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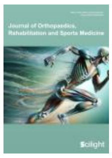

Review

Robotic-Assisted Total Knee Arthroplasty: Innovations, Outcomes, and Challenges—A Comprehensive Review

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Abstract: Background: Total knee arthroplasty (TKA) reliably relieves pain in end-stage knee osteoarthritis, yet up to 20% of patients report persistent dissatisfaction due to factors like component malalignment or soft-tissue imbalance. Robotic-assisted TKA has emerged to enhance surgical precision and enable patient-specific alignment strategies beyond the traditionally targeted neutral mechanical alignment. **Purpose:** To synthesize current knowledge on the role of robotic systems in TKA, including technological classifications, clinical outcomes, safety profile, economic considerations, and adoption challenges. **Methods:** We conducted a narrative review of literature on robotic-assisted total knee arthroplasty (RA-TKA) published from 2010 to 2025. Articles were primarily identified via PubMed searches, supplemented by reference review and expert recommendation. Of the 36 included studies, 8 were systematic reviews or meta-analyses, 2 randomized controlled trials, 6 registry or database studies, 14 cohort studies or case series, 3 narrative reviews or expert opinion papers, and 1 technical or biomechanical study. **Results:** Semi-active robotic TKA systems consistently improve bone-cutting accuracy and alignment precision, dramatically reducing alignment outliers beyond 3° of neutral compared to conventional techniques. Robotic TKA has been associated with reduced early postoperative pain, faster recovery, and shorter hospital stays. Mid-term outcomes appear equivalent or slightly improved relative to conventional TKA, with similar safety profiles. **Conclusion:** Robotic-assisted TKA enhances surgical precision and early recovery without increasing complication risk. Long-term benefits, overall cost-effectiveness, and broad applicability of this technology remain under investigation.

Keywords: total knee arthroplasty; robotic-assisted surgery; knee alignment; clinical outcomes

1. Introduction

Total knee arthroplasty (TKA) is one of the most successful treatments for advanced knee osteoarthritis, offering substantial pain relief and functional improvement. However, a subset of patients remains dissatisfied after TKA, often due to suboptimal implant alignment or soft tissue balancing issues. Recent literature has introduced the concept of "constitutional varus," where a neutral mechanical alignment may not be natural for all patients: Bellemans et al. reported that approximately 32% of men and 17% of women exhibit a natural varus knee alignment of ≥3°, suggesting that correcting these to neutral during TKA may be suboptimal [1]. These findings, along with the Coronal Plane Alignment of the Knee (CPAK) classification highlight that an individualized alignment approach may benefit certain patients. In this context, robotic-assisted TKA has gained traction to improve surgical precision and enable patient-specific alignment targets (whether traditional mechanical alignment or kinematic alignment tailored to the patient's anatomy) [2]. Notably, the adoption of robotic TKA has been rising in recent years (for example, in the United States, registry data show increasing utilization of robotic assistance in knee arthroplasty) [3].

A broader perspective of how robotics is reshaping orthopaedic workflows is outlined by St Mart et al., who emphasize the evolution from passive to semi-active robotic systems and their integration into clinical practice [4]. Robotic-assisted TKA systems aim to augment the surgeon's ability to plan and execute bone resections and component positioning with high accuracy. By integrating preoperative imaging and intraoperative guidance, robotic systems can help achieve alignment and balance goals more consistently than manual instrumentation. Improved precision is expected to enhance implant longevity and functional outcomes, addressing some causes of dissatisfaction. This review discusses the current landscape of robotic-assisted TKA, including how the introduction of robotics has changed the surgical workflow and the impact it has had on clinical outcomes. We also examine the safety profile and economic implications of robotic TKA, the learning curve for adopting this technology, and its current limitations. The evidence is drawn from recent peer-reviewed studies and meta-analyses to provide an up-to-date synthesis that is both scientifically rigorous and clinically relevant.

2. Methods

This narrative review aimed to synthesize current evidence on robotic-assisted total knee arthroplasty (RA-TKA), focusing on clinical outcomes, safety, cost-effectiveness, and barriers to adoption. Literature was identified primarily via PubMed searches targeting English-language articles published from January 2010 to June 2025, using the following keywords in various combinations: "robotic total knee arthroplasty", "robotic knee replacement", "clinical outcomes", "cost-effectiveness", "registry", "AI", and "learning curve". Additional studies were identified through reference review and expert recommendation to ensure comprehensive and balanced coverage of landmark contributions and relevant international perspectives.

Inclusion criteria were: (1) systematic reviews or meta-analyses, (2) randomized controlled trials, (3) prospective and retrospective cohort studies or registry analyses, and (4) narrative reviews or expert opinion addressing clinical outcomes, safety, economic analysis, or implementation of RA-TKA. Exclusion criteria included case reports, non-human studies, and non-English publications. No formal PRISMA methodology was applied, but an effort was made to maximize the breadth, quality, and recency of included literature.

A total of 36 articles were included in this review. See Table 1 for a breakdown by study type.

