

Current Concepts

Robotics in Total Knee Arthroplasty

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Conventional total knee arthroplasty (TKA) has been the gold standard for end-stage osteoarthritis patients. There is increased interest in robotic technology utilization for arthroplasty surgery to improve surgical precision and patient outcomes. In recent years, several companies have introduced a range of robotic systems that assist orthopedic surgeons to varying degrees in performing TKA. This review aims to analyze the current literature on the utilization of robotic systems for TKA surgery to provide an overview of its utilization for patients and surgeons and evaluate its outcomes and cost-effectiveness. Despite the promising findings reported in the literature on robotic-assisted TKA (RATKA), the actual long-term value of RATKA versus conventional TKA remains in question.

INTRODUCTION

Total knee arthroplasty (TKA) is a common surgical procedure used to manage advanced knee osteoarthritis, rheumatoid arthritis, and posttraumatic arthritis. With a progressively aging population and improvement in implant survivorship, there has been a significant increase in the number of TKA's performed yearly in the United States.¹ Historically, conventional TKA arthroplasty has been accepted as the gold standard surgery for advanced degenerative joint disease of the knee. Recently, robotic-assisted total knee arthroplasty (RATKA) has been introduced as a potential alternative surgical technique. Various robotic systems involving TKA are currently being introduced into medical practice.² This review will provide an overview of the current state of robotic systems available for TKA surgery.

REVIEW PROCESS

This was a systematic review of the literature in PubMed dating back to 2007. The following keywords were utilized to search for literature: Robotics, Total Knee Arthroplasty, Orthopedic Surgery, TKA, and Arthroplasty. This effort resulted in 80 citations, from which relevant studies were selected for review. Forty-one citations were excluded as irrelevant. The full papers of the remaining 39 citations were

assessed to select those primary studies directly related to robotics in total knee arthroplasty.

LIMITATION IN CONVENTIONAL TOTAL KNEE ARTHROPLASTY

Conventional TKA is the most common method for performing the procedure. This surgical procedure uses pre-operative films, anatomical landmarks such as Whiteside's line and the transepicondylar axis, and manually positioned alignment tools to guide bone resection.² The previously standard mechanical approach allowed for a uniform alignment from patient to patient and has been the gold standard for alignment.³ In recent years, there has been an increase in the popularity of anatomic and kinematic alignment methods.³

Proper implant positioning is critical when evaluating surgical methods, as resulting aseptic loosening is a cause of overall TKA failure.⁴ The popular belief was that the bone resections needed to place the TKA implants within 3 degrees of the mechanical axis to improve implant survivorship.⁵ The logic behind the historically held TKA alignment target was based on cement being able to resist compressive but not shear forces, thereby leading to early aseptic loosening for a malaligned TKA. Because conventional instrumentation often had many alignment outliers, navigation, and robotic systems were developed to provide more precise bone resection and implant alignment. At the

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same time, the dogma of needing alignment to be within 3 degrees of the mechanical axis was being challenged to say the margin of error is likely broader. According to Paratte *et al.*, it was determined that a postoperative mechanical axis of 3° did not increase implant survival rate and that utilizing this benchmark was of little value.⁶ Because conventional instrumentation can reliably provide precision within 6 degrees of the mechanical axis, it has further fueled the debate on whether robotic systems can provide added value to the procedure.

AVAILABLE ROBOTIC SYSTEMS FOR TOTAL KNEE ARTHROPLASTY

Currently, there are active, semi-active, and passive robotic systems that depend on the surgeon's level of control over the robot.⁷ The active robotic system autonomously makes tibial and femoral resections while the semi-active robot provides intra-operative feedback to the surgeon regarding deviation from reference parameters.⁸ The passive systems, also known as computer-assisted or navigation systems, use reference points to provide surgeon recommendations regarding the positioning of the surgical tool without any autonomous procedural capabilities.⁸

