

Review Article

# Advances in the Clinical Application of Robotic-assisted Knee Arthroplasty

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## Abstract

As the population ages, the number of patients with osteoarthritis of the knee has increased dramatically. Surgery, particularly total knee arthroplasty, has proven to be a highly effective treatment for end-stage osteoarthritis of the knee. Robotic surgical techniques have become particularly important to further improve surgical outcomes and safety, and to minimize intraoperative injuries and postoperative complications. Studies have shown that surgical robots have advantages in improving the precision and personalization of knee arthroplasty, but they also come with limitations such as increased operative time and rising healthcare costs. Therefore, it is particularly important to understand the current application of robotic knee arthroplasty and consider its future trends. By systematically organizing and analyzing the relevant literature, this study reviewed the development history and current status of domestic and international clinical applications of knee arthroplasty surgical robots, evaluated the advantages and limitations of robot-assisted knee arthroplasty, and explored their future development, with the aim of providing a reference basis for the research and development and clinical application of knee arthroplasty surgical robots in the future, so as to guide the adoption of corresponding measures to improve development of robot-assisted knee arthroplasty.

## Keywords

Knee Arthroplasty, Robot Surgery, Clinical Efficacy, Research Progress

## 1. Introduction

With the increasing trend of aging society, the number of patients with joint diseases such as osteoarthritis of the knee is increasing dramatically, which has become a key health challenge that seriously threatens the quality of patients' daily lives. Knee arthroplasty is a commonly used treatment for knee osteoarthritis, which can not only delay the progression of the disease and alleviate the pain symptoms, but also improve knee function and quality of life [1]. Several clinical studies have confirmed the effectiveness and feasibility of knee arthroplasty for the treatment of various end-stage and

advanced severe knee diseases [2, 3]. However, traditional knee arthroplasty requires a high level of experience and skill on the part of the surgeon, and the surgical results are susceptible to human factors, with problems such as inaccurate prosthesis position and high incidence of postoperative complications [4]. Therefore, how to ensure the safety, accuracy and repeatability of knee arthroplasty has become the focus of current research. With the continuous progress and development of current robot-assisted technology, robot-assisted knee arthroplasty reflects good results in im-

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proving surgical accuracy, lower limb force line reconstruction, prosthesis selection, etc. It also has good results in reducing bleeding, relieving postoperative pain and swelling, and improving knee flexion mobility [5-7]. By reviewing and analyzing the results of previous studies, this study now reviews the progress of clinical application of robot-assisted knee arthroplasty, aiming to provide an important theoretical basis and objective reference for the development of robot-assisted knee arthroplasty treatment.

## 2. The Technological Evolution of Robot-assisted Knee Arthroplasty

### 2.1. The Historical Development of Robotics

The development of surgical robots is a product of the cross-fertilization of several disciplines, involving the fields of medicine, mechanical engineering, computer science and biomechanics. In 1985, a medical team based in Los Angeles, California, first applied an industrial robot, model PUMA560, to a neurosurgical biopsy procedure, an innovation that marked the first application of robotics in the medical field [8]. In 1992, the world's first official surgical robot ROBODOC was introduced, and began to be used in clinical surgery. ROBODOC is mainly used in orthopedic surgery for hip and knee replacement, marking the surgical robot from the concept of practical applications [9]. In early 2000, Intuitive Surgical Inc. introduced the landmark da Vinci surgical robot system, which is mainly used for minimally invasive laparoscopic surgery, greatly improving the accuracy of surgery and the speed of patient recovery [10]. The da Vinci Surgical Robot was approved by the FDA in 2000 and rapidly spread globally. Since then, many types of surgical robots have emerged worldwide, such as orthopedic surgical robots, oral surgical robots, neurosurgical surgical robots, etc., and the application fields of surgical robots have been continuously broadened. Orthopedic surgical robots, as one of the important development directions, have developed rapidly in the past 30 years, and a number of mature products have been put into clinical applications [11].