Table 1. Summary of the 36 studies included in the review, categorized by study type and corresponding references.

Study Type	Number (n)	References
Cohort studies/case series	14	[1,5–17]
Narrative reviews/expert opinion papers	3	[4,18,19]
Registry/database studies	6	[3,20–24]
Randomized controlled trials (RCTs)	2	[25,26]
Systematic reviews/meta-analyses	8	[27–35]
Technical/implant/biomechanical studies	1	[36]

2.1. Robotic Systems in TKA: Classification and Technical Overview

2.1.1. Classification by Level of Autonomy

Robotic systems in orthopaedic surgery are commonly classified as active, semi-active, or passive based on the degree of robotic control. Active robots can execute bone cuts autonomously once programmed, an early example was the ROBODOC system used experimentally in TKA, which demonstrated high accuracy but raised safety concerns (such as intraoperative fractures) due to complete robotic control and lack of human tactile feedback [4]. Semi-active (haptic) robots, which comprise most modern TKA systems, require the surgeon to perform the bone cutting or preparation but within constraints defined by the robot. These systems provide real-time feedback or resistance to prevent the surgeon from deviating beyond the planned resection boundaries. Examples include the Stryker Mako robotic-arm system, which uses a preoperative CT scan to plan bone cuts and then guides the surgeon via a rigid robotic arm with haptic boundary control, and the Zimmer Biomet ROSA system, a robotic assistant that can precisely position cutting jigs or instruments according to a digital plan. Semi-active systems retain surgeon involvement in the critical steps while enhancing precision, thereby aiming to improve outcomes without sacrificing safety. Passive systems (sometimes called computer-assisted navigation or handheld robotic systems) do not perform any bone cutting or manipulation themselves but rather guide the surgeon via computer feedback or intelligent instruments. These include imageless optical navigation systems (which some consider a form of passive robotic assistance) and handheld robotic cutting tools like the Smith & Nephew NAVIO/CORI system, where the surgeon uses a handheld burr that only cuts when positioned correctly. Passive systems can improve alignment accuracy while relying on the surgeon's manual execution. These robotic platforms for total knee arthroplasty have evolved along distinct trajectories across different regions of the world. In the United States and Europe, commercially established systems such as MAKO (Stryker), ROSA (Zimmer Biomet), and VELYS (DePuy Synthes) dominate clinical practice. By contrast, in Asia, several next-generation platforms have emerged to address cost, accessibility, and population-specific anatomical variations. Examples include the MISSO robotic system in India, designed with affordability and local patient needs in mind, and the SkyWalker™ system developed in China, which has demonstrated accurate bone resection and alignment in early clinical studies [5,18]. These regional differences underscore both the global momentum of robotic-assisted arthroplasty and the diverse strategies pursued to balance precision, cost-effectiveness, and scalability for distinct healthcare settings.

2.1.2. Image-Based and Imageless Systems

Robotic TKA platforms also differ in how they obtain anatomic information. Image-based systems (such as Mako) utilize preoperative imaging—most often a CT scan—to construct a 3D model of the patient's knee anatomy and allow preoperative planning of component alignment, sizing, and orientation. The advantage of CT-based planning is the availability of a highly detailed map of bony anatomy and any deformities, the downsides include additional radiation exposure, increased cost, and the need for time and resources to obtain and process the scan. Some newer systems (e.g., ROSA) can generate a 3D model from calibrated X-rays, aiming to reduce the CT burden. In contrast, imageless systems rely on intraoperative mapping of the patient's anatomy. The surgeon digitizes anatomic landmarks with a probe or uses intraoperative sensors, and the robot's software creates a virtual model. Imageless robots avoid the cost and radiation of a CT and streamline workflow by allowing planning to occur in the operating room. However, they depend on the accuracy of point-to-point surface mapping, incomplete or imprecise landmark acquisition can affect the model. In practice, once sufficient anatomical landmarks are sampled, imageless systems achieve high accuracy for bone cuts and implant positioning, although subtleties of the patient's anatomy (like complex deformities) may be captured more completely with a preoperative CT.

2.1.3. Major Commercial Robotic TKA Platforms

The landscape of FDA (U.S. Food and Drug Administration)-approved or CE (Conformité Européenne)-marked robotic systems for TKA includes a mix of large-console robotic arms and more compact handheld units. The Mako system (Stryker) is a semi-active robotic arm that gained widespread use for unicompartmental knee and total hip arthroplasty before being adapted to TKA. It requires a CT-based plan, during surgery, arrays fixed to the patient's femur and tibia allow the robot to know the limb position in space. After registering the patient's anatomy, the surgeon uses the robotic arm to perform bone resections. The haptic feedback prevents cutting outside the predefined boundaries. The ROSA system is another semi-active platform that can utilize calibrated X-rays or imageless intraoperative mapping for planning, and it assists the surgeon by positioning cutting guides and instruments according to the digital plan. An additional image-free next-generation robotic-assisted system is the VELYS™ Robotic-Assisted Solution (DePuy Synthes) designed to assist surgeons during total knee arthroplasty (TKA). It utilizes advanced technology to accurately map the knee's bony anatomy, enabling intraoperative planning of component positioning while preserving soft tissues, ensuring precise, efficient, and accurate execution of the surgical plan [6]. NAVIO/CORI is a handheld robotic system where the surgeon guides a burr, and the device only permits cutting within the planned boundaries. Other systems and prototypes (e.g., THINK TSurgical's Solution One, successor to ROBODOC) continue to emerge, but all share the goal of improving bony preparation and implant placement accuracy in TKA.

