

## Robot-Assisted Total Knee Arthroplasty: A Literature Review of Accuracy, Complications, Cost-Effectiveness, and Clinical Outcomes

Deria Zahra Fatihah<sup>1\*</sup>, Juniarto Jaya Pangestu<sup>2</sup>, Norman Zainal<sup>3</sup>

Universitas Yarsi, Indonesia

Email: deriazahra.fatihah@gmail.com\*

---

### ABSTRACT

---

#### Keywords:

Knee Osteoarthritis, Total Knee Arthroplasty, Robotic TKA, RA-TKA, Conventional TKA, Accuracy, Complications, Cost-Effectiveness

Background: Conventional Total Knee Arthroplasty (C-TKA) still faces challenges with high patient dissatisfaction rates, often linked to malalignment. Robot-Assisted TKA (RA-TKA) was developed to improve surgical precision. Despite its rapid adoption, there are conflicting findings regarding its advantages over C-TKA, along with concerns about cost and the learning curve. Objective: This literature review aims to comprehensively analyze and compare RA-TKA with C-TKA, focusing on four domains: (1) surgical accuracy and alignment; (2) complication rates; (3) cost-effectiveness; and (4) clinical outcomes. Findings: The review found that RA-TKA consistently demonstrates superior accuracy in restoring the mechanical axis (HKA) and coronal alignment, significantly reducing the number of outliers. RA-TKA also facilitates dynamic soft tissue balancing. However, findings regarding sagittal plane accuracy (e.g., tibial slope) remain contradictory across different robotic platforms. RA-TKA consistently requires longer operative times, especially during the learning curve, and introduces new technical risks such as pin failure and pin-site fractures. While the risk of major complications (e.g., PJI) is comparable, RA-TKA shows a lower risk of postoperative stiffness (arthrofibrosis). Evidence on mid-term revision rates remains inconclusive. Cost-effectiveness analysis shows that the high initial capital cost necessitates a very high procedural volume to achieve cost efficiency. Conclusion: RA-TKA offers clear advantages in coronal alignment precision but is offset by high costs, longer operative times, and specific robotic complications.

---

### INTRODUCTION

Knee Osteoarthritis (KOA) is a common chronic articular disease, characterized by high morbidity and disability that burdens public health (Pavlidis, 2023; Sittlington & Harvey, 2018). As the population ages, the prevalence of KOA continues to increase (Geng et al., 2023). For end-stage degenerative knee osteoarthritis patients who no longer respond to conservative therapy, Total Knee Arthroplasty (TKA) is a highly effective surgical procedure to relieve pain and restore function (Varacallo et al., 2025). As a result, the demand for primary procedures continues to increase exponentially (Guo et al., 2025), with the volume continuing to increase every year (Varacallo et al., 2025).

Although conventional TKA (C-TKA) has shown good long-term results, significant challenges remain. C-TKA relies heavily on manual instrumentation and surgeon expertise to achieve precise implant placement (Mostafa et al., 2025). These limitations pose challenges in achieving consistent optimal component alignment, where malalignment has been shown to correlate with suboptimal functional outcomes, increased wear, and potential for premature

implant failure (Mostafa et al., 2025). This uncertainty in accuracy and reproducibility (Fan et al., 2025) is believed to contribute to the still high rate of reported patient dissatisfaction, which reaches 30% (Canovas & Dagneaux, 2018).

To overcome these limitations, Robotic-Assisted Surgery (RAS) technology has been adopted in orthopedic surgery to improve precision (Guo et al., 2025). Modern orthopedic robotic systems are classified as autonomous (active), semi-autonomous (semi-active), or teleoperated (Fan et al., 2025). These systems are also differentiated based on imaging navigation needs: some are CT-based that require pre-operative 3D planning (e.g. MAKO), while others use imageless technology that relies on intra-operative anatomical registration (e.g. ROSA, Navio, CORI) (Fan et al., 2025). The implementation of Robot-Assisted TKA (RA-TKA) is based on the potential to improve accuracy, precision, facilitate reproducibility, and reduce the variability of surgical techniques (Fan et al., 2025). RA-TKA specifically aims to improve alignment (Mostafa et al., 2025).

Although early studies have shown that RA-TKA can reduce complication rate (CR) and are superior in alignment accuracy (Daoub et al., 2025), the existing literature still presents conflicting findings (Mostafa et al., 2025). In addition, comprehensive evaluations of long-term outcomes are still scarce (Guo et al., 2025), and there are concerns about the learning curve, increased operating time, and cost-effectiveness (Zhang et al., 2025). Given the rapid clinical adoption of RA-TKA, there is a critical need for high-quality evidence synthesis. Therefore, this literature review is important to systematically evaluate the latest evidence. This review aims to comprehensively analyze and compare RA-TKA with conventional C-TKA techniques. The analysis will focus specifically on four critical domains: (1) surgical accuracy, especially mechanical alignment and component placement precision; (2) the number of perioperative and postoperative complications; (3) cost-effectiveness related to technology acquisition; and (4) short- and medium-term clinical outcomes, including patient-reported functional outcomes (PROMs) and recovery (Daoub et al., 2025).

The urgency of this research is underscored by the growing global need for knee arthroplasty, especially in aging populations. As RA-TKA continues to be adopted in clinical practice, understanding its comparative benefits and drawbacks is critical to informing healthcare policy and surgical practice. This study seeks to fill the gap in the literature by conducting a detailed comparison between RA-TKA and C-TKA, focusing on key factors such as surgical accuracy, complication rates, cost-effectiveness, and clinical outcomes.

This research will contribute to the ongoing discourse on RA-TKA by providing updated, evidence-based insights that can guide surgical practices and policy decisions. The findings aim to clarify whether the substantial initial and operational costs of RA-TKA are justified by improved patient outcomes and long-term savings. Moreover, by exploring the learning curve associated with robotic-assisted surgery, the study will address practical concerns related to the technology's integration into routine clinical workflows.

The objective of this study is to systematically evaluate and compare the outcomes of RA-TKA and C-TKA, providing a clearer understanding of the benefits and limitations of robotic assistance in knee arthroplasty. Ultimately, this research aims to provide actionable recommendations for healthcare providers and policymakers, ensuring that resources are allocated efficiently while optimizing patient outcomes.

By assessing the cost-effectiveness and clinical outcomes of RA-TKA versus C-TKA, this study will offer valuable insights for hospitals and healthcare systems considering the adoption of robotic technologies in orthopedic surgeries. The expected benefits include a reduction in long-term revision rates, a decrease in postoperative complications, and improved patient satisfaction, which will have a significant impact on the quality of care provided to knee osteoarthritis patients.

