

ROBOTICS IN TKA: STATE OF THE ART AND FUTURE PERSPECTIVES

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ABSTRACT – Robotic-assisted total knee arthroplasty (RA-TKA) has revolutionized knee replacement surgery, offering the potential for improved surgical precision, implant alignment, and patient-specific outcomes. This narrative review focuses on the current status of RA-TKA, examining the evidence supporting its use, the technological advancements achieved to date, and its integration into clinical practice. While RA-TKA has demonstrated superior accuracy in implant positioning and soft tissue management compared to conventional techniques, its impact on long-term functional outcomes and implant survivorship remains under evaluation. Challenges such as high costs, increased operative times, and the need for specialized training continue to hinder its widespread adoption. Looking to the future, innovations in artificial intelligence (AI), machine learning, and augmented reality (AR) are expected to enhance the capabilities of robotic systems, improving efficiency, personalization, and accessibility. This review emphasizes the importance of ongoing research to address current limitations, optimize workflows, and assess the cost-effectiveness of RA-TKA. By understanding its present applications and future prospects, stakeholders can better navigate the evolving role of robotics in advancing knee arthroplasty outcomes.

KEYWORDS: Total knee replacement, Robotics, Accuracy, Technology, Navigation.

INTRODUCTION

Knee osteoarthritis (OA) is a significant public health issue, affecting a considerable portion of the adult population, particularly the elderly. It impacts approximately 10-15% of the general adult population, with prevalence rising sharply in individuals over the age of 60, where it can affect up to $30-40\%^{1,2}$.

Total knee arthroplasty (TKA) is a widely used and effective solution for treating knee OA, significantly improving pain relief and joint function for many patients^{3,4}. However, patient satisfaction continues to be a concern, with reported satisfaction rates varying between 82% and 89%^{5,6}.

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To overcome the issue of patient dissatisfaction and the perception of an "unnatural knee" after TKA, various alignment options and surgical philosophies have been developed to better replicate natural knee anatomy and kinematics^{7,8}.

In response to the need for more personalized and precise implant positioning to better replicate natural knee anatomy and kinematics, technologies such as navigation systems and robotic-assisted surgery have emerged⁹.

The purpose of this review is to provide an in-depth analysis of the current state of robotic-assisted surgery in total knee arthroplasty, examining its advancements, clinical outcomes, and limitations. Additionally, it will explore future perspectives and potential innovations in the field, aiming to highlight how robotics can further enhance precision, personalization, and patient satisfaction in knee replacement surgery.

HISTORY OF ROBOTIC TECHNOLOGIES

The evolution of technology in total knee arthroplasty (TKA) in order to enable surgeons to achieve more accuracy and precision began with the introduction of computer-assisted surgery (CAS), specifically navigation systems, in the late 1990s¹⁰. Navigation technology aimed to improve the accuracy of implant placement by providing real-time feedback on alignment and positioning¹¹. Surgeons could use this data to make adjustments during the procedure, which helped reduce errors compared to traditional, manual methods¹². Although navigation systems enhanced precision and improved surgical outcomes, the majority of studies in the literature agree that navigation has not resulted in significant clinical advantages in terms of mid-to-long-term outcomes or patient satisfaction, despite its role in improving alignment accuracy^{13,14}.

Building on the principles of navigation, robotic-assisted surgery was developed in the early 2000s, marking a significant advancement in TKA^{15,16}. Unlike navigation, robotic systems offered not only guidance but also physical assistance during surgery, using robotic arms to perform bone cuts and implant positioning with millimetric precision. These systems also facilitated improved soft tissue balancing and coronal alignment, addressing key factors in long-term implant success^{17,18}.

IMAGE-BASED VS. IMAGELESS ROBOTIC SYSTEMS

Robotic-assisted TKA uses computer software to create a virtual three-dimensional (3D) model of the patient's specific bony anatomy, enabling the surgeon to pre-plan bone cuts, component size, and positioning⁹. This surgical plan is then mapped intraoperatively to the patient's anatomy using navigational software.

