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REVIEW

The role of next-generation robotic systems in transforming knee arthroplasty: precision and beyond

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Abstract

Robotic-assisted total knee arthroplasty (RATKA) signifies a paradigm shift in orthopedic surgery, offering enhanced precision, implant alignment, and functional outcomes. Despite extensive research, gaps persist in understanding the clinical advantages, adoption challenges, and cost-effectiveness of RATKA. This review critically examines the evolution of RATKA technologies, focusing on their impact on patient outcomes, learning curves, and cost considerations. It also explores innovative robotic systems, including the MISSO robotic platform, developed in India. While designed to accommodate specific anatomical requirements, MISSO demonstrates the adaptability to cater to global patient demands, addressing the needs of diverse populations worldwide. By integrating advanced algorithms, real-time feedback, and autonomous capabilities, RATKA systems achieve sub-millimeter precision, minimize soft tissue trauma, and expedite recovery. Systems like the fully autonomous CUVIS Joint Robot and surgeon-guided ROSA and CORI Knee platform showcase superior accuracy in implant placement and ligament balancing compared to conventional techniques. This review is not limited to the Indian healthcare system but provides a global perspective for orthopedic surgeons and patients. It highlights the transformative potential of RATKA across various healthcare settings, addressing challenges such as high costs, steep learning curves, and regulatory barriers. Through comprehensive analysis and comparisons, the review bridges critical gaps in the literature and proposes strategies for overcoming limitations, fostering broader adoption of robotic technologies. By offering nuanced insights, this work aims to guide the orthopedic community toward achieving optimal patient outcomes and advancing the global standards of knee arthroplasty.

Keywords Robotic assisted total knee arthroplasty · Conventional total knee arthroplasty · Learning curve · Quality of life · Cost-effectiveness

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Introduction

Background on knee replacement surgery

The landscape of knee replacement surgeries has undergone a profound transformation driven by technological advancements, fundamentally reshaping orthopaedic practices. Starting from basic joint replacement techniques to today's era characterized by precise medical approaches, the incorporation of robotic-assisted systems into knee replacement surgeries marks a crucial progression.

Traditionally, knee replacement surgeries have played a vital role in alleviating pain and restoring function for individuals grappling with degenerative joint diseases [1–3]. However, conventional methods have encountered difficulties in achieving accuracy and tailoring treatment plans to individual patients [4, 5]. The emergence of robotic-assisted (RA) surgery has transformed this scenario, heralding a new phase characterized by surgical precision and customized patient care [6].

Rationale and knowledge gap

The integration of robotic technology into orthopedic surgery marks a transformative paradigm shift, leveraging the convergence of advanced imaging techniques, artificial intelligence (AI), and biomechanical principles. These advancements promise greater precision, enhanced pre-operative planning, and adaptability during surgery, collectively raising the standard of patient care.

Despite the growing adoption of robotic-assisted total knee arthroplasty (RA-TKA) and a steadily expanding body of clinical evidence [3, 6, 7], there remains a lack of comprehensive and comparative evaluations that synthesize the current capabilities, limitations, and real-world performance of available robotic systems. Much of the existing literature is fragmented—focused on individual platforms, small-scale outcome analyses, or technical aspects—leaving surgeons with limited guidance on how to navigate the evolving robotic landscape in a practical, evidence-based manner. A consolidated review addressing technological evolution, learning curves, cost considerations, and clinical implementation strategies is needed to support informed decision-making among prospective users.

Objective

This review aims to provide a structured and comparative analysis of the major robotic systems currently used in total knee arthroplasty. By evaluating key features such as technological platforms, surgical accuracy, learning curves, clinical outcomes, cost-effectiveness, and implementation models, this article seeks to inform orthopedic surgeons and healthcare institutions about the practical considerations and evidence-based value of robotic-assisted knee arthroplasty in contemporary practice.

Overview of robotic systems in knee arthroplasty

The advent of RA orthopedic surgery marked a technological leap, driven by advancements in navigation, imaging, and robotics. Early systems like ROBODOC pioneered active robotic applications, initially in hip arthroplasty, later extending to knee surgeries, setting a milestone in precision and personalization in orthopedic surgery [5, 8–13]. Earlier research highlights the nascent phase of robotic-assisted orthopedic surgery [14, 15]. Survivorship analysis was pivotal in evaluating the long-term efficacy of these systems. A randomized controlled trial by Honl et al. [14] demonstrated RA technology's advantages in pre-operative planning and procedural accuracy but noted drawbacks, including high revision rates, increased muscle damage, higher dislocation risk, and prolonged surgery duration. Furthermore, research conducted by Bargar et al. [15] reported that there were no notable differences in postoperative results between RA and conventional surgical techniques. Contemporary robotic platforms have since undergone significant technological refinement, and recent literature increasingly reports improved accuracy, shorter recovery times, fewer complications, and better patient satisfaction. Modern RA platforms, such as Mako, Navio, ROSA, CUVIS, and MISSO, have significantly improved precision in implant positioning, ligament balancing, and soft tissue preservation [12]. It has also helped enhance surgeons' capabilities with real-time feedback, advanced visualization, and haptic guidance, transitioning from passive systems that provided limited guidance to active platforms that dynamically optimize implant positioning and alignment [6, 13]. Table 1 presents a chronological overview of leading robotic systems in knee arthroplasty, summarizing their platform characteristics, control types, imaging requirements, and key features [modified from Bagaria et al. [10]].

The Mako system (Stryker, Mahwah, NJ, USA) revolutionized orthopedic robotics by offering a semi-active RA platform controlled by surgeons. Research also shows improved accuracy in TKA with enhanced prosthesis positioning, ligament balance, and knee dynamics, contributing to better function and longevity [16–19]. Kayani et al. [20] and Sires et al. [21] further demonstrated its feasibility and accuracy in achieving optimal alignment parameters in knee replacements.

