Current Reviews in Musculoskeletal Medicine (2020) 13:309–317
https://doi.org/10.1007/s12178-020-09625-z

THE USE OF TECHNOLOGY IN ORTHOPAEDIC SURGERY—INTRAOPERATIVE AND POST-OPERATIVE MANAGEMENT (C KRUEGER AND S BINI, SECTION EDITORS)

Robots in the Operating Room During Hip and Knee Arthroplasty

Paul L. Sousa[1] • Peter K. Sculco[2] • David J. Mayman[2] • Seth A. Jerabek[2] • Michael P. Ast[2] • Brian P. Chalmers[2]

Abstract

Purpose of the Review The utilization of technology has increased over the last decade across all surgical specialties. Robotic-assisted surgery, among the most advanced surgical technology, applied to hip and knee arthroplasty has experienced rapid growth in utilization, surgical applications, and robotic platforms. The goal of this study is to provide a comprehensive review of the most commonly utilized robotic platforms for hip and knee arthroplasty and the most up to date literature on the benefits and limitations of robotic arthroplasty.

Recent Findings Studies consistently demonstrate that that robotic-assisted surgery during total hip arthroplasty (THA), total knee arthroplasty (TKA), and unicompartmental knee arthroplasty (UKA) improves component position and alignment. There is also growing evidence that robotic-assisted UKA improves clinical outcomes and implant survivorship and, therefore, may be cost-effective. However, there remains to be convincing evidence that robotic-assisted arthroplasty improves clinical outcome measures or reduces revision rates for THA and TKA. Potential disadvantages of robotic arthroplasty remain, including a learning curve, potential for additional radiation exposure preoperatively, and the financial costs.

Summary Robotic hip and knee arthroplasty remains attactive as studies show that it consistently improves implant position and alignment over conventional techniques. There is growing evidence that robotic UKA may improve patient outcomes and reduce revision rates, but further study is needed. In addition, further and longer-term studies are needed to determine if improved component position and alignment in TKA and THA leads to improved clinical outcomes and reduced revision rates.

Keywords Total hip replacement · Total knee replacement · Unicompartmental knee replacement · Robotics · Clinical outcomes · Implant alignment

Introduction

The utilization of robots in the operating room is increasing across multiple surgical subspecialties. More specifically, robotic-assisted surgery for hip and knee arthroplasty has rapidly evolved in the last several years, now with nearly every major implant company developing or offering a robot [1–3]. In a statewide database, use of robotic total knee arthroplasty increased over 500% from 2009 to 2013 [1]. Since the original more primitive robotic systems utilized in hip and knee arthroplasty, several other robotic systems have been developed with more advanced and variable features. While robotic arthroplasty represents only 5–7% of cases overall [2, 3], nearly 12% total knee arthroplasty and 17% of surgeons used a form of computer assistance in New York State for 2015 [3•]. Several potential benefits of robotic-assisted surgery include enhanced surgical planning, improved component positioning, real-time information about soft tissue tensioning and balance,

This article is part of the Topical Collection on *The Use of Technology in Orthopaedic Surgery—Intraoperative and Post-Operative Management*

✉ Brian P. Chalmers
chalmersb@hss.edu

Paul L. Sousa
sousa.paul@mayo.edu

Peter K. Sculco
sculcop@hss.edu

David J. Mayman
maymand@hss.edu

Seth A. Jerabek
jerabeks@hss.edu

Michael P. Ast
astm@hss.edu

[1] Department of Orthopedic Surgery, Mayo Clinic, 200 First Street SW, Rochester, MN 55905, USA

[2] Adult Reconstruction and Joint Replacement, Hospital for Special Surgery, 535 East 70th street, New York, NY 10021, USA

and restoration of hip length and offset [4–9]. On the other hand, opponents cite a high financial cost, the need for preoperative advanced imaging for many systems, pin sites for array placement, increased operative times, and learning curves as major disadvantages [10, 11]. Furthermore, robots are not universally equivalent, and different systems offer specific technologies and designs with unique advantages and disadvantages [12–14]. As with any new technology, further study and longer follow-up are necessary to critically evaluate the use of robots in the operating room. Primary goals of this review are to describe contemporary robotic systems available; to summarize radiographic and clinical outcomes for total hip arthroplasty (THA), total knee arthroplasty (TKA), and unicompartmental knee arthroplasty (UKA); and to outline on specific limitations and disadvantages of robotic arthroplasty.

Robotic System Designs

Robotics is a non-descript term for many available technologies in hip and knee arthroplasty. Most major arthroplasty implant companies already have or are developing robotic systems for use in the operating room [12–14]. However, robotic systems and designs are not uniform. Systems differ based on the amount of control provided to the robot and the surgeon with systems being generally categorized as active, passive, and semi-active designs. Some of these systems also require preoperative advanced imaging. Lastly, systems may only be compatible with specific implant designs or companies. For the arthroplasty surgeon, it is important to understand these key differences, along with their advantages and disadvantages.

Robotic Autonomy

The major robotic categories of passive, semi-active, and active (autonomous) are based on the amount of autonomy delivered to both the surgeon and the robot [12–14]. Passive systems enhance the surgeon's ability to carry out tasks under direct supervision, while active systems complete tasks entirely independent of the surgeon. Semi-active systems have a more nuanced relationship. Haptic feedback is one example of a semi-active system, providing tactile feedback to the surgeon, which helps define specific boundaries (i.e., for surgical resection or safety). Landmarks are defined preoperatively or intraoperatively to create a 3-dimensional representation of the patient's anatomy. Computer software then generates specific limits in the 3-dimensional field. The surgeon becomes aware of these limits through a variety of feedback mechanisms. Many semi-active systems provide tactile feedback (vibratory), but may include visual and auditory feedback as well [12•]. Furthermore, semi-active systems can restrict the speed and position of cutting instruments. Some systems employ speed modulation to areas of specific concern (i.e., resections intimate to the collateral ligaments of the knee or the posterior border of the tibia), while others limit surgical resection to defined preopertiave or intraoperative boundaries. The major goals of a semi-active system are to reduce deviations from the surgical plan and prevent gross intraoperative errors to ensure a safe procedure with well-aligned components.