In image-based systems, the 3D model is generated from preoperative imaging, such as computed tomography (CT) or magnetic resonance imaging (MRI)^{19,20}. These systems provide the advantage of detailed preoperative planning, including implant size and orientation selection, but come with increased costs and the risk of additional radiation exposure^{21,22}.

In contrast, imageless systems generate the surgical plan intraoperatively by capturing detailed registration of the bony surfaces and joint kinematics after arthrotomy^{23,24}. While imageless systems avoid the need for preoperative imaging, they rely on the accurate intraoperative registration of bony landmarks by the surgeon, making them more susceptible to human error. Thus, both approaches have their strengths and limitations, balancing the precision of preoperative planning against the real-time adaptability and potential inaccuracies introduced during surgery.

Passive, Semi-Active, Active Robotic Systems

Passive robotic systems have seen limited adoption in total knee arthroplasty (TKA) due to their reliance on computer-assisted or navigation technology that provides visual guidance to the surgeon through an overhead display²⁵. These systems allow for surgical planning, but the execution of the procedure depends heavily on the surgeon's manual input throughout the operation and therefore still carries the risk of human error. Furthermore, they lack haptic feedback mechanisms, meaning there are no physical restraints to ensure precise bone preparation or implant positioning^{26,27}.

As a way to overcome, semi-active and fully active robotic systems have been proposed in order to provide more refined control and improved precision in TKA procedures.

Semi-active systems, in particular, allow the surgeon to guide the robotic arm while performing bone preparation²⁸.

Active robotic systems create the surgical plan offline based on preoperative CT scans and during the operation function autonomously, under the surgeon's supervision, without requiring continuous real-time guidance²⁹. After the surgeon completes the initial approach, protects the soft tissues, and attaches the limb to a fixed device, the robotic arm is activated to independently perform the bone resections^{30,31}.

Open/Closed Systems

The terms "open" and "closed" platform refer to whether the system allows the flexibility to select any type of prosthesis for implantation or is restricted to a specific proprietary prosthesis. The primary advantage of open platforms is the compatibility with a wide range of implant designs from different manufacturers, offering greater flexibility in selecting implants that best suit the patient's needs³². However, this versatility comes with a downside: the lack of implant design specificity and limited biomechanical data to optimize implant positioning. As a result, outcomes may be predictable and more dependent on the type of prosthesis³².

On the other hand, closed platforms provide more detailed biomechanical data and precise implant positioning for the specific prostheses they support. In this case, the downside is their restrictiveness, offering compatibility only with specific implant models³³. This limits the surgeon's options, as they may need to use implants tied to the platform rather than their preferred designs and this reduces the freedom of choice for the surgeon^{34,35}.

Robotic Systems

Several robotic platforms are available for TKA, each offering different approaches to enhancing surgical precision, implant positioning, and alignment. These systems vary in their reliance on preoperative imaging, real-time intraoperative adjustments, and the level of surgeon control vs. robotic automation³⁶.

Below are brief descriptions of the most prominent robotic systems used in TKA today:

