Tomasz Jęczmień, Agata Zaleska, Jan Zabrzyński

Department of Orthopedics and Traumatology, Faculty of Medicine, Collegium Medicum in Bydgoszcz, Nicolaus Copernicus University in Torun, Poland

Robotic assistance in total knee arthroplasty

Corresponding author:

Tomasz Jęczmień
Department of Orthopedics and Traumatology, Faculty of Medicine, Collegium Medicum in Bydgoszcz, Nicolaus Copernicus University in Torun, Poland
Jagiellońska 13/15 St., 85–067 Bydgoszcz
e-mail: tomekjeczmien@gmail.com

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ABSTRACT

Introduction: Total knee arthroplasty is acknowledged as a gold standard for treating degenerative knee joint diseases, and optimal implant positioning is crucial for successful outcomes. Robotic-assisted TKA emerges as a promising solution for enhancing precision in implant positioning, despite potential drawbacks such as increased surgical duration and associated costs. Various robotic systems, including open, closed, passive, semi-active, and active types, are available on the market, such as ROBODOC®, MAKO®, ROSA®, and NAVIO® each one with certain features.

Objectives: The primary objectives of this study are to comprehensively analyze the learning curve, short-term and long-term clinical outcomes, and prospects associated with robotic assistance in TKA.

Results: The learning curve associated with robotic TKA shows the gradual reduction in operation time as surgeons gain experience. Studies underline the importance of surgeon familiarity and experience in optimizing the benefits of robotic assistance. Long-term outcomes obtained through follow-up studies, indicate improved precision in maintaining mechanical axis and alignment of components. Comparative studies between manual and robotic-assisted TKA reveal enhanced compartment balancing and improved patient satisfaction with the latter. The pros of robotic assistance are increased precision, reduced complications, and improved patient satisfaction. Cons include higher maintenance costs and longer operation times during the learning period.

Conclusions: Robotic assistance in TKA offers substantial benefits in terms of implant positioning accuracy and patient outcomes. The learning curve is seen as a temporary challenge that diminishes with surgeon experience. Despite concerns about increased costs and potential complications, the long-term advantages may outweigh these issues. Continued research and evaluation are required to refine techniques, enhance efficiency, and make these advancements accessible to a broader population.

Keywords: robotics, total knee arthroplasty, TKA, robotic assistance, arthroplasty

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Introduction

Robots, by definition: any automatically operated machines that replaces human effort, are commonly used in many aspects of life. Unimate, invented by George Devol and his collaborator Joseph Engelberger, is considered the first industrial robot. Introduced to the market in 1961, was originally designed to handle hot and hazardous tasks in factories, such as lifting and manipulating materials [1]. However, the introduction of robots into the operating room occurred more than 20 years later in the 1980s, when Hap Paul, DVM, and William Bargar, MD developed the Robodoc — orthopedic image-guided system used in prosthetic hip replacement. Simultaneously computer assisted system were used in neurosurgery and otolaryngology [2].

Nowadays, there has been a notable surge in the adoption of robotic technology in orthopedic procedures. This trend is evident in the increased utilization rates, such as the rise in technology-assisted TKAs from 1.2% in 2005 to 7% in 2014 in USA [3]. Additionally, there's been a significant uptick in patient interest, as reflected by the growing number of searches for 'Robotic Knee Arthroplasty' on platforms like Google Trends [4]. The journal with the highest number of publications in this area is the "Journal of Arthroplasty" [5]. The three most common orthopedic surgical areas utilizing robots are the spine, hip, and knee. In the case of the knee, the procedures include total knee arthroplasty (TKA), unicompartmental knee arthroplasty (UKA), with a single mention of anterior cruciate ligament (ACL) reconstruction. The future of also traumatology looks promising, as robotics has significant potential in fracture repair surgeries [6].

TKA is a gold standard in the treatment of degenerative knee joint diseases. While its popularity persists — in the USA there is a projected increase of 673% in the demand for TKA [7] — achieving optimal implant positioning remains crucial for successful outcomes. Robotic-assisted TKA (RATKA) has emerged as a promising solution to enhance precision in implant positioning. However, the adoption of robotic devices is associated with prolonged surgical duration compared to standard techniques and potentially increasing anesthesia time [8].

This article aims to compare the learning curve, operative times, complications, outcomes and future associated with robotic-assisted TKA through an analysis of various studies.