Preoperative Advanced Imaging

Advanced imaging in the form of magnetic resonance imaging (MRI) or computed tomography (CT) can be used to create 3-dimensional representations of patient anatomy. From this, intraoperative referencing can use landmarks to create active spatial feedback between the instruments and the patient [12–14]. Reference points are typically bony landmarks that are registered intraoperatively in relation to a static marker. The marker (reference frame) is typically a temporary array statically fixed to the patient's appendicular skeleton. A key advantage to image-based systems is preoperatively planning. Three-dimensional imaging provides the surgeon information about preoperative alignment, accurate size measurements, and in some cases extrapolated data on gap balancing or optimal implant position. With the aid of computer software, a surgeon can devise a complete surgical plan, including alignment, component position, and implant sizing, prior to the operating room and adjust plans intraoperatively. However, advanced imaging is not routine prior to hip and knee arthroplasty for most surgeons, which undoubtedly adds front-end cost, patient inconvenience, and potential radiation exposure (CT).

While image-based systems cross-reference the patient anatomy to data from preoperative advanced imaging, imageless systems rely on the surgeon to provide accurate points of reference during the procedure. Imageless systems utilize the intraoperative data to generate a 3-dimensional representation of the patient anatomy solely from anatomical landmarks. Imageless systems relieve the burden and cost of preoperative advanced imaging, but also limit the role of preoperative planning. The surgeon must create an accurate model of the patient's anatomy as well as determine target alignment, implant sizing, and position intraoperatively which are only as accurate as the data the surgeon is inputting into the system.

Closed vs Open

Closed systems limit implant selection, while open systems leave implant selection to the discretion of the surgeon [12•]. Moreover, closed systems may further limit implant selection not only to one implant manufacturer, but to certain types of implant systems of a specific manufacturer. Beyond the obvious restrictions to the surgeon, closed systems may have further contractual implications as they are often negotiated between device companies and hospitals or hospital systems [12•]. In contrast, open systems lack specificity. In practice, general bone cuts can be planned, but techniques specific to a certain implant cannot be employed. Furthermore, there is a lack of data on optimal kinematics for each specific implant design. Therefore, open systems, while allowing greater implant flexibility, have a lower level of precision [12, 14]. Surgeons should carefully scrutinize these benefits and limitations before broadly adopting a system.

Specific Robotic Systems

Robodoc/TCAT® (Curexo Technology, Fremont, CA/Think Surgical Inc., as of 2014, Think Computer Assisted Tool)

ROBODOC/TCAT® is an open, active, image-based (CT) system that uses a robotic mill to accurately make boney resections for TKA and THA. First, implemented in 1992 , it was one of the first use of robotics in total joint arthroplasty. The clinical success and utility has been demonstrated in a series of clinical trials [15]. TCAT workflow starts with advanced imaging, which is used to design a virtual preoperative plan. The surgeon uses the “ORTHODOC” workstation to download advanced imaging and the software aides in planning implant positioning. Surgical markers are used to cross-reference the anatomy with advanced imaging. Finally, a fully automated, milling robotic arm executes bone removal for implant positioning; unlike other robotic systems, the plan cannot be adjusted intraoperatively but rather it executes the predetermined planned.

Mako® (Robotic Arm Interactive Orthopedic System (Rio); Mako Stryker, Fort Lauderdale, FL) Fig. 1

The MAKO® is a closed, semi-active, image-based (CT) system that that is now FDA approved for THA, TKA, and UKA. The surgical plan is determined preoperatively; stereotactic references are fixed with pins above and below the target joint. Then, a robotic arm assists in bone resection with the end effector (either a burr or saw cutting tool at the end of the arm). Real-time referencing helps guide resection based on the predetermined plan that can be adjusted intraoperatively. The surgeon is aware of specific boundaries through haptic feedback and specific spatial limits when the surgeon deviates from planned resection [16].

Rosa (ROSA® Knee System, Zimmer Biomet, Warsaw, IN)

ROSA® is a semi-open (as it may be used with several implants from one manufacturer), passive/semi-active, computer system used to make boney resections for TKA that does not require preoperative advanced imaging. Reference frames are statically fixed to both the tibia and femur, and joint surfaces are registered to the system. Then, a robotic arm assists in the placement of conventional cutting jigs for the planned resection. In contrast to the above systems, there is no haptic feedback during boney resection, and boney resections are performed by the surgeon with conventional instruments. Furthermore, no advanced imaging is required to regenerate 3-dimension models of the patient’s anatomy [9]. Lastly, the computing software and instruments allow the surgeon to measure soft tissue tension intraoperatively.

Navio® (Blue Belt Technologies, Plymouth, MN) Fig. 2

Navio® is a semi-open, semi-active, system that uses spatial referencing to create a virtual representation of the patient’s hard tissues for UKA, PFA, and TKA that does not require preoperative advancedimaging. Mounting pins are used on the femur and tibia for spatial referencing intraoperatively. The system utilizes a semi-autonomous, hand-held cutting tool with safeguards for cutting accuracy. The mechanism is different than haptic feedback. The protective controls limit instrument speed, and will retract the cutting burr when spatial deviations occur. Furthermore, the cutting burr can be used to perform the boney resections directly or simply create pilot holes for accurate cutting jig placement. In the latter, conventional cutting jigs may be used for boney resection.