2.2. Intraoperative and Postoperative Outcomes

A primary rationale for employing robotic assistance in TKA is the promise of improved intraoperative accuracy (in alignment, bone resection precision, and ligament balance), which is expected to yield better postoperative outcomes such as pain relief, function, and implant longevity.

2.2.1. Alignment Accuracy and Implant Positioning

Multiple studies have confirmed that robotic-assisted TKA improves the consistency of achieving target alignment and component positioning compared to conventional techniques. In a landmark randomized trial, no patients in the robotic TKA group had a postoperative mechanical axis alignment beyond 3° of neutral, whereas 12 patients in the conventional group did—a significant reduction in outliers [25]. This indicates that robotic guidance can virtually eliminate large alignment errors that sometimes occur with manual jigs. Robotic systems have also shown superior accuracy in reproducing the planned bone resection parameters. For example, the tibial resection slope and depth and the femoral component rotation are more consistently on target with robotics, which can translate to better femoral-tibial gap balance. The same trial also noted improved flexion–extension gap balance in the robotic group compared to manual instrumentation [25]. Similarly, a comparative radiographic study found that component rotational alignment (a critical factor for patellofemoral tracking and knee kinematics) was more accurate with robot assistance, with reduced variability in femoral component rotation versus the surgical epicondylar axis [7]. In essence, robotic technology enhances the surgeon's ability to hit the alignment as planned.

The impact of this improved accuracy is evident in radiographic outcomes. Several systematic analyses have demonstrated fewer radiographic outliers in coronal alignment with robotic TKA. For instance, a meta-analysis of randomized trials reported significantly fewer outliers of the mechanical axis and component alignment in robot-assisted TKA compared to manual TKA [25]. Such precise alignment may contribute to more even load distribution across the knee and potentially better implant longevity (though long-term data are still forthcoming). Another benefit of robotic preoperative planning is the ability to account for patient-specific anatomy: for example, in patients with extra-articular femoral deformities where traditional intramedullary guides would be inaccurate, robotic systems can still achieve accurate alignment by referencing the 3D model rather than the abnormal bony anatomy. A 2022 case series illustrated that in knees with significant post-traumatic deformities, robot-assisted TKA achieved excellent coronal plane correction and component placement, enabling successful TKA in cases that would present significant technical difficulty using standard instruments [8].

2.2.2. Soft Tissue Balancing and Ligament Releases

A well-balanced knee is crucial for function and patient satisfaction. Robotic systems provide quantitative data on ligament balance and gap sizes throughout the range of motion. The surgeon can adjust virtual resection parameters to optimize balance before making any real bone cuts. One study observed that using robotic-arm assistance allowed surgeons to achieve alignment goals while minimizing collateral ligament releases, effectively using precise bone cuts to manage soft-tissue balance instead of extensive release techniques [9]. Additionally, some robotic platforms offer intraoperative sensing (for example, ROSA's optional ligament tension sensor) to guide incremental adjustments in alignment or component position based on real-time ligament tension feedback. The overall effect is that robotic TKA can protect soft tissues: by avoiding inadvertent over-resection or malposition that would require aggressive soft-tissue correction, the integrity of ligaments and surrounding structures is better preserved. This likely contributes to less postoperative pain and stiffness for patients.

2.2.3. Intraoperative Blood Loss

Another intraoperative outcome of interest is surgical blood loss. Robotic TKA often forgoes the use of intramedullary femoral alignment rods (which are used in conventional instrumentation to guide distal femoral cutting jigs)—these rods can elevate intramedullary pressure and cause bleeding and fat embolization. Robotic procedures also involve more measured bone resection without repeated recuts. In a 2018 study comparing robotic and manual TKA, the robotic TKA group had a significantly smaller drop in postoperative haemoglobin levels, suggesting reduced intraoperative blood loss [10]. This was attributed to the elimination of femoral canal broaching and the more controlled bone cuts. Less blood loss and fluid extravasation could contribute to reduced postoperative swelling and pain, thereby aiding recovery.

2.2.4. Early Postoperative Pain and Recovery

Improved surgical precision and reduced soft-tissue trauma with robotics appear to confer benefits in early postoperative recovery. In a prospective cohort study, patients who underwent robotic-arm–assisted TKA experienced significantly less pain in the first few days after surgery and required less opioid analgesia than those who had a conventional TKA [10]. They also achieved functional milestones sooner: on average, the robotic TKA patients performed an independent straight leg raise earlier and had greater knee flexion at discharge. These patients required fewer in-hospital physiotherapy sessions to reach discharge criteria and had a shorter hospital length of stay (median 77 h vs. 105 h) [10]. Another matched cohort study reported analogous findings at early follow-up—patients who received robotic-assisted TKA had better functional scores, higher Knee Society Scores and Oxford Knee Scores, and a higher percentage were able to walk independently earlier, compared to a matched manual TKA cohort [11].