### 2.2. Types of Surgical Robotic Systems

Surgical robotic systems are categorized into three types according to the human-robot interaction mode and the degree of robot automation: (1) passive systems; (2) semi-automatic systems; and (3) active systems [12]. Passive systems only ensure the accuracy and precision of pendulum positioning in osteotomy surgery, but do not have the ability to perform osteotomy maneuvers autonomously. Therefore, the surgeon must personally operate the robot to complete the surgical process; the active system does not rely on the surgeon and can autonomously perform surgical operations such as osteotomy according to preoperative planning and

intraoperative conditions; the semi-active system is between the passive and active systems, and it is the most common system at present, and its main feature is that the main surgeon controls the robot's robotic arm to carry out osteotomies under the supervision of the system, and in the process of the surgery the robotic system is able to provide immediate feedback to ensure the accuracy of the osteotomy operation and reduce the discrepancy with the pre-defined surgical plan. In addition, the system can effectively protect the ligaments and soft tissues near the joints from damage [13]. Robotic systems can be categorized into closed and open systems according to the degree of openness; closed systems limit the surgeon's choice of prosthesis, with which the matching prosthesis needs to be purchased from the same manufacturer, whereas open systems do not limit the surgeon's choice of type of prosthesis, providing maximum flexibility and the ability to accommodate different brands and types of prosthesis. Robotic systems can be categorized into CT-based robotic systems, X-ray-based robotic systems, and image-free robotic systems, depending on the preoperative imaging data required.

### 2.3. Technical Characteristics and Modes of Operation of the Main Existing Robotic Systems

ROBODOC/TSolution-One system: this system has been in use since 1992 and was the first active robotic system used for arthroplasty [14]. In 2014, THINK Surgical completed the acquisition of Curexo Technology, Inc. and subsequently based on the ROBODOC system, further development and renamed it the TSolution-One system, which was successfully approved by the FDA in 2019. The TSolution-One system is an open, active robotic surgical system that relies on CT scan data and consists of two subsystems: the TPLAN and the TCAT. Prior to the surgery, a CT scan of the patient's knee joint needs to be images are transferred to the TPLAN workstation for data processing and development of a surgical plan. Subsequently, a surgical plan based on the CT images will be uploaded to the TCAT system. The TCAT system limits its operating range by matching with the surgical plan and automatically performs the grinding and osteotomy processes without direct manipulation by the surgeon [15]. Distinguished from other robotic surgical systems, the TSolution-One system can only perform surgery according to a predefined plan and does not have the ability to make real-time adjustments to the surgical plan [16].

MAKO System: The MAKO Orthopedic Robotic System is currently the most widely used joint replacement robotic system in the world [17]. The MAKO system is a closed, semi-active robotic system that relies on CT scan data, and it was approved by the US FDA in 2008 to perform total knee replacement surgery. Prior to surgery, the surgeon analyzes the patient's 3D CT scan data in order to create a personalized surgical plan that determines the most appropriate size

of the artificial knee joint for the patient and the precise placement of the prosthesis. During surgery, the surgeon receives real-time 3D skeletal images of the patient and motion parameters of the knee, using the knee's range of motion to assess joint deformity and ligament laxity. This information helps the surgeon make timely adjustments to the surgical plan to ensure that the surgery is performed according to the specific anatomy of the patient's knee joint [18].

**NAVIO system:** this system is a closed, semi-active robotic system that does not rely on imaging data, and was approved by the FDA for unicondylar knee arthroplasty (UKA) and patellofemoral arthroplasty (PFA) in 2012, and was approved for total knee arthroplasty (TKA) in 2017 [19]. Similar to other systems that do not require imaging data, the NAVIO system does not require the acquisition of images of the patient's knee prior to surgery. It relies on the built-in optical navigation technology and the image data-free system to collect information about the bone structure by the surgeon marking and registering the bony landmarks of the knee joint during surgery, which in turn constructs a three-dimensional model of the knee joint [20]. Unlike traditional stationary surgical robots, the NAVIO robot has a handheld design, which makes surgical operations more flexible and convenient [21]. The surgeon can freely move the robot to achieve the optimal surgical position and angle according to the surgical needs.

**ROSA System:** The system is a semi-active robotic system that has a closed design and can either use x-ray imaging data or operate without it. The system received FDA approval for TKA in 2019. After marking bony landmarks in the knee and confirming the surgical plan, the ROSA system provides flexibility for the surgeon by allowing them to adjust the surgical plan based on the each patient's knee anatomy and ligament tension to adjust the surgical plan in real time. This process does not rely on a 3D model constructed based on the patient's preoperative knee imaging data [22].