Total Hip Arthroplasty

Implant Position

Both MAKO and ROBODOC/TCAT have demonstrated improved accuracy for acetabular positioning as well as femoral offset and leg length [5, 17, 18]. In one study, MAKO® THA demonstrated 100% precision in a matched-cohort study for obtaining an acetabular position in the Lewinnek safe zone for anteversion and inclination in comparison with only 80% for manual placement and 92% for Callanan safe zone vs 62% for manual ($p < 0.01$) [17•]. Two retrospective studies showed similar results. One multicenter study showed that 95% of cups were placed within 5° of the preoperative surgical plan [17•]. Another retrospective review of nearly 2000 THAs demonstrated a greater percentage of acetabular components in both Lewinnek and Callanan safe zones for robotic-assisted vs conventional techniques [19]. Cadaveric studies have supported inclination and anteversion accuracy exceeding 5 times greater than manual placement [18]. Additionally, one cadaveric study showed more accurate leg length and femoral offset compared with conventional instrumentation [5•], while others have found no difference [19]. Lastly, MAKO® may also benefit from greater preservation of acetabular bone stock. Eccentric reaming or excessive resection may contribute to soft tissue impingement, aseptic loosening, and altered hip-center position. Similarly, ROBODOC/

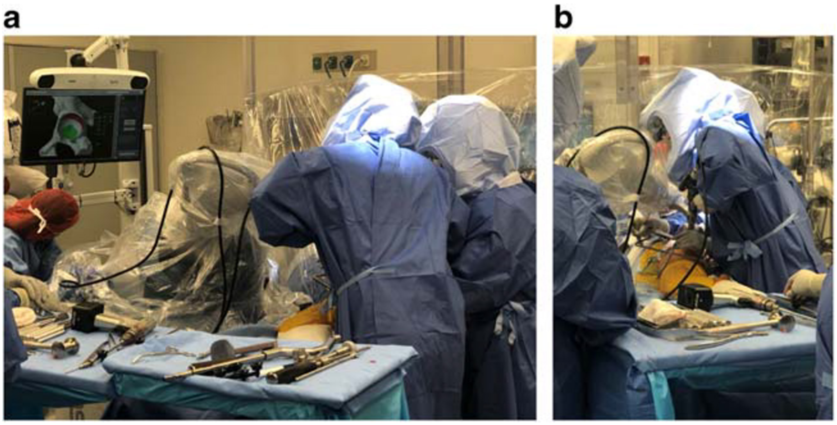

Fig. 1 Photographs of intraoperative acetabular component position planning (**a**) based on a preoperative CT scan and haptic guided acetabular reaming (**b**) with the Mako robototic system for a total hip arthroplasty

TCAT® has demonstrated improved fit, fill, and alignment of the femoral component with no intraoperative fractures in a prospective randomized clinical trial [20].

Clinical Outcomes

While some studies have shown improved outcomes with robotic THA, most studies have shown equivalent clinical outcome measures between robotic and conventional THA. Retrospective data of 100 robotic THA and 100 manual THA the year prior to using the specific robotic system showed a significantly improved accuracy in abduction and anteversion, as well as a higher UCLA scores, MHHS (Modified Harris Hip Score), and a lower dislocation rate at 2 years [21]. Bargar et al. in a randomized multicenter clinical trial of one robotic THA system (76) vs conventional instrumentation [22] showed improved pain and WOMAC scores at 14 years. However, UCLA activity, Harris Hip Scores, and VAS scores were similar between groups [8]. Moreover, kinematic gait analysis and pelvic and hip motion remain similar between conventional THA and robotic THA [23]. One potential clinical advantage of the femoral milling system is a lower rate of intraoperative embolic events compared with standard broaching [24]. However, it should be noted that systematic review and meta-analysis has been unable to detect any significant differences in patient-reported outcomes for THA [25].

Total Knee Arthroplasty

Implant Position

There is large support in the literature for improved radiographic alignment and component position with robotic TKA. MAKO® TKA has shown fewer outliers > 3° from neutral mechanical axis [4, 26, 27]. Additionally, a recent matched-cohort study suggested that MAKO® TKA more accurately reproduced posterior condylar offset and patellar height compared with conventional TKA [28]. ROBODOC/TCAT® has shown less errors > 1° of error in all planes in comparison with conventional techniques [20, 29–31]. Moreover, many studies have demonstrated a reduction in radiographic outliers, specifically for mechanical access alignment [26, 32]. Among the four clinical randomized trials, the studies revealed no outliers (± 3° from mechanical axis) with the use ROBODOC/TCAT®, outlier rates of between 19 and 24% with conventional instruments [30, 32–34]. Long-term follow-up for a RCT of ROBODOC/TCAT® vs conventional TKA with large numbers, 750 vs 766 TKA's, showed fewer outliers for mechanical axis alignment with ROBODOC®, 14 vs 26%; however, no difference in tibial slope, femoral