- ROBODOC (THINK Surgical Inc., Fremont, CA, USA) is an active, image-based, open system. First developed in 1992 and now marketed as TSolution-One by Think Surgical Inc. (formerly Curexo Technology), this system is image-guided (using CT scans), fully autonomous (requiring no surgeon intervention), and features an open platform compatible with any implant. Despite its advanced capabilities, adoption of fully active robotic TKA systems has been limited due to the high cost of installation and the elevated risk of complications during the learning phase²⁵.
- Mako (Stryker, Mako Surgical Corp., Fort Lauderdale, FL, USA) is a semi-active, image-based closed system. It is a platform that uses preoperative CT imaging to create a 3D model of the patient's anatomy to guide bone resection, implant sizing, and positioning³⁷. Once bony landmarks are registered and validated, the system generates a digital model of the knee. It also enables intraoperative adjustments to component positioning, using patient-specific alignment and ligament balancing data, before finalizing the bone resection. This semi-active robotic system halts the saw if bone resection deviates from the preoperative plan's predefined parameters within 0.5 mm of the planned surgical cuts³⁸.
- ROSA (Zimmer Biomet, Warsaw, IN, USA) represents a semi-active image-dependent or imageless, closed system²³. One approach involves creating a 3D virtual model by combining data from preoperative X-rays with surface landmarks registered intraoperatively, reducing errors from inaccurate data. X-rays are cheaper, expose patients to less radiation, and avoid additional visits compared to CT scans. Alternatively, a second method relies solely on intraoperative landmark registration for 3D modeling, decision-making, and resection planning, offering comparable accuracy without preoperative imaging. Once the planning phase is completed, the surgeon is enabled to perform with a manual saw the femoral and tibial cuts thanks to the robotic arm, which positions a cutting block according to the surgeon's preference for bone preparation. Furthermore, another feature of the robot is the validation tool, which can be applied to the prepared surfaces to ensure the resections align with the surgical plan³⁹.

- CORI (Smith & Nephew, Inc., Memphis, TN, USA) is a semi-active imageless closed system⁴⁰. Intraoperatively, a probe is used to map the bony anatomy of the distal femur and tibia. The system allows the surgeon to operate with a handheld robotic burr on a sculpting tool, which automatically slows down or retracts if it deviates from the boundaries of the surgical plan. Although the burr can be used to complete all bone preparation, most surgeons opt for a hybrid approach in primary TKA. This involves using the robotic tool to create holes for standard cutting jigs, after which a bone saw is manually used to prepare the femur and tibia⁴¹.
- VELYS robotic-assisted solution (VRAS) (Depuy, Warsaw, IN, USA) is a semi-active, imageless, closed system. It represents one of the latest innovations in robotic technology for total knee arthroplasty. As an imageless system, VRAS does not require preoperative CT scans, with a consequent reduction in preparation time, costs, and radiation exposure for the patient. This robotic system is closed and, therefore, exclusively the ATTUNE Knee System by DePuy Synthes can be used, which is a widely used knee implant that enables precise and well-informed decision-making during surgery. In literature, early studies have shown promising outcomes for VRAS in TKA, indicating its potential value in improving surgical accuracy and patient outcomes⁴².
- The SkyWalker[™] robotic arm system (model OSR-1000, developed by MicroPort OrthoBot Co. Ltd. in Suzhou, China) is a semi-active, imageless, closed platform primarily derived from the technology of the Robodoc and MAKO systems. Created by Chinese researchers, this new robotic device aims to deliver safety, efficiency, and precision in minimally invasive settings. However, the effectiveness of this innovative robotic technique still requires more in-depth research for full evaluation⁴³.

The details of the different robotic systems are summarized in Table 1.

FUNCTIONAL ALIGNMENT AND IMPLANT POSITIONING

Functional alignment (FA) is regarded as an evolution of the traditional kinematic alignment (KA) method, made possible by advancements in robotic technology⁴⁴. This approach aims to restore the natural obliquity of the joint line and balance the knee flexion-extension gap through precise adjustments of the tibial and femoral components, thereby minimizing the need for soft tissue releases⁴⁵. The integration of robotic systems is essential for accurately assessing implant position, resection thickness, joint gaps, and limb alignment during surgery.

In functional alignment, the femoral component is adjusted in the coronal plane from a starting point of 0° to the mechanical axis to ensure appropriate balancing between the medial and lateral