**Skywalker system:** the Skywalker surgical robotic system is a robotic system developed in China in recent years, and it is the first FDA-approved Chinese-made total knee replacement surgical robot, which is a closed, semiactive robotic system that requires CT image data, and its preoperative planning system can construct a three-dimensional knee model based on the preoperative CT scan images to formulate the surgical plan to guide intraoperative osteotomies, lower limb force line adjustments, and prosthesis placement [23].

### 3. Clinical Applications of Robotic Systems in Knee Arthroplasty

**ROBODOC system:** this system is the more technologically mature and most widely used active robotic system on the market today. Yang et al [24] conducted a retrospective analysis of 102 patients who underwent total knee arthro-

plasty found that although the clinical outcomes and long-term survival rates were similar between the two groups, in terms of radiographic outcomes, the robotic-assisted total knee arthroplasty group had significantly fewer postoperative lower limb force alignment abnormalities were significantly less than in the conventional total knee arthroplasty group. This suggests that the use of the Robodoc robot better maintains the patient's physiologic anatomy, reduces the patient's postoperative pain, and shortens the time required for rehabilitation. In a prospective clinical trial conducted by Liow et al [25], 60 participants were randomly assigned to two different groups. Of these, 31 participants underwent ROBODOC-assisted total knee arthroplasty, while the other 29 participants underwent conventional total knee arthroplasty. The results of the study showed that in the ROBODOC-assisted group, precise reconstruction of the coronal plane lower extremity force line was achieved in all participants. In contrast, four participants in the conventional surgery group had lower limb force line deviations of more than  $\pm 3^\circ$ . Furthermore, a follow-up study conducted by Liow et al [26] on the same group of patients revealed that at 6 months after surgery, there was no significant difference in KSS scores and functional recovery between the robotically assisted group and the conventional surgery group. However, when followed up to 2 years after surgery, the robotic-assisted group showed superior functional recovery. Similarly, in a study conducted by Kim et al [27] who had a mean follow-up period of 13 years, they observed that the TKA group assisted with the ROBODOC system did not show statistically significant differences between the conventional TKA group and the robotic-assisted TKA group in terms of KSS scores, WOMAC scores, UCLA activity scores, and mobility.

**MAKO system:** In the field of joint surgery, the most popular robotic surgical system is the semi-active, closed-platform MAKO robotic system. Sires et al [28] performed MAKO robotic-assisted total knee arthroplasty in 45 cases and calculated the difference between preoperatively planned and actual osteotomies and coronal alignment, and found that the accuracy of preoperatively planned osteotomies and final lower limb coronal alignment was very high using the MAKO robotic surgical system. It was found that the accuracy of preoperatively planned osteotomies and final coronal alignment of the lower extremity was very high using the MAKO robotic surgical system. Zhang et al [29] pointed out that MAKO robot-assisted TKA was more effective than traditional manual TKA, with no postoperative surgical complications, and the patients' postoperative lower limb force line and prosthesis position were within  $1^\circ$  on average, but the surgical time ( $110.67 \pm 80.56$ ) min was longer than that of traditional surgery ( $80.56 \pm 4.64$ ) min. Liu et al [30] noted that MAKO robot-assisted TKA treatment was effective, the incision healed well, there were no serious complications during the follow-up period, and postoperative pain and knee function were significantly improved, but the

operation time was longer. Cao et al [31] conducted a retrospective study on the clinical data of patients with MAKO robot-assisted TKA, and found that the patients' postoperative unicondylar prostheses were well-positioned, and there was no abnormal deviation value of the prosthesis angle comparing with 1 year after the operation, and there were no serious postoperative complications, and there were only two cases of anterior knee pain, and one case of posterolateral knee pain. This study concluded that MAKO-assisted medial knee UKA has significant clinical efficacy in the mid-term, with few complications and good prognostic recovery. Yin et al [32] compared the differences in the effects of conventional simple surgery and MAKO robot-assisted UKA for elderly patients with osteoarthritis of the knee as an example, including pain symptoms, perioperative related indexes, and the results were that the robot-assisted UKA took a long time to operate, but the time of intraoperative tourniquet use was significantly shorter, with less blood loss, lower VAS scores, and higher KSS scores of the affected knee joints. This study concludes that robot-assisted UKA has precise efficacy, can effectively realize the purpose of precise surgical treatment, has good safety, and better repairs the patient's knee joint function. Combined with the above analysis, it is concluded that MAKO robot-assisted knee arthroplasty has significant near-term results, and is safe and reliable, but the long operation time and long-term efficacy need to be demonstrated.