## **METHOD**

This literature review was conducted by systematically searching PubMed and Google Scholar databases for studies related to Robot-Assisted Total Knee Arthroplasty (RA-TKA) and Conventional Total Standardization (C-TKA). The search period is focused on publications between 2020 and 2025 to ensure up-to-date coverage of the literature. The keywords used included "robot-assisted TKA," "conventional total knee arthroplasty," "surgical accuracy," "complications," "cost-effectiveness," and "clinical outcomes." Inclusion criteria include observational studies, clinical trials, and meta-analyses that explicitly compare RA-TKA with C-TKA. Studies that do not present direct comparisons, non-English studies, and for which the full text is not available are excluded from the analysis. Data were systematically extracted and qualitatively analyzed to synthesize findings related to the four main domains of this review.

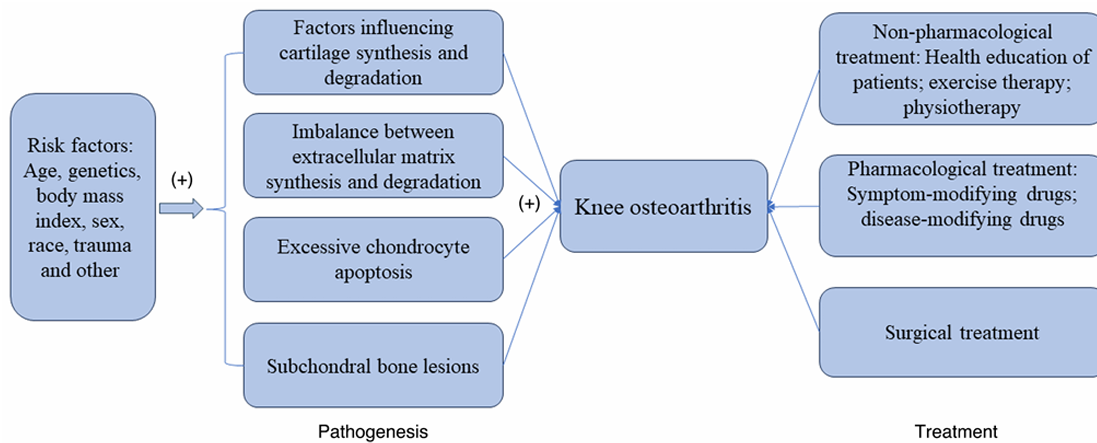
Several important limitations were found in this review. Heterosubpopulation of patients with specific clinical conditions and comorbidities that are comprehensive and limiting generalization of outcomes. In addition, the lack of high-quality long-term data makes it difficult to conclude about implant survival and the long-term effects of RA-TKA. Publication bias is also a potential error, as studies with negative or neutral results may be underreported. Finally, differences in robotic technology between platforms can produce diverse results and limit the universal application of the findings.

## **RESULT AND DISCUSSION**

### **Robot Assisted-TKA**

#### **Definition of Robot-Assisted Surgery (RAS)**

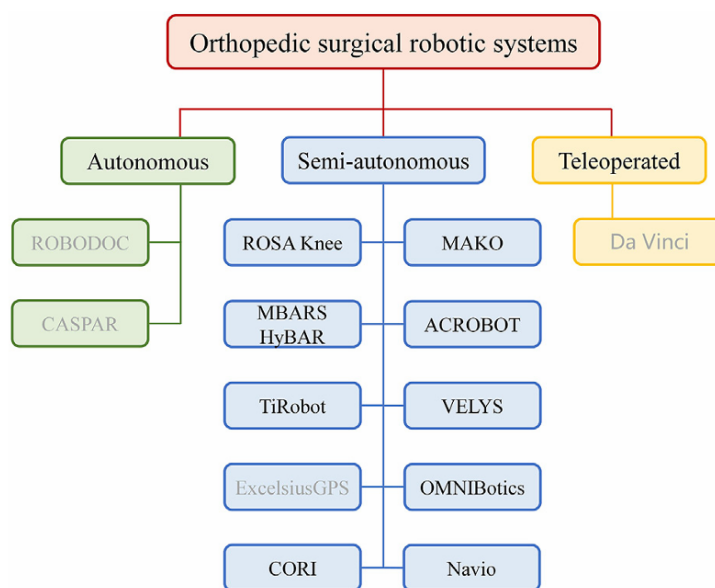
Robot-Assisted Surgery (RAS) in orthopaedics, especially in the context of Total Knee Arthroplasty (TKA), is a significant evolution of minimally invasive surgery (MIS) (Rivero-Moreno et al., 2023). This technology is defined as a surgical procedure in which advanced robotic systems which integrate medical science, robotics, and engineering (Rivero-Moreno et al., 2023) are used to assist surgeons. Its main objective is to improve control, flexibility and precision of movement within narrow anatomical spaces or during complex procedural steps, beyond what is possible to achieve with traditional techniques (Biswas et al., 2023). In TKA, the role of RAS has evolved from being a mere ancillary tool to an important technology that not only improves surgical precision but also enables intraoperative individualization (Burger et al., 2025). The system is designed to address fundamental surgical challenges by improving accuracy, minimizing inter-operator variability, and enabling customization of surgical planning (Kholinne et al., 2025). Its key benefits include the ability to filter out the surgeon's natural hand tremors and minimize accidental inaccuracies (Rivero-Moreno et al., 2023).



**Figure 1. Pathogenesis and Management of Knee Osteoarthritis 1**

It is important to understand that current robotic systems, such as those used in TKA, are not designed to act independently or replace surgeons (Rivero-Moreno et al., 2023). Instead, they serve as remote extensions that are fully controlled by experts

surgeons, often portrayed as master-slave manipulators. The fundamental difference between RAS and non-robotic computer-assisted surgery (CAS) lies in the execution aspect. While traditional CAS (often referred to as navigation) focuses on providing visual guidance or digital maps, RAS actively participates in the physical execution of the task. RAS is part of a larger umbrella of computer-integrated-surgery (CIS), which leverages patient-specific information and imaging to revolutionize planning and execution. CAS provides a 'map', while RAS provides a physical 'guided vehicle' or 'boundary guard'. Technically, RAS systems can be classified as tele-surgical robots (in which the surgeon in the master console controls the slave's robotic arm), image-guided robots (which can perform autonomous or semi-autonomous tasks such as bone milling based on image guidance), or cooperative (hands-on) robots (where the surgeon holds the device directly, and the robot provides stability or active restraint) (Biswas et al., 2023).