By three months post-op, many robotic TKA patients demonstrated near-normal gait patterns faster than their conventional counterparts. One hypothesized mechanism for these early benefits is the reduced inflammatory response associated with robotic surgery. A 2022 retrospective study trial directly investigated the perioperative inflammatory milieu and found that robotic-arm TKA was associated with significantly lower serum levels of inflammatory markers, specifically, serum IL-6 levels on postoperative day 1 were lower in the robotic group (median 11.4 pg/mL) compared with the manual group (24.6 pg/mL). Likewise, CRP levels on day 3 were markedly reduced in the robotic cohort (76.1 mg/L) versus the conventional cohort (124.4 mg/L) [12]. These findings support the idea that robotic TKA causes less tissue insult possibly due to more precise bone cutting (less collateral damage to adjacent tissues) and avoidance of intramedullary instrumentation—leading to a reduced inflammatory response. This blunted inflammation correlates with less pain and quicker early functional gains. Potentially, we can also consider that robotic-assisted TKA may contribute to greater patient confidence and satisfaction, possibly offering psychological benefits, though such effects should be regarded with caution.

2.2.5. Mid-Term Clinical Outcomes

While early outcomes clearly favor robotic TKA in terms of pain reduction and functional recovery, these differences tend to diminish over time as both robotic and conventional TKA patients progress through standard rehabilitation and healing. By one year postoperatively, multiple studies have reported comparable clinical outcomes between robotic and manual TKA with respect to pain, range of motion, and general functional scores. A systematic review and meta-analysis of randomized controlled trials found no statistically significant differences in 12-month Forgotten Joint Scores or Oxford Knee Scores between robotic and conventional TKA groups, although the robotic group did experience greater early pain relief and improved alignment accuracy [27].

Certain patient-reported outcome measures, particularly those sensitive to knee function, have shown improved results with robotic-assisted techniques. In a multicenter study, we can observe a marked increase in Forgotten Joint Scores—from 17.5 preoperatively to 76.7 at over two years—indicating reduced joint awareness and suggesting that robotic-assisted TKA may enhance functional integration and patient satisfaction [13]. Other metrics such as patient satisfaction rates at five years were similarly high in both groups, and objective scores (e.g., WOMAC, Oxford Knee Score) tended to converge, underscoring that both techniques ultimately yield good results in the hands of experienced surgeons.

2.2.6. Long-Term Outcomes

While robotic-assisted TKA has demonstrated early advantages in recovery and alignment, longer-term outcomes beyond five years remain under investigation. Early generations of robotic systems—primarily active or semi-active platforms introduced in the 2000s—did not consistently yield superior implant longevity compared to conventional TKA. A meta-analysis of comparative studies found similar mid-term outcomes in functional scores and implant survivorship, suggesting that improved alignment had not yet translated into measurable reductions in wear or loosening [28]. These early studies, however, were often limited by small sample sizes and outdated hardware.

With the advent of more precise, image-based robotic platforms, there is renewed interest in whether minimizing alignment outliers and optimizing soft-tissue balance may reduce long-term failure risks such as polyethylene wear, loosening, and instability over 10–20 years. Recent studies have begun to address this question: for example, a 10-year follow-up found no significant difference in implant survivorship between robotic and manual TKA [26].

Larger series and registry-based cohorts currently in follow-up will be critical for determining whether outcome trajectories eventually diverge. As of now, robotic-assisted TKA achieves at least equivalent mid-term clinical success compared to conventional TKA, while offering better early postoperative recovery. Moreover, early evaluations suggest these benefits are achieved without compromising outcomes during the learning curve, and without introducing higher complication or revision rates [14].

2.3. Safety and Complications

Any new surgical technology must be rigorously evaluated for safety. For robotic-assisted TKA, key questions include whether using a robot introduces any additional intraoperative or perioperative risks, and whether complication rates differ from those of traditional TKA. The accumulated evidence to date indicates that robotic TKA is a safe procedure with a complication profile comparable to—and in certain aspects potentially better than conventional TKA.

2.3.1. Intraoperative Safety and Accuracy Checks

Robotic systems have multiple built-in safety features designed to prevent errors. In semi-active systems with haptic feedback, the robot will physically prevent the saw or burr from cutting outside the planned resection area, reducing the risk of accidental damage to critical structures like ligaments or neurovascular bundles. This safeguard arguably makes the precision of bone cuts higher and catastrophic errors less likely. For example, the risk of notching the anterior femoral cortex (which can happen if a distal femoral cut is made with the saw in excessive flexion or too deep) is minimized because the digital plan factors in the patient's bone anatomy and the robot stops the saw at the set depth. Furthermore, robotic software often forces the surgical team to verify key steps (for instance, to re-register anatomy if a tracker moves, or to confirm planned resection dimensions before cutting), which can catch potential mistakes before they affect the patient. These factors contribute to a strong safety record in published series of robotic TKA.