NAVIO system: Du et al [33] who studied the effect of Navio robotic system-assisted UKA surgery by retrospective analysis, found that Navio robotic system-assisted UKA surgery had a more satisfactory efficacy, which helped to correct the patients' internal and external knee deformity, improve the rotational biomechanical properties of the knee, and had no effect on the establishment of the lateral inter-compartmental space. Canetti et al [34] who conducted a retrospective analysis of 28 patients who underwent UKA surgery were retrospectively analyzed and the results showed that patients in the robot-assisted surgery group had a faster but comparable degree of motor recovery compared to patients in the conventional surgery group.

ROSA system: Seidenstein et al [35] evaluated the osteotomy accuracy and stability of the ROSA system in a study involving 14 ROSA system-assisted TKA procedures and 20 conventional TKA procedures. The results showed that the lower extremity HKA angle averaged ( $0.8^\circ \pm 0.6^\circ$ ) in the ROSA system-assisted group compared with ( $2.0^\circ \pm 1.6^\circ$ ) in the conventional surgery group. In cases where the error in HKA angle was within  $3^\circ$ , the ROSA system-assisted group reached 100%, compared with 75% in the conventional group, and in cases where the error was within  $2^\circ$ , the ROSA system-assisted group reached 93%, compared with 60% in the conventional group. This indicated that the ROSA system-assisted group was more precise and stable in the neutral alignment of the lower limb force lines and the frequency of outliers was lower ( $P < 0.05$ ). In addition, in the ROSA system-assisted group, the difference between the actual and

planned osteotomy angles was less than  $0.6^\circ$  and the standard deviation was less than  $0.4^\circ$  for each of the items, except for the femoral prosthesis flexion angle of ( $1.3^\circ \pm 1.0^\circ$ ). Similarly, the difference between the actual and planned osteotomy thicknesses in the ROSA-assisted group was less than 0.7 mm, and the standard deviation was less than 0.7 mm, which indicates that the ROSA system is excellent in terms of the accuracy and stability of osteotomies.

Skywalker system: Skywalker robot-assisted TKA is widely used in clinical practice with remarkable efficacy due to individualization, standardization, and precision. Guo et al [36] investigated the effect and learning curve of Skywalker orthopedic robot-assisted TKA for surgical patients, and found that robot-assisted TKA has a short learning curve, which can achieve satisfactory imaging and clinical results at the initial stage of use, and helps to improve patients' postoperative knee joint function and knee joint range of motion. An et al. [37] compared the difference between the recent results of traditional TKA and Skywalker orthopedic surgical robot-assisted TKA in patients with TKA, for example, and found that the recent results of Skywalker robot-assisted TKA were more significant and helped to improve the knee function and range of motion of the knee after surgery compared with the traditional TKA. The results found that the Skywalker robot-assisted TKA has more significant near-term results, and compared with the traditional TKA, it can help to improve the patients' pain symptoms and promote the functional repair of the knee joint, and there are no serious adverse events such as loosening of the prosthesis, infection and other serious adverse events in the postoperative X-ray, and the position of the prosthesis is good, and the strength of the lower limb has improved significantly. All of the above reported results confirm that Skywalker robot-assisted TKA has good near-term results and is safe and reliable, however, the long-term effects are not yet clear, and need to be further demonstrated and analyzed in the future.

The above study shows that robot-assisted knee arthroplasty has achieved satisfactory results in clinical practice, as it not only accurately assists osteotomies, but also more effectively protects the soft tissues around the knee joint.