Table 1 Chronological evolution of robotic systems in total knee arthroplasty: platforms, indications, and functional attributes. Modified and expanded from Bagaria et al. [10]

Name	Manufacturer	Launch year	System platform	Indication	FDA clearance	Robotic control Type	Cutting modality	Imaging requirement	Current status	Features
Mako	Stryker Mahwah, NJ	2005	Closed platform	Unicompartmental knee arthroplasty, patellofemoral arthroplasty, total knee arthroplasty, total hip arthroplasty	2015	Semi-active	Saw burr	CT-based preoperative planning	Widely adopted	Restricts bone resection to predefined boundaries; supports multiple joint types
Navio	Smith & Nephew Memphis, TN	2012	Closed platform	Unicompartmental knee arthroplasty, patellofemoral arthroplasty, total knee arthroplasty	2017	Semi-active	Burr-based resection	Image-free, optical navigation	Widely used	Allows freehand sculpting of bone; resects only pre-planned bone volume using imageless tracking
ROSA	Zimmer Biomet Warsaw, IN	2018	Closed platform	Total knee arthroplasty	2019	Active	Haptic-guided cutting block (no saw)	X-ray based	Limited clinical deployment	Utilizes a haptic resection guide for alignment; lacks integrated cutting mechanism
OMNIBotics®	Corin Group, UK/USA	2019	Closed platform	Total knee arthroplasty	2019	Semi-active	Motorized jigs + ligament balancing	Image-free	Selective clinical use	Predictive ligament balancing; intraoperative alignment modeling
TSolution One®	Think Surgical, USA	2019	Open platform	Total knee arthroplasty	2019	Filly- Active	Milling-based robotic arm	CT-based	Limited adoption	Open implant platform; evolved from ROBODOC; automated milling

Table 1 (continued)

Name	Manufacturer	Launch year	System platform	Indication	FDA clearance	Robotic control Type	Cutting modality	Imaging requirement	Current status	Features
Cuvis	Curexo, Inc. South Korea	2020	Closed platform	Total knee arthroplasty	2020	Fully automatic	Automated milling	3D CT-based planning based	Actively in use	Fully autonomous bone milling; eliminates need for cutting guides; compact design with adjustable cutting speed and high intraoperative flexibility
CORI	Smith & Nephew, USA	2020	Closed platform	Unicompartmental and total knee arthroplasty	2020	Semi- active	Burr-based handheld tool	Image-free optical mapping	Replacing NAVIO	Successor to NAVIO with improved workflow and compact hardware
Velys	DePuy Synthes (J&J), USA	2021	Closed platform	Total Knee Arthroplasty	2021	Semi-active	Cutting block–guided saw	Image-free camera navigation	Emerging adoption	Compact, imageless system; integrates with ATTUNE implants
MISSO	Meril Healthcare Pvt. Ltd., India	2024	Closed platform	Total knee arthroplasty	CDSCO Approved; CE and FDA approvals pending	Fully active	Robotic milling with AI-guided precision	3D CT-based planning	Currently used in India	Sub-millimeter accuracy; AI-driven surgical planning; compact design suitable for smaller operating rooms; real-time intraoperative adjustments; cost-effective solution for broader accessibility

Manufactured by Smith and Nephew (Pittsburgh, USA), the Navio platform is a handheld robotic tool designed to assist with real-time navigation, allowing for precise bone contouring and accurate implant placement [22]. Lonner et al. [23] emphasize its high accuracy, with only 8.5% of RA-TKAs exceeding a ± 3° accuracy threshold, reflecting its precision and reproducibility.

The ROSA Knee System (Zimmer-Biomet, Canada) combines advanced imaging, AI, and real-time 3D modeling to personalize knee arthroplasty. It facilitates optimal implant positioning and ligament balancing, eliminating the need for customized implants [24–26]. Parratte et al. [27] and subsequent studies highlight its accuracy in achieving planned bone cuts and angles, with deviations typically under 1 degree [28, 29].

A notable advancement in Smith & Nephew's robotic portfolio is the transition from the NAVIO system to its successor, the CORI Surgical System [30]. Introduced in 2020, CORI retains the handheld robotic features of NAVIO but incorporates enhanced intraoperative data acquisition, faster mapping, and improved haptic feedback. Unlike NAVIO, which requires preoperative imaging, CORI operates as an image-free platform, streamlining workflow while maintaining precision. A randomized, triple-blinded trial in Poland compared NAVIO, CORI, and manual TKA in 215 patients. It found similar functional outcomes (KOOS, ROM, VAS) across groups and no difference in complication rates. Notably, CORI offered equivalent precision in implant placement relative to NAVIO and manual techniques, albeit without significant improvement in patient-reported outcomes [30]. An imageless robotic accuracy study confirmed that NAVIO/CORI systems achieved significantly better radiological alignment and fewer outliers compared to conventional TKA [31].

The CUVIS Joint Robot System (CUREXO, South Korea, supported by Meril Life Sciences, India) introduces fully autonomous capabilities, performing pre-operative planning, bone cuts, and implant placement with minimal human intervention [32–34]. Studies demonstrate its sub-millimeter precision and improved implant positioning, minimizing soft tissue trauma and reducing the necessity for broad capsular and ligamentous release [35–37]. Going beyond the active-assist paradigm, this system incorporates autonomous capabilities enabling it to independently perform the preoperative planning, cuts, and intra-operative adjustments [33, 34]. Leveraging advanced algorithms and sensors, it navigates joint anatomy, makes real-time adjustments, and executes precise cuts and implant placements with minimal human intervention [33, 35].

