JOINTS 2025; 3: e1523

Category: Narrative Review

# ROBOTICS IN TKA: STATE OF THE ART AND FUTURE PERSPECTIVES

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

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

## INTRODUCTION

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

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

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

In response to the need for more personalized and precise implant positioning to better replicate natural knee anatomy and kinematics, technologies such as navigation systems and robotic-assisted surgery have emerged[9].

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

## HISTORY OF ROBOTIC TECHNOLOGIES

The evolution of technology in total knee arthroplasty (TKA) in order to enable surgeons to achieve more accuracy and precision began with the introduction of computer-assisted surgery (CAS), specifically navigation systems, in the late 1990s[10]. Navigation technology aimed to improve the accuracy of implant placement by providing real-time feedback on alignment and positioning[11]. Surgeons could use this data to make adjustments during the procedure, which helped reduce errors compared to traditional, manual methods[12]. Although navigation systems enhanced precision and improved surgical outcomes, the majority of studies in the literature agree that navigation has not resulted in significant clinical advantages in terms of mid-to-long-term outcomes or patient satisfaction, despite its role in improving alignment accuracy[13,14].

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

## IMAGE-BASED *VS*. IMAGELESS ROBOTIC SYSTEMS

Robotic-assisted TKA uses computer software to create a virtual three-dimensional (3D) model of the patient's specific bony anatomy, enabling the surgeon to pre-plan bone cuts, component size, and positioning[9]. This surgical plan is then mapped intraoperatively to the patient's anatomy using navigational software.

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

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

### Passive, Semi-Active, Active Robotic Systems

Passive robotic systems have seen limited adoption in total knee arthroplasty (TKA) due to their reliance on computer-assisted or navigation technology that provides visual guidance to the surgeon through an overhead display[25]. These systems allow for surgical planning, but the execution of the procedure depends heavily on the surgeon's manual input throughout the operation and therefore still carries the risk of human error. Furthermore, they lack haptic feedback mechanisms, meaning there are no physical restraints to ensure precise bone preparation or implant positioning[26,27].

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

Semi-active systems, in particular, allow the surgeon to guide the robotic arm while performing bone preparation[28].

Active robotic systems create the surgical plan offline based on preoperative CT scans and during the operation function autonomously, under the surgeon's supervision, without requiring continuous real-time guidance[29]. After the surgeon completes the initial approach, protects the soft tissues, and attaches the limb to a fixed device, the robotic arm is activated to independently perform the bone resections[30,31].

## Open/Closed Systems

The terms "open" and "closed" platform refer to whether the system allows the flexibility to select any type of prosthesis for implantation or is restricted to a specific proprietary prosthesis. The primary advantage of open platforms is the compatibility with a wide range of implant designs from different manufacturers, offering greater flexibility in selecting implants that best suit the patient's needs[32]. However, this versatility comes with a downside: the lack of implant design specificity and limited biomechanical data to optimize implant positioning. As a result, outcomes may be predictable and more dependent on the type of prosthesis[32].

On the other hand, closed platforms provide more detailed biomechanical data and precise implant positioning for the specific prostheses they support. In this case, the downside is their restrictiveness, offering compatibility only with specific implant models[33]. This limits the surgeon's options, as they may need to use implants tied to the platform rather than their preferred designs and this reduces the freedom of choice for the surgeon[34,35].

## Robotic Systems

Several robotic platforms are available for TKA, each offering different approaches to enhancing surgical precision, implant positioning, and alignment. These systems vary in their reliance on preoperative imaging, real-time intraoperative adjustments, and the level of surgeon control *vs.* robotic automation[36].

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

- ROBODOC (THINK Surgical Inc., Fremont, CA, USA) is an active, image-based, open system. First developed in 1992 and now marketed as TSolution-One by Think Surgical Inc. (formerly Curexo Technology), this system is image-guided (using CT scans), fully autonomous (requiring no surgeon intervention), and features an open platform compatible with any implant. Despite its advanced capabilities, adoption of fully active robotic TKA systems has been limited due to the high cost of installation and the elevated risk of complications during the learning phase[25].
- Mako (Stryker, Mako Surgical Corp., Fort Lauderdale, FL, USA) is a semi-active, image-based closed system. It is a platform that uses preoperative CT imaging to create a 3D model of the patient's anatomy to guide bone resection, implant sizing, and positioning[37]. Once bony landmarks are registered and validated, the system generates a digital model of the knee. It also enables intraoperative adjustments to component positioning, using patient-specific alignment and ligament balancing data, before finalizing the bone resection. This semi-active robotic system halts the saw if bone resection deviates from the preoperative plan's predefined parameters within 0.5 mm of the planned surgical cuts[38].
- ROSA (Zimmer Biomet, Warsaw, IN, USA) represents a semi-active image-dependent or imageless, closed system[23]. One approach involves creating a 3D virtual model by combining data from preoperative X-rays with surface landmarks registered intraoperatively, reducing errors from inaccurate data. X-rays are cheaper, expose patients to less radiation, and avoid additional visits compared to CT scans. Alternatively, a second method relies solely on intraoperative landmark registration for 3D modeling, decision-making, and resection planning, offering comparable accuracy without preoperative imaging. Once the planning phase is completed, the surgeon is enabled to perform with a manual saw the femoral and tibial cuts thanks to the robotic arm, which positions a cutting block according to the surgeon's preference for bone preparation. Furthermore, another feature of the robot is the validation tool, which can be applied to the prepared surfaces to ensure the resections align with the surgical plan[39].