**Figure 2. System categories of RAS in Orthopaedics 5**

## Types of Robotic Systems in Foreign Workers

These various technical approaches result in different types of robotic systems used in TKA, which can be further classified based on their Level of Autonomy (LoA) as well as their dependence on imaging. Active robots exhibit a high degree of autonomy, where the machine physically performs preprogrammed tasks, such as bone cutting, while surgeons supervise (Biswas et al., 2023). The MAKO (Stryker) system, which is described as a semi-autonomous, robotic-arm-assisted (Burger et al., 2025) system, and the ROSA (Zimmer Biomet) system are prime examples. Here, the surgeon holds a cutting instrument (such as a saw blade), and the robotic arm provides tactile feedback or physical restraint (Ejnisman et al., 2024), actively preventing cuts beyond predetermined limits. CT-based systems, such as MAKO and ROSA, require pre-operative CT scans to create detailed 3D plans (Ejnisman et al., 2024). The OMNIBotics (Corin) system uses imageless bone morphing technology to build intraoperative 3D models (Biswas et al., 2023). Similarly, the Cori Surgical System (Smith & Nephew) does not require pre-operative drawings; instead, surgeons use an optically tracked tool to 'paint' or map bone anatomy in real-time in the operating room, which the system then uses to create a 3D plan (Biswas et al., 2023). Solution One also relies on preoperative CT imaging for its TPLAN workstations. This reliance on CT allows for highly accurate planning before surgery begins. Instead, imageless systems were developed to eliminate the need for pre-operative CT scans, which could potentially reduce the cost and exposure to radiation. The OMNIBotics (Corin) system uses imageless bone morphing technology to build 10 intraoperative 3D models. Similarly, Cori Surgical System (Smith & Nephew) does not require pre-operative drawings; instead, surgeons use an optically tracked tool to 'paint' or map bone anatomy in real-time in the operating room, which the system then uses to create a 3D plan 10.

**Table 1.** Summary of orthopaedic surgical robotic systems for applications in Knee Arthroplasty 5

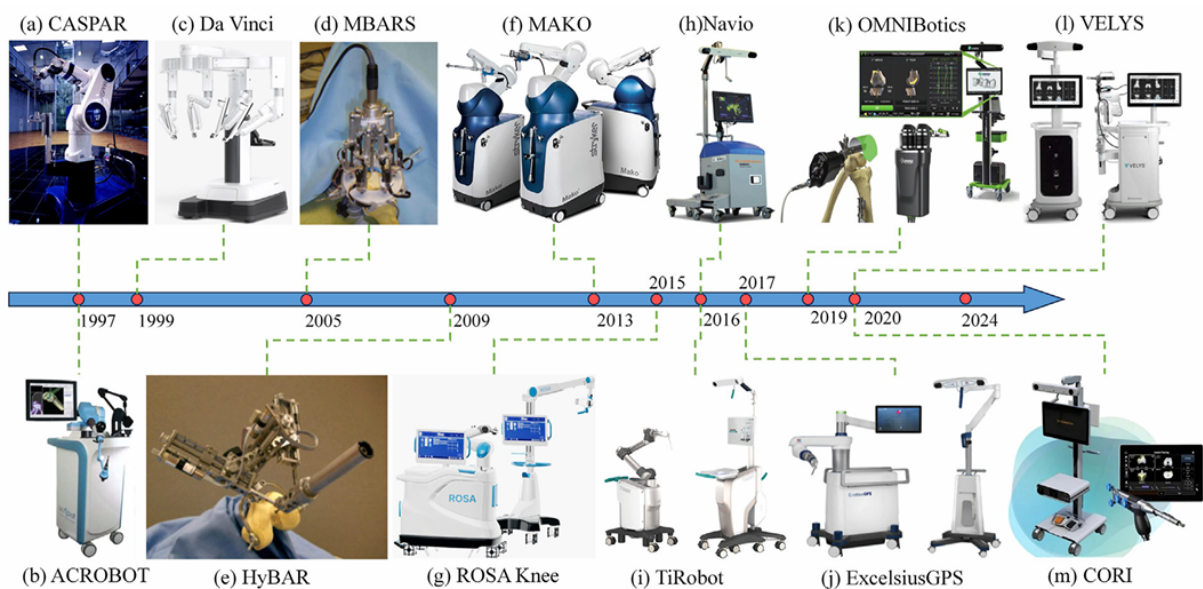
Robotics System	Developer	Surgical Procedures That Can Be Performed	Key Features	Superiority	Limitations
<b>ROSA Knee</b>	Room Biomet	TKA	Provides 3D intraoperative planning and real-time data without image guidance	Real-time acquisition of intraoperative landmarks	Requires additional clamping
<b>MAKO</b>	Stryker Surgical	TKA, UKA, PFA	Provides 3D planning, real-time monitoring, and haptic feedback	Provide haptic feedback	Multiple points of alignment, preoperative dependence on CT
<b>ACROBOT</b>	Acrobot	TKA, UKA	Provides tactile feedback and active retention system	Active safety retainer system	Preoperative dependence on CT, radiation exposure

<b>TiRobot</b>	TINAVI Medical Technologies	TKA	Sub-millimeter optical tracking and better radiation protection	High accuracy and radiation protection	Lacks haptic feedback
<b>VELYS</b>	Johnson	TKA	Provide free guidance on patient-specific imaging and TKA surgeries	Provide patient-specific surgery	Lacks haptic feedback
<b>OMNIBotics</b>	Corin Group	TKA	Cutting with mini robots, providing image-free guidance and intelligent safety system	Active spacers help improve the surgical exterior	Relatively complex setup for bone-attached robots
<b>Navio</b>	Smith and Nephew	TKA, UKA, PFA	Provides real-time intraoperative imaging and monitoring without preoperative CT	No CT required, reduced radiation exposure and imaging time	Lacks haptic feedback
<b>CORI</b>	Smith and Nephew	TKA, UKA	Provide real-time imaging and monitoring during the procedure; Compact and portable system	Fast, portable setup	Long learning curve

### Key Components of Technology

The functional success of all these types of systems, whether active or semi-active, CT-based or imageless, depends on the integration of several key technology components. The first component is pre-operative (or intraoperative in the case of imageless) software planning. The computational algorithm translates anatomical data either from pre-surgical images or surface mapping into a patient-specific three-dimensional virtual reconstruction of the knee joint (Ejnisman et al., 2024). This software, like the TPLAN workstation, allows surgeons to simulate, select implant size, and determine the optimal alignment and depth of resection before bone cutting is performed (Xing et al., 2024). The second component is the navigation system and sensors. The system serves as a 'GPS' for the procedure, which tracks in real-time the position of the patient's instruments, robots, and anatomy. Most systems, including MAKO, VELYS, and CUVIS-spine, use optical trackers or cameras that detect optical markers or reflective arrays (Biswas et al., 2023). The OMNIBotics system also uses sensors to validate the patient's range of motion. The third component is the intraoperative anatomy registration system, which is a crucial process for matching the 3D virtual plan to the physical anatomy of the patient on the operating table. This is achieved through bone registration (Kholinne et al., 2025). Tracker arrays (as in the TINAVI system) or pins are rigidly inserted into the femur and tibia (Xing et al., 2024). The surgeon then touches the predetermined anatomical landmarks