The MISSO Robotic System (Meril Healthcare Pvt. Ltd, Gujarat, India) represents the most recent innovation in surgical robotics, designed, developed, and manufactured in India [38]. This state-of-the-art, fully active surgical robotic technology assists surgeons with personalized preplanning and precise cutting, enhancing surgical accuracy and outcomes. Equipped with advanced features like an optical tracking sensor, a 6-axis articulated robotic arm, and superior safety sensors, the system enables real-time gap checks and intra-operative modifications to the surgical plan [38]. With repeat precision of less than 0.5 mm and positioning accuracy under 1 mm, the MISSO Robotic System ensures sub-millimeter precision and optimal alignment. It offers various cutting options, including full and partial cuts, with the ability to change the cutting order and perform intra-operative gap balancing. The system provides real-time assistance, with an emergency stop function and minimal human intervention, reducing the risk of infection and human error. It is a fully automatic milling tool that accurately maneuvers based on calculated values, effortlessly handling complex cuts, even on narrow surfaces like lug holes and box cuts. This makes the MISSO Robotic System a cutting-edge surgical robot, setting new standards for precision and efficiency in orthopedic procedures catering to the anatomical needs of the global population [38].

The successive development of robotic systems for TKA reflects a continual effort to address the limitations of previous generations and align with evolving clinical needs. Early platforms prioritized accuracy in bone preparation and implant positioning but were limited by complex workflows, steep learning curves, and high procedural times. This led to the emergence of semi-active systems such as Mako and Navio, which offered haptic feedback and improved user control. Subsequent innovations, including ROSA and CUVIS, introduced AI-based planning, soft tissue balancing, and full automation to reduce intraoperative variability and enhance safety. More recent systems like CORI and MISSO emphasize compact designs and cost-effective deployment tailored to diverse healthcare environments. Thus, the launch of each robotic system represents a technological response to improve usability, precision, efficiency, and accessibility across varied surgical settings.

Clinical outcomes and patient benefits

Registry-based evidence

In recent years, national joint registries have begun documenting the outcomes of RA-TKA, offering valuable real-world insights. The American Joint Replacement Registry (AJRR) began recording robotic assistance data in 2017 [39]. According to the AJRR 2022 Annual Report, the use of robotic systems in primary TKA increased from 1.9% in 2017 to 11.6% in 2021, reflecting a growing adoption trend [40]. A large-scale registry-based study analyzing 9,220 Medicare-aged patients from the AJRR reported no statistically significant difference in two-year revision rates between RA-TKA and conventional TKA (1.16% vs. 1.3%; $p = 0.6$) [41]. The study also noted a slightly higher early risk of infection and mechanical loosening with RA-TKA, which was attenuated after risk adjustment [41]. Similarly, the Australian Orthopaedic Association National Joint Replacement Registry (AOANJRR) concluded that short-term revision risks were comparable between robotic and conventional TKA, further supporting the safety of robotic adoption in clinical practice [42]. These registry-based findings highlight the comparable early survivorship of RA-TKA and underscore the need for longer-term outcomes data.

Clinical studies

Navio surgical system

Research exploring the Navio Surgical System has consistently prioritized investigations into clinical outcomes and patient-centric advantages. Despite longer surgery times (NAVIO: +44.5 min), NAVIO demonstrated superior accuracy in femoral component rotational alignment [mean radiographic scores: NAVIO 1.48° than manual TKA (mTKA) 3.15°)] and reduced blood loss (NAVIO: 1.74, mTKA: 2.32) [30]. Significant differences in alignment were found between the mTKA and the robotic system, as well as in KOOS scores (NAVIO: 87.05, mTKA: 81.76). There were no differences in post-operative ROM, visual analog scale (VAS) scores, or complication rates between the groups [30]. Recent investigations have showcased accelerated return to sporting activities (4.2 vs. 10.5 months) with robotic-assisted surgery compared to conventional approaches, alongside improvements in functional capacity and reductions in pain levels [43]. Notably, 100% of patients undergoing NAVIO-assisted procedures returned to sports, underscoring the system's efficacy in facilitating post-operative rehabilitation [43]. Furthermore, the NAVIO system has been associated with a lower incidence of complications resulting in early discharge from the hospital [44].

Mako robotic-arm assisted technology:

The Mako Robotic-Arm Assisted Technology has been subject to extensive scrutiny aimed at delineating its influence on clinical outcomes. A prospective cohort study by Kayani et al. [45] furnished invaluable insights into the mid-term ramifications of Mako-assisted TKA, highlighting the improvement in patient-reported outcomes, mitigated post-operative discomfort, and expedited recovery, thus fostering augmented overall clinical efficacy. The study also reported that the RATKA is significantly correlated with diminished post-operative pain ($p < 0.001$ on days 0, 1, 2, and pre-discharge), reduced opioid utilization ($p < 0.001$), decreased requirement for physical therapy sessions (mean 9 vs 5 sessions), shortened duration until ambulation of the operated limb (mean 71.1 vs 42.5 h), and improved ROM immediately preceding hospital discharge [45]. Moreover, post-operative functional scores and patient contentment exhibited marked improvement post-intervention.

Recent data show that patients undergoing TKA utilizing MAKO experience a reduction in pain scores at post-operative 6-month period compared to cTKA, with similar outcomes at one year [45]. MAKO-assisted TKA is associated with superior postoperative ROM at both discharge and 90 days, lower early postoperative pain levels, reduced need for analgesics, enhanced WOMAC scores, and a shorter duration of hospital stay (77 h compared to 105 h), irrespective of the complexity of the case [44].

ROSA knee system

The impact of the ROSA Knee System on clinical outcomes continues to be a topic of active investigation [29, 46]. In a cadaveric study, Seidenstein et al. [47] illustrated statistically superior accuracy and fewer alignment outliers for RA-TKA compared to conventional approaches. Particularly noteworthy were the precision of bone resection angles, with robotic-assisted procedures achieving accuracy levels well below 0.6° and standard deviations below 0.4° [47]. Conversely, Shin et al. [48] reported high accuracy in achieving coronal alignment but identified reduced precision in the sagittal plane. Kenanidis et al. [49] found no significant differences in patient-reported outcome measures (PROMs) or overall knee satisfaction between robotic-assisted and conventional TKA at three months post-surgery. However, by six months, the robotic-assisted group demonstrated higher Forgotten Joint (FJS) and Oxford Knee scores (OKS), experienced less pain, and showed a stronger willingness to undergo the procedure again. Similarly, studies by Parratte et al. [50] and Batailler et al. [51] reported significantly better Knee Society Knee and Functional scores at six months postoperatively in patients who underwent RA-TKA. Robotic technology, when used for anatomo-functional implant placement in primary TKA, supports restoration of native knee alignment and physiological ligament balance, facilitating a quicker recovery compared to mechanically adjusted techniques [50, 51]. Additionally, Mancino et al. [52] observed superior postoperative Knee Society Knee and Function scores at 12 months with RATKA, along with notable improvements in ROM compared to navigation-assisted TKA.