2.3.2. Early Postoperative Complications

A large comparative study has indicated that robotic TKA does not increase the risk of early postoperative complications and may even reduce it compared to conventional techniques [20]. Rates of typical complications such as deep infection, wound-healing problems, deep vein thrombosis, or the need for manipulation under anesthesia for stiffness have been found to be comparable between robotic and conventional TKA groups [10,11]. In some reports, robotic TKA patients even had a slightly lower incidence of certain technical complications. The more precise bone cuts might reduce the occurrence of femoral notching and related periprosthetic femur fractures, though such events are rare in both robotic and manual TKA, with incidence estimates ranging from 0.3% to 2.5% after primary TKA [19]. Overall, the early and mid-term data suggest that robotic TKA is at least as safe as conventional TKA, with notable improvements in some early recovery parameters and potentially subtle advantages in patient-perceived outcomes within a few years after surgery. TKA may be further optimized by incorporating additional strategies aimed at improving postoperative recovery outcomes. One such approach involves the use of metal-backed tibial component preferred over all-polyethylene tibial inserts due to their slightly lower revision rates as reported in prosthetic preference studies [29]. Additionally, the selection of specific TKA implant designs, such as posterior-stabilized (PS) versus cruciate-retaining (CR), may contribute to marginal gains in knee flexion and functional outcomes, with PS implants offering a slight advantage in some cases [30].

2.3.3. Implant Fixation and Durability

There were initial theoretical concerns that extremely precise cuts made by a robot could, in some cases, lead to less "bite" or purchase for cement if the cut surfaces were very smooth or if components were placed with minimal error (potentially reducing the micro-interlocking of cement). However, no clinical studies have shown higher rates of aseptic loosening with robotic TKA. On the contrary, by achieving optimal alignment and balance, robotics could reduce eccentric loading of the implant, potentially lowering the long-term risk of loosening. Early to mid-term follow-ups have shown no differences in radiographic signs of implant fixation between robotic and manual techniques—for example, specialized studies using radio stereometric analysis (RSA) have found comparable micromotion, indicating stable fixation in both groups [31]. Thus, there is no evidence that robotics adversely affects implant seating or longevity in the medium term.

2.3.4. Unique Complications Related to Robotics

Robotic TKA does introduce a few unique considerations. One is the need for fixation pins where the tracking arrays attach to the bones, these pins perforate the cortex and could, in rare instances, serve as stress risers or entry points for infection. Cases of pin-related fractures in TKA are extremely rare (more commonly reported in hip surgery when pins were placed in the femur for navigation), but finite element analysis has demonstrated that large-diameter pins in osteoporotic bone significantly elevate stress concentrations at the pin site, reinforcing this as a plausible theoretical risk [36]. Surgeons mitigate this by avoiding high-stress locations for pin placement (staying away from diaphyseal bone or joint margins and often using multiple smaller pins rather than one large one). Another theoretical risk involves potential robotic or software malfunctions during the procedure, potentially causing a bone cut in an incorrect location. In practice, the semi-active design of current systems prevents the robot from acting on its own—the surgeon is always in control of the cutting tool—so a software glitch would more likely result in the system pausing or shutting down rather than an unrestrained erroneous cut. Modern robotic platforms have rigorous system checks and redundant safety interlocks, for instance, the surgeon typically has a foot pedal or trigger that immediately deactivates the robotic enforcement if needed.

2.3.5. Soft Tissue Protection

Interestingly, robotic systems may reduce certain soft-tissue injuries. Because the bone resections are planned and executed to avoid excessive tightness or imbalance, the need for extensive soft-tissue releases (e.g., a large medial release in a varus knee) is less common, which in turn lowers the risk of instability from over-release. Soft-tissue injuries like avulsion of the patellar tendon or rupture of the posterior cruciate ligament (in cruciate-retaining TKA) have not been linked specifically to robotic usage. These remain risks in any TKA and appear unrelated to whether a robot is used. Additionally, the robotic arm's force limits provide a safety margin—if the arm encounters unexpected resistance (for example, if the leg moves suddenly), it will stop or alert rather than pushing through with force. A human with a powered saw might inadvertently apply more force and cause a structure to yield, in this sense, the robot can act as a guardian of the joint. One report highlighted the role of robotic-arm assistance in soft-tissue preservation, noting that the precision of bone cuts obviates the need to repeatedly insert or adjust cutting jigs (each manual manipulation of the joint can put stress on ligaments and soft tissues) [25]. Reduced manual manipulation of instruments within the joint may also lower the risk of soft-tissue contusions.