In orthopedic practice today, there are several robotic systems currently being used: Active ROBODOC™ (Fremont, CA, USA) and semi-active systems MAKO™ (Stryker, Mako Surgical Corp., Fort Lauderdale, FL, USA), NAVIO™ (Smith & Nephew, Memphis, TN, USA), ROSA™ (Zimmer Biomet, Warsaw, IN, USA), VRAS™ (Depuy Synthes, Johnson & Johnson, USA), and OMNIBotics™ (OMNIlife Science, Raynham, MA, USA).^{7,9,10} One of the earliest ideas of robotics in the realm of TKA was ROBODOC, introduced in 1992.¹¹ ROBODOC allows the surgeon to input guidelines for the procedure, which is subsequently performed entirely autonomously.¹¹ In recent years, ROBODOC was renamed to TSolution-One, a robotic system allowing accurate component placement and hip-knee-ankle mechanical axis.¹² In addition, the MAKO system is one of the most well-recognized robotic systems in robotic TKA.¹³ The MAKO system allows the surgeon to manually control and operate the robot within a predetermined range of restrictions.¹¹ The MAKO system can predict gaps in a virtual environment and measure actual gaps during surgery while providing intraoperative feedback regarding deviation from those predetermined parameters; this occurs before any physical bone cutting, allowing for increased accuracy and precision.¹⁴ However, MAKO requires three-dimensional imaging of the patient's bone and creating an operative plan that can be modified during surgery.⁸ This allows for an improved preoperative implant size and positioning plan. In addition, another semi-active robotic system includes NAVIO. NAVIO is an imageless, handheld robotic system that allows for real-time planning and gap evaluation while also providing real-time intraoperative feedback to the surgeon semi-autonomously.¹⁵ Similarly, ROSA [Figure 1] and OMNIBotics are semi-active systems with slight differences. The ROSA system can be utilized both pre- and intra-operatively in comparison to the OMNIBotics systems,

which can only be utilized intra-operatively. The ROSA system can convert 2D images into 3D images for planning purposes while functioning as an utterly imageless system similar to OMNIBotics.⁹ This dynamic functionality allows for better gap balancing and ligament tensioning due to both systems.⁹ Finally, the VRAS system is another semi-active robotic system that collects information about both bone anatomy and soft tissue envelope intra-operatively to allow the surgeon to place the TKA implant accurately.¹⁶ Utilizing this system has increased bone cut accuracy and efficiency.¹⁶ The differences between the various systems proposed by companies are based on whether the robot is image-based or not and the brand specificity regarding the implants.

PATIENT OUTCOMES FOR ROBOTIC TOTAL KNEE ARTHROPLASTY

Robotic systems have been developed to improve precision during TKA surgery. Soft tissue injury can occur during surgery due to excessive retraction or manipulation of soft tissues, resulting in pain, swelling, and extended recovery times. Implant alignment and soft tissue balancing in surgery are believed to have a major impact on the success rate of TKA.¹⁷ During surgery, patella subluxation and eversion are notable reasons that can result in soft tissue damage.¹⁸ In a case series by Kholpas *et al.*, it was determined that in all RATKA cases, subluxation of the tibia and eversion of the patella was not required in comparison to conventional TKA surgery, demonstrating the potential for less soft tissue damage with RATKA.¹⁸ In an additional study by Marchand *et al.*, intraoperative outcomes regarding extension and flexion gaps and the robotic system's ability to predict implant sizes were evaluated to demonstrate the advantages of RATKA during surgery.¹⁹ This study indicated minimal differences in extension and flexion gaps post-op. In addition, the robotic system was successful 98% of the time in predicting implant component sizes within one size of what was used.¹⁹ In comparison, acetate templating has accurately predicted implant component size 91% of the time.²⁰

Despite these promising findings, the long-term value of RATKA versus conventional TKA remains in question. In a randomized control trial comparing RATKA to conventional TKA, Adamska *et al.* were unable to identify clear superiority in clinical outcomes of RATKA in comparison to conventional TKAs.²¹ Similarly, in a systematic review and meta-analysis, Ruangsomboon *et al.* concluded that although RATKA allows for increased radiographic precision, this may be clinically insignificant given current data comparing RATKA versus conventional TKA.²² Additionally, in a retrospective case-control series, Khan *et al.* explored the minimally clinically important difference (MCID) between RATKA and conventional TKA patients. It was demonstrated that RATKA reduced pain and improved functional recovery at 4-6 weeks. However, at one year, the functional outcomes were equivalent for RATKA and conventional TKA.²³ Current literature suggested that patients reported higher satisfaction scores for those undergoing RATKA than



Figure 1. ROSA™ (original image)

those who underwent conventional methods.²⁴ On the other hand, Xu *et al.*, in a prospective randomized cohort study, suggested that RATKA decreases trauma by decreasing the time required for bone cutting and reducing mechanical errors during implant positioning.²⁵ This favors patients' satisfaction and minimizes post-operative inflammatory response.²⁵ Overall, the current published literature suggests a wide range of outcomes of RATKA. No complete and definitive study suggests significant improvement with the use of RATKA. Long-term outcomes must be evaluated, and more randomized controlled studies must be conducted to compare the two methodologies better.