A comprehensive meta-analysis encompassing 1112 cases underscored the superiority of RATKA over conventional techniques, as evidenced by WOMAC scores, Knee Society Score (KSS), flexion ROM, and walking distance. Moreover, recent clinical retrospective investigations have reported improved knee and function KSS scores at six months with personalized alignment techniques facilitated by the ROSA Knee System [25].

CUVIS joint robot system

The impact of CUVIS Joint Robotic System on clinical outcomes has been rigorously investigated, with studies by Lee et al. [34] Patil et al. [33], Patil [35], Londhe et al. [36, 53], and Murugasen et al. [54] offering comprehensive insights. These studies illustrate the critical aspects of patient care, including functional recovery, pain management, and overall patient satisfaction, thereby enriching our understanding of the clinical advantages conferred by this state-of-the-art robot.

Following the utilization of the Cuvis for TKA, the postoperative mean HKA axis was recorded at 0.9°, with no outliers observed [35, 36]. In all cases, the coronal and sagittal implant alignments were achieved within 1.2° of the planned targets, demonstrating a high level of precision in component positioning following RATKA [54].

The CUVIS system offers notable advantages, particularly minimizing soft tissue damage by confining the cutting saw within a fixed stereotactic field, guided by 3D imaging [37]. This approach results in improved implant positioning, reducing the need for extensive capsule and ligament release, enhancing control over bone cuts, and reducing the risk of soft tissue exposure and trauma. The fully automated active robotic Cuvis joint system has an excellent safety profile as none of the RA-TKA patients had any device-related complications [55].

Surgical precision and customization

Navio surgical system

Image-free robotic-aided techniques rely on intraoperative manual mapping of bone surfaces to register anatomical landmarks. This process generates a 3D virtual model in real time, allowing surgical planning to be performed during the procedure itself [44]. In contrast to conventional methods, these systems do not require preoperative 3D imaging or advanced planning. However, the accuracy of the registration process is contingent on the surgeon's ability to precisely capture anatomical reference points intraoperatively, introducing a potential for operator-dependent variability [56]. The Navio Surgical System is engineered to improve surgical precision by providing real-time feedback and guidance during knee replacement procedures. Research studies have evaluated the accuracy of the Navio system in achieving optimal implant positioning and precision offered by CT-free navigation, a key feature of the Navio system, in enhancing surgical outcomes [29, 57].

During CTKA, component alignment typically relies on intra- and extramedullary rods or manual caliper measurements of resected bone. This technique, however, may introduce alignment errors, leading to suboptimal implant positioning, patient dissatisfaction, and early prosthesis failure. In contrast, the NAVIO system has demonstrated high precision, with alignment accuracy reported between 0.2°–0.5° and 0.5 mm across all three anatomical planes—coronal (varus/valgus angle), sagittal (femoral flexion angle), and axial (femoral resection depth). The deviation between preoperative plans and postoperative radiographs is minimal [44]. Furthermore, only 8.5% of RATKAs using this platform fall outside the ± 3° accuracy threshold, underscoring its consistency and reliability. Additionally, measurements of soft-tissue laxity show an average deviation of just 0.9 mm in both medial and lateral compartments from 0° to 90° of flexion, which reduces to approximately 1 mm in the mid-flexion range, indicating excellent soft-tissue balance throughout the motion arc [44].

Mako robotic-arm assisted technology

The precision of bone resection and implant placement achieved utilizing Mako technology is widely acknowledged. Jung et al. [58] explored the learning curves associated with Mako-assisted TKA and underscored the system's capacity to attain accurate and reproducible outcomes, thereby enhancing the precision of the surgical procedure [58]. Several cadaver-based investigations have validated the system's exceptional precision, demonstrating only minor differences between the preoperative plan and the executed bone resections. Reported deviations include approximately 0.1 mm for the extension gap, a range of − 2 mm to 2 mm for the flexion gap, 1.1° for posterior slope, and 0.9° for rotational alignment. Furthermore, these studies indicate a notably lower incidence of soft tissue trauma during bone preparation compared to cTKA [58].

ROSA knee system

The ROSA Knee System integrates advanced imaging and real-time 3D modeling to elevate surgical precision [13]. Bolam et al. [59] evaluated the accuracy of post-operative imaging, highlighting the system's proficiency in achieving precise implant positioning and alignment. Cadaveric evaluations of RATKA have shown remarkable accuracy, with all bone resection angles deviating less than 0.6° from the planned values and standard deviations consistently under 0.4°. Final limb alignment in the robotic cohort was also highly precise, with accuracy within 1° and all cases falling within a 3° margin of error—most notably, a greater proportion achieved alignment within 2° and 3° [44]. Building on this, Parratte et al. [27] utilized the ROSA robot in

TKA and found near-zero mean differences between planned and actual resection angles, though with slightly broader standard deviations exceeding 1°. Importantly, the ROSA demonstrated outstanding consistency in limb alignment, with 99.9% of HKA angles falling within ± 3° of the surgical plan—outperforming traditional methods like computer navigation (87.2%) and manual instrumentation (69.9%). Additionally, 99% of the coronal, sagittal, and rotational alignment parameters achieved with ROSA remained within a 3° threshold of the intended values, underscoring its reliability across multiple anatomical planes [60].

CUVIS joint robot system

In a meticulous examination conducted by Lee et al. [34], the precision of the CUVIS system is comprehensively evaluated, shedding light on the accuracy of surgical procedures achieved with it.