Table 1. Main features of robotic systems used in joint arthroplasty.			
Robotic system	Active/ semi-active	Imageless/image- based system	Open/ closed systemy
ROBODOC (THINK Surgical Inc., Fremont, CA, USA)	Active	Image-based	Open
Mako (Stryker, Mako Surgical Corp., Fort Lauderdale, FL, USA)	Semi-active	Image-based	Closed
ROSA (Zimmer biomet, Warsaw, IN, USA)	Semi-active	Image-based or Imageless	Closed
CORI (Smith & nephew, Inc., Memphis, TN, USA)	Semi-active	Imageless	Closed
VELYS robotic-assisted solution (VRAS) (Depuy, Warsaw, IN, USA)	Semi-active	Imageless	Closed
SkyWalker™ (model OSR-1000, developed by MicroPort OrthoBot Co. Ltd. in Suzhou, China)	Semi-active	Imageless	Closed

compartments. In the sagittal plane, the component is positioned to prevent femoral notching while adhering to the natural bowing of the bone. The axial alignment of the femoral component is typically determined based on the posterior condylar axis (PCA) by the robot. Moreover, conventionally, femoral orientation is also assessed in relation to the transepicondylar axis (TEA), which is considered a more anatomical reference for rotational alignment. The combined use of these two landmarks helps optimize the positioning of the femoral component, reducing the risk of malrotation and improving the ligamentous balance of the implant.

Meanwhile, the tibial component is positioned to restore the natural inclination of the joint line in both the coronal and sagittal planes, avoiding a valgus position. Minimal adjustments to the tibial positioning may also be incorporated to further refine the balance of the knee^{46,47}.

Robotic-assisted total knee arthroplasty has shown significant advantages over manual TKA in terms of precision in component positioning in the coronal, sagittal, and axial planes⁴⁸. The higher precision in sagittal plane positioning allows for more accurate gap balancing, a critical factor in achieving optimal knee function and longevity after surgery.

Rossi et al⁴⁹ demonstrated that the ROSA Knee System enables high accuracy in bone resections during total knee arthroplasty, with deviations from planned surgical angles consistently under 1 mm or 1 degree, confirming its precision in implant positioning⁴⁹. Moreover, the ROSA Knee System's potential to individualize implant alignment during total knee arthroplasty has been highlighted. By leveraging robotic assistance, the system enables precise, patient-specific alignment in three dimensions, optimizing ligament balancing and implant positioning^{47,50}.

As compared to image-less navigation systems, Mancino et al⁵¹ compared a novel image-less robotic-assisted total knee arthroplasty with an established image-less navigated technique to assess implant positioning accuracy. Their retrospective analysis of 172 cases showed that the robotic technique achieved significantly smaller deviations from target angles for femoral and tibial components compared to navigation, particularly in femoral flexion and tibial alignment. This suggests that robotic total knee arthroplasty offers enhanced precision in implant positioning without increasing alignment outliers⁵¹.

In terms of coronal alignment, Kayani et al⁵² have demonstrated that the femoral and tibial components, as well as tibial slope, in robotic TKA showed a closer alignment with the surgical plan as compared to manual TKA⁵². Also, the posterior condylar offset ratio (PCOR) showed significantly smaller differences between pre- and post-operative values in robotic TKA compared to manual TKA, as demonstrated by Sultan et al⁵³.

Moreover, Mahoney et al⁵⁴ found that using robotic-assisted TKA led to greater precision in the external rotation of the femoral component relative to the transepicondylar axis, though this improvement was not statistically significant⁵⁴.

FUNCTIONAL OUTCOMES

While improved alignment and positioning are critical, the relationship between these factors and clinical outcomes remains complex⁵⁵.

Despite the theoretical advantages of RA-TKA, there is considerable variability in outcomes reported across studies. Factors such as the degree of preoperative deformity, individual patient anatomy, and the specific robotic platform used can influence results.

One advantage of functional alignment in RA-TKA is the restoration of the patient's native phenotype by enabling more precise component positioning and alignment. Studies⁵⁶ suggest that robotic systems enhance the replication of pre-arthritic knee alignment, optimizing joint balance. This improved restoration of the native phenotype has been associated with better functional outcomes, including more natural gait patterns and improved range of motion^{57,58}.

Many studies^{59,60} have concluded that early post-operative outcomes in terms of pain and length of hospital stay are more favorable in RA-TKA. However, literature⁶¹⁻⁶³ agrees in concluding that there is no statistically significant superiority in long-term functional outcomes measured with PROMs.