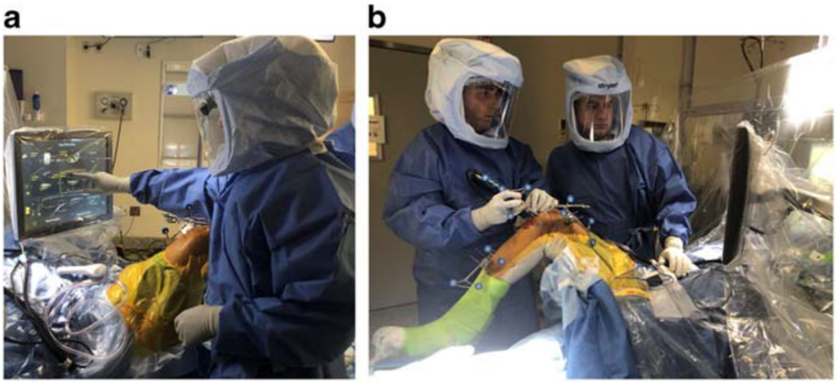

Fig. 2 Photographs of intraoperative customization of implant positioning and alignment (**a**) after bony registration and utilization of the burring tool to prepare the bone (**b**) with the Navio robotic system for a unicompartmental knee arthroplasty

flexion, mechanical alignment, joint line height, and posterior femoral offset could be demonstrated. Additionally, mean deviation from the transepicondylar axis and tibial rotation was similar groups [32•]. Similar to MAKO® and TCAT/ROBODOC®, one cadaveric study has reported mean deviation of less than 1° for femoral and tibial alignment using the Navio® system [9]. Resection depth was < 1 mm different than planned resection for all boney resections, and mechanical axis alignment was 0 ± 1° [9].

Clinical Outcomes

Beyond radiographic parameters, consistent advantages of robotic TKA have yet to be determined, with most studies showing equivalent clinical outcome scores between robotic and conventional TKA [30, 32, 34, 35]. Park and Lee demonstrated no detectable differences in Knee Society Scores at 4 years in a prospective randomized controlled trial using a robotic system [35]. In a recent large RCT of robotic (750) and conventional (766) TKA, no differences could be demonstrated between groups when evaluating the Knee Society Score, WOMAC, and ROM, at UCLA activity at mean 13 years [32•]. Furthermore, aseptic loosening and all-cause survivorship were similar at 15 years [32•]. Similarly, a large retrospective review of cruciate retaining robotic and conventional TKA showed similar clinical outcomes and survivorship at 10 years [26•]. In contrast, Liow et al. showed improved SF-36 vitality and emotional health at 2 years from a 60 patient RCT (29 robotic, 31 conventional), while no difference in KSS knee and function scores could be demonstrated [33•]. In a prospective cohort study, Kayani et al. [36] demonstrated improved early functional outcomes and shorter length of stay compared with conventional TKA. Additionally, some have suggested that robotic TKA may provide improved balancing with limited need for soft tissue release, but the data in this regard is not definitive [37, 38]. Systematic review and meta-analysis has been unable to detect significant differences in patient-reported outcomes for TKA [25].

Robotic Unicondylar Knee Arthroplasty

Implant Position

Data for the use of robotics has been most supportive for UKA, with consistently improved radiologic and clinical outcomes over conventional techniques [39–41]. In a prospective randomized study of 27 patients undergoing jig-based medial UKA vs robotic, Cobb et al. [42] reported tibiofemoral alignment within 2° of the planned position in the coronal plane for 100% of robotic UKAs and only 40% in the conventional group. Similarly, Bell et al. [43] used postoperative CT scans in a prospective randomized controlled study of 62 robotic UKAs vs 58 manual UKAs to show improved accuracy of femoral and tibial implant positioning for robotic UKA. Herry et al. [44] demonstrated improved restitution of the native joint line when comparing 40 manual UKAs vs 40 robotic UKAs in a retrospective study of consecutive cases. Additionally, robotic instrumentation can provide data on gap tensioning intraoperatively to fine-tune implant positioning for specific gap tension and limb alignement [45].

A specific point that warrants mention is surgeon experience. Errors in implant positioning and low case volume have been associated with higher rates of failure [46, 47]. One single-surgeon series demonstrated similar accuracy for tibial component alignment and tibial slope with manual techniques compared with published robotic outcomes [48]. With respect to low volume surgeons and/or those inexperienced in UKA, Kayani et al. [49] demonstrated no learning curve effect in robotic UKA for accuracy of achieving the planned femoral or tibial implant positioning, posterior condylar offset ratio, limb alignment, and restoration of native joint line.

Clinical Outcomes

Beyond improved radiographic accuracy, some data supports improvement in clinical outcomes and implant survivorship for robotic over conventional UKA. Kayani et al. [22] conducted a prospective cohort study on 146 patients that showed robotic UKA was associated with reduced postoperative pain, decreased opiate analgesia consumption, reduced inpatient physiotherapy, and decreased mean time to hospital discharge compared with conventional manual UKA. Blyth et al. [50] showed that robotic UKA had 55.4% less pain when compared with conventional UKA in the early postoperative period (< 8weeks) in a prospective randomized control trial on 139 patients. Moreover, the robotic UKA group had improved American Knee Society Score for 3 months following surgery, but no difference in functional outcomes at 1 year [50]. Cobb et al. [42] reported similar results with greater improvement in American Knee Society Score for robotic UKA at 6 and 18 weeks postoperatively in a prospective, randomized controlled trial of 13 robotic and 15 manual UKAs. The impact of robotic UKA may be even greater in high-demand patients. Gilmour et al. [51] performed a subgroup analysis of their large RCT to identify the 35 most active patients. In this subgroup, robotic UKA had greater improvements in Knee Society Scores, Oxford Knee Scores, and Forgotten Joint Scores compared with conventional manual UKA at 2 years [51]. Similarly, Canetti et al. [52] reviewed outcomes in 28 highly active patients undergoing lateral compartment UKA, and found that the robotic UKA group had earlier return to sporting activity than the conventional UKA patients. Batailler et al. [53] focused on survivorship for 80 conventional and 80 robotic UKAs, demonstrating fewer revisions for robotic UKA, 5 vs 9%. Furthermore, when evaluating why the revisions were completed in both cohorts, the authors found that 86% of revisions in the conventional group were secondary to component malposition or limb malalignment, compared with none of the revisions in the robotic group [53]. Overall survivorship of robotic UKA is excellent; a recent systematic review and prospective cohort study both showed survivorship free from revision of 97% at 6 years [39, 54].