The Cuvis Joint robot is programmed to execute movements within a predetermined range of 1 mm (as determined by the manufacturer). Unlike older systems, it does not necessitate the placement of registration tracks or Bone Milling Monitoring (BMM) sensors on the bone [61]. Functioning autonomously, the robotic arm follows a preprogrammed trajectory for each milling surface, guided by meticulously planned cutting paths and milling strategies. This approach minimizes the likelihood of injury to surrounding ligaments, blood vessels, and nerves when compared to traditional surgical methods. Integrated with a BMM system, the robot continuously gathers real-time data during the milling process. Should any unanticipated movement or bone shift exceed the preset safety threshold, the robotic arm automatically stops, thereby averting possible harm. Additionally, the milling speed can be adjusted throughout the procedure, allowing control by the operator [33].

A non-randomized, retrospective assessment aimed at evaluating the accuracy and precision of RATKA using the Cuvis Joint robot in maintaining resection thickness and angles was conducted [35]. The findings revealed high accuracy, with only minor discrepancies between the planned and executed bone resections. Resection thickness and angular deviations remained well within acceptable limits, with root mean square (RMS) errors measuring less than 1 mm across both tibial and femoral planes. Specifically, the average angular variation at the distal femoral plane was 0.77° in the varus/valgus (V/V) direction and 0.98° in flexion/extension (F/E). For the posterior femoral plane, deviations were 0.59° (V/V) and 1.5° (F/E), while the tibial plane showed mean differences of 0.76° (V/V) and 0.85° (F/E) [35]. The system provided real-time adjustments during surgery, contributing to better patient outcomes, including minimal soft tissue injury and quicker recovery times. The authors concluded that the fully automated Cuvis Joint robotic system enhances the accuracy of RATKA, supporting its efficacy and safety for knee osteoarthritis patients [35].

A study by Harish Kumar et al. [54] focused on femoral component rotation in RATKA for varus deformity. It highlighted the importance of personalized femoral component alignment to ensure optimal patellofemoral kinematics. The study observed significant deviations from the commonly accepted 3° external rotation (relative to the Posterior Condylar Axis), particularly in the Indian population, where the average Posterior Condylar Angle (PCA) was 1.9°. The study demonstrated that patient-specific femoral component rotation, achieved through robotic guidance, resulted in excellent functional outcomes and patellar tracking, reducing the need for soft tissue release and ensuring better balance in flexion and extension [54].

Another study by Londhe et al. [36] revealed that using the fully autonomous Cuvis Joint robot led to consistent external rotation of the femoral component relative to both the transepicondylar axis (TEA) and PCA. The mean external rotation was 1.45° with respect to the TEA and 2.36° with respect to the PCA, both statistically significant. These results demonstrated that the functional alignment technique in RATKA achieves patient-specific component rotation that significantly differs from the conventional 3° external rotation applied in traditional TKA. Importantly, no patellofemoral complications or premature loosening were observed at the one-year follow-up, supporting the effectiveness of robotic-assisted procedures for improving alignment and potentially enhancing patient outcomes [36].

Overall, these findings support the conclusion that RATKA provides better precision, more personalized treatment, and improved patient outcomes compared to traditional techniques.

Figure 1 outlines the pre-programmed milling path and its real-time adherence to planned trajectories, highlighting the system's capacity for precise bone resection. Figure 2 illustrates the integrated safety protocols, including bone movement monitoring and automatic stop features that prevent unintended soft tissue damage. These images support the described benefits of automation by providing visual evidence of both surgical accuracy and intraoperative risk mitigation achieved with advanced robotic platforms.

Table 2 presents the clinical outcomes, alignment precision and patient-reported satisfaction with various RATKAs.

Learning curve and surgeon training

Learning curves serve as valuable metrics for assessing the ease of adoptability of a novel technology or surgical procedure, offering insights into the proficiency attained by surgeons over successive repetitions [62].

Fig. 1 Pre-operative planning (J planner) using CT scans of patients. Fully automated Cuvis Joint robot generates 3D images in full extension (**A**, **B**) and 90 degrees flexion (**C**, **D**)

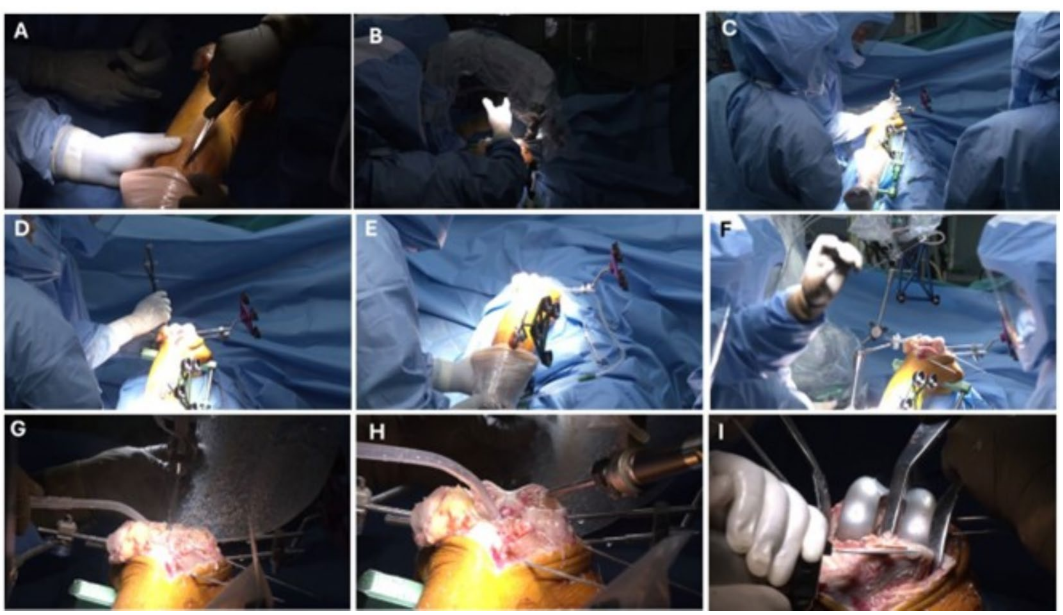

Fig. 2 Intraoperative steps involved on total knee arthroplasty using fully automated Joint robot

The Navio Surgical System, akin to other robotic platforms, requires surgeons to undergo specialized training to proficiently navigate its interface and utilize its features [57]. Another study focusing on the NAVIO system indicated a learning curve of 12 cases encompassing the steps of registration of bony surfaces, digital reconstruction, intraoperative planning, and bone resection [62]. Furthermore, Savov et al. [63] illustrated a learning curve of 11 cases based on total surgical time, while Kayani et al. [64] reported that proficiency in robotic TKA could be attained after performing seven cases. Notably, authors in another study indicated that there was no noticeable learning curve impact on the accuracy of implant positioning in utilizing RATKA [65].