To gain a clearer understanding of the clinical improvements associated with robotic-assisted knee arthroplasty, further studies are necessary that consider all these variables. By examining a broader range of factors influencing outcomes, future studies may be able to better identify the conditions under which robotic assistance can truly enhance patient satisfaction and clinical results.

COMPLICATIONS AND REVISION RATES

Earlier robotic systems were associated with a high rate of complications. Park and Lee⁶⁴ reported a complication rate of 19%, which included issues such as superficial infection, patellar tendon rupture and dislocation, supracondylar fracture, and peroneal nerve injury. However, these complications seemed to occur mainly in the early cases, likely due to the use of smaller incisions during the learning phase³⁶. After larger incisions were adopted, these issues were avoided. Technical failures were also noted, with intra-operative conversion to traditional total knee arthroplasty (TKA) due to technical issues with the ROBODOC system occurring in up to 30% of cases⁶⁵.

Newer robotic systems have reduced the rate of complications, but some issues are still to be debated. Mechanical weakness from pinholes in robotic total knee arthroplasty (TKA) can lead to feared complications such as femoral or tibial shaft fractures. A study⁶⁶ found that the incidence of pin-site femoral fractures was 1.4%, typically occurring around 12.6 weeks post-surgery, often preceded by unusual thigh pain. These fractures usually result from minor trauma and are treated with intramedullary fixation. To mitigate this risk, it has been suggested to place pins in periarticular areas, which are more resilient to stress, and to use smaller pins⁶⁷. Pin-site infections are another concern, although their overall incidence is low, at approximately 0.47%⁶⁸. Other iatrogenic injuries may include patellar tendon ruptures, patellar dislocations, fractures, and peroneal nerve injuries³⁶. While some studies^{52,69} suggest robotic TKA is associated with fewer injuries compared to conventional methods, others indicate a higher incidence of iatrogenic injuries with active robotic systems. Additionally, robotic procedures tend to result in greater estimated blood loss, potentially due to longer operative times. However, robotic TKA does not require opening the femoral canal, which could theoretically reduce blood loss. Robotic systems are designed to decrease post-TKA stiffness through precise alignment, but the literature⁷⁰ has reported stiffness as a complication following robotic TKA. The present review highlighted that longer surgical times are a consistent issue with robotic systems, which can increase the risk of infection, particularly when surgical time exceeds 120 minutes. Recent reviews^{71,72} found a higher incidence of deep prosthetic joint infections with robotic TKA (1.6-1.7%) compared to conventional methods (0.44-1.0%).

There is limited data on the rate of deep prosthetic joint infection (PJI) in robotic TKA. The most recent studies^{73,74} in the literature concluded that the use of robotics in TKA is not associated with a higher rate of PJI in the early post-operative phase.

Learning Curve

The learning curve typically refers to the number of cases required to achieve consistent outcomes. In the context of robotic total knee arthroplasty (TKA), this often includes evaluating the reduction in surgical time. Literature agrees that the learning curve for robotic TKA varies from 10 to 50 cases^{75,76}. Importantly, these studies found no increased risk of complications during the learning phase associated with the current robotic technology⁷⁷. This marks a significant improvement over earlier systems, which reported high early complication rates and increased soft tissue damage during their learning phases, including injuries to the patellar tendon due to inadequate surgical exposure.

COSTS AND ECONOMIC IMPACT

One of the most critical aspects of integrating robotics into knee prosthetic surgery is the financial burden it imposes on healthcare systems⁷⁸. These costs can significantly impact the accessibility and scalability of robotic-assisted surgeries, raising important questions about cost-effectiveness, reimbursement policies, and the balance between the clinical advantages and financial feasibility for both hospitals and patients⁷⁹.

