# The Evolution of CT-Based Robotic Systems in Total Knee Arthroplasty: From Precision Tools to Intelligent Surgical Partners

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**Learning Point of the Article:**

The true contribution of computed tomography based robotics in total knee arthroplasty lies not in replacing the surgeon, but in enabling more informed, consistent, and individualized surgical decisions through the integration of advanced imaging, real-time intraoperative feedback, and data-driven technologies.

**Abstract**

Total knee arthroplasty (TKA) is one of the most successful orthopaedic procedures; however, achieving consistent implant alignment, soft-tissue balance, and optimal patient satisfaction remains challenging. These limitations have driven the evolution of surgical technologies from conventional instrumentation and computer navigation to Computed Tomography (CT)-based robotic systems. Over the past three decades, CT-based robotic systems have evolved from early autonomous platforms to contemporary technologies that include both semi-active haptic-guided systems and next-generation autonomous robotic platforms, enabling patient-specific planning, precise bone preparation, and reproducible surgical execution. Contemporary robotic platforms have further expanded the role of robotics beyond precision toward individualized alignment and data-driven decision-making. In this editorial, we review the major milestones in the development of CT-based robotic systems, summarize the available clinical evidence supporting their use, and highlight the expanding global and Indian experience. We also discuss emerging innovations, including artificial intelligence (AI), machine learning (ML), predictive analytics, and digital surgical ecosystems, that are expected to further advance precision, personalization, and value-based care in knee arthroplasty.

**Keywords:** Robotic-assisted total knee arthroplasty; Implant alignment; Soft-tissue balance; Computed tomography; Artificial intelligence; Augmented reality; Indigenous innovation.

## Introduction

Over the past three decades, the goals of total knee arthroplasty (TKA) have evolved beyond achieving durable implant fixation and pain relief toward restoring patient-specific knee biomechanics, functional alignment, and a more natural-feeling joint. This paradigm shift has been driven by advances in implant design, alignment philosophies, imaging, and digital surgical technologies, all aimed at improving the precision and reproducibility of knee reconstruction. Against this backdrop, few innovations have influenced the practice of TKA as profoundly as computed tomography (CT)-based robotic systems. Their evolution has not simply introduced another surgical technology; it has fundamentally changed how surgeons plan, execute, and increasingly personalize knee arthroplasty [1]. The focus has therefore shifted from merely achieving accurate implant positioning to data-driven surgical planning and execution [2].

This evolution has been driven by the need to overcome the limitations of conventional TKA. Early robotic systems focused on improving the consistency of bone preparation through

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autonomous execution, whereas subsequent semi-active platforms enhanced surgeon control and facilitated wider clinical adoption. Today, CT-based robotic systems have evolved into intelligent technologies that support more informed and individualized surgical decision-making [3]. In this editorial, we examine how each stage in the evolution of CT-based robotic systems addressed the shortcomings of its predecessor, discuss their impact on surgeons and patients, acknowledge the remaining challenges, and consider the technologies likely to shape the next generation of knee arthroplasty.

## Evolution of Surgical Planning: From Mechanical Alignment to Three-Dimensional Patient-Specific Reconstruction

The primary objective of TKA was to achieve reproducible implant positioning using standardized alignment principles, predominantly mechanical alignment (MA) [4]. Conventional instrumentation relied on intramedullary and extramedullary guides together with two-dimensional (2D) radiographs and intraoperative anatomical landmarks to determine component orientation. Although this approach has produced excellent long-term survivorship, it assumes that a single alignment philosophy can be applied uniformly across patients despite considerable variability in native knee anatomy, constitutional alignment, and bony morphology [2,4]. Consequently, achieving precise implant positioning and soft-tissue balance remained highly dependent on surgical experience and intraoperative judgement, particularly in knees with severe deformity or atypical anatomy [5].

The introduction of computer-assisted navigation represented the first major step towards digital arthroplasty by providing real-time intraoperative information on limb alignment and implant positioning. However, navigation remained fundamentally a guidance technology. Surgical planning was still largely based on intraoperative assessment, bone preparation relied entirely on manual execution, and surgeons had limited ability to visualize patient anatomy before entering the operating theatre (OT) [6].