Disadvantages of Robotic Hip and Knee Arthroplasty

Cited disadvantages to robotic arthroplasty include increased surgical time, learning curves, and added financial costs. Multiple studies have demonstrated increased surgical time, with most averaging 15–25 additional minutes for total knee and total hip arthroplasty alike [30, 55, 56]. Once surmounted, RAS required an additional 25 min compared with conventional TKA with the use of one specific robotic system [30, 34]. Using cost estimates from Dehaan et al., this translates into an additional cost of $1625 per surgery ($65/min of operative time) for TKA [57]. This argument may not hold true with contemporary robotic systems compared with previous reports with the ROBODOC® system [30, 56]. More contemporary studies show a net-even operative times after a small learning curve for robotic TKA, with no impact on accuracy of implant positioning [49, 58]. Beyond the financial costs associated with increased operative time, lengthy operative time has been associated with increased risk for prosthetic joint infection [59]; however, to date, there is no compelling data that robotics in the operating room increase infection rates in hip and knee arthroplasty. Still, the costs for patients undergoing advanced imaging preoperatively must be considered in many systems.

There is a definitive learning curve when adopting new technology in the operating room. Some early reports suggested that technical complications can lead to aborted surgical plans in up to 10% of cases [11, 33, 60]. Most aborted procedures were the result of repetitive failure messages, lengthy re-registering patients, and impending risk to the patellar tendon [10]. While this is less common with modern technologies and surgeon experience, it may be an early disadvantage. The learning curve may be slightly longer in terms of operative time and accurate acetabular positioning for robotic THA (35 cases), as reported in a single-surgeon experience [55]. As mentioned above, the learning curve seems shorter for robotic UKA for accuracy of planned femoral or tibial positioning, posterior condylar offset ratio, limb alignment, and restoration of native joint line [49].

One of the most cited and significant disadvantages of robotic hip and knee arthroplasty are the financial cost of the current devices. Costs associated with robotic surgery include fixed costs (equipment purchase and maintenance fees) as well as variable costs (advanced preoperative imaging and cleaning fees). Start-up costs can be upwards of $800,000 for some robotic systems [33•]. Operating costs contribute as well, quoted at over $1200 per case for some systems [33•]. The requirement of preoperative advanced imaging poses additional risk of radiation exposure to patients (in the case of CT scans) as well as the added cost to the patient ($1500–2000). From a break-even analysis, robotic systems would need to reduce costs in the long run or add benefits to the patient. Cost-effectiveness would be achieved if robotics could lower the rate of hip and knee revision arthroplasty, which can range from $49,360 to $93,600 per episode of care [61]. Interestingly, recent reports have suggested potential cost savings for some robotic TKAs. A review of Medicare data showed a reduction in overall 90-day costs by $2391 for one robotic TKA system in a matched retrospective cohort study. The major difference in cost was attributed to fewer patients being discharged to rehab or skilled nursing facility, fewer readmissions, shorter length of stay, and less home health aide utilization; however, this analysis may be biased as there are a number of variables that were not analyzed in the aforementioned study that contribute to discharge disposition and length of stay beyond the use of robotics in the operating room [62]. The best data for a potential cost savings analysis may be for robotic UKA. At least 1 study has shown that when total cost of care is considered and Markov decision analysis is used that robotic-assisted UKA is actually more cost-effective than manual surgery when the number of cases exceeds 94 annually, failure rates are less than 1.2% at 2 years, and patient age is considered [63, 64]. However, all of these findings should be interpreted with caution as several additional costs with robotic technology can be overlooked.

Conclusion

The use of robotic assistance in the operating room for hip and knee arthroplasty continues to grow and more robots are being introduced annually. While many systems exist in the USA, surgeons should be aware of key differences in autonomy, the type of cutting tool for each robot, the possible requirement for preoperative advanced imaging, and options for implant selection. Moreover, surgeons should understand the most up to date literature regarding the outcomes of robots in the operating room. To date, several reports show improved precision of implant positioning in THA, TKA, and UKA for robotic-assisted surgery compared with conventional techniques. Namely, robotics may allow surgeons to be more precise and achieve a narrower curve of implant placement with fewer outliers. Consistent data on substantially decreased revision rates and improved implant survivorship is lacking for robotic THA and TKA, but there is growing evidence for robotic over conventional UKA. This type of analysis will likely only increase as with time since the implementation of more modern robotic systems.

Disadvantages of robotic hip and knee arthroplasty include increased operative times, the learning curve associated with new technology, and, most importantly, added financial costs. Long-term data and further clinical evaluation will help to define the role of robotics in hip and knee arthroplasty and to determine if improved implant positioning in TKA and THA leads to improvement in implant survivorship over time.

Compliance with Ethical Standards

Conflict of Interest Brian Chalmers and Paul Sousa have nothing to disclose.

Peter Sculco is a paid consultant for Lima Coporate, Intellijoint Surgical, and EOS imaging; he has also received research support from Intellijoint Surgical.

David Mayman receives stock options from OrthAlign, Imagen, Insight, and Wishbone; he is a board member of the Knee Society; he is a paid consultant and has received research support from Smith and Nephew.