- CORI (Smith & Nephew, Inc., Memphis, TN, USA) is a semi-active imageless closed system[40]. Intraoperatively, a probe is used to map the bony anatomy of the distal femur and tibia. The system allows the surgeon to operate with a handheld robotic burr on a sculpting tool, which automatically slows down or retracts if it deviates from the boundaries of the surgical plan. Although the burr can be used to complete all bone preparation, most surgeons opt for a hybrid approach in primary TKA. This involves using the robotic tool to create holes for standard cutting jigs, after which a bone saw is manually used to prepare the femur and tibia[41].
- VELYS robotic-assisted solution (VRAS) (Depuy, Warsaw, IN, USA) is a semi-active, imageless, closed system. It represents one of the latest innovations in robotic technology for total knee arthroplasty. As an imageless system, VRAS does not require preoperative CT scans, with a consequent reduction in preparation time, costs, and radiation exposure for the patient. This robotic system is closed and, therefore, exclusively the ATTUNE Knee System by DePuy Synthes can be used, which is a widely used knee implant that enables precise and well-informed decision-making during surgery. In literature, early studies have shown promising outcomes for VRAS in TKA, indicating its potential value in improving surgical accuracy and patient outcomes[42].
- The SkyWalker™ robotic arm system (model OSR-1000, developed by MicroPort OrthoBot Co. Ltd. in Suzhou, China) is a semi-active, imageless, closed platform primarily derived from the technology of the Robodoc and MAKO systems. Created by Chinese researchers, this new robotic device aims to deliver safety, efficiency, and precision in minimally invasive settings. However, the effectiveness of this innovative robotic technique still requires more in-depth research for full evaluation[43].

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

## FUNCTIONAL ALIGNMENT AND IMPLANT POSITIONING

Functional alignment (FA) is regarded as an evolution of the traditional kinematic alignment (KA) method, made possible by advancements in robotic technology[44]. This approach aims to restore the natural obliquity of the joint line and balance the knee flexion-extension gap through precise adjustments of the tibial and femoral components, thereby minimizing the need for soft tissue releases[45]. The integration of robotic systems is essential for accurately assessing implant position, resection thickness, joint gaps, and limb alignment during surgery.

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

**Table 1.** Main features of robotic systems used in joint arthroplasty.

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

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

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

Robotic-assisted total knee arthroplasty has shown significant advantages over manual TKA in terms of precision in component positioning in the coronal, sagittal, and axial planes[48]. The higher precision in sagittal plane positioning allows for more accurate gap balancing, a critical factor in achieving optimal knee function and longevity after surgery.

Rossi et al[49] demonstrated that the ROSA Knee System enables high accuracy in bone resections during total knee arthroplasty, with deviations from planned surgical angles consistently under 1 mm or 1 degree, confirming its precision in implant positioning[49]. Moreover, the ROSA Knee System's potential to individualize implant alignment during total knee arthroplasty has been highlighted. By leveraging robotic assistance, the system enables precise, patient-specific alignment in three dimensions, optimizing ligament balancing and implant positioning[47,50].

As compared to image-less navigation systems, Mancino et al[51] compared a novel image-less robotic-assisted total knee arthroplasty with an established image-less navigated technique to assess implant positioning accuracy. Their retrospective analysis of 172 cases showed that the robotic technique achieved significantly smaller deviations from target angles for femoral and tibial components compared to navigation, particularly in femoral flexion and tibial alignment. This suggests that robotic total knee arthroplasty offers enhanced precision in implant positioning without increasing alignment outliers[51].

In terms of coronal alignment, Kayani et al[52] have demonstrated that the femoral and tibial components, as well as tibial slope, in robotic TKA showed a closer alignment with the surgical plan as compared to manual TKA[52]. Also, the posterior condylar offset ratio (PCOR) showed significantly smaller differences between pre- and post-operative values in robotic TKA compared to manual TKA, as demonstrated by Sultan et al[53].

Moreover, Mahoney et al[54] found that using robotic-assisted TKA led to greater precision in the external rotation of the femoral component relative to the transepicondylar axis, though this improvement was not statistically significant[54].

## FUNCTIONAL OUTCOMES

While improved alignment and positioning are critical, the relationship between these factors and clinical outcomes remains complex[55].

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

One advantage of functional alignment in RA-TKA is the restoration of the patient's native phenotype by enabling more precise component positioning and alignment. Studies[56] suggest that robotic systems enhance the replication of pre-arthritic knee alignment, optimizing joint balance. This improved restoration of the native phenotype has been associated with better functional outcomes, including more natural gait patterns and improved range of motion[57,58].

Many studies[59,60] have concluded that early post-operative outcomes in terms of pain and length of hospital stay are more favorable in RA-TKA. However, literature[61-63] agrees in concluding that there is no statistically significant superiority in long-term functional outcomes measured with PROMs.

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

## COMPLICATIONS AND REVISION RATES

Earlier robotic systems were associated with a high rate of complications. Park and Lee[64] reported a complication rate of 19%, which included issues such as superficial infection, patellar tendon rupture and dislocation, supracondylar fracture, and peroneal nerve injury. However, these complications seemed to occur mainly in the early cases, likely due to the use of smaller incisions during the learning phase[36]. After larger incisions were adopted, these issues were avoided. Technical failures were also noted, with intra-operative conversion to traditional total knee arthroplasty (TKA) due to technical issues with the ROBODOC system occurring in up to 30% of cases[65].

Newer robotic systems have reduced the rate of complications, but some issues are still to be debated. Mechanical weakness from pinholes in robotic total knee arthroplasty (TKA) can lead to feared complications such as femoral or tibial shaft fractures. A study[66] found that the incidence of pin-site femoral fractures was 1.4%, typically occurring around 12.6 weeks post-surgery, often preceded by unusual thigh pain. These fractures usually result from minor trauma and are treated with intramedullary fixation. To mitigate this risk, it has been suggested to place pins in periarticular areas, which are more resilient to stress, and to use smaller pins[67]. Pin-site infections are another concern, although their overall incidence is low, at approximately 0.47%[68]. Other iatrogenic injuries may include patellar tendon ruptures, patellar dislocations, fractures, and peroneal nerve injuries[36]. While some studies[52,69] suggest robotic TKA is associated with fewer injuries compared to conventional methods, others indicate a higher incidence of iatrogenic injuries with active robotic systems. Additionally, robotic procedures tend to result in greater estimated blood loss, potentially due to longer operative times. However, robotic TKA does not require opening the femoral canal, which could theoretically reduce blood loss. Robotic systems are designed to decrease post-TKA stiffness through precise alignment, but the literature[70] has reported stiffness as a complication following robotic TKA. The present review highlighted that longer surgical times are a consistent issue with robotic systems, which can increase the risk of infection, particularly when surgical time exceeds 120 minutes. Recent reviews[71,72] found a higher incidence of deep prosthetic joint infections with robotic TKA (1.6-1.7%) compared to conventional methods (0.44-1.0%).