Bell et al. [19] provided evidence that the learning curve was reached at 29 cases with the NAVIO system. They reported that a fellowship-trained senior surgeon achieved

Table 2 Postoperative clinical outcomes associated with robotic-assisted TKA, including functional assessment scores, alignment precision, complication rates, and patient-reported satisfaction, as reported across selected peer-reviewed studies [12]

References	Robot utilized	Total number of cases		Follow up in months	Conclusion
		Robotic-assisted cases	Conventional cases		
Kayani et al. [20]	Mako	40	40	One	RA-TKA showed significantly lower postoperative pain ($p < 0.001$), reduced analgesic use ($p < 0.001$), smaller hemoglobin drops, earlier straight leg raise ($p < 0.001$), fewer physiotherapy sessions, and better knee flexion at discharge. Shorter hospital stays (3.2 vs. 4.4 days) ($p < 0.001$)
Cool et al. [79]	Mako	519	2595	Three	RA-TKA resulted in $2391 lower 90-day episode-of-care costs ($p < 0.001$), compared to manual TKA, driven by fewer readmissions and more favorable discharge destinations
Paratte et al. [50]	Rosa	15	15	–	Cadaveric comparison showed mean angular deviations < 1Â° and resection deviations < 0.7 mm; only femoral flexion angle showed notable difference (0.95Â°)
Sodhi et al. [69]	Mako	20	20	–	Initial RA-TKA cases had longer operative times (117 vs. 95 min) ($p < 0.05$), but final cases showed no significant difference (98 vs. 95 min) ($p > 0.05$), indicating a short learning curve
Lau et al. [31]	Navio	71	71	12	RA-TKA had fewer limb alignment outliers than cTKA. Though functional outcomes were similar, robotic cases had longer operative times, but shorter hospital stays
Chandrashekhar et al. [33]	Cuvis	500	–	–	The Cuvis system enabled precise implant placement and osteotomy through advanced robotic control in minimally invasive surgery; no comparator group

full proficiency after 29 cases, accompanied by a 26% overall improvement in arthroplasty efficiency over the course of the learning curve. Moreover, an immediate decrease in operative time was observed following the first twenty cases of the study. The average operative time for NAVIO-assisted TKAs was reported as 68.2 min, in comparison to CTKA's 51.7 min. However, after completing 40 cases, the surgeon's operative time was only 10 min longer than cTKA—an 18% increase—with no significant time difference observed beyond 80 cases [44].

A large observational study recently reported on the learning curve and initial complications of 500 CORI-assisted TKAs [66]. Surgeons achieved proficiency after approximately six cases, with low rates of minor complications (e.g., pin-site issues and bony over-resection), and no serious short-term adverse events [66].

Mako robotic-arm assisted technology

Zhang et al. [67] in a review article have discussed about the learning curve for Mako-assisted TKA, emphasizing the significance of experience and dedicated training in attaining proficiency with the system. Recent research suggests that RATKA initially requires marginally longer operative times—from incision to closure—than cTKA, with the first 20 MAKO cases averaging 82.5 min compared to 78.3 min for traditional procedures [68]. However, no major difference in mean operative time was observed in the next 20 cases [68]. Sodhi et al. [69] in their study, showed that the average operative duration for the initial 20 RATKAs procedures was notably longer than that observed in the final 20 cases. In another research, they noted that as surgeons and operating room personnel grew more familiar with the system, the operative durations for RATKA and cTKA were comparable [69]. Kayani et al. [64] also reported that operative time with RATKA improved rapidly, matching that of conventional TKA after just seven cases, without affecting the accuracy of implant positioning or limb alignment. Similarly, Stauss et al. [70] in a study comparing complex and non-complex revision TKA found no statistical significance in surgery duration. Comparable studies on the MAKO system revealed a wider range for the learning curve, spanning from 11 to 43 cases for operative time [62].

Although the MAKO robotic system is a relatively recent innovation in surgery, it has shown a rapid learning curve. Marchand et al. [71] observed a reduction in surgical durations over time, from 81 min at 1 month to 65 min at 6 months and 62 min at 1 year, despite initial increases in operative times with the innovative technology. Most available data pertaining to the MAKO platform suggests that a learning curve of seven to 41 cases is required to transition from the learning phase to a more proficient phase in RATKA [68].

ROSA knee system

The implementation of the ROSA Knee System entails a learning process, and investigations have been carried out to evaluate the effect of training on surgeon competence. A study on the learning curve associated with ROSA-assisted knee arthroplasty underscores the significance of ongoing training and feedback of the system [72].

According to Vanlommel et al. [73], the imageless ROSA system necessitates completing 6–11 cases to approach proficiency. Bolam et al.'s [59] investigation highlighted a learning curve ranging between 5 and 15 cases upon the introduction of this RATKA system, with no noteworthy differences in operative times between the learning and proficiency phases or within the RATKA group. The ROSA Knee robot demonstrates a concise learning curve, estimated at 8.7 to 9 cases, without compromising accuracy—offering greater precision than cTKA. Additionally, it shows no significant difference in operative times between robotic-assisted and conventional procedures, nor any increase in complication rates [59].