Seth Jerabek receives stock options from Imagen Technologies and has received research support, paid honoraria, consulting fees, and royalties from Stryker.

Michael Ast is a board member of AAHKS and EOA; he is a paid consultant for Stryker, Surgical Care Affiliates, Smith and Nephew, OrthAlign, and Conformis; he receives stock options from Osso VR and OrthAlign; he has received research support from Smith and Nephew.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

References

Papers of particular interest, published recently, have been highlighted as:
- Of importance

1. Naziri Q, Burekhovich SA, Mixa PJ, Pivec R, Newman JM, Shah NV, et al. The trends in robotic-assisted knee arthroplasty: a statewide database study. J Orthop. 2019;16(3):298–301.
2. • Antonios JK, Korber S, Sivasundaram L, et al. 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(1):88–95 **This study analyzes the US utlization data for robotic total knee arthroplasty, demonstrating that a little under 10% of TKA were performed using robotic assistance or computer navigation.**
3. • Boylan M, Suchman K, Vigdorchik J, Slover J, Bosco J. Technology-assisted hip and knee arthroplasties: an analysis of utilization trends. J Arthroplasty. 2018;33(4):1019–23 **This paper is a utilization analysis of robotic-assisted hip and knee arthroplasty in the USA and reports rates and trents of robotic arthroplasty.**
4. Hampp EL, Chughtai M, Scholl LY, Sodhi N, Bhowmik-Stoker M, Jacofsky DJ, et al. Robotic-arm assisted total knee arthroplasty demonstrated greater accuracy and precision to plan compared with manual techniques. J Knee Surg. 2019;32(3):239–50.
5. • Nodzo SR, Chang CC, Carroll KM, et al. Intraoperative placement of total hip arthroplasty components with robotic-arm assisted technology correlates with postoperative implant position: a CT-based study. *Bone Joint J.* 2018;100-B(10):1303–9 **This is a prospective study comparing the intedned intraoperative placement of total hip arthroplasty acetabular components and true acetabular component placement based on postoperative CT scans. The study reports accurate execution of preoperative plan for robotic total hip arthroplasty acetabular component placement.**
6. Kanawade V, Dorr LD, Banks SA, Zhang Z, Wan Z. Precision of robotic guided instrumentation for acetabular component positioning. J Arthroplast. 2015;30(3):392–7.
7. Gupta A, Redmond JM, Hammarstedt JE, Petrakos AE, Vemula SP, Domb BG. Does robotic-assisted computer navigation affect acetabular cup positioning in total hip arthroplasty in the obese patient? A comparison study. J Arthroplasty. 2015;30(12):2204–7.
8. Bargar WL, Parise CA, Hankins A, Marlen NA, Campanelli V, Netravali NA. Fourteen year follow-up of randomized clinical trials of active robotic-assisted total hip arthroplasty. J Arthroplast. 2018;33(3):810–4.
9. 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 Arthroplast. 2019.
10. Chun YS, Kim KI, Cho YJ, Kim YH, Yoo MC, Rhyu KH. Causes and patterns of aborting a robot-assisted arthroplasty. J Arthroplast. 2011;26(4):621–5.
11. Schulz AP, Seide K, Queitsch C, et al. Results of total hip replacement using the Robodoc surgical assistant system: clinical outcome and evaluation of complications for 97 procedures. Int J Med Robot. 2007;3(4):301–6.
12. • Jacofsky DJ, Allen M. Robotics in arthroplasty: a comprehensive review. J Arthroplasty. 2016;31(10):2353–63 **This is a critical review of available robotic technologies for total knee and hip arthroplasty through 2016. -This work provides a framework for comparisons between traditional robotic arthroplasty systems.**
13. • Subramanian P, Wainwright TW, Bahadori S, Middleton RG. A review of the evolution of robotic-assisted total hip arthroplasty. Hip Int. 2019;29(3):232–8 **This review paper outlines and is a food reference for available robotic THA systems. -This article also provides critical evaluation of benefits and drawbacks of robotic-assisted hip surgery similar to this paper.**
14. • Bautista M, Manrique J, Hozack WJ. Robotics in total knee arthroplasty. J Knee Surg. 2019;32(7):600–6 **Review of radiographic and clinical outcomes for robotic-assisted TKA through 2019.**
15. Bargar WL. Robots in orthopaedic surgery: past, present, and future. Clin Orthop Relat Res. 2007;463:31–6.
16. Lang JE, Mannava S, Floyd AJ, et al. Robotic systems in orthopaedic surgery. J Bone Joint Surg Br. 2011;93(10):1296–9.
17. • Domb BG, El Bitar YF, Sadik AY, Stake CE, Botser IB. Comparison of robotic-assisted and conventional acetabular cup placement in THA: a matched-pair controlled study. Clin Orthop Relat Res. 2014;472(1):329–36 **This study is a matched pair study analyzing acetabular component placement with robotic vs. conventional total hip arthroplasty. The study found radiographically more accurate positioning of acetabular components with robotic assitance compared to conventional techniques.**
18. Nawabi DH, Conditt MA, Ranawat AS, et al. Haptically guided robotic technology in total hip arthroplasty: a cadaveric investigation. Proc Inst Mech Eng H. 2013;227(3):302–9.
19. Domb BG, Redmond JM, Louis SS, Alden KJ, Daley RJ, LaReau J, et al. Accuracy of component positioning in 1980 total hip arthroplasties: a comparative analysis by surgical technique and mode of guidance. J Arthroplast. 2015;30(12):2208–18.