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

### Learning Curve

The learning curve typically refers to the number of cases required to achieve consistent outcomes. In the context of robotic total knee arthroplasty (TKA), this often includes evaluating the reduction in surgical time. Literature agrees that the learning curve for robotic TKA varies from 10 to 50 cases[75,76]. Importantly, these studies found no increased risk of complications during the learning phase associated with the current robotic technology[77]. This marks a significant improvement over earlier systems, which reported high early complication rates and increased soft tissue damage during their learning phases, including injuries to the patellar tendon due to inadequate surgical exposure.

## COSTS AND ECONOMIC IMPACT

One of the most critical aspects of integrating robotics into knee prosthetic surgery is the financial burden it imposes on healthcare systems[78]. These costs can significantly impact the accessibility and scalability of robotic-assisted surgeries, raising important questions about cost-effectiveness, reimbursement policies, and the balance between the clinical advantages and financial feasibility for both hospitals and patients[79].

The cost-effectiveness of robotic-assisted total knee arthroplasty has become a focal point of discussion as healthcare systems weigh the benefits of advanced technology against its financial implications. According to Vermue et al[80] procedures, robotic-assisted total knee arthroplasty becomes cost-effective when the annual case volume exceeds 253 procedures. While the initial investment in robotic systems is substantial, these high upfront costs can be mitigated by long-term savings[81]. Faster recovery times, shorter hospital stays and decreased post-acute care needs, such as fewer nursing services and less postoperative therapy, are all key contributors to lowering overall healthcare expenses. Additionally, patients undergoing RA-TKA often require less inpatient therapy and are discharged more quickly, further enhancing the financial benefits for hospitals and healthcare systems. Savings are ultimately driven by fewer readmissions, reduced reliance on rehabilitation services, and a more efficient postoperative care pathway[82].

While robotic-assisted knee arthroplasty offers several economic advantages, it is important to consider the significant additional costs that come with adopting this technology. These include expenses for specialized software, routine equipment maintenance, and disposable surgical tool[83]. Additional diagnostic imaging, such as preoperative CT or MRI scans, is often required, further increasing costs. Medical staff also require extensive training to use the technology effectively, adding to the financial burden[84]. Moreover, other indirect costs, such as longer setup times and the need for extra personnel during procedures, contribute to the overall increase in operational expenses[85].

Literature agrees that robotic TKA can be cost-effective, particularly in elevated-risk patient populations (e.g., younger patients, higher BMI, male sex) and larger practice settings, where the reduction in revision risk and associated quality-adjusted life year (QALY) gains justify the additional costs[86]. However, achieving cost-effectiveness depends on factors such as surgical precision, patient selection, and local economic conditions, emphasizing the importance of a risk-prioritized approach to optimize resource utilization[87].

## FUTURE PERSPECTIVES

As a future perspective in robotic surgery, we can explore immersive virtual reality (IVR), augmented reality (AR), and mixed reality (MR), such as the spectrum of extended reality technology integration, representing the intersection between advanced computing and imaging and their use in the operating room environment[88,89]. IVR also serves as an excellent teaching tool, providing surgical trainees of all levels access to a variety of techniques that accurately replicate real-life procedures without additional risks to the patient, costly resources (e.g., cadavers) or even the need for supervision[90]. AR-based navigation technologies have been shown to improve the accuracy of component positioning in hip and knee arthroplasty and MR allows even more freedom of control over CT reconstructions for preoperative planning as well as intraoperative visualization, requiring less preoperative calibration by the surgeon because the data can be adjusted intraoperatively by the surgeon[91,92]. The application of machine learning (ML) in KA has been useful for predicting implant size, reconstructing data, and assisting with component positioning and alignment; it enhances surgical precision and can help predict patients' outcomes[93,94]. AI can handle very large, complex datasets and generate predictions and decisions on KOA and TKA[94]. ML potentially improves surgical precision and reduces the cost of manual labor. Regarding value metrics, ML methods have been used to predict the length of hospital stay, hospitalization charges, and discharge disposition. It impacts the economic burden of TKA and thus potentially affects decisions on payment models in healthcare settings[93].

Those technologies have some current limitations, including: first, accuracy and generalizability are key obstacles, as very few models have been externally validated, and high AUC values do not necessarily translate to good clinical performance[95]. Second, a practical disadvantage of machine learning models is the need for large datasets to train them. These datasets often contain millions of unique data points and require hours or days of training, and additional datasets are needed to assess generalizability[96].

Third, a common concern about the use of artificial intelligence is the "black-box" nature of machine learning models. Machine learning algorithms' decision-making processes are complex, using hidden layers and unknown connections between inputs and outputs, resulting in poor understanding and difficult scientific interpretation of how they generate predictions and recommendations[97].

We can also explore their use in revision surgery that may be helpful for a reproducibly preoperative plan, contribute to accurate bone cuts and preserve more bone stock, and precise positioning of the final implant in revision total joint arthroplasty (TJA). For RA-TKA, the benefits mainly include accurate bone cutting and the ability to evaluate the type of alignment and mechanical alignment, which is often a challenge due to the loss of bony reference points after implant removal[98].