Clinical application and outcomes

Techniques and types of robots

Mapping of the patient anatomy is the first step in every robot assisted TKA or UKA. This is achieved in two main ways. First is preoperative CT and the other is intraoperative mapping with the use of hand probes [9]. Preoperative CT allows to reduce the operation time as it only takes 15 minutes on average. Better planning before surgery such as calculating angle that is required to be corrected and set preliminary plane of the osteotomy and simulate knee positioning is also a meaningful improvement. However it exposes the patient to harmful radiation of a typical CT scan with particular attention paid to the femoral head, knee and ankle. Moreover, it doesn't take into account changes in anatomy that can occur after obtaining the pictures and isn't as accurate in imaging soft tissue such as ligaments [9]. On the other hand, intraoperative mapping is better in identifying soft tissues, doesn't expose patients to radiation and allows to set the osteotomy plane more precisely, but it extends the operation time [9]. A correct soft tissue balance keeps the joint properly aligned between flexion and extension which directly translates into the implant durability. The initial step of a surgery includes placing markers in the femur and tibia, which the robot utilizes for geometric calculations to determine spatial orientation. The procedure, while initially time-consuming, offers benefits in terms of accuracy in component positioning and soft tissue preservation [10].

There are 3 main types of robots used in arthroplasty distinguished on the basis of surgeon control — passive, semi-active and active. Passive systems (e.g. Acrobat robotic system) are completely dependent on operator, active (e.g. ROBODOC, iBLOCK) make some of the cuts with no participation of a human and semi-active (e.g. Navio, MAKO) have a certain degree of autonomy and give surgeon feedback to prevent excessive removal of bone and soft tissue damage [11]. We can also differentiate systems based on choice of the implants later inserted into the patient's joint. Closed systems limit the choice to one producent or even specific line of one producent's implants and open systems leave the choice to the surgeon.

Clinical outcomes

The first RATKA was conducted in 2000, and subsequent studies highlighted improved precision, reduced postoperative swelling, and faster recovery of the full range of motion [12].

A ten-year follow-up study involving 102 patients who underwent RATKA explored the outcomes and implants durability. It indicated improved precision in maintaining the mechanical axis and alignment of femoral and tibial components. While it reported increase in the operation duration amounting to 30 minutes compared to traditional methods it also emphasized the effectiveness of robotic assistance in precise and individualized procedures. Range of motion for patients who underwent robotic procedure was higher by 1.9 on average. Aseptic loosening was present in 4.4% cases of standard procedure and only 2.7% of robotic ones. Complications and revisions were also less common in the latter amounting to 4.6% and 3.6% respectively in comparison to 5.6% and 4.4% for unassisted surgery [13].

The pivotal variable in total knee arthroplasty is the proper alignment of the implant. RATKA devices provide assistance in achieving maximum precision in implant positioning. While the initial adoption of robotic devices may extend the surgical duration, studies show that the learning curve contributes to a its gradual reduction. A study analyzed 240 RATKA procedures performed by two board-certified surgeons with similar experience [14]. It demonstrated a significant reduction in operation time as experience with RATKA increased suggesting that after several months of practice there might be no difference in length between the two methods.

Agarwal et Al. examined the comparative effectiveness of RATKA versus conventional TKA across a range of clinical and radiological outcomes. RATKA consistently demonstrated superior postoperative improvements in WOMAC and HSS scores, compared to conventional TKA. The study also highlighted the cost-effectiveness of robotic systems and training requirements. Annual added cost of investment ranges from 4000 up to 71000 US dollars [15].

Patient satisfaction outcomes

Gunaratne et al. identified four main reasons for patient dissatisfaction with TKA: sociodemographic, preoperative, intraoperative, and postoperative factors. Robotic-assist can help to minimize the impact of intraoperative factors such as less proximal tibial resection and inaccurate coronal alignment of the femoral component positively associated with lower satisfaction. However, factors such as fixation type, patella resurfacing or surgical techniques did not affect dissatisfaction. Patients' perception of alignment poorly correlated with true radiographic alignment, with dissatisfied patients more likely to misperceive their alignment [16].

Despite the limited correlation to surgical outcomes, robotic-assisted surgery may impact patient satisfaction which was confirmed by patient-reported outcome measures.

A short-term evaluation of patient satisfaction outcomes after RATKA demonstrated promising results. The study included 20 cases compared to 20 cases of manually performed TKA. Each patient was administered a WOMAC score six months after the surgery. Achieved data indicated lower pain levels, improved physical function, and higher overall satisfaction in patients who underwent RATKA compared to traditional TKA. Since patients' satisfaction is the main determinant of the direction of development of current medicine, the first method has a potential to become a new standard in the future [17].