20. Bargar WL, Bauer A, Borner M. Primary and revision total hip replacement using the Robodoc system. Clin Orthop Relat Res. 1998;354:82–91.
21. Illgen RLN, Bukowski BR, Abiola R, et al. Robotic-assisted total hip arthroplasty: outcomes at minimum two-year follow-up. Surg Technol Int. 2017;30:365–72.
22. Kayani B, Konan S, Tahmassebi J, Rowan FE, Haddad FS. An assessment of early functional rehabilitation and hospital discharge in conventional versus robotic-arm assisted unicompartmental knee arthroplasty: a prospective cohort study. Bone Joint J. 2019;101-B(1):24–33.
23. Bach CM, Winter P, Nogler M, Gobel G, Wimmer C, Ogon M. No functional impairment after Robodoc total hip arthroplasty: gait analysis in 25 patients. Acta Orthop Scand. 2002;73(4):386–91.
24. Hagio K, Sugano N, Takashina M, Nishii T, Yoshikawa H, Ochi T. Effectiveness of the ROBODOC system in preventing intraoperative pulmonary embolism. Acta Orthop Scand. 2003;74(3):264–9.
25. Karunaratne S, Duan M, Pappas E, Fritsch B, Boyle R, Gupta S, et al. The effectiveness of robotic hip and knee arthroplasty on patient-reported outcomes: a systematic review and meta-analysis. Int Orthop. 2019;43(6):1283–95.
26.• Yang HY, Seon JK, Shin YJ, Lim HA, Song EK. Robotic total knee arthroplasty with a cruciate-retaining implant: a 10-year follow-up study. Clin Orthop Surg. 2017;9(2):169–76 **This study reports 10-year outcomes of robotic vs conventional total knee arthroplasty; it demonstrates improved mechanical-axis alignment and component positioning for robotic TKA, but no difference in clinical outcomes or revision rates.**
27. Marchand RC, Khlopas A, Sodhi N, Condrey C, Piuzzi NS, Patel R, et al. Difficult cases in robotic arm-assisted total knee arthroplasty: a case series. J Knee Surg. 2018;31(1):27–37.
28. Sultan AA, Samuel LT, Khlopas A, Sodhi N, Bhowmik-Stoker M, Chen A, et al. 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;34:409–13.
29. Banerjee S, Cherian JJ, Elmallah RK, Jauregui JJ, Pierce TP, Mont MA. Robotic-assisted knee arthroplasty. Expert Rev Med Devices. 2015;12(6):727–35.
30.• Song EK, Seon JK, Park SJ, Jung WB, Park HW, Lee GW. Simultaneous bilateral total knee arthroplasty with robotic and conventional techniques: a prospective, randomized study. Knee Surg Sports Traumatol Arthrosc. 2011;19(7):1069–76 **This study is a randomized controlled trial of bilateral total knee arthroplasties, one done with conventional techniques and one with the Robodoc. the study reports fewer radiographic outliers with the Robodoc system compared with conventional techniques.**
31. Bellemans J, Vandenneucker H, Vanlauwe J. Robot-assisted total knee arthroplasty. Clin Orthop Relat Res. 2007;464:111–6.
32.• 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. 2019. **This study is a 10-year follow-up of a prospective RCT of robotic vs convention TKA. -The study showed that there was improved radiographic alignment but that implant survivorship and clinical outcomes were similar.**
33.• Liow MH, Xia Z, Wong MK, Tay KJ, Yeo SJ, Chin PL. Robot-assisted total knee arthroplasty accurately restores the joint line and mechanical axis. A prospective randomised study. J Arthroplasty. 2014;29(12):2373–7 **This study is a randomized controlled trial of robotic vs. conventional total knee arthroplasty. The study reports improved radiographic outcomes following robotic-assisted TKA but no difference was noted in clinical outcomes.**
34. Yim JH, Song EK, Khan MS, Sun ZH, Seon JK. A comparison of classical and anatomical total knee alignment methods in robotic total knee arthroplasty: classical and anatomical knee alignment methods in TKA. J Arthroplast. 2013;28(6):932–7.
35. Park SE, Lee CT. Comparison of robotic-assisted and conventional manual implantation of a primary total knee arthroplasty. J Arthroplast. 2007;22(7):1054–9.
36. Kayani B, Konan S, Tahmassebi J, Pietrzak JRT, Haddad FS. Robotic-arm assisted total knee arthroplasty is associated with improved early functional recovery and reduced time to hospital discharge compared with conventional jig-based total knee arthroplasty: a prospective cohort study. Bone Joint J. 2018;100-B(7):930–7.
37. Manning W, Ghosh M, Wilson I, Hide G, Longstaff L, Deehan D. Improved mediolateral load distribution without adverse laxity pattern in robot-assisted knee arthroplasty compared to a standard manual measured resection technique. Knee Surg Sports Traumatol Arthrosc. 2019.
38. Shalhoub S, Lawrence JM, Keggi JM, Randall AL, DeClaire JH, Plaskos C. Imageless, robotic-assisted total knee arthroplasty combined with a robotic tensioning system can help predict and achieve accurate postoperative ligament balance. Arthroplast Today. 2019;5(3):334–40.
39. Robinson PG, Clement ND, Hamilton D, Blyth MJG, Haddad FS, Patton JT. A systematic review of robotic-assisted unicompartmental knee arthroplasty: prosthesis design and type should be reported. Bone Joint J. 2019;101-B(7):838–47.
40. Lonner JH, Klement MR. Robotic-assisted medial unicompartmental knee arthroplasty: options and outcomes. J Am Acad Orthop Surg. 2019;27(5):e207–14.
41. Christ AB, Pearle AD, Mayman DJ, Haas SB. Robotic-assisted unicompartmental knee arthroplasty: state-of-the art and review of the literature. J Arthroplast. 2018;33(7):1994–2001.
42. Cobb J, Henckel J, Gomes P, et al. Hands-on robotic unicompartmental knee replacement: a prospective, randomised controlled study of the acrobot system. J Bone Joint Surg Br. 2006;88(2):188–97.
43. Bell SW, Anthony I, Jones B, MacLean A, Rowe P, Blyth M. Improved accuracy of component positioning with robotic-assisted unicompartmental knee arthroplasty: data from a prospective, randomized controlled study. J Bone Joint Surg Am. 2016;98(8):627–35.
44. Herry Y, Batailler C, Lording T, Servien E, Neyret P, Lustig S. Improved joint-line restitution in unicompartmental knee arthroplasty using a robotic-assisted surgical technique. Int Orthop. 2017;41(11):2265–71.
45. Plate JF, Mofidi A, Mannava S, et al. Achieving accurate ligament balancing using robotic-assisted unicompartmental knee arthroplasty. Adv Orthop. 2013;2013:837167.
46. Liddle AD, Pandit H, Judge A, Murray DW. Patient-reported outcomes after total and unicompartmental knee arthroplasty: a study of 14,076 matched patients from the National Joint Registry for England and Wales. Bone Joint J. 2015;97-B(6):793–801.
47. Murray DW, Parkinson RW. Usage of unicompartmental knee arthroplasty. Bone Joint J. 2018;100-B(4):432–5.
48. Bush AN, Ziemba-Davis M, Deckard ER, Meneghini RM. An experienced surgeon can meet or exceed robotic accuracy in manual unicompartmental knee arthroplasty. J Bone Joint Surg Am. 2019;101(16):1479–84.
49. Kayani B, Konan S, Pietrzak JRT, Huq SS, Tahmassebi J, Haddad FS. The learning curve associated with robotic-arm assisted unicompartmental knee arthroplasty: a prospective cohort study. Bone Joint J. 2018;100-B(8):1033–42.
50. Blyth MJG, Anthony I, Rowe P, Banger MS, MacLean A, Jones B. Robotic arm-assisted versus conventional unicompartmental knee arthroplasty: exploratory secondary analysis of a randomised controlled trial. Bone Joint Res. 2017;6(11):631–9.