2.3.6. Inflammatory and Healing Response

As noted in the outcomes section, there is evidence of a lower acute inflammatory response with robotic TKA [12]. This could have positive implications for wound healing and pain. Another subtle benefit is the absence of intramedullary reaming in robotic cases, which may reduce subclinical fat emboli and postoperative fevers that sometimes occur when the femoral canal is instrumented. In summary, the biologic response to TKA appears, if anything, attenuated with robotic assistance, and there is no evidence of any deleterious inflammatory or healing issues attributable to the robot. The reduced acute inflammatory burden associated with robotic TKA may offer a meaningful advantage, particularly in younger and more active patients (e.g., under age 50), where durability and functional outcomes are critical. Recent studies also highlight an increasing prevalence of robotic TKA in these populations, aligning with expectations of improved long-term performance [21].

2.4. Learning Curve and Early Safety

A concern with any new technology is whether the learning curve could introduce safety issues for early cases. Reassuringly, early adoption of robotics in a surgeon's practice has not been associated with higher complication rates [22,23]. This supports the notion that, with adequate training, the technology can be safely implemented without increasing perioperative risk. Most vendors require surgeons to attend training courses and have an experienced proctor assist during the first several cases, which likely contributes to the safe rollout.

2.4.1. Registry Data

National joint registries provide insight into real-world complication rates and implant longevity. Data from the administrative U.S. database from 2010 to mid-2017 demonstrated lower rates of prosthetic revision at 1 year and fewer instances of manipulation under anesthesia at both 90 days and one year postoperatively [22]. Similarly, the Nationwide Inpatient Sample database (the largest all-payer inpatient healthcare database in U.S.) affirms the ongoing trend that the average hospital stay was shorter for RA-TKA patients (1.89 days) compared to Conventional TKA patients (2.29 day) [23]. While available registry follow-up for robotic TKA is still relatively short, these findings echo the clinical trial data in suggesting that robotics has not introduced new failure modes in the early postoperative period. In conclusion, current evidence indicates that robotic-assisted TKA has a strong safety profile: it has not led to higher complication rates in comparative studies and, by improving surgical execution, it might even reduce certain rare complications related to malalignment or technical errors.

2.4.2. Learning Curve and Surgeon Adaptation

Introducing robotics into surgical practice entails a learning curve for surgeons and operating room teams. Encouragingly, published research suggests that the learning curve for modern robotic TKA systems is relatively short and manageable, and that patient outcomes during this learning phase are not compromised. One study reported that the earliest robotic TKA cases showed no complications and safety outcomes comparable to conventional procedures, with cumulative summation (CUSUM) analysis revealing that surgeons reached procedural proficiency after as few as three to six cases [15]. Furthermore, the study emphasizes an additional consideration, as the learning curve in robotic-assisted total knee arthroplasty extends beyond the surgeon to the entire surgical team. During the learning phase (mean operative time 111.5 ± 20.5 min), team performance, including scrub nurse coordination and operating room setup, required more time compared to the proficiency phase (mean 86.4 ± 19.1 min) and manual TKA (mean 80.6 ± 17.0 min) [15]. While no discernible learning curve effect was observed in terms of bone cutting accuracy or limb alignment, the study found that more experienced surgeons reached procedural proficiency earlier, with shorter bone cutting and robot times [16].

2.4.3. Initial Challenges

When first adopting a robotic system, surgeons must learn the nuances of the software, the registration process, and the OR workflow integration. This initial period can cause longer operative times and a sense of unfamiliarity or even anxiety among the team. Adopting robotic systems introduces unfamiliar steps, which can challenge the surgical team during the early phase [15]. The unfamiliar steps—such as computer-based planning and reliance on a machine—can be disconcerting at first for those trained entirely on manual methods. There is also the task of orchestrating the team (scrub nurses, technicians, anesthesiologists) to adapt to the new workflow (for example, everyone must be mindful not to bump the reference arrays and to allocate time for registration without rushing instrument handover).

2.4.4. Early Outcomes During the Learning Phase

Crucially, patient outcomes in a surgeon's initial robotic cases have not been inferior to those in later cases. A Chinese study evaluating three surgeons found that operative bone cutting errors remained consistently within approximately 1 mm, with no statistically significant differences among the surgeons and no evident learning curve observed [16]. This suggests that even as the team was learning, patients still received the benefits of robotic precision without complications or negative outcomes. Proper preparation likely plays a role here: most surgeons embarking on robotic TKA will train with cadaver labs or simulators and have vendor support during their initial live cases, which promotes an accelerated transition to proficiency. Another study also noted that patient satisfaction was high even in the early cases, implying that the advantages of the technology may be apparent from case one [11].

2.5. Cost-Effectiveness Considerations

The adoption of robotic technology in TKA brings significant cost implications, which must be justified by its benefits. Costs can be examined from the perspective of the healthcare provider (capital and operating costs) and the broader system or society (cost-effectiveness, cost per quality-adjusted life year, etc.). This section discusses the various cost components of robotic TKA and what is known about its cost-effectiveness.