A 2019 study aimed to determine if patient satisfaction could be improved with RATKA. One hundred twenty consecutive RATKA patients with real-time intraoperative information were compared to 103 manual instrument TKA patients. No demographic differences existed. The evaluation was conducted one year after the surgery. RATKA patients showed significantly higher satisfaction (94% vs. 82%) and better overall satisfaction scores (7.1 vs. 6.6). KSS function and knee scores were notably better postoperatively in the RATKA group [18].

Another study investigated the impact of early fulfillment of patient expectations on satisfaction following RATKA. 106 patients underwent RATKA and completed assessments preoperatively and at various postoperative intervals up to 2 years. Patients' expectations were assessed at 3 and 6 months post-TKA, and satisfaction levels were evaluated at 1 and 2 years. Results show that patients with greater than average expectation fulfillment at 3 and 6 months reported higher satisfaction scores at 1 year and 2 years post TKA. Additionally, comparison with a national TKA cohort study indicates that RATKA yields greater improvements in various outcomes, including pain, symptoms, sports and recreation, and quality of life [19].

Complications

Intraoperative complications of RATKA often involve issues with the marker, and soft tissue and bone injuries, while postoperative complications typically include superficial infections, cellulitis, and pin-hole fractures [20]. Park and Lee associates active robotic systems with higher risks of iatrogenic damage, such as patellar tendon rupture, patellar fracture, and common peroneal nerve injury [21]. However, newer studies indicate a significant reduction in soft tissue injuries with RATKA, resulting from the adoption of semi-active systems that provide feedback near cutting boundaries [22, 23].

Initial RATKA procedures often result in longer surgery times [24], which can increase the risk of complications such as anemia requiring transfusion, wound dehiscence, kidney failure, sepsis, surgical site infections, urinary tract infections, hospital readmission, and prolonged hospital stays [25]. Despite this, RATKA has been shown to reduce blood loss by 23.7% and decrease the risk of transfusion by 83% compared to conventional TKA [26].

Marker-related complications, such as displacement, fracture, or loosening, occur in about 0.6% of cases and may require conversion to conventional arthroplasty in 40% of these situations [27]. Pin-hole fractures, occurring in up to 1.3% of cases, usually present around 13 weeks post-surgery as low-energy fractures preceded by thigh pain. These fractures are often linked to suboptimal or transcortical marker placement [28], with larger marker diameters increasing the incidence [29]. If the pin fixation was unicortical, pin-related fractures were less frequent but the risk of marker displacement increased [30]. Most pin-hole fractures are non-displaced and treated non-operatively, while severe cases require intramedullary nailing [29]. Infections occur in approximately 0.6% of cases and are typically resolved with a 7-day course of oral antibiotics [23].

Future

The implementation of RATKA aims to achieve the highest precision, accuracy, and patient satisfaction while minimizing the need for revisions. Currently, the widespread adoption of robotic TKA is hindered by high investment costs, maintenance and preoperative procedures and prolonged surgery duration. Both factors effectively discourage young surgeons from undertaking such procedures due to lack of experience [31].

Another drawback of this technique is its limitation to specific types of prostheses [32]. On the other hand, robotic TKA ensures more precise component fitting and alignment of the joint axis, resulting in improved functionality and soft tissue protection. Statistics regarding publications on robotic TKA are evidence of growing interest in the procedure [33]. This provides prospects for obtaining a large amount of additional, evidence-based data in the near future. The development of artificial intelligence will undoubtedly contribute to the advancement of RATKA, particularly in three-dimensional preoperative planning. The next step towards harnessing the full potential of surgical robots will be to grant them greater autonomy through learning models and task algorithms for specific situations [33]. However, the future of RATKA will largely depend on the long-term results of conducted surgeries and patient satisfaction, which can only be expected in a few years.

Conclusions

Robotic assistance in total knee arthroplasty has demonstrated substantial benefits in terms of implant positioning accuracy, reduced complications, and improved patient satisfaction proven with follow-up visits [34]. The learning curve associated with these technologies results in a gradual reduction in operation time, emphasizing the importance of surgeon experience. While challenges such as increased costs and potential complications exist, the long-term benefits in terms of patient outcomes may outweigh these concerns [35]. The future of RATKA holds potential for further enhancements, particularly regarding artificial intelligence and robotic autonomy. Continued research and evaluation of newer robotic systems are essential to refine techniques, enhance efficiency, and make these advancements more widely accessible.

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