In a recent study, Leung et al[99] developed a deep learning model to predict the need for TKA directly from knee radiographs. This model outperformed traditional binary outcome models that rely on the Kellgren-Lawrence or Osteoarthritis Research Society International grades. The deep learning models incorporated additional image-based information that may not be captured by simple numerical grading systems. Therefore, further studies can be conducted to analyze the interaction between all these systems.

Further studies are needed to evaluate improvements in patient satisfaction and component survival for revision robotic-assisted TKA surgeries. We also need to evaluate the cost related to the robotic-assistance arm software and conduct further studies to determine whether the cost of obtaining the software is mitigated by the cost of the revision surgery[100].

Another important issue that has been increasingly addressed in the most recent literature is the proper management of the patella and anterior space in TKA to avoid patellofemoral joint imbalance, including overstuffing and understuffing. Functional alignment, combined with robotic assistance, allows for optimized femoral component positioning and better preservation of native knee kinematics[101]. Shatrov et al[102] analyzed 122 robotic-assisted TKAs using functional alignment principles and found that while the trochlea was always balanced in full extension, over 40% of cases were over- or under-stuffed in mid and deep flexion. Under-stuffing was more common in mid-flexion, while over-stuffing predominated in deep flexion. The study highlights the need to redefine patellofemoral joint (PFJ) over- and under-stuffing across the full range of motion and further investigate its biomechanical and clinical implications[102].

## DISCUSSION

This article emphasizes that robotic-assisted surgery represents a significant advancement over traditional methods, primarily by improving the precision of implant placement and soft tissue balancing. This precision is crucial for obtaining optimal outcomes; for example, misalignment can lead to complications and decreased longevity of the implant. However, the interpersonal variability of patients' satisfaction and long-term functional outcomes suggests that while the technology offers improved accuracy during surgery, it does not automatically lead to better clinical results. Despite reported satisfaction rates of 82-89%, literature states a lack of statistically significant superiority in long-term outcomes when comparing robotic-assisted TKA to conventional techniques[98,100,103]. This gap raises questions about the factors influencing patient satisfaction beyond surgical precision and highlights the complexity of the surgical experience, which may vary from preoperative expectations, postoperative recovery, individual patient anatomy, and functional requests. Future research should aim to explore these dimensions more exhaustively. Surgeon training and the learning curve of the robotic-assisted technologies are crucial, and this can significantly impact patient safety[77].

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

## CONCLUSIONS

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

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

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

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**Acknowledgements:**

The authors would like to express their gratitude to all colleagues and institutions who contributed to the discussion and development of this manuscript. Their insights and expertise have been invaluable in shaping this work.

**Funding:**

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

**Availability of Data and Materials:**

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

**Conflict of Interest:**

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

**Ethics Approval and Informed Consent:**

Not applicable.

**Authors' Contributions:**

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

## REFERENCES

1. Sharma L. Osteoarthritis of the Knee. N Engl J Med 2021; 384: 51-59.
2. Michael JW, Schlüter-Brust KU, Eysel P. The epidemiology, etiology, diagnosis, and treatment of osteoarthritis of the knee. Dtsch Arztebl Int 2010; 107: 152-62. Erratum in: Dtsch Arztebl Int 2010; 107: 294.
3. Rönn K, Reischl N, Gautier E, Jacobi M. Current surgical treatment of knee osteoarthritis. Arthritis 2011; 2011: 454873.
4. Fibel KH, Hillstrom HJ, Halpern BC. State-of-the-Art management of knee osteoarthritis. World J Clin Cases 2015; 3: 89-101.
5. Kahlenberg CA, Nwachukwu BU, McLawhorn AS, Cross MB, Cornell CN, Padgett DE. Patient Satisfaction After Total Knee Replacement: A Systematic Review. HSS J 2018; 14: 192-201.
6. Bourne RB, Chesworth BM, Davis AM, Mahomed NN, Charron KD. Patient satisfaction after total knee arthroplasty: who is satisfied and who is not? Clin Orthop Relat Res 2010; 468: 57-63.
7. Matassi F, Pettinari F, Frasconà F, Innocenti M, Civinini R. Coronal alignment in total knee arthroplasty: a review. J Orthop Traumatol 2023; 24: 24.
8. Rivière C, Iranpour F, Auvinet E, Howell S, Vendittoli PA, Cobb J, Parratte S. Alignment options for total knee arthroplasty: A systematic review. Orthop Traumatol Surg Res 2017; 103: 1047-1056.
9. Innocenti B, Bori E. Robotics in orthopaedic surgery: why, what and how? Arch Orthop Trauma Surg 2021; 141: 2035-2042.
10. Shatrov J, Parker D. Computer and robotic-assisted total knee arthroplasty: a review of outcomes. J Exp Orthop 2020; 7: 70.
11. Van der List JP, Chawla H, Joskowicz L, Pearle AD. Current state of computer navigation and robotics in unicompartmental and total knee arthroplasty: a systematic review with meta-analysis. Knee Surg Sports Traumatol Arthrosc 2016; 24: 3482-3495.
12. Li J, Zhang Y, Gao X, Dou T, Li X. Accelerometer-based navigation vs. conventional techniques for total knee arthroplasty (TKA): a systematic review and meta-analysis of randomized controlled trials. Arthroplasty 2022; 4: 35.
13. Li JT, Gao X, Li X. Comparison of iASSIST Navigation System with Conventional Techniques in Total Knee Arthroplasty: A Systematic Review and Meta-Analysis of Radiographic and Clinical Outcomes. Orthop Surg 2019; 11: 985-993.
14. Lee DY, Park YJ, Hwang SC, Park JS, Kang DG. No differences in mid- to long-term outcomes of computer-assisted navigation versus conventional total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc 2020; 28: 3183-3192.
15. Blakeney WG, Vendittoli PA. The Future of TKA. 2020 Jul 1. In: Rivière C, Vendittoli PA, editors. Personalized Hip and Knee Joint Replacement [Internet]. Cham (CH): Springer; 2020. Chapter 15.
16. Singh J, Patel P. Robotics in Arthroplasty: Historical Progression, Contemporary Applications, and Future Horizons With Artificial Intelligence (AI) Integration. Cureus 2024; 16: e67611.
17. Sicat CS, Chow JC, Kaper B, Mitra R, Xie J, Schwarzkopf R. Component placement accuracy in two generations of handheld robotics-assisted knee arthroplasty. Arch Orthop Trauma Surg 2021; 141: 2059-2067.
18. Bollars P, Janssen D, De Weerdt W, Albelooshi A, Meshram P, Nguyen TD, Lacour MT, Schotanus MGM. Improved accuracy of implant placement with an imageless handheld robotic system compared to conventional instrumentation in patients undergoing total knee arthroplasty: a prospective randomized controlled trial using CT-based assessment of radiological o. Knee Surg Sports Traumatol Arthrosc 2023; 31: 5446-5452.
19. Kafelov M, Batailler C, Shatrov J, Al-Jufaili J, Farhat J, Servien E, Lustig S. Functional positioning principles for image-based robotic-assisted TKA achieved a higher Forgotten Joint Score at 1 year compared to conventional TKA with restricted kinematic alignment. Knee Surg Sports Traumatol Arthrosc 2023; 31: 5591-5602.