(Burger et al., 2025) with a guided probe, or (in an imageless system) 'paints' the entire surface of the bone, to register the position of the bones in 3D space relative to the navigation system. Finally, the fourth and most distinguishing component is the robotic arm/haptic boundary. It is the physical effector of the system. In active robots, this arm executes the cutting autonomously. In more common semi-active systems, robotic arms create haptic boundaries or stereotactic boundaries (Kholinne et al., 2025). When the surgeon manipulates the cutting tool (e.g. a burr on the Cori system or a saw blade on the MAKO), the robotic arm will provide tactile feedback and physically hold the tool from going beyond the haptic windows that have been planned in the software. These physically enforced virtual limitations drastically reduce the risk of manual errors, protect iatrogenic soft tissue, and ensure that the bone resection performed conforms to the pre-operative plan with sub-millimeter precision of 10 millimeters.



**Figure 3. Overview of the variations of orthopedic robotic products 5**

### Accuracy and precision of components

The fundamental evaluation of Robot-Assisted Total Knee Arthroplasty (RA-TKA) centers on its ability to improve surgical accuracy beyond conventional techniques. This precision is not only measured as a unit, but as an amalgamation of several critical factors: mechanical axis restoration, placement of individual femoral and tibial components, dynamic quantification and execution of soft tissue balance, as well as consistency of those results regardless of the surgeon's learning curve. Recent literature highlights the superiority of robotics in some of these aspects, although it also identifies specific areas that require further investigation, particularly the difference in performance between accuracy in the coronal and sagittal fields.

### Mechanical Axis Deviation

Restoration of the mechanical axis (MA), measured as Hip-Knee-Ankle (HKA) angle, is a key goal in TKA to ensure optimal load distribution and improve long-term implant survival. Comparisons between RA-TKA and conventional TKA consistently show that robotic technology significantly reduces deviation from the targeted neutral axis. This advantage

becomes very real in challenging surgical scenarios. For example, in the case of conversion TKA after failed High Tibial Osteotomy (HTO) in which the proximal anatomy of the tibia has changed and traditional landmarks become unreliable RA-TKA (using the Mako system)

demonstrate significantly superior accuracy (Baek et al., 2024). The study found that the robotics group achieved an average postoperative mechanical axis of  $1.7^\circ$  (compared to  $2.4^\circ$  in the conventional group) and, more importantly, drastically reduced outlier rates by Baek et al., (2024). The study defined an outlier as a deviation of  $>3^\circ$  from the neutral axis, which occurred in 35.0% of conventional TKA patients, but only in 13.3% of RA-TKA patients. This reduction of outliers is a key metric emphasized throughout the literature. Other studies focusing on the ROSA system also confirmed the high precision of the coronal field. Shin et al. (2022) reported that the accuracy of HKA was "exceptionally accurate", with 89.19% of cases being within the  $3^\circ$  target. Similarly, Petrillo et al. (2025) found significant HKA accuracy on the same system with only 3.6% outliers (Petrillo et al., 2025). Even in tightly controlled cadaveric settings using the new ROPA system, Yi et al. (2024) noted negligible mean differences in HKA, which were  $-0.21^\circ \pm 1.06^\circ$ . The clear consensus from various platforms (Mako, ROSA, ROPA) and clinical scenarios (primary, failed HTO, cadaveric) is that robotic assistance provides measurable consistency in achieving planned mechanical axis targets.

### **Component Placement**

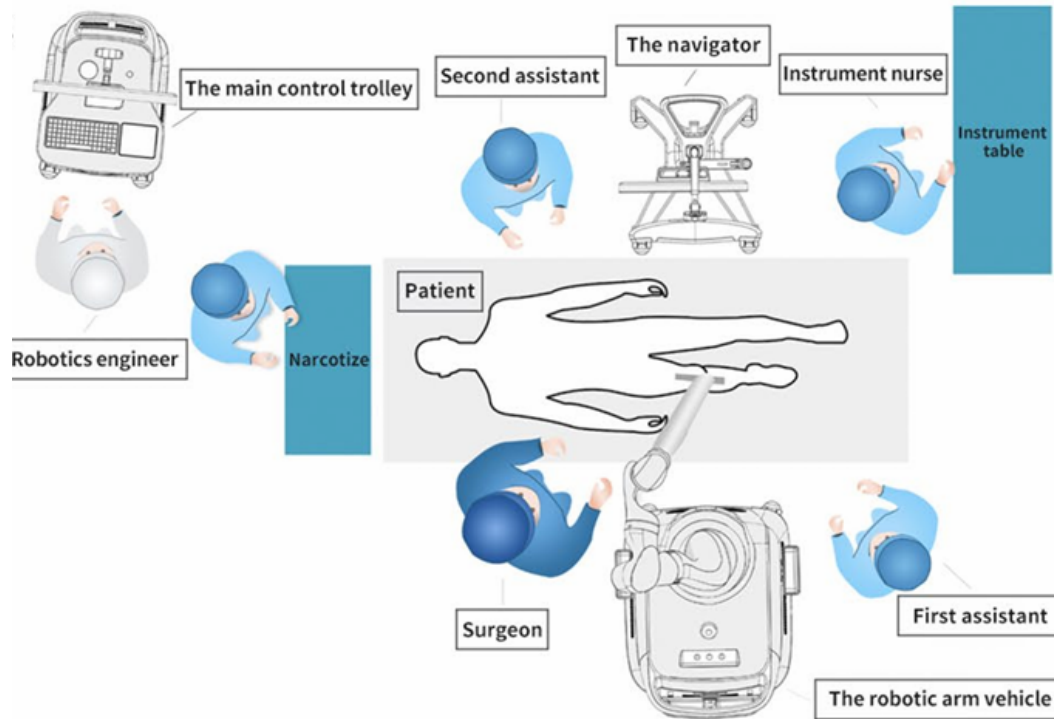
Beyond composite HKA measurements, the accuracy of RA-TKA is evaluated on its ability to execute placement of individual femoral and tibial components. This is where the literature analysis reveals a significant dichotomy: near-perfect accuracy in the coronal field versus the disputed accuracy in the sagittal field.