The cost-effectiveness of robotic-assisted total knee arthroplasty has become a focal point of discussion as healthcare systems weigh the benefits of advanced technology against its financial implications. According to Vermue et al⁸⁰ procedures, robotic-assisted total knee arthroplasty becomes cost-effective when the annual case volume exceeds 253 procedures. While the initial investment in robotic systems is substantial, these high upfront costs can be mitigated by long-term savings⁸¹. Faster recovery times, shorter hospital stays and decreased post-acute care needs, such as fewer nursing services and less postoperative therapy, are all key contributors to lowering overall healthcare expenses. Additionally, patients undergoing RA-TKA often require less inpatient therapy and are discharged more quickly, further enhancing the financial benefits for hospitals and healthcare systems. Savings are ultimately driven by fewer readmissions, reduced reliance on rehabilitation services, and a more efficient postoperative care pathway⁸².

While robotic-assisted knee arthroplasty offers several economic advantages, it is important to consider the significant additional costs that come with adopting this technology. These include expenses for specialized software, routine equipment maintenance, and disposable surgical tool⁸³. Additional diagnostic imaging, such as preoperative CT or MRI scans, is often required, further increasing costs. Medical staff also require extensive training to use the technology effectively, adding to the financial burden⁸⁴. Moreover, other indirect costs, such as longer setup times and the need for extra personnel during procedures, contribute to the overall increase in operational expenses⁸⁵.

Literature agrees that robotic TKA can be cost-effective, particularly in elevated-risk patient populations (e.g., younger patients, higher BMI, male sex) and larger practice settings, where the reduction in revision risk and associated quality-adjusted life year (QALY) gains justify the additional costs⁸⁶. However, achieving cost-effectiveness depends on factors such as surgical precision, patient selection, and local economic conditions, emphasizing the importance of a risk-prioritized approach to optimize resource utilization⁸⁷.

FUTURE PERSPECTIVES

As a future perspective in robotic surgery, we can explore immersive virtual reality (IVR), augmented reality (AR), and mixed reality (MR), such as the spectrum of extended reality technology integration, representing the intersection between advanced computing and imaging and their use in the operating room environment^{88,89}. IVR also serves as an excellent teaching tool, providing surgical trainees of all levels access to a variety of techniques that accurately replicate real-life procedures without additional risks to the patient, costly resources (e.g., cadavers) or even the need for supervision⁹⁰. AR-based navigation technologies have been shown to improve the accuracy of component positioning in hip and knee arthroplasty and MR allows even more freedom of control over CT reconstructions for preoperative planning as well as intraoperative visualization, requiring less preoperative calibration by the surgeon because the data can be adjusted intraoperatively by the surgeon^{91,92}. The application of machine learning (ML) in KA has been useful for predicting implant size, reconstructing data, and assisting with component positioning and alignment; it enhances surgical precision and can help predict patients' outcomes^{93,94}. Al can handle very large, complex datasets and generate predictions and decisions on KOA and TKA⁹⁴. ML potentially improves surgical precision and reduces the cost of manual labor. Regarding value metrics, ML methods have been used to predict the length of hospital stay, hospitalization charges, and discharge disposition. It impacts the economic burden of TKA and thus potentially affects decisions on payment models in healthcare settings⁹³.

Those technologies have some current limitations, including: first, accuracy and generalizability are key obstacles, as very few models have been externally validated, and high AUC values do not necessarily translate to good clinical performance⁹⁵. Second, a practical disadvantage of machine learning models is the need for large datasets to train them. These datasets often contain millions of unique data points and require hours or days of training, and additional datasets are needed to assess generalizability⁹⁶.

Third, a common concern about the use of artificial intelligence is the "black-box" nature of machine learning models. Machine learning algorithms' decision-making processes are complex, using hidden layers and unknown connections between inputs and outputs, resulting in poor understanding and difficult scientific interpretation of how they generate predictions and recommendations⁹⁷.

We can also explore their use in revision surgery that may be helpful for a reproducibly preoperative plan, contribute to accurate bone cuts and preserve more bone stock, and precise positioning of the final implant in revision total joint arthroplasty (TJA). For RA-TKA, the benefits mainly include accurate bone cutting and the ability to evaluate the type of alignment and mechanical alignment, which is often a challenge due to the loss of bony reference points after implant removal⁹⁸.