In robot-assisted TKA surgery, the robotic arm is able to accurately position itself to the designated osteotomy area according to preset commands, thus reducing errors that may occur during surgery due to manual control by the operator. In addition, the robotic system is capable of performing three-dimensional preoperative planning, calculating the angle and thickness of the osteotomy based on the preset line of force of the lower limb during standing and the rotational alignment of the femur and tibia to ensure that the height of the joint line is appropriate after surgery. Ultimately, the amount and angle of osteotomies were precisely executed based on the calculations, which helped to balance the flexion-extension gap as well as the medial-lateral gap more efficiently during surgery. Hampp et al [66] grouped 12 cadaveric specimens, with one group undergoing robot-



ic-assisted TKA and the other group undergoing conventional TKA. They assessed the positional deviation of the prosthesis in both groups by postoperative imaging. The results of the study showed that in the coronal and sagittal planes, the positional deviation of the prostheses in the robotic-assisted TKA group was generally smaller than that in the conventional TKA group, both for the femoral and tibial prostheses. In a study of robotic-assisted TKA surgery, data from 37 patients who underwent this procedure showed that the mean osteotomy errors for the distal femur, anterior femur, and proximal tibia were  $0.38 \text{ mm} \pm 0.32 \text{ mm}$ ,  $0.44 \text{ mm} \pm 0.27 \text{ mm}$ , and  $0.37 \text{ mm} \pm 0.30 \text{ mm}$ , respectively. In addition, 94% of the patients had their actual osteotomies remain within a deviation of preoperative planning of 1 mm or less [28]. In summary, the robot-assisted TKA was able to achieve precise osteotomies, which provided a solid foundation for accurate implantation of the prosthesis. In addition, the robotic system was able to accurately assist in determining the line of force and rotational alignment of the lower limb, quantifying the angle and amount of osteotomies more accurately, thus reducing the possibility of needing to repeat osteotomies due to operational errors.

In addition to precise osteotomy operation, proper soft tissue balance and good soft tissue protection are equally one of the key factors determining the success of knee arthroplasty. Some studies have shown that robotic-assisted knee arthroplasty can better protect the soft tissues around the knee joint [64]. In a cadaveric specimen study conducted by Khlopas et al [40], they evaluated the effectiveness of robotic-assisted TKA versus conventional TKA in protecting soft tissues during surgery. It was found that robot-assisted TKA performed better in protecting the medial and lateral collateral ligaments and was able to preserve the tibial attachment point of the posterior cruciate ligament intact. In contrast, two of the seven cadaveric specimens in the conventional surgery group showed medical damage or even complete rupture of the tibial attachment point of the posterior cruciate ligament. Furthermore, in a retrospective analysis performed by Siebert et al [65], they compared the changes in postoperative thigh circumference between patients in the robot-assisted TKA group and those in the conventional TKA group. It was found that patients in the robotic-assisted TKA group had a lower incidence of periprosthetic soft-tissue swelling than those in the conventional TKA group, and there were no major adverse events in the robotic-assisted TKA group. In conclusion, robotic-assisted knee arthroplasty provides better soft tissue balancing because the robotic arm is able to accurately position itself to the predefined osteotomy area and immobilize itself there to perform the osteotomy, ensuring that the bones and soft tissues outside the area are not damaged, thus greatly reducing the risk of intraoperative injury to the posterior cruciate ligament and the medial and lateral collateral ligaments. In addition, robotic-assisted TKA eliminates the need for intramedullary positioning of the femur, eliminating the need for intramedullary position-

ing rods during the procedure, which effectively reduces the incidence of intramedullary hemorrhage. Furthermore, robot-assisted TKA does not require intraoperative tibial subluxation and patellar valgus, thus reducing the risk of potential injury to the patellar tendon, quadriceps tendon, and soft tissues around the popliteal fossa, which is one of the reasons for the lesser soft tissue swelling in patients after robot-assisted knee arthroplasty [40].

