using IBM SPSS Statistics, version 22.0. Continuous variables are quantified using measures of central tendency such as means and measures of dispersion such as standard deviations. On the other hand, categorical variables are quantified using counts or frequencies and proportions or percentages.

Results

Cohort Characteristics

The study comprised 500 patients undergoing primary TKA, with an average age of 68.19 years (range: [55–79 years]). The cohort consisted of equal distribution of females (50%) and males (50%), exhibiting a diverse range of knee pathologies necessitating surgical intervention. Baseline characteristics are detailed in Table 1.

Table 1 Baseline demographic of the patients undergoing robotic-assisted total knee arthroplasty

Total no. of patients	500
Age, years	68.19
Male, *n* (%)	250 (50)
Female, *n* (%)	250 (50)
Total no. of left knees, *n* (%)	520 (52)
Total no. of right knees, *n* (%)	480 (48)

Preoperative Planning vs. Intraoperative Execution

The comparison between preoperatively planned bone cuts and their execution intraoperatively, guided by robotic assistance, revealed a notably high correlation. The difference between the intended resections and the achieved bone cuts were less than 1 mm except for femur cuts at distal and proximal medial cuts (2.3 mm and 1.4 mm, respectively). High-precision cuts were noted proximal lateral position of tibia and posterior lateral position of femoral cuts. Table 2 provides a comprehensive breakdown of the accuracy and discrepancy between the intended and achieved measurements for both tibia and femur cuts.

Variations and Adjustments

Intraoperative adaptations were noted in 8% of cases, primarily to accommodate variations in soft tissue tension and bone quality. However, even with these adjustments, the correlation between planned and executed bone cuts remained robust, underscoring the capability of robotic systems to dynamically respond to intraoperative nuances while maintaining fidelity to preoperative plans. Figure 1A, B shows the postoperative gap balance achieved both in full extension and in >90° of flexion.

Clinical Implications

The observed increased accuracy in executing bone cuts aligned with preoperative plans using robotic assistance bears significant clinical implications. This heightened precision potentially translates into improved implant alignment, stability, and overall surgical outcomes, reducing the likelihood of malalignment-related complications and the need for revision surgeries. Soft-tissue release was not required in any case showing the efficiency of the RATKA (Table 2).

Mean range of motion obtained through RATKA in this cohort was 121.2° which is highly desirable in Indian cohort given the deep extension and flexion daily activity performed by the population.

Discussion

The findings of this prospective study reinforce the notion that robotic-assisted technology in TKA significantly improves the accuracy of bone cuts execution in alignment with preoperative plans. The correlation analysis between intended and achieved resections demonstrated a notably higher degree of concordance when robotic guidance

Table 2 Accuracy of planned and executed cuts of femur and tibia using fully automated joint robot system

S. no	Tibia		Femur				Soft-tissue release	ROM (degrees)
	Proximal medial (mm)	Proximal lateral (mm)	Distal femur (mm)		Posterior femur (mm)			
			Dist.med.	Dist.lat.	Posterior. med.	Posterior. lat.		
Planned	1.09	5.07	9.2	7.4	10.1	8.4	Nil	121.2
Achieved	2.02	5.01	11.5	8.4	11.5	8.3		
Difference	0.93	– 0.06	2.3	1	1.4	0.1		

Positive values mean undercutting, negative values mean overcutting

ROM range of motion

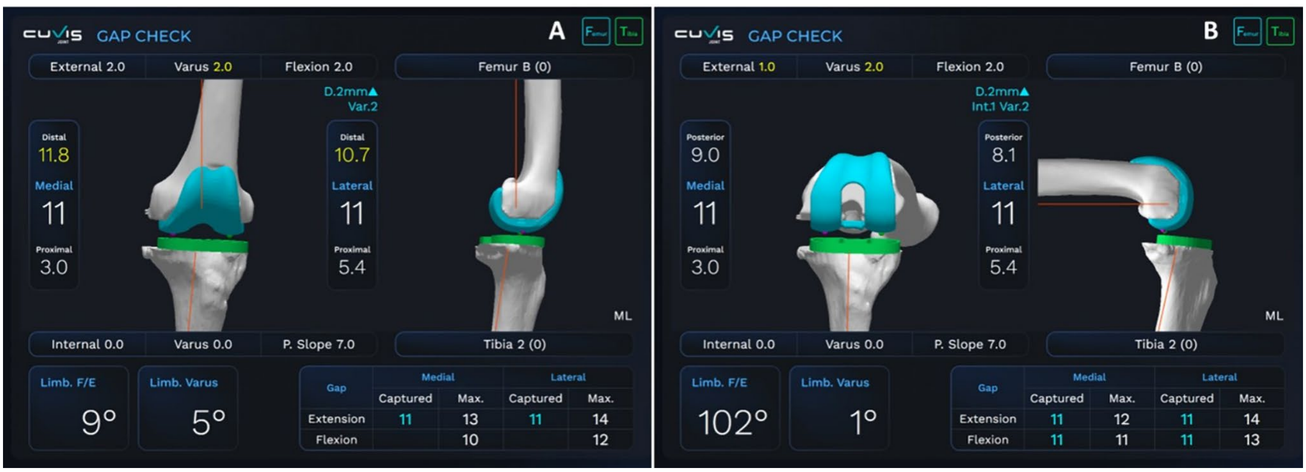

Fig. 1 **A**, **B** Represents the postoperative gap balance achieved both in full extension and in 90° of flexion