In the coronal field, the data shows a clear advantage. Baek et al. (2024) recorded higher accuracy for femur coronal inclination ( $90.0^\circ$  vs  $91.6^\circ$ ) and tibial coronal inclination ( $90.3^\circ$  vs  $91.3^\circ$ ) compared to conventional TKA 15. Shin et al. (2022) corroborate this, reporting that the alpha (femoral coronal) and beta (tibial coronal) angles are very accurate, with 100% and 91.89% of cases being within  $3^\circ$  of the plan, respectively (Shin et al., 2022). Petrillo et al. (2025) observed similar results for Lateral Distal Femoral Angle (LDFA) and Medial Proximal Tibial Angle (MPTA), with outlier rates ( $>3^\circ$ ) of 0% and 5.7%, respectively, 18.

However, this consensus is broken when analyzing the sagittal plane, specifically tibial slope and femoral flexion. The sagittal plane is where some studies have identified inconsistencies. Shin et al. (2022) are most critical, stating that the ROSA system "fails" (falls short) in the sagittal plane. They found the gamma (femoral sagittal) and delta (tibial slope) angles to be "inaccurate", with only 77.14% and 74.29% of cases achieving the  $3^\circ$  target (Shin et al., 2022). Petrillo et al. (2025) echo these concerns; although the Distal Femoral Flexion (DFF) is accurate, they noted a "statistically significant difference" between the planned and achieved Tibial Slope (TS) values, concluding that the ROSA system is "less accurate" in the sagittal plane (Petrillo et al., 2025). Hasegawa et al. (2024) also found in their comparison that femoral sagittal cutting error was smaller in NAVIO, and the ROSA group showed a significant femoral cutting error in the direction of extension (Hasegawa et al., 2024).

Interestingly, these findings are not universal. Baek et al. (2024), using the Mako system, found superior accuracy for tibial sagittal inclination in the robotic group ( $90.5^\circ$  vs  $91.4^\circ$ ) 15. Similarly, a cadaveric study by Yi et al. (2024) using the ROPA system found very high accuracy for the Posterior Tibial Slope (PTS) with an average difference of only  $0.03^\circ \pm 0.29^\circ$

(Yi et al., 2024). This discrepancy suggests that sagittal accuracy challenges may be specific to a particular platform, or are artifacts of in vivo applications—as hypothesized by Petrillo et al. (2025), that the saw blade may flex in sclerotic bone. Joint line restoration is intrinsically related to these parameters, and the improved accuracy in polyethylene liner thickness reported by Baek et al. (2024) suggests a more precise overall restoration.



**Figure 4. Schematic diagram of position on the use of ROPA TKA in operating room 17**

### Soft Network Balance

RA-TKA's ability to quantify and respond to intraoperative soft tissue data in real-time is a major advance over traditional measured resection. Systems such as NAVIO and ROSA allow surgeons to manually apply varus and valgus stress across the entire range of motion (ROM) and validate soft tissue laxity. Robotic technology then facilitates the planning of bone pieces based on this dynamic feedback, rather than just on static bone landmarks. The clinical impact of this is profound. In the study of Baek et al. (2024) in complex cases of failed HTO, the robotic group was able to achieve the desired ligament balance by using a significantly thinner polyethylene liner (Baek et al., 2024). These findings imply that robotic bone pieces are more accurately placed to match the patient's ligament sheath, thus avoiding the need to "stuff the joint" with thicker polyethylene to correct mid-flexion instability. The ROPA cadaveric study also highlights intraoperative visualization of flexion and extension gaps, which allows surgeons to confirm adjustments based on soft tissue conditions (Yi et al., 2024). Thus, robotics facilitates a paradigm shift from rigid mechanical alignment to more personalized procedures (e.g., kinematic or functional alignment), in which the ligament balance determines the position of the final component and contributes directly to joint stability.

## Learning Curve

The implementation of new technologies always presents a learning curve, which has the potential to affect precision and operating time. The literature presents a nuanced view of this. A direct comparison between the systems shows that the type of instrumentation itself is important; Hasegawa et al. (2024) found that ROSA (saw-based) has a shorter operating time than NAVIO (handheld burring device-based) (Hasegawa et al., 2024). The study by Shin et al. (2022) provides an interesting insight: the surgeons in the study were new to the ROSA system (although they were experienced with Computer-Assisted Surgery or CAS). However, they did not find a statistically significant improvement in accuracy from the first case to the subsequent 16 cases. The authors hypothesize that the observed sagittal inaccuracy is not due to the surgeon's learning curve, but rather to potential systemic problems with the robotic arm haptics, such as undetected "pin drift" or "pin skid." In contrast, Petrillo et al. (2025) explicitly exclude their first 10 cases to account for

learning curve and then found that "the surgeon's experience had no impact on alignment accuracy" (Petrillo et al., 2025). The cadaveric study by Yi et al. (2024) fully mitigated this factor by using surgeons who were already "trained and familiar" with the ROPA system before the experiment began (Yi et al., 2024). Collectively, these data show that the learning curve for RA-TKA is multifaceted. While basic competencies in workflows can be achieved quickly, mastery of haptic interactions and platform-specific pitfall avoidance may be separate challenges. However, the main benefit is that once the learning curve is resolved, the robotic system provides a higher level of precision and consistency of results especially in complex cases compared to the variability inherent in conventional techniques (Baek et al., 2024).

## Operative Parameters and Complications

Analysis of operative parameters and complication profiles is a crucial aspect in evaluating the viability and advantages of Robot-Assisted Total Knee Arthroplasty (RA-TKA) compared to Conventional Total Knee Arthroplasty (C-TKA). These parameters directly affect surgical efficiency, patient morbidity, and short-term clinical outcomes. The literature review identified surgery time, bleeding management, as well as the incidence of technical errors as the main operative parameters, while complications were divided into common post-TKA complications and specific complications directly related to the use of robotic technology.

### Operating Hours

The most consistent finding in the comparative literature was the longer duration of operation at RA-TKA. Several meta-analyses and systematic reviews confirm that RA-TKA significantly extends 21 operating times. This prolongation of duration is not due to the bone cutting procedure itself, but rather to the additional steps required by robotic technology (León-Muñoz & Moya-Angeler, 2025). Key contributing factors include the time required for the insertion and removal of tracer pins in the femur and tibia, the process of registering the patient's anatomy into the robotic system, and intraoperative planning (Nogalo et al., 2023). In addition, complex preoperative preparations such as installation, calibration, and testing of robotic equipment also add up to the total time in operating room (Liang et al., 2025).