20. Calliess T, Ettinger M, Savov P, Karkosch R, Windhagen H. Individualized alignment in total knee arthroplasty using image-based robotic assistance: Video article. Orthopade 2018; 47: 871-879.
21. Mont MA, Cool C, Gregory D, Coppolecchia A, Sodhi N, Jacofsky DJ. Health Care Utilization and Payer Cost Analysis of Robotic Arm Assisted Total Knee Arthroplasty at 30, 60, and 90 Days. J Knee Surg 2021; 34: 328-337.
22. Smith-Bindman R, Lipson J, Marcus R, Kim KP, Mahesh M, Gould R, Berrington de González A, Miglioretti DL. Radiation dose associated with common computed tomography examinations and the associated lifetime attributable risk of cancer. Arch Intern Med 2009; 169: 2078-2086.
23. Batailler C, Hannouche D, Benazzo F, Parratte S. Concepts and techniques of a new robotically assisted technique for total knee arthroplasty: the ROSA knee system. Arch Orthop Trauma Surg 2021; 141: 2049-2058.
24. Mancino F, Rossi SMP, Sangaletti R, Lucenti L, Terragnoli F, Benazzo F. A new robotically assisted technique can improve outcomes of total knee arthroplasty comparing to an imageless navigation system. Arch Orthop Trauma Surg 2023; 143: 2701-2711.
25. Park SE, Lee CT. Comparison of robotic-assisted and conventional manual implantation of a primary total knee arthroplasty. J Arthroplasty 2007; 22: 1054-1059.
26. Konyves A, Willis-Owen CA, Spriggins AJ. The long-term benefit of computer-assisted surgical navigation in unicompartmental knee arthroplasty. J Orthop Surg Res 2010; 5: 94.
27. Banks SA. Haptic robotics enable a systems approach to design of a minimally invasive modular knee arthroplasty. Am J Orthop (Belle Mead NJ) 2009; 38: 23-27.
28. Antonios JK, Korber S, Sivasundaram L, Mayfield C, Kang HP, Oakes DA, Heckmann ND. Trends in computer navigation and robotic assistance for total knee arthroplasty in the United States: an analysis of patient and hospital factors. Arthroplast Today 2019; 5: 88-95.
29. Złotnicki JP, O'Malley MJ. Learning curve for robot- and computer-assisted knee and hip arthroplasty. In: Lonner JH, ed. Robotics in knee and hip arthroplasty. Cham: Springer International Publishing, 2019: 37-43.
30. Mancino F, Cacciola G, Malahias MA, De Filippis R, De Marco D, Di Matteo V, A G, Sculco PK, Maccauro G, De Martino I. What are the benefits of robotic-assisted total knee arthroplasty over conventional manual total knee arthroplasty? A systematic review of comparative studies. Orthop Rev (Pavia) 2020; 12: 8657.
31. Jinnah AH, Luo TD, Plate JF, Jinnah RH. General concepts in robotics in orthopedics. In: Lonner JH, ed. Robotics in knee and hip arthroplasty. Cham: Springer International Publishing, 2019; 27-35.
32. Jacofsky DJ, Allen M. Robotics in Arthroplasty: A Comprehensive Review. J Arthroplasty 2016; 31: 2353-2363.
33. Siddiqi A, Mont MA, Krebs VE, Piuzzi NS. Not All Robotic-assisted Total Knee Arthroplasty Are the Same. J Am Acad Orthop Surg 2021; 29: 45-59.
34. Fu X, She Y, Jin G, Liu C, Liu Z, Li W, Jin R. Comparison of robotic-assisted total knee arthroplasty: an updated systematic review and meta-analysis. J Robot Surg 2024; 18: 292.
35. Sousa PL, Sculco PK, Mayman DJ, Jerabek SA, Ast MP, Chalmers BP. Robots in the Operating Room During Hip and Knee Arthroplasty. Curr Rev Musculoskelet Med 2020; 13: 309-317.
36. Jhurani A, Agarwal P, Ardawatia G, Sahni H, Srivastava M. Functional and radiological outcomes of computer-assisted and handheld robotic total knee arthroplasty: A prospective randomised study. Knee 2025; 56: 84-93.