2.5.1. Upfront Capital Costs

Purchasing a robotic system is a major investment for a hospital or surgical center. Depending on the platform and configuration, a robot for TKA can cost on the order of $0.5–1 million (USD) or more. This does not include the cost of required imaging (if CT scans are needed, that adds expense per patient unless the facility already has that capability) and the disposables for each case (e.g., specialized burrs, pins, draping for the robot), as well as annual maintenance/service contracts for the robot hardware and software. These fixed costs mean that robotic TKA incurs higher initial expenses. However, the cost per case decreases as volume increases. A cost-effectiveness study demonstrated that robotic arm assisted total knee replacement is economically justified when performed in hospitals with more than 49 procedures per year [24]. At this threshold, the procedure provided a small improvement in quality-adjusted life—6.18 years versus 6.17 years with conventional surgery—at an additional cost that falls within commonly accepted value thresholds, the analysis also showed that robotic surgery was considered cost-effective in 50.4% of simulations based on standard healthcare spending benchmarks, with hospital procedure volume being the most influential factor affecting its economic value [24]. In other words, busy arthroplasty centers can distribute the robot's cost across many cases, whereas a smaller hospital might not justify the purchase if only few TKAs are done annually. Notably, national policies and payer decisions have started to recognize the value proposition of robotic-assisted TKA based on emerging cost-effectiveness data. For example, a decision-analytic model for Medicare-aged patients in the United States demonstrated cost-effectiveness—measured by cost per quality-adjusted life year (QALY)—when annual procedural volume exceeded approximately 49–50 cases per year (at a willingness-to-pay threshold of $50,000/QALY) [24].

2.5.2. Perioperative Costs and Savings

Each robotic case may involve a slightly longer operative time (especially early in adoption), which has an associated cost—operating room time is expensive when considering staffing and anesthesia. If a robotic TKA takes 15 min longer than a conventional one, it would incrementally increase cost. However, studies have examined whether certain cost savings might offset this. For example, if robotic TKA patients have shorter hospital stays, that is a direct cost savings. In one cohort study, the robotic TKA patients had about a 28-h shorter hospital length of stay on average compared to manual TKA patients, which in many health systems could translate to nearly a full day's worth of hospital charges saved [10]. Early mobilization and better pain control with robotics could also reduce the need for expensive inpatient rehabilitation or extended physical therapy, potentially yielding further savings. Some analyses suggest that if the robotic approach can reliably reduce length of stay or rehabilitation needs, those savings can partially counterbalance the added intraoperative expense [10].

Another potential cost factor is implant longevity. If robotic TKA were to significantly reduce long-term failure rates (due to better alignment and less wear), it could avoid the need for costly revision surgeries down the line. Revision TKA is far more expensive than primary TKA, so even a modest decrease in 10- to 15-year revision rates could make robotics cost-saving in the long run. However, this benefit remains speculative until long-term data confirm any difference in revision rates. Currently, since mid-term clinical outcomes appear similar between robotic and manual TKA, economic analyses tend to focus on perioperative costs.

2.5.3. Cost-Effectiveness Analyses

Hoeffel et al. examined the economic and healthcare resource utilization outcomes for robotic and manual TKA across multiple studies and found that direct surgical costs (due to longer operative times and the robot usage fees) are indeed higher for robotic TKA, but there were trends toward lower postoperative costs in the robotic group (such as shorter inpatient stays and possibly lower readmission or post-acute rehabilitation costs) [32]. Overall, the difference in total episode-of-care cost between robotic and manual TKA was small in most analyses. Many studies reported no significant difference in overall cost per case when factoring in the entire 90-day episode of care [32]. Essentially, the higher intraoperative costs were balanced by slight reductions in postoperative resource utilization for robotic TKA. Some healthcare systems also encourage protocols like outpatient or rapid-recovery arthroplasty. Robotic precision might facilitate same-day discharges, which, if achieved, can significantly reduce the cost per case. Future developments may also expand the role of robotic assistance beyond primary TKA, including its application in more complex cases such as revision implants. This may help reduce intraoperative fracture risk by enabling more accurate bone preparation for sleeves or enhancing cone placement to prevent late fractures, thus supporting long-term fixation and alignment stability critical factors for avoiding complications [33]. The potential benefits of robotic-assisted techniques extend to patellar resurfacing decisions and implant type selection, both of which influence outcomes and reoperation rates. Evidence supports patellar resurfacing to improve knee scores and reduce the risk of secondary procedures [34]. Robotic systems should not be regarded as exclusive to total knee arthroplasty (TKA), as their precision is increasingly applicable to procedures like unicompartmental knee arthroplasty (UKA). In this context, patient-reported outcomes such as the Forgotten Joint Score (FJS) have proven clinically relevant, with validated thresholds for minimal important difference and patient-acceptable symptom state. These benchmarks offer valuable reference points for assessing satisfaction and consistency across robotic knee procedures, potentially reducing variability in outcomes among different arthroplasty types [17]. However, some analyses present a less favorable outlook. Hospitals must consider the opportunity cost of the capital spent on a robot—could those funds have improved care elsewhere? Also, maintaining proficiency and utilization of the robot is necessary to gain value, an underused robot still incurs maintenance costs without much return. These factors mean that the financial viability of a robotic program can vary greatly depending on the institution's circumstances.