These limitations paved the way for CT-based robotic systems, which fundamentally transformed preoperative planning through high-resolution three-dimensional (3D) reconstruction of the knee. This allowed detailed assessment of bone morphology, rotational landmarks, deformity patterns, and implant sizing before surgery, providing a more comprehensive anatomical understanding than conventional planning methods [1,7]. By shifting much of the surgical planning to the preoperative stage, CT-based robotics improved surgical preparedness and established the foundation for more consistent execution during surgery.

## Evolution of Surgical Execution: From Autonomous Automation to Intelligent Surgical Assistance

While 3D-CT planning represented a major advance in preoperative decision-making, its clinical value ultimately depended on how accurately the planned resections could be reproduced during surgery [8]. Early CT-based robotic systems therefore focused on minimizing human variability in bone preparation. The introduction of ROBODOC (Integrated Surgical Systems, USA) in the early 1990s marked the first successful application of active robotic technology in orthopaedic surgery. Using the preoperative CT plan, the system autonomously milled bone according to predefined resection parameters, achieving a level of execution consistency that exceeded that of conventional instrumentation [1,9].

Despite these technological achievements, autonomous systems faced important practical limitations. Complex workflows, prolonged operative times, high infrastructure costs, and reduced intraoperative flexibility limited widespread adoption. More importantly, many surgeons were reluctant to relinquish direct control of bone preparation, highlighting that

**Table 1: Evolution of CT-Based Robotic Systems in TKA: From Mechanical Assistance to Cognitive Surgery**

| Stage | Representative Platform(s) | Defining Innovation | Major Limitation Addressed | Clinical Significance |
|---|---|---|---|---|
| Conventional TKA | Manual instrumentation | Mechanical alignment using conventional guides | — | Good long-term survivorship but dependent on surgical experience |
| Computer Navigation | BrainLAB Knee Navigation, Stryker Navigation System | Real-time alignment guidance | Improved alignment assessment | Enhanced guidance, but bone preparation remained manual |
| Active Robotics | ROBODOC | Autonomous CT-based bone preparation | Reduced variability in bone cuts | Demonstrated high execution accuracy but limited by workflow complexity |
| Semi-active Robotics | RIO / MAKO | Haptic-guided robotic assistance | Restored surgeon control while maintaining precision | Improved clinical adoption and surgical workflow |
| Contemporary CT-based Autonomous Robotics | CUVIS Joint | Optical tracking, dynamic registration | Improved intraoperative adaptability | Supports individualized, data-informed surgery |
| | Indigenous MISSO Joint System | Optical tracking, intelligent software, dynamic registration | | |
| Future Cognitive Robotics | AI-integrated robotic platforms | Predictive analytics, digital twins, machine learning | Beyond execution toward surgical intelligence | Personalized, evidence-driven arthroplasty |

successful robotic technology needed to complement surgical judgement rather than replace it. The evolution of robotic-assisted (RA) TKA was therefore shaped as much by surgeon acceptance as by engineering innovation [1,3,9].

This realization led to the development of semi-active robotic systems, which fundamentally changed the surgeon–robot relationship. Rather than performing bone preparation autonomously, systems such as Robotic Arm Interactive Orthopaedic (RIO) (MAKO Surgical Corp., USA) introduced haptic boundaries that constrained saw or burr movement within predefined resection limits while allowing the surgeon to retain complete control of instrument manipulation [10]. This collaborative approach preserved the accuracy of robotic execution while improving intraoperative flexibility, surgeon confidence, and clinical acceptance [2,3]. Following Stryker's acquisition of MAKO Surgical in 2013, RIO technology was further developed into the MAKO robotic-arm platform, which became the most widely adopted CT-based robotic platform worldwide for TKA. Its integration of CT-based preoperative planning, haptic-guided bone preparation, and streamlined surgical workflow played a pivotal role in accelerating the global acceptance and established semi-active robotics as the contemporary standard for CT-based RATKA [11].

Contemporary CT-based robotic platforms have continued this progression beyond simple haptic guidance. Systems such as CUVIS Joint (CUREXO Inc., South Korea) and India's indigenous MISSO robotic platform (Meril Healthcare Pvt. Ltd., Vapi, India) integrate advanced optical tracking, dynamic registration, robotic arm technology, and increasingly intelligent software that continuously monitors bone position and surgical execution [12]. The role of robotics has therefore evolved from autonomous execution to actively assisting surgical decision-making throughout the procedure, reflecting a broader transition from automation to intelligent surgical assistance [2,12]. The progressive evolution of CT-based robotic systems, from conventional instrumentation to contemporary intelligent platforms, is summarized in Table 1.