CUVIS joint robot system

The fully automatic CUVIS Joint Robot System, as a recent innovation, demands careful attention to the learning curve and training requirements. A study by Londhe et al. [53] delves into the learning curve, highlighting the importance of structured training and gradual integration into clinical practice. In the realm of RATKA, surgical teams can achieve time neutrality within a concise timeframe, typically after surpassing approximately 10 RATKA procedures [53]. Notably, operative times specific to robotic procedures were prolonged in the initial 10 cases. However, beyond the 18th case, no statistically significant difference in operative time was observed. This delineates an inflection point occurring within the first 18 cases, marking the transition of the surgeon from the learning to the proficiency phase of the active RATKA procedure [53].

The learning curve and surgeon training constitute critical considerations in the implementation of robotic joint knee replacement systems. Each system, whether it's the Navio, Mako, ROSA or the CUVIS, presents its unique challenges and training requirements. Studies such as these provide valuable insights into the learning process, facilitating surgeons and healthcare institutions in developing effective training protocols for the successful integration of robotic-assisted technologies.

Cost analysis

Understanding the financial implications is crucial for healthcare institutions and policymakers when evaluating the feasibility and cost-effectiveness of integrating these advanced technologies.

Navio surgical system

The Navio Surgical System, despite its precision advantages, may incur expenses that influence its adoption. Studies, exemplified by Hua et al.'s [74] research, undertake a thorough cost analysis encompassing equipment, maintenance, and additional resources essential for Navio-assisted TKA. The Navio system comes at a cost of approximately $500,000. Moreover, as it operates on image-free software, the need for a pre-operative CT scan is eliminated, thereby restricting additional associated expenses [75]. In an independent analysis by Yeroushalmi et al. [76], the cost-effectiveness of the Navio system was assessed, showing that its economic viability is closely tied to surgical volume. The incremental cost-effectiveness ratio (ICER) was calculated at $14,737 for each revision prevented when performing 100 procedures per year.

Mako Robotic-Arm Assisted Technology, as a prominent system, has undergone extensive economic evaluations. The cost-effectiveness of Mako-assisted TKA is illustrative in research that scrutinizes direct costs as well as considering potential downstream savings associated with enhanced patient outcomes [77]. The evaluation of cost-effectiveness considers multiple elements, such as the cost of the robotic system, hospitalization fees, medication expenses (particularly opioids), complication rates, and the need for revision surgeries [77].

Concurrently, Cotter et al. and Cool et al. observed that patients undergoing RATKA using Mako experience statistically lower 90-day costs—up to $2090 lower compared to cTKA [78, 79].

The economic impact of the ROSA Knee System has also been a subject of investigation [80]. A recent study conducted a cost–benefit analysis comparing RATKA with cTKA using Medicare fee-for-service data. The study found that the 90-day end-of-care (EOC) costs were notably lower for the RATKA group. This cost reduction was attributed to several factors, including shorter length of stay (LOS), a higher proportion of patients discharged to their homes, decreased readmission rates, and fewer days spent in skilled nursing facilities (SNFs) and receiving home health visits among service users [78].

The cost analysis of the fully automatic CUVIS and MISSO Joint Robot System is an evolving area of research. As these systems gain traction, studies providing insights into the financial aspects associated with the robots, considering factors such as initial investment, maintenance, and potential cost savings could be determined.

Additionally, despite the added costs linked with CT-scans, a previous study reveals that the 90-day EOC costs were notably lower for RATKA patients [79]. This indicates that the adoption of this advanced imaging modality does not result in a net increase in overall healthcare costs for patients and payers within this specific context [79].

While the high upfront and maintenance costs of robotic systems remain a key concern, varying funding models and institutional factors influence their economic viability. For instance, Vermue et al. [68] and Rajan et al. [81] used decision-analytic Markov models to demonstrate that RATKA becomes cost-effective at patient volumes of ≥ 24–50 cases/year, emphasizing the impact of annual procedure throughput on per-case costs. Additionally, Hua & Salcedo showed that at a mid-volume hospital (50 RATKA/year), the incremental cost-effectiveness ratio (ICER) was $41,331 per QALY, below commonly accepted willingness-to-pay thresholds [74].

Furthermore, alternative payment approaches—such as leasing agreements, pay-per-case usage, and public–private partnerships—can significantly reduce initial capital burdens and facilitate adoption in lower-volume or resource-constrained settings [82]. Such models allow smaller institutions to integrate robotic platforms without large upfront expenditure, aligning clinical benefits with economic feasibility.

Table 3 presents the advantages and limitations of joint robots and Table 4 provides a practical comparison of Robotic TKA platforms, including imaging needs, Learning Curve, funding models, and Institutional fit.

Challenges and future developments

Robotic knee replacement faces challenges such as high initial costs, ongoing maintenance expenses, and the financial burden of training and consumables, complicating widespread adoption. Additionally, learning curves vary based on surgeons' prior experience, necessitating structured training programs and initial support from manufacturers. Standardizing protocols and regulatory compliance for safety and performance remain a significant hurdles, with robotic systems lacking the clear standards seen in other industries.

Future advancements may focus on integrating advanced imaging technologies, enabling real-time, high-resolution feedback and tactile guidance for improved precision. Artificial intelligence (AI) and machine learning (ML) are poised to revolutionize robotic surgery through predictive models, automated surgical planning, and real-time decision support. Miniaturization of robotic systems, such as the TMINI device, aims to enhance portability, compatibility with surgical workflows, and safety, ensuring efficient deployment in diverse settings. These developments promise to improve procedural accuracy, patient outcomes, and overall system adaptability.

Limitations

This review highlights the potential of RATKA while acknowledging its limitations. The lack of long-term outcome data and limited economic feasibility studies restrict comprehensive evaluation. Variability across robotic systems and the reliance on studies from high-volume centers introduce challenges in generalizing findings to diverse patient populations and routine clinical settings. Furthermore, the review identifies gaps in the representation of regional and demographic-specific healthcare scenarios, particularly in the Indian context, where economic constraints and accessibility issues remain significant barriers to adoption. Another limitation of this review is that it primarily focuses on RATKA and does not explore the growing body of literature related to robotic-assisted unicompartmental knee replacement (RAUKR). Emerging data suggest that RAUKR may offer significant advantages over its manual counterpart in terms of implant alignment, precision, and long-term outcomes. However, a detailed comparison or evaluation of RAUKR systems was beyond the scope of this review and warrants dedicated analysis in future studies.