COST AND LEARNING CURVE CONSIDERATIONS FOR ROBOTIC-ASSISTED TOTAL KNEE ARTHROPLASTY

Understanding practicality is critical when gauging the feasibility of utilizing robotic systems to assist with TKA. A retrospective review conducted by Eason *et al.* noted a significant increase in surgical time, from 75 minutes using conventional methods to 79 minutes using RATKA. However, surgical times after completing 64 cases were faster than those using conventional methods, though these results proved to be statistically insignificant.²⁶ Several studies similarly suggest that operative times were similar to those of conventional methods after the initial learning curve. This displayed increase in proficiency suggests the feasibility of utilizing RATKA.²⁷ According to various studies, the learning curve ranged between 7-43 cases.²⁷ Furthermore, Shatrov *et al.* suggested a significant decrease in total operating length after the 30th case, and improvements occur early during the learning phase.²⁸ Another

study suggests that a mean of 8 minutes of increased time using RATKA was not clinically significant, citing that this technology can be regularly incorporated into orthopedic practices.²⁹

The cost-effectiveness of implementing a robotic system is an important consideration in a hospital setting. With RATKA, there has been a reduced inventory of instrument trays and a reduced cost of sterilization associated with the surgical procedure.²⁹ Also, savings were displayed in shorter patient stays, reduced prescribed opioids, and decreased instrument reprocessing fees.³⁰ Furthermore, lower 30, 60, 90-day, and one-year postoperative costs and healthcare utilization.³¹ Overall, it was shown that RATKA is associated with lower costs compared to conventional methods, even when including the cost of CT scans.³² Also, patients who had RATKA were less likely to utilize inpatient services and skilled nursing facilities, adding to the decreased cost of RATKA post-operatively.^{9,10,33} Finally, though it is important to consider the cost-benefit of RATKA, it is also important to consider the high up-front and maintenance cost of these systems while determining the feasibility of incorporating such systems into orthopedic practice.¹³ Additionally, the most widely used robotic systems are not implant agnostic. Because surgical facilities rarely only utilize a single implant system, the facilities must undertake the capital expense for each implant system used by the surgeons.

AMERICAN ACADEMY OF ORTHOPAEDIC SURGEONS CLINICAL PRACTICE GUIDELINE³⁴

The American Academy of Orthopaedic Surgeons suggests no significant difference in function, outcomes, and com-

Table 1. Summary of advantages and disadvantages of conventional TKA vs. RATKA

Conventional Total Knee Arthroplasty (TKA)	Robotic-assisted Total Knee Arthroplasty (RATKA)
Advantages	
Reliably provide precision within 6 degrees of mechanical axis ⁶	Autonomous bone resection capability
One-year post-operative functional outcomes were the same as RATKA ²³	Capability to predetermine range of restrictions while performing bone resections ¹¹
No significant difference in surgical times after completing 64 cases]when compared to RATKA ²⁶	Intraoperative feedback based on predetermined measurements ⁸
	Convert 2D images to 3D images for planning purposes before surgery ⁹
	Subluxation of the tibia and eversion of the patella is not required ¹⁸
	Successful 98% of the time in predicting implant component sizes within one size ¹⁹
	Reduced pain 4-6 weeks post-operative ²³
	Higher patient satisfaction scores ²⁴
	Decreased trauma due to reduced time for bone cutting ²⁵
Disadvantages	
High number of alignment outliers	Unable to identify clear clinical outcome superiority in comparison to conventional methods ²¹
Subluxation of the tibia and eversion of the patella is required	Increased radiographic precision may be clinically insignificant ²²
Predicted implant component size 91% of the time ²⁰	Higher start-up cost ¹³

plications in the short term when comparing robotic-assisted and conventional TKA. This was a limited recommendation due to variability in robotic systems utilized between studies and conflicting evidence regarding clinical outcomes and accuracy.^{35,36} Further, there was concern regarding excess radiation associated with necessary preoperative imaging for robotic technology. The AAOS argues that practitioners must thoroughly examine evidence when using a robotic system. In addition, robotic systems will further require long-term randomized controlled trials to more thoroughly determine overall clinical efficacy and practicality.

CONCLUSION

Historically, conventional instrumentation has been utilized for bone resection in primary TKA. However, robotic systems were seen as a potential solution to improve and better optimize TKA surgical procedures. With the introduction of robotic-assisted systems – including passive, active, and semi-active systems in TKA, there has been increased research comparing the efficacy of incorporating such robotic systems into the realm of orthopedic surgery. However, insufficient data and studies exist to determine any potential increased effectiveness, efficiency, and patient outcomes of integrating robotic methods into TKA surgery. As robotics becomes increasingly popular and the value-based healthcare landscape moves towards prioritizing efficiency and quality care, further research is needed

to compare the parameters between conventional TKA surgical methods versus robotic-assisted methods.

DECLARATION OF CONFLICT OF INTEREST

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DECLARATION OF ETHICAL APPROVAL FOR STUDY

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DECLARATION OF INFORMED CONSENT

There is no information in the submitted manuscript that can be used to identify patients.

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