## Evolution of Clinical Value: What Has CT-Based Robotics Really Changed?

The success of any technological innovation is ultimately determined not by its engineering sophistication but by its ability to improve clinical practice and patient care. Over the past three decades, the evolution of CT-based robotic systems has expanded their value beyond improving bone-cut accuracy [1,5]. Modern robotic platforms have expanded the role of robotics from accurate bone preparation to quantitative intraoperative assessment, enabling surgeons to evaluate alignment, ligament balance, and component positioning throughout the procedure. As a result, robotics has supported the growing acceptance of personalized alignment philosophies and has encouraged a more balanced approach between anatomical restoration and mechanical stability [13]. Rather than relying solely on visual estimation and surgical experience, surgeons can now integrate measurable intraoperative data into decision-making, particularly in complex deformities where conventional instrumentation may be less reliable [2,5].

RATKA has also been associated with fewer soft-tissue releases, more predictable gap balancing, reduced early postoperative pain, and faster functional recovery [14]. However, improvements in patient-reported outcome measures (PROMs) and implant survivorship remain less consistent, with many comparative studies demonstrating equivalent medium-term clinical outcomes despite superior radiological accuracy. These findings highlight an important clinical reality: successful TKA depends not only on accurate implant placement but also on appropriate patient selection, implant design, rehabilitation, and surgical judgment that supports continuous improvement in patient care [3,15,16].

## Global Adoption and the Indian Perspective

The adoption of CT-based RATKA has expanded steadily over the past decade, evolving from a technology confined to specialized centres into an increasingly established component of contemporary arthroplasty practice worldwide. As clinical experience and supporting evidence have grown, several robotic platforms have been integrated into routine practice across North America, Europe, and Asia, reflecting a global shift towards precision-guided and technology-enabled knee arthroplasty [17]. In India, increasing awareness, improving healthcare infrastructure, and the expanded availability of advanced robotic systems have accelerated this transition. An important milestone has been the development of indigenous technologies such as the MISSO robotic platform, which combines CT-based preoperative planning with robotic-assisted surgical execution [18]. Such innovations have the potential to improve accessibility, reduce dependence on imported systems, and support the wider adoption of precision arthroplasty in resource-conscious healthcare settings while fostering continued technological innovation within the country. Indian surgeons have increasingly contributed to the growing body of evidence supporting RATKA through clinical research and early experience with both imported and indigenous platforms [12,18].

## The Next Frontier: Intelligent and Cognitive Robotic TKA

The progression of CT-based robotic systems is far from complete. Although current CT-based robotic systems have substantially improved the technical execution of TKA, the next phase of innovation is expected to be driven less by greater mechanical precision and more by intelligent decision-making. Artificial intelligence (AI) is expected to play a central role in this transformation. Machine learning algorithms trained on thousands of robotic procedures may soon be capable of predicting optimal implant size, component position, alignment strategy, and soft-tissue balancing based on patient-specific anatomy and preoperative imaging [19]. In this evolving paradigm, robotics will function not only as a precision-guided surgical tool but also as a cognitive assistant capable of individualized preoperative planning, predicting functional outcomes, and helping surgeons optimize implant positioning and soft-tissue balance based on real-time data rather than replacing clinical judgement [19,20].

Emerging concepts such as patient-specific digital twins may further extend the capabilities of CT-based robotic systems by enabling virtual simulation of different alignment strategies and implant positions before surgery. Although still largely confined to research settings, these computational models have the potential to support more individualized surgical planning and predictive decision-making in the future [21]. Cloud-based learning platforms could further enable robotic systems to continuously improve through large-scale anonymized datasets, facilitating evidence-driven refinement of implant positioning, alignment philosophies, and rehabilitation pathways. These developments may also support more personalized implant selection and postoperative care while reducing variability between surgeons and institutions [7,20].