However, this longer duration is greatly influenced by the learning curve or learning curve 8. Various studies cited by Nogalo et al. (2023) and Zhang et al. (2025) show that time efficiency increases significantly after the surgeon goes through a number of initial cases. This

learning curve varies between systems; some studies suggest 7 cases, 10 cases (cited by Nogalo et al., 2023), 11 cases, 16 cases for MAKO, 25 for NAVIO, and 6-11 for ROSA, up to 11-43 cases of 20. This learning curve phenomenon is affirmed by Guo et al. (2025), who in their study found no significant difference in operating time and attributed the variations reported in the literature more to the "proficiency of the surgical team" than to the inherent limitations of the robotic method itself. During this early learning phase, the anxiety of the surgical team was also reported to be higher, which could affect the efficiency of the workflow (Nogalo et al., 2023).

### **Tissue Bleeding and Trauma**

Evaluations of blood loss and tissue trauma show highly contradictory findings in the literature. On the one hand, some studies argue that RA-TKA has the potential to reduce blood loss. Liang et al. (2025) stated that the robotic approach helps reduce blood loss and drainage volume. Theoretically, this advantage stems from the fact that many RA-TKA systems do not require the opening of an intramedullary canal for the cutting guide, unlike conventional C-TKA (Geng et al., 2023). In addition, robotic precision in bone cutting and the potential for better soft tissue protection are expected to minimize surgical trauma (Zhang et al., 2025).

On the other hand, strong counter-evidence is also present. Nogalo et al. (2023) in their systematic review, cited several studies that found "greater" or "more" estimated blood loss in the RA-TKA group. This paradox is often directly attributed to the previous parameter: a longer duration of operation. Increased procedure time inherently exposes the tissue for longer, potentially negates the benefit of non-opening of the medular canal. Thus, the current literature is divided on whether RA-TKA provides consistent clinical benefits in terms of bleeding reduction compared to C-TKA.

### **Technical Errors**

Although designed to improve precision, the RA-TKA system introduces a new category of potential failures, namely technical errors related to hardware and software. The literature identifies "aborting the RA-TKA procedure" and converting it to manual C-TKA as a significant drawback (Nogalo et al., 2023). The incidence of this forced conversion has reportedly ranged from 1% to 12% in some study series. This failure can

occur at various stages of the procedure. A study by Chun et al. (2011), cited by Nogalo et al. (2023), classifies these failures as occurring during preoperative planning, after the patient is anesthetized (before the incision), after surgical exposure (before grinding), or most disturbingly, in the middle of a milling procedure.

Anatomical registration errors and tracking failures are the main causes. Fan et al. (2025) highlight that problems with any aspect of the equipment can force the discontinuation of the procedure. In particular, failures associated with tracking pins such as loose, detached, or broken pins can force the discontinuation of robotic surgery, with one study reporting this as the cause in 61% of termination cases. Liang et al. (2025) also noted "sudden mechanical failure" as a risk associated with the surgical team's ignorance of the system, especially during the 22-day learning curve.

## **Common Complications of Post-TKA**

When comparing common post-TKA complications, the current literature consensus suggests that RA-TKA has a safety profile comparable to C-TKA, with no significant increased risk in most major complications (García-Sanz et al., 2025). Common complications such as deep vein thrombosis (DVT), pulmonary embolism (PE), and neurovascular injury are recognized as inherent risks of the TKA procedure itself, regardless of the technology used (Fan et al., 2025).

Specifically, a meta-analysis by Syarif et al. (2025) provides quantitative data on the relative risk (RR) for the main complications. They found no statistically significant differences for periprosthetic joint infection (PJI) (RR=0.76), periprosthetic fractures (RR=0.73), or aseptic loosening (RR=0.98). These findings support the statement that RA-TKA poses no additional risk of infection or implant failure compared to C-TKA (Syarif et al., 2025).

However, one notable exception reported is in the incidence of postoperative knee stiffness or arthrofibrosis. The same meta-analysis by Syarif et al. (2025) found that the RA-TKA group had a significantly lower risk of postoperative knee stiffness (RR=0.57) compared to the mTKA group. Although Nogalo et al. (2023) also noted reports of post-RA-TKA rigidity, meta-analysis findings by Syarif et al. (2025) suggest that robotic precision in component placement and soft tissue balancing may contribute to better recovery of range of motion and a lower incidence of arthrofibrosis (Griffin et al., 2023).

## **Robotic Specific Complications**

In addition to the technical failures that led to the conversion, the use of RA-TKA introduced a unique set of complications not found in C-TKA, which were almost entirely related to the use of fixation tracer pins (Nogalo et al., 2023). These pin-related complications are the most frequently cited risks specific to robotics (Syarif et al., 2025).

These complications include pin-site infection, loose pins, or pin displacement. Infection at the pin site, although generally superficial, was reported to have an incidence of about 0.47% in some 17 reviews. A more severe complication is a fracture of the pin-site. It is a distinct clinical entity from a common periprosthetic fracture. The incidence of these pinhole fractures is reported to vary, with some reviews citing figures as low as 0.065% to 0.2%, while other studies cited by Nogalo et al. (2023, citing Beldame et al., 2010) reported incidences as high as 1.4% in a single series of cases.

In addition, iatrogenic soft tissue injuries due to the robotic arm itself (as distinct from soft tissue trauma due to surgical exposure) have been reported, including patellar tendon rupture, patellar dislocation, and peroneal nerve injury (Nogalo et al., 2023). However, it should be noted that these iatrogenic complications are reported to be more common in autonomous robotic systems (older generations) compared to more modern semi-autonomous (haptic) systems, where the surgeon still controls the cutters (Zhang et al., 2025).

## **Revised Numbers**

Evaluation of whether RA-TKA reduces the risk of medium-term revision still yields mixed and inconclusive evidence. The main indicator for long-term revision is aseptic loosening. As mentioned earlier, a meta-analysis by Syarif et al. (2025) found no statistically significant difference in the risk of aseptic loosening between the two groups (RR=0.98),

suggesting that from an implant failure perspective, RA-TKA may not offer a clear advantage (Syarif et al., 2025).

However, other literature cited by Zhang et al. (2025) shows a contradictory picture. One study cited found that the RA-TKA group (using ROBODOC) had a 10-year higher survival rate than the C-TKA. In contrast, another study also cited by Zhang et al. (2025) found

similar prosthesis survival rates between RA-TKA, C-TKA, and TKA with navigation (Baek et al., 2024). This lack of high-quality long-term data and conflicting findings means that the RA-TKA's claims of superiority in reducing the current medium- to long-term revision numbers cannot be definitively proven.

## **Analysis Cost-Effectiveness**

### **Robotic Cost Components**

The main financial burden of adopting an R-TKA is the substantial initial capital cost. Reports say the purchase price of the robotic unit ranges from \$500,000 to more than \$1 million. Ruangsomboon et al. (2025) also highlight "substantial capital expenditure" as a major barrier, with one of their analysis scenarios using a capital cost figure of US\$611,060. These fees don't stop at the initial purchase; There are also significant ongoing operational costs. This includes an estimated annual maintenance fee of \$40,000 to \$150,000, as well as software licensing fees. Further, each procedure requires robot-specific instruments and disposables, such as cutting guides, drapes, and burrs, which add up to a cost per case of about \$300 to more than \$1,000 (Jevnikar et al., 2025). The RACER-knee protocol study also identified "case-specific disposable equipment" as a cost component that needs to be taken into account (Griffin et al., 2023).