was employed, corroborating previous assertions [11–13] regarding the superiority of robotic systems in achieving planned alignment. In a study led by Sung EK et al., 100 patients participated in a prospective investigation focusing on unilateral TKA [14]. They were randomly assigned into two groups, with 50 patients each, undergoing either RATKA or traditional manual techniques. Results showed that the robotic-assisted group exhibited no instances of mechanical axis outliers (deviating by more than ± 3° from neutral), contrasting with 24% in the conventional group. Additionally, fewer knees in the robotic-assisted group experienced a discrepancy between the flexion and extension gaps exceeding 2 mm. The study concluded that RATKA appeared to decrease the occurrence of mechanical axis alignment deviations and enhance the achievement of balanced flexion–extension gaps. Remarkably, no significant differences were observed in clinical scores or complications between RATKA and conventional manual techniques [14]. In our study, we found similar outcomes where the difference between the intended resections and the achieved bone cuts were less than 1 mm except for femur cuts (distal and proximal medial position). The high and improved ROM signifies the efficacy of RATKA reiterating the safety and high precision achieved with of RATKA. In another study conducted by the surgical team led by the same author, high rates of enhanced alignment precision were observed among thirty patients undergoing bilateral sequential TKA. Their research revealed that employing robotic-assisted implantation for one knee and conventional implantation for the other led to improved alignment precision. This enhancement, coupled with favorable clinical outcomes, holds promise for positively influencing both clinical and radiological results [15]. Similar to these studies, in our research involving 500 patients, we were able to achieve and execute the planned cuts along with improved ROM and clinical outcomes.

The precise execution of bone cuts is pivotal in determining the alignment, stability, and overall success of TKA. Robotic assistance, through its ability to translate preoperative plans into precise intraoperative execution, offers orthopedic surgeons a level of accuracy unattainable through conventional techniques [16, 17]. This increased precision not only augments implant alignment and stability but also potentially mitigates issues such as component malpositioning and limb malalignment, often associated with poorer long-term outcomes and revision surgeries [18]. Similar to our results, in a research by David G Deckey et al. concluded that RA-TKA exhibits notably superior accuracy and precision in planning both component positioning and final polyethylene insert thickness. Their study encompassed 220 consecutive patients who were randomly assigned to either conventional TKA or RATKA. The enhanced accuracy and consistency of RA-TKA could prove significant as more precise objectives for component positioning are established and tailored to each patient's specific needs [19].

The observed improved accuracy of less than 1 mm in both tibial and femur cuts in executing planned bone cuts can be attributed to the robustness of robotic systems in adapting to intraoperative conditions [20]. Real-time feedback and continuous updates during surgery enable adjustments to account for variations in soft tissue tension, bone quality, and overall limb alignment [21]. Planned cuts are based on CT planning while actual cuts depend on intraoperative soft tissue status which is balanced by altering bony resection hence there is some difference between planned and actual cuts. Intraoperative complications such as excessive bleeding, unforeseen bone defects, or unexpected ligamentous laxity can disrupt the planned procedure and necessitate adjustments. Inadequate exposure of the surgical site or difficulty in accessing anatomical landmarks due to factors like obesity or scarring can hinder accurate execution of the planned procedure. However, no such instances were observed while utilizing fully automated Cuvis Joint robot [22]. Human error, including surgical team communication breakdowns, distraction, fatigue, or lack of experience, can contribute to deviations from the planned procedure. Such adaptability serves as a critical factor in achieving closer adherence to preoperative plans, reducing intraoperative deviations as observed in our study resonating the studies' precision and accuracy.

The implications of this study resonate deeply within the realm of surgical practice. Orthopedic surgeons embracing robotic assistance stand to benefit from heightened precision, potentially reducing outliers and complications associated with implant malalignment. Moreover, the increased accuracy in bone cuts execution may translate into improved functional outcomes, enhanced implant survivorship, and reduced rates of revision surgeries, underscoring the transformative impact of robotic technology on TKA [5, 20, 21].

Limitations and Future Directions

While this study establishes a strong correlation between planned and executed bone cuts with robotic assistance, certain limitations must be acknowledged. Variations in bone quality, and individual surgeon techniques remain influential factors that might affect intraoperative decisions, potentially impacting the achieved cuts' fidelity to the planned resections. CPAK classification and grade of the deformity (recent stage and grade classification) also impact the decision-making. Future studies could delve deeper into mitigating these limitations and exploring strategies to further optimize the precision of robotic-assisted TKA.

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Data availability The datasets generated during and/or analyzed during the current study is the part of the article and are available from the corresponding author on reasonable request.

Declarations

Conflict of Interest Neeraj Adkar, Mangesh Patil, Swapnil Vaidya, Rajendra Kumbar, Ravi Kerhalkar, Girish Mote, Satwik Thareja, Prajwal Sadalagi, and Supreet Bajwa declare that they have no conflict of interest.

Ethical Standard Statement This article does not contain any studies with human or animal subjects performed by the any of the authors. The study adhered to ethical guidelines and received approval from the institutional review board (Maharashtra Institute of Medical Education & Research (MIMER), Maharashtra, India)

Informed Consent All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (Maharashtra Institute of Medical Education & Research (MIMER), Maharashtra, India) and with the Helsinki Declaration of 1975, as revised in 2008 (5). Informed consent was obtained from all patients for being included in the study.

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