37. Roche M. The MAKO robotic-arm knee arthroplasty system. Arch Orthop Trauma Surg 2021; 141: 2043-2047.
38. Batailler C, Fernandez A, Swan J, Servien E, Haddad FS, Catani F, Lustig S. MAKO CT-based robotic arm-assisted system is a reliable procedure for total knee arthroplasty: a systematic review. Knee Surg Sports Traumatol Arthrosc 2021; 29: 3585-3598.
39. Parratte S, Price AJ, Jeys LM, Jackson WF, Clarke HD. Accuracy of a New Robotically Assisted Technique for Total Knee Arthroplasty: A Cadaveric Study. J Arthroplasty 2019; 34: 2799-2803.
40. Adamska O, Modzelewski K, Szymczak J, Świderek J, Maciąg B, Czuchaj P, Poniatowska M, Wnuk A. Robotic-Assisted Total Knee Arthroplasty Utilizing NAVIO, CORI Imageless Systems and Manual TKA Accurately Restore Femoral Rotational Alignment and Yield Satisfactory Clinical Outcomes: A Randomized Controlled Trial. Medicina (Kaunas) 2023; 59: 236.
41. Weaver DJ, Deshmukh S, Bashyal R, Bagaria V. Complications and Learning Curve Associated with an Imageless Burr-Based (CORI) Robotic-Assisted Total Knee Arthroplasty System: Results from First 500 Cases. Indian J Orthop 2024; 58: 1109-1117.
42. Clatworthy M. Patient-Specific TKA with the VELYS™ Robotic-Assisted Solution. Surg Technol Int 2022; 40: 315-320.
43. Xia R, Zhai Z, Zhang J, Yu D, Wang L, Mao Y, Zhu Z, Wu H, Dai K, Yan M, Li H. Verification and clinical translation of a newly designed "Skywalker" robot for total knee arthroplasty: A prospective clinical study. J Orthop Translat 2021; 29: 143-151.
44. Shatrov J, Battelier C, Sappey-Marinier E, Gunst S, Servien E, Lustig S. Functional Alignment Philosophy in Total Knee Arthroplasty - Rationale and technique for the varus morphotype using a CT based robotic platform and individualized planning. SICOT J 2022; 8: 11. Erratum in: SICOT J 2022; 8: 18.
45. Clark GW, Steer RA, Khan RN, Collopy DM, Wood D. Maintaining Joint Line Obliquity Optimizes Outcomes of Functional Alignment in Total Knee Arthroplasty in Patients With Constitutionally Varus Knees. J Arthroplasty 2023; 38: S239-S244.
46. Van de Graaf VA, Chen DB, Allom RJ, Wood JA, MacDessi SJ. Functional alignment in total knee arthroplasty best achieves balanced gaps and minimal bone resections: an analysis comparing mechanical, kinematic and functional alignment strategies. Knee Surg Sports Traumatol Arthrosc 2023; 31: 5118-5127.
47. Rossi SMP, Benazzo F. Individualized alignment and ligament balancing technique with the ROSA® robotic system for total knee arthroplasty. Int Orthop 2023; 47: 755-762.
48. Zhang J, Ndou WS, Ng N, Gaston P, Simpson PM, Macpherson GJ, Patton JT, Clement ND. Robotic-arm assisted total knee arthroplasty is associated with improved accuracy and patient reported outcomes: a systematic review and meta-analysis. Knee Surg Sports Traumatol Arthrosc 2022; 30: 2677-2695. Erratum in: Knee Surg Sports Traumatol Arthrosc 2022; 30: 2696-2697.
49. Rossi SMP, Sangaletti R, Perticarini L, Terragnoli F, Benazzo F. High accuracy of a new robotically assisted technique for total knee arthroplasty: an in vivo study. Knee Surg Sports Traumatol Arthrosc 2023; 31: 1153-1161.
50. Zhang EJX, Yeo W, Liu EX, Chen JY, Pang HN, Yeo SJ, Liow LMH. Does robotic surgical assistant (ROSA) functionally aligned TKA lead to higher satisfaction than conventional mechanically aligned TKA: A propensity-matched pair analysis. J Orthop 2025; 63: 93-97.