In a recent study, Leung et al⁹⁹ developed a deep learning model to predict the need for TKA directly from knee radiographs. This model outperformed traditional binary outcome models that rely on the Kellgren-Lawrence or Osteoarthritis Research Society International grades. The deep learning models incorporated additional image-based information that may not be captured by simple numerical grad-

ing systems. Therefore, further studies can be conducted to analyze the interaction between all these systems.

Further studies are needed to evaluate improvements in patient satisfaction and component survival for revision robotic-assisted TKA surgeries. We also need to evaluate the cost related to the robotic-assistance arm software and conduct further studies to determine whether the cost of obtaining the software is mitigated by the cost of the revision surgery¹⁰⁰.

Another important issue that has been increasingly addressed in the most recent literature is the proper management of the patella and anterior space in TKA to avoid patellofemoral joint imbalance, including overstuffing and understuffing. Functional alignment, combined with robotic assistance, allows for optimized femoral component positioning and better preservation of native knee kinematics¹⁰¹. Shatrov et al¹⁰² analyzed 122 robotic-assisted TKAs using functional alignment principles and found that while the trochlea was always balanced in full extension, over 40% of cases were over- or under-stuffed in mid and deep flexion. Under-stuffing was more common in mid-flexion, while over-stuffing predominated in deep flexion. The study highlights the need to redefine patellofemoral joint (PFJ) over- and under-stuffing across the full range of motion and further investigate its biomechanical and clinical implications¹⁰².

DISCUSSION

This article emphasizes that robotic-assisted surgery represents a significant advancement over traditional methods, primarily by improving the precision of implant placement and soft tissue balancing. This precision is crucial for obtaining optimal outcomes; for example, misalignment can lead to complications and decreased longevity of the implant. However, the interpersonal variability of patients' satisfaction and long-term functional outcomes suggests that while the technology offers improved accuracy during surgery, it does not automatically lead to better clinical results. Despite reported satisfaction rates of 82-89%, literature states a lack of statistically significant superiority in long-term outcomes when comparing robotic-assisted TKA to conventional techniques^{98,100,103}. This gap raises questions about the factors influencing patient satisfaction beyond surgical precision and highlights the complexity of the surgical experience, which may vary from preoperative expectations, postoperative recovery, individual patient anatomy, and functional requests. Future research should aim to explore these dimensions more exhaustively. Surgeon training and the learning curve of the robotic-assisted technologies are crucial, and this can significantly impact patient safety⁷⁷.

Future developments in robotic surgery will include the integration of artificial intelligence and machine learning^{88,91}. These advancements could facilitate preoperative planning and intraoperative decision-making, potentially leading to even greater improvements in surgical outcomes. However, as these technologies evolve, ongoing research will be necessary to rigorously assess their efficacy and safety.

CONCLUSIONS

Robotic TKA enhances resection accuracy, implant alignment, and joint balancing, potentially lowering revision rates. It may also reduce overall healthcare costs by shortening hospital stays, decreasing therapy needs, and lowering readmission rates; however, further studies are needed to confirm these cost savings.

Despite improved radiological outcomes, RA-TKA has not yet shown superior long-term functional results compared to conventional TKA. Its limitations include high software and hardware costs, additional radiation exposure with image-based platforms, and longer operative times during the learning curve.

Future advancements may integrate extended reality, artificial intelligence, deep learning, and machine learning to enhance preoperative planning, intraoperative guidance, and surgical precision. Further research is essential to justify continued investment in robotics, ensuring long-term benefits and supporting the integration of emerging technologies in TKA.

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The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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The authors declare no conflict of interest related to the present study. FB and SMPR declare a consulting contract with Zimmer Biomet.

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Not applicable.

AUTHORS' CONTRIBUTIONS:

SMPR conceptualized the study; AM and MA conducted the research; LA and RS contributed to manuscript drafting; AM and MA wrote the manuscript; SMPR and FB reviewed and revised the final version.

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