## Challenges and Future Directions

Despite these advances, several challenges continue to influence the widespread adoption of CT-based RATKA. High capital investment, additional preoperative CT imaging, maintenance costs, infrastructure requirements, and the learning curve remain important barriers, particularly in resource-constrained healthcare systems [3,7]. Nevertheless, technological sophistication alone should not define the future of RATKA. The greatest challenge over the coming decade will be demonstrating that these innovations translate into meaningful improvements in patient-centred outcomes, long-term implant survivorship, accessibility, and healthcare value [22]. As robotic systems become increasingly intelligent, they must remain transparent, evidence-based, and surgeon-directed [23]. The future of CT-based robotics is therefore unlikely to be one in which surgeons are replaced by machines, but rather one in which human expertise is strengthened through data-driven intelligence, allowing more consistent, personalized, and value-based knee arthroplasty.

## Conclusion

The evolution of CT-based robotic systems in TKA reflects the ongoing pursuit of more precise, predictable, and patient-centered arthroplasty. By improving surgical accuracy, robotic technology is reshaping how surgeons plan, perform, and continuously refine knee arthroplasty, laying the foundation for more intelligent and evidence-informed care. Equally important, CT-based robotics has redefined the role of technology in OT. Rather than replacing surgical expertise, contemporary robotic systems have evolved into collaborative tools that enhance reproducibility, reduce variability, and support informed intraoperative decision-making. While challenges related to cost, infrastructure, radiation exposure, and long-term clinical validation remain, the trajectory of innovation suggests that future robotic platforms will extend well beyond precision-guided surgery. The integration of AI, predictive analytics, and digital surgical ecosystems is expected to further advance personalized and evidence-based arthroplasty. Ultimately, the true measure of success will not be how accurately robots execute bone cuts, but how effectively they help surgeons improve outcomes and restore function for every patient undergoing TKA.

### Clinical Message

The evolution of CT-based robotic systems reflects a shift from precision-guided bone preparation to intelligent surgical assistance. As these technologies continue to advance, their role will increasingly be to support personalized, data-driven decision-making while complementing, rather than replacing, surgeon expertise.

**Declaration of patient consent:** The authors certify that they have obtained all appropriate patient consent forms. In the form, the patient has given the consent for his/ her images and other clinical information to be reported in the journal. The patient understands that his/ her names and initials will not be published and due efforts will be made to conceal their identity, but anonymity cannot be guaranteed.

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## References


1. Elliott J, Shatrov J, Fritsch B, Parker D: Robotic-assisted knee arthroplasty: an evolution in progress. A concise review of the available systems and the data supporting them. Arch Orthop Trauma Surg. 2021, 141:2099–117. 10.1007/s00402-021-04134-1.

2. Deckey DG, Rosenow CS, Verhey JT, Brinkman JC, Mayfield CK, Clarke HD, Bingham JS: Robotic-assisted total knee arthroplasty improves accuracy and precision compared to conventional techniques. The Bone & Joint Journal. 2021, 103-B:74–80. 10.1302/0301-620X.103B6.BJJ-2020-2003.R1.

3. Cantivalli A, Cottino U, Bonasia DE, Rosso F, Rossi R: Robotic Systems in Knee Surgery: Current Concepts and Future Perspectives. Prosthesis. 2023, 5:1257–74. 10.3390/prosthesis5040086.

4. Blakeney WG, Vendittoli P-A: The Future of TKA. In: Rivière C, Vendittoli P-A, eds. Personalized Hip and Knee Joint Replacement. Springer International Publishing: Cham; 2020. 169–74.10.1007/978-3-030-24243-5_15.

5. Mancino F, Fontalis A, Kayani B, Magan A, Plastow R, Haddad FS: The current role of CT in total knee arthroplasty. Bone Joint J. 2024, 106-B:892–7. 10.1302/0301-620X.106B9.BJJ-2023-1303.R1.

6. Van Der List JP, Chawla H, Joskowicz L, Pearle AD: Current state of computer navigation and robotics in unicompartmental and total knee arthroplasty: a systematic review with meta-analysis. Knee surg sports traumatol arthrosc. 2016, 24:3482–95. 10.1007/s00167-016-4305-9.

7. Batailler C, Swan J, Sappey Marinier E, Servien E, Lustig S: New Technologies in Knee Arthroplasty: Current Concepts. JCM. 2020, 10:47. 10.3390/jcm10010047.

8. Jacofsky DJ, Allen M: Robotics in Arthroplasty: A Comprehensive Review. The Journal of Arthroplasty. 2016, 31:2353–63. 10.1016/j.arth.2016.05.026.