## 4. Advantages and Limitations of Robot-Assisted Knee Arthroplasty

### 4.1. Advantages of Robot-Assisted Technology

#### 4.1.1. Strong Personalization

Each patient has a different knee structure, degree of pathology and physical condition. Robot-assisted knee arthroplasty allows preoperative planning based on the patient's CT or MRI scan data to customize the most suitable surgical plan for the patient. This personalized treatment not only improves the relevance of the surgery, but also enhances the success rate and patient satisfaction [38]. Zheng et al [57] used 3D printing technology to create patient-specific knee prostheses, thus better adapting to the individual's anatomical structure and soft-tissue characteristics, and the results showed that the majority of the patients gained good balance and movement trajectory within a short period of time after the surgery, with a high level of overall satisfaction. The study concluded that soft tissue balance and lower limb force line alignment can be achieved in most cases through robotics and optimized design of patient-specific prostheses, thus improving the outcome of total knee arthroplasty.

#### 4.1.2. High Precision

By applying high-precision sensors, combined with 3D imaging technology and complex algorithms, the knee replacement robotic system can achieve millimeter-level precision operation during surgery, which is far more than that of the human surgeon's unarmed operation. This high-precision operation ensures that the angle, depth, and position of prosthesis implantation are precise and accurate, which helps to improve surgical outcomes and reduce the chance of complications due to operational errors [39]. It is difficult to make intraoperative osteotomy plane adjustments of 1-5° in conventional surgery, but robotic-assisted surgery can accomplish this and adjustments can be made with a lateral, medial, or intermediate fulcrum, so the gap balance can be fine-tuned with great precision, which will greatly improve accuracy, while reducing soft tissue loosening, as well as surgical trauma. Moon et al [58] compared the accuracy of robotic-assisted and conventional artificial knee arthroplasty with precision and showed that the likelihood of a 3° or greater deviation in robot-assisted artificial knee arthroplasty

was almost 0. Agarwal et al [59] reviewed 22 studies on the comparison of robot-assisted TKA with conventional TKA in 2020, and the results of the study showed that, in terms of the imaging assessment, 14 studies found that robot-assisted TKA procedures were more precise in the recovery of post-operative force lines and more consistent in alignment, with greater improvement in postoperative WOMAC and HSS scores with robotic-assisted TKA compared to conventional TKA.

#### 4.1.3. Fast Postoperative Recovery

Compared with traditional open surgery, robotic-assisted knee arthroplasty usually uses smaller incisions and less soft-tissue release, causing less damage and bleeding to the surrounding tissues, and providing effective protection for the soft tissues around the knee joint [40], thus reducing the level of postoperative pain and the risk of infection, and avoiding medically induced surgical trauma. At the same time, due to the less traumatic and more precise surgery, patients are often able to regain joint function and daily living ability more quickly after surgery, which greatly accelerates the patient's recovery. Kayani et al [60, 61] pointed out in their report that robotic-assisted arthroplasty caused less damage to the surrounding tissues and less inflammatory response compared to conventional surgery, which was reflected in a lower inflammatory factor elevation magnitude. In addition, patients had a faster recovery process after surgery, with shorter hospital stays, less pain, and a more favorable return of joint mobility. Robotic-assisted surgery has also shown benefits in recent clinical scores.

#### 4.1.4. Reduced Complications

During traditional TKA surgery, the accuracy of osteotomy and soft tissue balancing may be compromised if the surgeon is inexperienced or limited by visual errors and the precision of surgical instruments. The knee replacement robot's high-precision surgical operations and personalized pre-operative planning help to reduce the incidence of post-operative complications such as loosening of the prosthesis, infection, pain and post-operative swelling. In addition, the knee replacement robot system monitors the surgical process in real time, detecting and correcting possible deviations in a timely manner, further ensuring the safety and effectiveness of the surgery.

#### 4.1.5. Reduced Prosthetic Wear

Robot-assisted knee arthroplasty has a high survival rate within ten years and good patient satisfaction [41]. In traditional knee arthroplasty, most of the implant position is determined by the doctor's experience and preoperative X-rays, and the artificial knee joint is not tightly articulated with the bone surface, which results in severe wear and tear of the bone joint. The emergence of robotic system can make the artificial knee joint and the bone surface close together.