51. Mancino F, Rossi SMP, Sangaletti R, Caredda M, Terragnoli F, Benazzo F. Increased accuracy in component positioning using an image-less robotic arm system in primary total knee arthroplasty: a retrospective study. Arch Orthop Trauma Surg 2024; 144: 393-404.
52. Kayani B, Konan S, Huq SS, Tahmassebi J, Haddad FS. Robotic-arm assisted total knee arthroplasty has a learning curve of seven cases for integration into the surgical workflow but no learning curve effect for accuracy of implant positioning. Knee Surg Sports Traumatol Arthrosc 2019; 27: 1132-1141.
53. Sultan AA, Samuel LT, Khlopas A, Sodhi N, Bhowmik-Stoker M, Chen A, Orozco F, Kolisek F, Mahoney O, Smith L, Malkani A, Molloy RM, Mont MA. Robotic-Arm Assisted Total Knee Arthroplasty More Accurately Restored the Posterior Condylar Offset Ratio and the Insall-Salvati Index Compared to the Manual Technique; A Cohort-Matched Study. Surg Technol Int 2019; 34: 409-413.
54. Mahoney O, Kinsey T, Sodhi N, Mont MA, Chen AF, Orozco F, Hozack W. Improved Component Placement Accuracy with Robotic-Arm Assisted Total Knee Arthroplasty. J Knee Surg 2022; 35: 337-344.
55. Fozo ZA, Ghazal AH, Hesham Gamal M, Matar SG, Kamal I, Ragab KM. A Systematic Review and Meta-Analysis of Conventional Versus Robotic-Assisted Total Knee Arthroplasty. Cureus 2023; 15: e46845.
56. Van de Graaf VA, Clark GW, Collopy D, Wood JA, Chen DB, MacDessi SJ. Functional alignment minimizes changes to joint line obliquity in robotic-assisted total knee arthroplasty: a CT analysis of functional versus kinematic alignment in 2,116 knees using the Coronal Plane Alignment of the Knee (CPAK) classification. Bone Jt Open 2024; 5: 1081-1091.
57. Choi BS, Kim SE, Yang M, Ro DH, Han HS. Functional alignment with robotic-arm assisted total knee arthroplasty demonstrated better patient-reported outcomes than mechanical alignment with manual total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc 2023; 31: 1072-1080.
58. Lee JH, Kwon SC, Hwang JH, Lee JK, Kim JI. Functional alignment maximises advantages of robotic arm-assisted total knee arthroplasty with better patient-reported outcomes compared to mechanical alignment. Knee Surg Sports Traumatol Arthrosc 2024; 32: 896-906.
59. Fary C, Cholewa J, Ren AN, Abshagen S, Anderson MB, Tripuraneni K. Multicenter, prospective cohort study: immediate postoperative gains in active range of motion following robotic-assisted total knee replacement compared to a propensity-matched control using manual instrumentation. Arthroplasty 2023; 5: 62.
60. Parratte S, Van Overschelde P, Bandi M, Ozturk BY, Batailler C. An anatomo-functional implant positioning technique with robotic assistance for primary TKA allows the restoration of the native knee alignment and a natural functional ligament pattern, with a faster recovery at 6 months compared to an adjusted mechanica. Knee Surg Sports Traumatol Arthrosc 2023; 31: 1334-1346.
61. Kim YH, Yoon SH, Park JW. Does Robotic-assisted TKA Result in Better Outcome Scores or Long-Term Survivorship Than Conventional TKA? A Randomized, Controlled Trial. Clin Orthop Relat Res 2020; 478: 266-275. Erratum in: Clin Orthop Relat Res 2021; 479: 1407.
62. Bensa A, Sangiorgio A, Deabate L, Illuminati A, Pompa B, Filardo G. Robotic-assisted mechanically aligned total knee arthroplasty does not lead to better clinical and radiological outcomes when compared to conventional TKA: a systematic review and meta-analysis of randomized controlled trials. Knee Surg Sports Traumatol Arthrosc 2023; 31: 4680-4691.
63. Alrajeb R, Zarti M, Shuia Z, Alzobi O, Ahmed G, Elmhiregh A. Robotic-assisted versus conventional total knee arthroplasty: a systematic review and meta-analysis of randomized controlled trials. Eur J Orthop Surg Traumatol 2024; 34: 1333-1343.
64 . Park SE, Lee CT. Comparison of robotic-assisted and conventional manual implantation of a primary total knee arthroplasty. J Arthroplasty 2007; 22: 1054-1059.
65. Chun YS, Kim KI, Cho YJ, Kim YH, Yoo MC, Rhyu KH. Causes and patterns of aborting a robot- assisted arthroplasty. J Arthroplasty 2011; 26: 621-625.
66. Beldame J, Boisrenoult P, Beaufils P. Pin track induced fractures around computer-assisted TKA. Orthop Traumatol Surg Res 2010; 96: 249-255.
67. Yun AG, Qutami M, Pasko KBD. Do bicortical diaphyseal array pins create the risk of periprosthetic fracture in robotic-assisted knee arthroplasties? Arthroplasty 2021; 3: 25.
68. Held MB, Gazgalis A, Neuwirth AL, Shah RP, Cooper HJ, Geller JA. Imageless robotic-assisted total knee arthroplasty leads to similar 24-month WOMAC scores as compared to conventional total knee arthroplasty: a retrospective cohort study. Knee Surg Sports Traumatol Arthrosc 2022; 30: 2631-2638.
69. Song EK, Seon JK, Yim JH, Netravali NA, Bargar WL. Robotic-assisted TKA reduces postoperative alignment outliers and improves gap balance compared to conventional TKA. Clin Orthop Relat Res 2013; 471: 118-26. Erratum in: Clin Orthop Relat Res 2012; 470: 2627.
70 . Venosa M, Logroscino G, Romanini E, et al. Robotic-assisted hip and knee revision arthroplasty: A scoping review. J Exp Orthop 2025; 12: e70285.
71. Desouza C, Shetty V. Cutting through infection risk: robotic-assisted vs. conventional total knee replacement surgery – a meta-analysis. Arch Orthop Trauma Surg 2025; 145: 203.
72. Raj S, Bola H, York T. Robotic-assisted knee replacement surgery & infection: A historical foundation, systematic review and meta-analysis. J Orthop 2023; 40: 38-46.
73. LaValva SM, Chiu YF, Fowler MJ, Lyman S, Carli AV. Does Computer Navigation or Robotic Assistance Affect the Risk of Periprosthetic Joint Infection in Primary Total Knee Arthroplasty? A Propensity Score-Matched Cohort Analysis. J Arthroplasty 2024; 39: 96-102.
74. LaValva SM, Chiu YF, Fowler MJ, Lyman S, Carli AV. Robotics and Navigation Do Not Affect the Risk of Periprosthetic Joint Infection Following Primary Total Hip Arthroplasty: A Propensity Score-Matched Cohort Analysis. J Bone Joint Surg Am 2024; 106: 582-589.
75. Mahure SA, Teo GM, Kissin YD, Stulberg BN, Kreuzer S, Long WJ. Learning curve for active robotic total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc 2022; 30: 2666-2676.
76. Stegelmann SD, Butler J, Eaddy SG, Davis T, Davis K, Miller R. Learning curve for imageless robotic-assisted total knee arthroplasty in non-fellowship trained joint replacement surgeons. J Orthop 2023; 45: 72-77.
77. Sodhi N, Khlopas A, Piuzzi NS, Sultan AA, Marchand RC, Malkani AL, Mont MA. The Learning Curve Associated with Robotic Total Knee Arthroplasty. J Knee Surg 2018; 31: 17-21. Erratum in: J Knee Surg 2018; 31: 370.