9. Chan J, Auld TS, Long WJ, Kreuzer S, Campanelli V, Liebelt R, Kissin YD: Active Robotic Total Knee Arthroplasty (TKA): Initial Experience with the TSolution One ® TKA System. Surg Technol Int. 2020, 37:299–305.

10. Vermue H, Batailler C, Monk P, Haddad F, Luyckx T, Lustig S: The evolution of robotic systems for total knee arthroplasty, each system must be assessed for its own value: a systematic review of clinical evidence and meta-analysis. Arch Orthop Trauma Surg. 2022, 143:3369–81. 10.1007/s00402-022-04632-w.

11. Available from: https://www.strykermeded.com/media/2238/makopartial-knee_medial-unicondylar-resurfacing_surgical-reference-guide.pdf.: Stryker. MakoTMPartial Knee | Surgical Reference Guide. Accessed on 2026-07-03.

12. Rudraraju RT, Londhe SB, Aneja K, Machaiah PK, Bajwa S, Singh D: The role of next-generation robotic systems in transforming knee arthroplasty: precision and beyond. J Robotic Surg. 2025, 19:393. 10.1007/s11701-025-02560-6.

13. Aneja K, Shyam A: Personalized Alignment Strategies and the Need for Customization in Total Knee Arthroplasty: The Role of MISSO Joint Robotic System. Jocr. 2025, 15:1–5. 10.13107/jocr.2025.v15.i08.5862.

14. Spitzer A, Gorab R, Barrett W, Nassif N, Hunter M, Leslie I, Robotic-assisted total knee arthroplasty reduces soft-tissue releases which improves functional outcomes: A retrospective study. Knee. 2024, 49:52–61. 10.1016/j.knee.2024.05.008.

15. Desai KB, Mulpur P, Jayakumar T, Suhas Masilamani AB, Ranjan A, Gurava Reddy AV. Adoption of robotics in arthroplasty- a survey of perceptions, utilization and challenges with technology amongst Indian surgeons. J Ortho 2023, 46:51–7. 10.1016/j.jor.2023.10.019.

16. Kayani B, Konan S, Huq SS, Tahmassebi J, Haddad FS. Robotic-arm assisted total knee arthroplasty has a learning curve of seven cases for integration into the surgical workflow but no learning curve effect for accuracy of implant positioning. Knee Surg Sports Traumatol Arthrosc. 2019, 27:1132–41. 10.1007/s00167-018-5138-5.

17. Tiwari A, Bagaria V. Global adoption of robotic-assisted total knee arthroplasty: a review of trends and drivers from 2020 to 2025. J Robotic Surg. 2026, 20:271. 10.1007/s11701-026-03220-z.

18. Aneja K, Karineravanda Machaiah P, Shyam A. Indigenous Innovation in Orthopedic Robotics: Making Joint Replacement Affordable in India. Jocr. 2026, 16:431–6. 10.13107/jocr.2026.v16.i03.7010..

19. Elkohail A, Soffar A, Khalifa AM, Omar I, Mosaad M, Abdulaziz M, et al. AI-Enhanced Surgical Decision-Making in Orthopedics: From Preoperative Planning to Intraoperative Guidance and Real-Time Adaptation. Cureus. Published Online First: 19 September 2025. 10.7759/cureus.92762.

20. Von Eisenhart-Rothe R, Hinterwimmer F, Graichen H, Hirschmann MT. Artificial intelligence and robotics in TKA surgery: promising options for improved outcomes? Knee surg sports traumatol arthrosc. 2022, 30:2535–7. 10.1007/s00167-022-07035-x.

21. Diniz P, Grimm B, Garcia F, Fayad J, Ley C, Mouton C, Oeding JF, et al. Digital twin systems for musculoskeletal applications: A current concepts review. Knee surg sports

traumatol arthrosc. 2025, 33:1892–910. 10.1002/ksa.12627.

22. Alzarooni A, Ali RM, Aftab A. A Comprehensive Review of Operative Considerations, Surgical Techniques, Outcomes, and Future Perspectives in Total Knee Arthroplasty. Cureus. Published Online First: 11 October 2025. 10.7759/cureus.94345.

23. Bullock M, Danoff JR. Beyond Precision: Why the Future of Robotic Joint Arthroplasty Demands Continued Research. Arthroplasty Today. 2026, 40:. 10.1016/j.artd.2026.102071.

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