Through precise osteotomy and prosthesis placement, it ensures that the prosthesis matches perfectly with the anatomical structure of the patient's knee joint, reduces the shrinkage of the life span of the prosthesis due to loosening or wear and tear of the prosthesis, and reduces the risk of re-operation. In addition, a personalized surgical plan helps to improve the stability and durability of the prosthesis. As a result, patients undergoing robotic-assisted knee replacement can enjoy better surgical results and a longer prosthesis life than with conventional surgery.

### 4.2. Limitations of Robot-Assisted Technology

#### 4.2.1. Cost Considerations

Robot-assisted surgical systems are costly, including the costs of equipment acquisition, maintenance, consumables, and specialized training, which has led to a significant increase in surgical costs [42]. For some patients, the high cost of surgery may be a major deterrent to undergoing robotic-assisted knee arthroplasty. Li et al [56] found that computer-assisted orthopedic systems (CAOS) were cost-effective in the field of joint replacement at higher surgical volumes through a systematic review and analysis. Therefore, the impact of different procedure volumes on the cost-effectiveness of CAOS and how to optimize CAOS technology to improve its affordability can be explored in subsequent studies. Vermue et al [62] simulated the health status of a 67-year-old patient requiring total knee replacement surgery for osteoarthritis for 20 years postoperatively, based on a payment system in the United States, by using a Markov decision-analysis model. and estimated potential healthcare costs over the next 20 years. Their results showed that in order to prove the cost-effectiveness of robot-assisted surgery, each robot would need to perform at least 253 surgeries per year.

#### 4.2.2. Scope of Application

While robotic-assisted surgery has shown great benefits in knee replacement, there are certain limits to its use. Doctors need to conduct a comprehensive assessment based on the patient's specific condition, age, physical condition, and economic condition to determine whether the technology is suitable for treatment of certain specific types of knee lesions or complexities, and robotic assistance may not be the best choice, requiring comprehensive consideration of the patient's specific situation and surgical needs [43].

#### 4.2.3. Dependence on Equipment and Technology

Robot-assisted surgery is highly dependent on advanced equipment and sophisticated technical support. The surgical process of robotic-assisted knee arthroplasty includes pre-operative planning, robot calibration, bone surface registration, bone cutting and grinding, and prosthesis implantation. Problems with any of the equipment components of the ro-

botic system can result in forced termination of the surgery. Failure of bone surface registration, damage to the storage disc, modeling errors, and damage to the control program are all specific problems that were not present in the original manual surgery. Therefore, in case of equipment failure or insufficient technical support, the smooth operation may be affected. In addition, in order to operate the robotic system proficiently, the operator needs to receive specialized training, which increases the complexity and time cost of preparing for surgery [44].

#### 4.2.4. Surgical Time and Learning Curve

Robot-assisted surgical systems place higher demands on the operating skills of physicians. Doctors need to familiarize themselves with the operating interface of the system, understand the technical characteristics of the robot, and master the skills of completing surgical operations with the assistance of the robot. This process requires a long period of practice and experience accumulation, resulting in the so-called “learning curve” [45]. For less experienced surgeons, this learning process can be long and challenging. Although knee replacement robots can improve surgical precision and safety, they may lead to longer operative times in some cases [48]. A meta-analysis of robot-assisted UKA and conventional UKA by Weber et al. [63] showed that the mean operative time in the robotic group was 15.4 min longer than in the conventional group, with a 95% CI of (10.2, 20.6). This was mainly due to the complexity of operating the system, the need for the surgeon to adapt to the new surgical modality, and to deal with possible contingencies. The prolonged operation time may increase the anesthesia risk and hospitalization time of patients, which puts some pressure on medical resources.

#### 4.2.5. Long-term Effects to Be Proven

Robot-assisted knee arthroplasty, as an emerging technology, needs to be further validated for its long-term outcomes [46]. Although studies have shown that this technology can significantly improve surgical outcomes and patient satisfaction in the short term, research on its long-term efficacy, prosthesis longevity, and possible long-term complications still needs to be deepened [47]. This requires that medical institutions and research institutes continue to pay attention to and follow up on patients' treatment in order to accumulate more clinical data and experience.

## 5. Research Progress and Future Trends

Although the future is full of uncertainty, the progress of things is often accompanied by the identification and resolution of problems, as well as continuous refinement and optimization. The evolution of robotic knee arthroplasty is no exception. Despite the current challenges and limitations, this will not prevent robot-assisted joint arthroplasty from

becoming an irreversible trend in the evolution of the field of joint surgery. The problems currently faced are also expected to be effectively addressed in the future as the technology advances.