51. Gilmour A, MacLean AD, Rowe PJ, Banger MS, Donnelly I, Jones BG, et al. Robotic-arm-assisted vs conventional unicompartmental knee arthroplasty. The 2-year clinical outcomes of a randomized controlled trial. J Arthroplast. 2018;33(7S):S109–15.
52. Canetti R, Batailler C, Bankhead C, Neyret P, Servien E, Lustig S. Faster return to sport after robotic-assisted lateral unicompartmental knee arthroplasty: a comparative study. Arch Orthop Trauma Surg. 2018;138(12):1765–71.
53. Batailler C, White N, Ranaldi FM, Neyret P, Servien E, Lustig S. Improved implant position and lower revision rate with robotic-assisted unicompartmental knee arthroplasty. Knee Surg Sports Traumatol Arthrosc. 2019;27(4):1232–40.
54. Kleeblad LJ, Borus TA, Coon TM, Dounchis J, Nguyen JT, Pearle AD. Midterm survivorship and patient satisfaction of robotic-arm-assisted medial unicompartmental knee arthroplasty: a multicenter study. J Arthroplast. 2018;33(6):1719–26.
55. Redmond JM, Gupta A, Hammarstedt JE, Petrakos AE, Finch NA, Domb BG. The learning curve associated with robotic-assisted total hip arthroplasty. J Arthroplast. 2015;30(1):50–4.
56. 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(1):118–26.
57. DeHaan AM, Adams JR, DeHart ML, Huff TW. Patient-specific versus conventional instrumentation for total knee arthroplasty: peri-operative and cost differences. J Arthroplast. 2014;29(11):2065–9.
58. Sodhi N, Khlopas A, Piuzzi NS, Sultan AA, Marchand RC, Malkani AL, et al. The learning curve associated with robotic total knee arthroplasty. J Knee Surg. 2018;31(1):17–21.
59. Pugely AJ, Martin CT, Gao Y, Schweizer ML, Callaghan JJ. The incidence of and risk factors for 30-day surgical site infections following primary and revision total joint arthroplasty. J Arthroplast. 2015;30(9 Suppl):47–50.
60. Davies BL, Rodriguez y Baena FM, Barrett AR, et al. Robotic control in knee joint replacement surgery. Proc Inst Mech Eng H. 2007;221(1):71–80.
61. Bozic KJ, Kamath AF, Ong K, Lau E, Kurtz S, Chan V, et al. Comparative epidemiology of revision arthroplasty: failed THA poses greater clinical and economic burdens than failed TKA. Clin Orthop Relat Res. 2015;473(6):2131–8.
62. Cool CL, Jacofsky DJ, Seeger KA, Sodhi N, Mont MA. A 90-day episode-of-care cost analysis of robotic-arm assisted total knee arthroplasty. J Comp Eff Res. 2019;8(5):327–36.
63. Moschetti WE, Konopka JF, Rubash HE, Genuario JW. Can robot-assisted unicompartmental knee arthroplasty be cost-effective? A Markov decision analysis. J Arthroplasty. 2016;31(4):759–65.
64. Clement ND, Deehan DJ, Patton JT. Robot-assisted unicompartmental knee arthroplasty for patients with isolated medial compartment osteoarthritis is cost-effective: a Markov decision analysis. Bone Joint J. 2019;101-B(9):1063–70.