### **Clinical Economic Impact**

This high initial investment is justified by technology proponents with the potential for downstream cost savings, which primarily stem from two main clinical impacts. The first is the potential savings from shorter hospital stays. Various analyses show that R-TKA is associated with better early functional recovery, thereby shortening the length of stay (LOS) of patients. Jevnikar et al. (2025) cited an analysis that found that the average LOS in R-TKA was 1.9 days compared to 2.3 days in conventional TKA, and the proportion of patients who were discharged directly home was higher. The second clinical economic impact, and the most significant in the long term, is the potential cost savings from reducing complications and revisions. R-TKA is predicted to reduce downstream costs related to mechanical complications, infections, and transfusion needs (Jevnikar et al., 2025). Goudazi et al. (2025) also noted that R-TKA can "reduce the need for revision". Nonetheless, these savings are not always guaranteed and are highly context-dependent. A study by Ruangsomboon et al. (2025) in Thailand, for example, found that in their base case scenario, R-TKA is not cost-effective because the complication rate in the conventional TKA group is already relatively low, so the savings from complication reduction are not enough to cover the high cost of capital.

### **Economic Analysis Model**

To measure the balance between additional costs and improvements in health outcomes, the most commonly used economic analysis model is cost-utility analysis, which measures

costs per Quality-Adjusted Life Year (QALY) earned. This model was used extensively in the study provided 28 and planned in the RACER protocol 25. The results of the cost per QALY analysis are highly dependent on the context of the health system, especially on the willingness-to-pay (WTP) threshold in the country. This becomes relevant when comparing studies from developed countries (HICs) versus middle-income countries (MICs). Ruangsomboon et al. (2025) explicitly state that the conclusions of HICs (such as the United States or Belgium) may not apply directly to MICs because the WTP threshold in MICs is much lower. This is evident from existing studies: in Iran, R-TKA was found to be cost-effective with an Incremental Cost-Effectiveness Ratio (ICER) of \$12,037 per QALY, which is below the country's WTP threshold (\$16,153) (Goudazi et al., 2025). In contrast, in Thailand, R-TKA in the base case was found to be cost-ineffective with an ICER of US\$7,436 per QALY, which is above Thailand's WTP threshold (US\$4,888) (Ruangsomboon et al., 2025).

### **Implementation Challenges in the Indonesian Health System**

The different findings between Thailand and Iran, both of which are MICs, highlight specific implementation challenges that Indonesia's health system is likely to face. The first challenge is budget constraints. High capital and operational costs are a major obstacle to the limited allocation of the health budget. Second, the volume factor of the procedure strongly determines the cost-effectiveness (Jevnikar et al., 2025). Jevnikar et al. (2025) emphasize that high-volume centers are more likely to achieve cost efficiency. The study of Ruangsomboon et al. (2025) is even more specific, suggesting that the new R-TKA can be cost-effective if one robot is used for at least 640 cases per year. This reliance on high volumes implies a major challenge in the distribution of facilities in Indonesia. Implementation is likely to be limited to high-volume tertiary academic hospitals in urban centers, creating a geographic access gap. Finally, the cost burden is borne by the hospital (for capital and maintenance) and potentially by the patient (Ruangsomboon et al., 2025). Indonesia's health system needs to conduct a local cost-effectiveness analysis to determine the relevant WTP threshold, to ensure that the adoption of this expensive technology provides commensurate value to the population.

## **CONCLUSION**

This literature review evaluates the comparison of Robot-Assisted Total Knee Arthroplasty (RA-TKA) with Conventional TKA (C-TKA) in four critical domains: accuracy, complications, cost-effectiveness, and clinical outcomes. The strongest evidence supports RA-TKA on surgical accuracy. The literature consistently shows RA-TKA excels in restoring mechanical axis (HKA) and coronal alignment, as well as significantly reducing the number of outliers. RA-TKA also facilitates dynamic balance of soft tissues. However, accuracy in sagittal planes, such as the tibial slope, is still inconsistent and debatable between robotic platforms. The major complication profile of RA-TKA is comparable to that of C-TKA, with the added benefit of a lower risk of postoperative knee stiffness (arthrofibrosis). However, this advantage is offset by longer operating times, especially during the learning curve, and the introduction of robotics-specific risks. This includes technical failures that require intraoperative conversion as well as tracker pin-related complications, such as infection or pinhole fractures. The evidence on blood loss and the medium-term revised figure is still inconclusive. The biggest obstacle to the adoption of RA-TKA is cost-effectiveness. Very high initial capital costs plus ongoing operating costs create a huge financial burden. Cost efficiency

relies heavily on very high volume of procedures to justify initial investment through potential downstream savings, such as shorter hospitalizations. Overall, RA-TKA is a technology that offers a real advantage in coronal alignment precision, yet is offset by high costs and a unique set of operational challenges.