Strengths

Despite these limitations, the review offers several strengths. It provides a thorough exploration of technological advancements and their impact on surgical precision, patient outcomes, and satisfaction. The focus on India-specific challenges enriches the global understanding of RATKA's applicability in resource-limited settings. By addressing multi-dimensional aspects such as learning curves, cost-effectiveness, and customization, the review serves as a comprehensive guide for healthcare professionals and policymakers. Its critical discussion of current challenges and future directions paves the way for advancing robotic orthopedic surgery.

Conclusions

In conclusion, the challenges faced by robotic joint knee replacement systems encompass financial considerations, the learning curve for surgeons, and regulatory aspects. Future developments may involve advanced imaging integration, AI and ML applications, and efforts to miniaturize and make these systems more portable. These

Table 3 Robotics: advantages and limitations

S. no.	Names	Advantages	Limitations
1.	Digi-Match™ ROBODOC®	Ideal post-operative mechanical alignment through individualization of the distal femoral resection angle; Accurate rotational alignment of the femoral component; Accurate machining of bone surfaces with a milling device; and Good maintenance of bone temperature during machining, preventing bone injury	Planning cannot be adjusted intraoperatively ROBODOC is not equipped with an integrated irrigation system Surgical staff are required on-site to control the robot, provide technical assistance, and rectify intraoperative workspace errors as required Not yet demonstrated to be cost-effective, primarily due to insufficient evidence on long-term implant survivorship
2.	Navio	Provides accuracy and precision Consistent results Accurately placed components Customized planning No CT-scan required	The longer operative time compared to traditional methods, as the system requires detailed pre-operative planning and intraoperative mapping, which can extend the duration of surgery Surgeons using NAVIO face a significant learning curve. The system's complexity requires training and experience to achieve proficiency, which may initially lead to variability in outcomes Unlike some fully autonomous systems, NAVIO is semi-autonomous and relies heavily on the surgeon's input during bone resection, which can limit precision in certain complex cases when compared to fully autonomous robots
3.	MAKO	When the Mako system is activated, surgeons are constrained to the preoperative plan, as the robot prevents bone cutting beyond the defined surgical boundaries. This reduces the risk of human error Blood loss may be minimized due to reduced exposure of unnecessary bone surfaces that could otherwise contribute to bleeding Rehabilitation times tend to be shorter During surgery, the system captures the patient's native joint motion, aiding in the reduction of undue strain on surrounding soft tissues and ligaments	High cost and time-consuming pre-operative planning Surgical time is likely to be slightly longer than with traditional joint replacements, exposing patients to theoretically greater risk of infection
4.	ROSA	Delivers Highly Accurate Resections and Limb Alignment It provides surgeons with enhanced precision and accuracy in bone resections The system incorporates real-time cut values and validation features to ensure accurate alignment during the procedure It provides both image-based and imageless workflows, allowing greater flexibility according to the surgeon's preference Reduced Instrumentation	Any technical malfunctions or system failures during surgery could disrupt the procedure and require quick and effective troubleshooting While the robot enhances precision, surgical outcomes still depend on the surgeon's skills and experience in utilizing the technology effectively The system can be expensive to acquire and maintain, potentially increasing the overall cost of joint replacement procedures
5.	CUVIS Joint Robot-Fully automatic	Bone registration using a probe 3D bone model generation with fast and easy CT image data Reduces the surgery preparation time through 3D modeling Various cutting options—Full & partial cutting Intra-operative gap check—Pre/Intra/Post Real-time system monitoring Emergency stop Manual guide of the robot arm Precise pre-surgical planning is executed every time Sub-millimeter dimensional accuracy and optimal alignment	As a newer technology, there is limited long-term clinical data on the outcomes and longevity of implants placed using the Cuvis Joint system compared to traditional methods or other robotic systems

Table 4 Practical comparison of robotic TKA platforms: imaging needs, learning curve, funding models, and institutional fit

Robot system	Imaging requirement	Learning curve	Supported funding models	Best fit for
Mako	CT-based	7–20 cases	Capital purchase, bundled leasing with service contracts [83]	High-volume centers needing precision and multi-joint support
ROSA	X-ray/imageless	6–11 cases	Direct purchase, institutional funding [44]	Mid- to high-volume public or academic hospitals
CORI	Imageless	6–10 cases	Pay-per-use, lease-to-own models [83]	Small to mid-sized centers with budget flexibility
CUVIS	CT-based	~ 18 cases	Institutional or public–private partnerships (PPPs) [83]	Public hospitals and international markets
MISSO	CT-based + AI	~ 10–15 cases	Institutional funding; flexible regional models (India) [83]	Resource-sensitive environments with growing demand

considerations shape the ongoing evolution of robotic technologies in the field of orthopedic surgery.

For surgeons considering robotic adoption, selecting the appropriate system requires balancing several factors beyond technological sophistication. Key considerations include platform compatibility with preferred implant systems, the degree of robotic assistance (passive, semi-active, or fully active), intraoperative workflow integration, and the availability of structured training. Additionally, cost models—whether capital purchase or pay-per-use—must align with institutional case volumes and financial viability. Image-free systems may offer logistical advantages in lower-resource settings, whereas CT-based systems may provide superior preoperative planning in complex anatomies. Rather than recommending a specific platform, there should be a choice tailored to the surgeon's case mix, experience level, infrastructure, and long-term institutional goals. Such strategic selection is essential to optimize patient outcomes while ensuring sustainable integration of robotic technology into clinical practice.

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Declarations

Conflict of interest Dr. Dolly Singh is a full-time Employee of Meril Healthcare Pvt. Ltd., Vapi, India. All other authors declare no conflict of interest.

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