2.5.4. Reimbursements and Financial Incentives

While robotic-assisted TKA holds promise for improving surgical outcomes, its adoption is not uniform across healthcare settings, leading to significant disparities in access and equity. Schmerler et al. demonstrated that access to RA-TKA is significantly influenced by socioeconomic and demographic factors, with patients treated in private institutions and those from higher-income backgrounds being more likely to receive robotic surgery compared to those managed in public hospitals or from underserved communities [3]. This variation is compounded by the high upfront costs of robotic systems, which are more readily absorbed by well-funded private centers, whereas many public hospitals, particularly those serving vulnerable or rural populations, may struggle to justify or afford such investments [24].

National reimbursement models further modulate these inequities; for instance, lack of additional reimbursement for robotic procedures in public systems may disincentivize adoption outside of high-volume, resource-rich private centers. These disparities raise important questions about equitable access to surgical innovation and highlight the risk that RA-TKA may disproportionately benefit populations already advantaged in healthcare delivery.

An additional consideration in anticipating the future of surgical innovation is the rapid progression of artificial intelligence capabilities. The integration of robotics with AI-driven predictive models, such as random forests and neural networks, offers a compelling clinical advantage. These technologies have demonstrated potential in accurately forecasting postoperative complications, optimizing implant selection, and individualizing perioperative management. Such advancements may enhance clinical outcomes, improve resource efficiency, and support value-based reimbursement frameworks that prioritize risk-adjusted, precision-driven care [35]. These considerations underscore the role of patient-centered factors in influencing adoption decisions and suggest that psychological preparedness and educational engagement may complement institutional financial evaluations of robotic TKA programs. In parallel, financial incentives and reimbursement structures remain critical determinants of how quickly and widely robotic TKA is implemented in clinical practice. In summary, robotic TKA can be economically justified in the right context—typically high-volume centers with an emphasis on enhanced recovery—but careful implementation and continuous outcome monitoring are key. Maximizing the utilization of the robot, leveraging its benefits for faster recovery, and rigorously evaluating outcomes and costs will determine whether a robotic program truly adds value. As more long-term outcome data emerge, especially regarding implant longevity, the overall value proposition of robotic TKA will become clearer.

3. Conclusions

Robotic-assisted total knee arthroplasty represents a significant evolution in the approach to knee replacement surgery. The evidence amassed over the past decade demonstrates that this technology can enhance the precision of TKA, leading to consistently improved alignment and implant positioning compared to conventional techniques. Early adopters have reported that patients benefit from reduced postoperative pain, faster functional recovery, and high satisfaction in the early period after robotic TKA—all achieved without an increase in perioperative complications.

At mid-term follow-up, robotic TKA appears to perform at least as well as traditional TKA, with some indications of superior patient-perceived outcomes. However, it is equally clear that robotic TKA is not a panacea. Long-term data are still needed to determine whether the higher upfront costs and procedural investments yield meaningful improvements in implant durability or patient outcomes over the span of decades. The current literature suggests that if robotics confers a long-term advantage, it may be in reducing edge-case failures (for example, cases of extreme malalignment that lead to premature wear or failure) rather than dramatically changing the fate of the average well-done TKA.

From a practical standpoint, the introduction of robotics has proven safe and feasible, with a relatively quick learning curve and a strong safety profile. These factors support continued adoption and study of the technology. Surgeons incorporating robotics should do so with careful training and patient selection, and they should contribute their outcomes to joint registries or studies so that the orthopaedic community can collectively learn and refine best practices. Robotic TKA also paves the way for a more personalized approach to knee arthroplasty—one that can account for each patient’s unique anatomy and alignment philosophy (whether mechanical, kinematic, or hybrid) and execute it with high fidelity. As the technology matures, future systems will likely further integrate soft tissue balancing feedback and advanced sensors and possibly enable remote or autonomous surgical functionalities. Such innovations, combined with accumulating clinical evidence, will clarify the full value of robotic assistance.

In conclusion, robotic-assisted TKA is a transformative tool that, when applied thoughtfully, enhances the surgical precision and consistency of knee arthroplasty. It offers measurable improvements in accuracy and early recovery without compromising safety, addressing some longstanding challenges in TKA such as alignment outliers and component placement variability. The decision to utilize robotics should be guided by an understanding of its benefits, limitations, and resource implications. With ongoing research and technological advances, robotic TKA may become an integral part of optimizing outcomes for patients undergoing knee replacement in the years to come.

Author Contributions

U.G.L.: conceptualization, supervision, writing—review and editing; M.D.B.: methodology, data curation, writing—original draft preparation; M.L.: investigation, visualization, validation; A.d.S.: resources, formal analysis, writing—review and editing; P.D.: supervision, critical revision of the manuscript for important intellectual content. All authors have read and agreed to the published version of the manuscript.

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