## REFERENCES

- Baek, J. H., Lee, S. C., Lee, D. N., Heo, J., Kim, T., & Ahn, S. (2024). Better accuracy of robotic-assisted total knee arthroplasty compared to conventional technique in patients with failed high tibial osteotomy. *PLOS ONE*. <https://doi.org/10.1371/journal.pone.0313391>
- Biswas, P., Sikander, S., & Kulkarni, P. (2023). Recent advances in robot-assisted surgical systems. *Biomedical Engineering Advances*, 6, 100109. <https://doi.org/10.1016/j.bea.2023.100109>
- Burger, J., Fan, W., Gansiniec, S., Reinders, C., Kienzle, S., & Gwinner, C. (2025). Real-world outcomes of robotic total knee arthroplasty: Five years' experience in a non-academic center. [*Journal name not provided in source*], 1–12.
- Canovas, F., & Dagneaux, L. (2018). Quality of life after total knee arthroplasty. *Orthopaedics & Traumatology: Surgery & Research*, 104(1), S41–S46. <https://doi.org/10.1016/j.otsr.2017.04.017>
- Daoub, A., Qayum, K., Patel, R., Selim, A., & Banerjee, R. (2025). Robotic assisted versus conventional total knee arthroplasty: A systematic review and meta-analysis of randomised controlled trials. *Journal of Robotic Surgery*, 18(1), 1–10. <https://doi.org/10.1007/s11701-024-02048-9>
- Ejnisman, L., Antonioli, E., Cintra, L., Souza, D. O., & Augusto, L. (2024). Robot-assisted knee arthroplasty: Analyzing the learning curve and initial institutional experience. *Computational and Structural Biotechnology Journal*, 24, 343–349. <https://doi.org/10.1016/j.csbj.2024.04.013>
- Fan, X., Wang, Y., Zhang, S., Xing, Y., Li, J., & Ma, X. (2025). Orthopedic surgical robotic systems in knee arthroplasty: A comprehensive review. [*Journal name not provided in source*], 1–13.
- Fan, X., Wang, Y., Zhang, S., Xing, Y., Li, J., & Ma, X. (2025). Orthopedic surgical robotic systems in knee arthroplasty: A comprehensive review. [*Journal name not provided in source*], 1–13.
- García-Sanz, F., Sosa-Reina, M. D., Jaén-Crespo, G., González-de-la-Flor, Á., Villafañe, J. H., & Romero-Morales, C. (2025). Redefining knee arthroplasty: Does robotic assistance improve outcomes beyond alignment? An evidence-based umbrella review. [*Journal name not provided in source*], 1–14.
- Geng, R., Li, J., Yu, C., Zhang, C., Chen, F., & Chen, J. (2023). Knee osteoarthritis: Current status and research progress in treatment (Review). [*Journal name not provided in source*], 1–11.
- Goudazi, Z., Jafari, M., Kiyaei, A., Ravangard, R., Hashemi, S. A., & Keshavarz, K. (2025). Cost-effectiveness analysis of robotic-arm assisted total knee arthroplasty (TKA) versus conventional TKA in Iranian population. [*Journal name not provided in source*], 1–10.
- Griffin, J., Davis, E. T., Parsons, H., Mannion, E. G., Khatri, C., & Ellard, D. R. (2023). Robotic arthroplasty clinical and cost effectiveness randomised controlled knee (RACER-knee): A study protocol. [*Journal name not provided in source*], 1–9.
- Guo, J., Jin, Z., & Xia, M. (2025). Evaluating surgical outcomes: Robotic-assisted vs. conventional total knee arthroplasty. [*Journal name not provided in source*], 4.

- Hasegawa, M., Tone, S., Naito, Y., & Sudo, A. (2024). Comparison of accuracy and early outcomes in robotic total knee arthroplasty using NAVIO and ROSA. *Scientific Reports*, 1–8. <https://doi.org/10.1038/s41598-024-53789-4>
- Jevnikar, B. E., Khan, S. T., Emara, A. K., Elmenawi, K. A., Deren, M., & PiuZZi, N. S. (2025). Robotic total hip and knee arthroplasty: Economic impact and workflow efficiency. *Journal of Robotic Surgery*.
- Kholinne, E., Gani, K. S., & Mitchel. (2025). Robotic-assisted total knee replacement: Pioneering precision and the future of joint reconstruction. *Universa Medicina*, 1–2.
- León-Muñoz, V. J., & Moya-Angeler, J. (2025). Robotic assistance in total knee arthroplasty surgery: Necessity or trend? *Expert Review of Medical Devices*, 22(7), 653–656. <https://doi.org/10.1080/17434440.2025.2512042>
- Liang, H., Hao, Y., & Yu, W. (2025). Comparing robot-assisted and conventional surgery in knee replacement: A meta-analysis of surgical-site wound complications and recovery outcomes. *Asian Journal of Surgery*, 48(2), 1027–1033. <https://doi.org/10.1016/j.asjsur.2024.10.154>
- Mostafa, O., Malik, M., Qayum, K., Ishaq, U., & Tr, F. E. (2025). Robotic-assisted versus conventional total knee arthroplasty: A systematic review and meta-analysis of alignment accuracy and clinical outcomes. *[Journal name not provided in source]*.
- Nogalo, C., Meena, A., Abermann, E., & Fink, C. (2023). Complications and downsides of the robotic total knee arthroplasty: A systematic review. *Knee Surgery, Sports Traumatology, Arthroscopy*, 31(3), 736–750. <https://doi.org/10.1007/s00167-022-07031-1>
- Pavlidis, G. (2023). Deploying artificial intelligence for anti-money laundering and asset recovery: the dawn of a new era. *Journal of Money Laundering Control*, 26(7), 155–166.
- Petrillo, S., Migliorini, F., Moretti, G., & Romagnoli, S. (2025). Accuracy of ROSA knee system in bone cuts orientation during total knee arthroplasty: An observational study. *[Journal name not provided in source]*, 1–9.
- Rivero-Moreno, Y., Echevarria, S., Vidal-Valderrama, C., Pianetti, L., Cordova, J., & Navarro-Gonzalez, J. (2023). Robotic surgery: A comprehensive review of the literature and current trends. *[Journal name not provided in source]*, 15(7).
- Ruangsomboon, P., Ruangsomboon, O., Isaranuwachai, W., Zywiell, M. G., & Naimark, D. M. (2025). Cost-effectiveness of robotic-assisted versus conventional total knee arthroplasty: An analysis from a middle income country. *Acta Orthopaedica*, 716–725.
- Shin, C., Crovetti, C., Huo, E., & Lionberger, D. (2022). Unsatisfactory accuracy of recent robotic assisting system ROSA for total knee arthroplasty. *[Journal name not provided in source]*.
- Sittlington, S., & Harvey, J. (2018). Prevention of money laundering and the role of asset recovery. *Crime, Law and Social Change*, 70(4), 421–441.
- Syarif, I., Warman, F. I., Sibarani, T., & Idulhaq, M. (2025). Complications of robotic assisted total knee arthroplasty vs manual total knee arthroplasty: A systematic review and meta-analysis. *[Journal name not provided in source]*, XXVII, 1507–1516.
- Varacallo, M. A., Luo, T. D., Mabrouk, A., & Johanson, N. A. (2025). Total knee arthroplasty techniques. *[Journal name not provided in source]*, 1–15.
- Xing, P., Qu, J., Feng, S., Guo, J., & Huang, T. (2024). Comparison of the efficacy of robot-assisted total knee arthroplasty in patients with knee osteoarthritis with varying severity deformity. *[Journal name not provided in source]*.
- Yi, J., Gao, Z., Huang, Y., Liu, Y., Zhang, Y., & Chai, W. (2024). Evaluating the accuracy of a new robotically assisted system in cadaveric total knee arthroplasty procedures. *[Journal name not provided in source]*, 8, 1–10.

Zhang, H., Jiang, X., Jin, B., Zhang, H., & Liang, J. (2025). Current developments in robotic assistance technology for total knee arthroplasty: A comprehensive overview. *Journal of Orthopaedic Surgery and Research*. <https://doi.org/10.1186/s13018-025-05490-z>