In the last decade, more and more joint surgeons have begun to favor the use of robotic-assisted techniques in their clinical practice. At the same time, the amount of research literature on robotic-assisted total knee arthroplasty has been growing year after year, and research interest in this area continues to be high [49]. At the same time, artificial intelligence technology is rapidly advancing, and some preliminary clinical studies have shown that artificial intelligence has demonstrated positive clinical outcomes in joint replacement surgery [50]. As the mobile Internet moves into the 5G era, network speeds have increased significantly, and coupled with enhanced computer processing power, remote network operation and high-definition video communication have become possible, which will allow the technology of remote-controlled robotic-assisted total knee arthroplasty to move toward practicality [51].

In the future, knee arthroplasty robots are expected to deeply integrate artificial intelligence technology to enable automated preoperative image segmentation and autonomous surgical planning. This means that the robot will be able to automatically design the optimal lower limb line of force and prosthesis placement according to each patient's anatomy and functional needs. Meanwhile, during surgery, the robot is able to display ligament tension and joint motion trajectories in real time, providing visual guidance for surgery [52]. The future vision of robotics will further expand into the field of revision joint replacement surgery. By reducing metal noise, the robot is able to effectively assess skeletal defects and plan an individualized preoperative repair of the skeletal defect, including determining the ideal position of the screws. During surgery, with the assistance of the robotic arm, it is possible to accurately repair the skeletal defect, ideally place the prosthesis, as well as appropriately place the screws, thereby reducing the risk of damage to blood vessels and nerves [53]. Accurate prosthesis placement and proper soft tissue balancing not only enhance patient satisfaction, but also significantly increase the satisfaction and confidence of the joint surgeon [54]. In the future, knee replacement prostheses are expected to be highly customizable, which will depend on further advances in imaging, 3D printing, and computer technology, as well as the support of relevant regulations. Only with robotic assistance will it be possible to ensure that fully personalized knee replacement prostheses are accurately placed. As joint replacement prosthesis technology advances, joint replacement surgical robots will evolve in parallel. The design of the robotic arms will become more flexible and compact, and their size is expected to decrease significantly. In addition, the efficiency of future arthroplasty robots is expected to increase significantly, and the cost is expected to decrease dramatically.

## 6. Conclusion

Knee arthroplasty has a wide range of applications and precise efficacy, and has good application advantages in the treatment of osteoarthritis of the knee, while robot-assisted knee arthroplasty can effectively make up for the shortcomings of traditional knee arthroplasty, and through the interventions of preoperative planning system, high-precision osteotomy, and proper fixation of the prosthesis, it can obtain the ideal near-term effect, which is mainly embodied in the precise reconstruction of the lower limb force line, improvement of the function of the knee joint, intraoperative less bleeding and fewer complications. Overall, robotic-assisted knee arthroplasty has made significant progress, but still faces some challenges that need to be addressed, such as longer operative time, higher cost, and the fact that most of the studies are short-term, single-center follow-up studies. Therefore, it is recommended to strengthen the training of physicians to help them quickly master the technology and get through the learning curve; meanwhile, more long-term, multicenter clinical studies should be conducted to more accurately assess the application advantages of robotic-assisted knee arthroplasty. Based on these research results, the level of robot-assisted knee arthroplasty will be continuously improved. In addition, attention should be paid to good preoperative evaluation of patients, combining the differences in bone density, health status, family financial status, and severity of the disease, to choose the appropriate robotic-assisted joint replacement surgery, in order to improve the patient's precise and personalized treatment results. It is believed that with the current 5G communication technology and the emergence of artificial intelligence, it can enable the further development of robot-assisted knee arthroplasty.

## Abbreviations

FDA	Food and Drug Administration
TKA	Total Knee Arthroplasty
UKA	Unicondylar Knee Arthroplasty

## Author Contributions

**Ziyue Liu:** Conceptualization, Resources, Writing—original draft

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## Conflicts of Interest

All authors of this paper declare that they have no conflicts of interest.

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