78. Rajan PV, Khlopas A, Klika A, Molloy R, Krebs V, Piuzzi NS. The Cost-Effectiveness of Robotic-Assisted Versus Manual Total Knee Arthroplasty: A Markov Model-Based Evaluation. J Am Acad Orthop Surg 2022; 30: 168-176.
79. Liao G, Duoji J, Mu L, Zhang Y, Liu X, Cai D, Zhao C. Efficiency assessment of intelligent patient-specific instrumentation in total knee arthroplasty: a prospective randomized controlled trial. J Orthop Surg Res 2024; 19: 593.
80. Vermue H, Tack P, Gryson T, Victor J. Can robot-assisted total knee arthroplasty be a cost-effective procedure? A Markov decision analysis. Knee 2021; 29: 345-352.
81. Ong KL, Coppolecchia A, Chen Z, Watson HN, Jacofsky D, Mont MA. Robotic-Arm Assisted Total Knee Arthroplasty: Cost Savings Demonstrated at One Year. Clinicoecon Outcomes Res 2022; 14: 309-318.
82. Cotter EJ, Wang J, Illgen RL. Comparative Cost Analysis of Robotic-Assisted and Jig-Based Manual Primary Total Knee Arthroplasty. J Knee Surg 2022; 35: 176-184.
83. Alexander K, Karunaratne S, Sidhu V, Fritsch B, Gupta S, Horsley M, Guzman M, Boyle R, McBride K, Steffens D. Evaluating the cost of robotic-assisted total and unicompartmental knee arthroplasty. J Robot Surg 2024; 18: 206.
84. Kolessar DJ, Hayes DS, Harding JL, Rudraraju RT, Graham JH. Robotic-Arm Assisted Technology's Impact on Knee Arthroplasty and Associated Healthcare Costs. J Health Econ Outcomes Res 2022; 9: 57-66.
85. Leal J, Cochrane NH, Kim BI, Holland CT, Hallows R, Seyler T. A Cost Analysis of Traditional Versus Robotic Total Knee Arthroplasty Performed With an Imageless, Second-generation Robotic System. Orthopedics 2024; 47: 365-371.
86. Hickey MD, Masri BA, Hodgson AJ. Can Technology Assistance be Cost Effective in TKA? A Simulation-Based Analysis of a Risk-prioritized, Practice-specific Framework. Clin Orthop Relat Res 2023; 481: 157-173.
87. Losina E, Walensky RP, Kessler CL, Emrani PS, Reichmann WM, Wright EA, Holt HL, Solomon DH, Yelin E, Paltiel AD, Katz JN. Cost-effectiveness of total knee arthroplasty in the United States: patient risk and hospital volume. Arch Intern Med 2009; 169: 1113-1121; discussion 1121-1122.
88. Goh GS, Lohre R, Parvizi J, Goel DP. Virtual and augmented reality for surgical training and simulation in knee arthroplasty. Arch Orthop Trauma Surg 2021; 141: 2303-2312.
89. Gregory TM, Gregory J, Sledge J, Allard R, Mir O. Surgery guided by mixed reality: presentation of a proof of concept. Acta Orthop 2018; 89: 480-483.
90. McCloy R, Stone R. Science, medicine, and the future. Virtual reality in surgery. BMJ 2001; 323: 912-915.
91. Tsukada S, Ogawa H, Nishino M, Kurosaka K, Hirasawa N. Augmented reality-based navigation system applied to tibial bone resection in total knee arthroplasty. J Exp Orthop 2019; 6: 44.
92. Verhey JT, Haglin JM, Verhey EM, Hartigan DE. Virtual, augmented, and mixed reality applications in orthopedic surgery. Int J Med Robot 2020; 16: e2067.
93. Lee LS, Chan PK, Wen C, Fung WC, Cheung A, Chan VWK, Cheung MH, Fu H, Yan CH, Chiu KY. Artificial intelligence in diagnosis of knee osteoarthritis and prediction of arthroplasty outcomes: a review. Arthroplasty 2022; 4: 16.
94. Myers TG, Ramkumar PN, Ricciardi BF, Urish KL, Kipper J, Ketonis C. Artificial Intelligence and Orthopaedics: An Introduction for Clinicians. J Bone Joint Surg Am 2020; 102: 830-840.
95. Fontana MA, Lyman S, Sarker GK, Padgett DE, MacLean CH. Can Machine Learning Algorithms Predict Which Patients Will Achieve Minimally Clinically Important Differences From Total Joint Arthroplasty? Clin Orthop Relat Res 2019; 477: 1267-1279.
96. Nichols JA, Herbert Chan HW, Baker MAB. Machine learning: applications of artificial intelligence to imaging and diagnosis. Biophys Rev 2019; 11: 111-118.
97. Price WN. Big data and black-box medical algorithms. Sci Transl Med 2018; 10: eaao5333.
98. Wu XD, Zhou Y, Shao H, Yang D, Guo SJ, Huang W. Robotic-assisted revision total joint arthroplasty: a state-of-the-art scoping review. EFORT Open Rev 2023; 8: 18-25.
99. Leung K, Zhang B, Tan J, Shen Y, Geras KJ, Babb JS, Cho K, Chang G, Deniz CM. Prediction of Total Knee Replacement and Diagnosis of Osteoarthritis by Using Deep Learning on Knee Radiographs: Data from the Osteoarthritis Initiative. Radiology 2020; 296: 584-593.
100. MacAskill M, Blickenstaff B, Caughran A, Bullock M. Revision Total Knee Arthroplasty Using Robotic Arm Technology. Arthroplast Today 2021; 13: 35-42.
101. Kafelov M, Batailler C, Servien E, Lustig S. Restoration of the anterior compartment after robotic total knee arthroplasty significantly improves functional outcome and range of motion at 1 year. Knee Surg Sports Traumatol Arthrosc 2025; 33: 319-328.
102. Shatrov J, Coulin B, Batailler C, Servien E, Brivio A, Barrett D, Walter B, Lustig S. Redefining the concept of patellofemoral stuffing in total knee arthroplasty. J ISAKOS 2025; 10: 100364.
103. Kayani B, Konan S, Ayuob A, Onochie E, Al-Jabri T, Haddad FS. Robotic technology in total knee arthroplasty: a systematic review. EFORT Open Rev 2019; 4: 611-617.