

Current topics in robotic-assisted total hip arthroplasty: a review

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Abstract

Total hip arthroplasty (THA) is among the most successful procedures of modern medicine, yet failures and complications continue to occur, leaving room for improvement. Robotics is a cutting-edge technology that tries to improve joint arthroplasty surgery. There is some evidence that shows that robotic-assisted THA improves implant positioning, but less is known about its effect on clinical outcomes or the rate of complications. This article reviews the literature on robotic-assisted THA to elucidate the history, advantages, disadvantages, and current clinical understanding of this procedure.

Keywords

Arthroplasty, robotics

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Introduction

Total hip arthroplasty (THA) is a widely performed procedure that is often considered 1 of the most successful to have been developed in modern medical history. However, THA failure remains a problem, with dislocation and mechanical loosening being the most common complications leading to revision surgery.¹ In recent years, applications of robotic technology have emerged as a potential answer to these concerns. An aim of robotic assistance in joint arthroplasty is to reduce component malposition due to human error, leading to full restoration of kinematics, decreased instability or impingement, and improved patient outcomes. Although accumulating evidence has shown promising results, robotic-assisted THA remains relatively uncommon and overall, less developed compared to other surgical fields. The purpose of this article was to review the current literature on the results of robotic-assisted THA.

This study was approved by the IRB (IRB ID: 5276).

History and context

ROBODOC

The first robotic assistance system used in THA was the ROBODOC Surgical System (THINK Surgical; Fremont,

California, United States).² ROBODOC used a robotic arm to mill into the femoral neck, preparing a canal for the cementless stem implantation. Preoperative computed tomography (CT) imaging was loaded as an input into a computer workstation, which generated a 3D virtual model of the joint and produced a surgical plan customised to the patient's anatomy. The robotic arm was fully automated, executing the femoral-side procedure according to the surgical plan with high precision. Once the robot was active, the only input by the surgeon was an emergency stop.

ROBODOC was first introduced in 1992, as 1 of the first instances of robotic assistance in a surgical procedure.² The system underwent a number of clinical trials in the United States and Germany, demonstrating it was both safe and effective.^{3–5} However, the original company behind ROBODOC, Integrated Surgical Systems, was the

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subject of a 2004 class-action lawsuit in Germany and became financially insolvent.⁶ ROBODOC was subsequently acquired by its current owners, Curexo Technology Corporation, now known as THINK Surgical. Nonetheless, the system received Food and Drug Administration (FDA) approval in 2008. In addition, a next-generation robotic system based on ROBODOC technology called TSolution One (THINK Surgical; Fremont, California) has been cleared by the FDA. ROBODOC has also expanded to applications in knee arthroplasty.

CASPAR

A similar system that has been used in THA is CASPAR (Universal Robot Systems; Rastatt, Germany). Like ROBODOC, CASPAR used preoperative CT and computer assistance to automatically mill a femoral canal and guide positioning of the stem implant. Results for the use of this system in THA were mixed. A study by Wu et al.⁷ that used cadaveric femurs concluded that using CASPAR resulted in significantly more accurate femoral preparation and stem positioning.^{7,8} However, a study by Mazoochian et al.⁹ on postoperative CT found that femoral anteversion angles deviated significantly from the surgical plan, suggesting low precision of implantation.

Perhaps most problematically, an outcomes study found that CASPAR patients did not have better improvement in Harris Hip Scores and in fact had significantly less improvement in Merle d'Aubigné-Postel scores compared to a control group of manual THA patients.¹⁰ The same study found that intraoperatively, patients who underwent THA with CASPAR had significantly longer procedure times and more blood loss. Postoperatively, they had significantly worse abductor function and a higher incidence of Trendelenburg's sign compared to the control patients. In addition, although these differences were not found to be statistically significant, the CASPAR group had higher rates of complications, revision surgeries, and heterotopic ossification. The company behind CASPAR eventually went out of business, and the system is currently not in use.¹¹ The issues found with the CASPAR system illustrate some of the challenges and concerns that come with the use of robotics in THA.

MAKO

A more recent development in the field of robotic-assisted THA was the introduction of the MAKO Robotic Arm Interactive Orthopedic System (Stryker Corporation; Kalamazoo, MI, USA). Like the systems discussed above, MAKO operates through a robotic arm guided by a 3D computer model derived from CT scan. The acetabulum and femur are registered using a series of intraoperative checkpoints. This allows for a real-time model that guides navigation for acetabular reaming.¹² The

system also guides placement of the implants, which are loaded onto the robotic arm. Unlike the designs of ROBODOC and CASPAR, the robotic arm of the MAKO system is not fully automated and is instead based on haptic feedback technology. The surgeon retains partial control of the action of the robotic arm during the implantation. If their action deviates from the boundaries of the surgical plan, the robotic arm provides tactile resistance. Further deviation will trigger an audio alert and shut down the robotic arm. Thus, MAKO's navigation system uses a collaboration of user input and robotic guidance rather than an automated execution of the surgical plan.

The first THA using the MAKO system was performed in October of 2010. In 2015, it was announced that MAKO had received FDA approval for its use in the hip. MAKO is also used in unicompartmental and total knee arthroplasty.

Advantages

Femoral broaching and stem implantation

There is a growing body of evidence that robotic assistance does succeed in improving the accuracy and precision of implant placement for THA. Since the first applications of robotics for femoral-side milling and implantation, there has been relevant literature on the placement and fit of the stem. In the first clinical trial of a femoral-side robotic assistance system, Bargar et al.⁴ found that 65 ROBODOC patients had significantly better medial fit, lateral fit, and fill of the stem compared to 62 manual THA control patients as measured on anteroposterior radiographs.⁴ The ROBODOC group also had superior axial seating and alignment as well as less radiolucencies. Notably, no patients in the ROBODOC groups suffered a fracture. Honl et al.⁵ found that varus-valgus orientation of the stem was better in ROBODOC patients compared with manual implantation. Nishihara et al.¹³ evaluated postoperative radiographs and CT images and concluded that using ROBODOC allows for superior implant fit and alignment while reducing the risk of fracture relative to the manual technique.

A study by Schneider and Kalender¹⁴ determined that the overall geometric accuracy of robotic-assisted THA was similar between the ROBODOC and CASPAR systems and was reliably within 0.5 mm and 0.3 degrees for critical parameters.¹⁴ The Wu et al.⁷ cadaveric study found that CASPAR improves femoral preparation and implantation, increasing bone contact from 60.1% manually to 93.2% with assistance and decreasing mean gap width from 0.77 mm manually to 0.20 mm with assistance.⁷ A study of synthetic femora suggested that using CASPAR results in more stable implants.⁸ However, other studies have suggested that the type of stem used may significantly affect the stability of CASPAR-assisted implantation.^{15,16}

Acetabular reaming and cup implantation

With the advent of MAKO, robotic assistance also has the capability to improve placement of the acetabular cup implant. The Lewinnek safe zone (30–50° inclination, 5–25° anteversion) and the Callanan modification (30–45° inclination, 5–25° anteversion) have been established as critical parameters for successful THA.^{17,18} Studies have suggested that accurate positioning of the cup is challenging and unreliable with manual THA. Bosker et al.¹⁹ found that among 200 THAs, 70.5% were placed within the Lewinnek safe zone. In a study of 1823 THAs, Callanan et al.¹⁸ found that only 50.3% were placed within the modified safe zone. Improper cup positioning can have serious consequences including dislocation, impingement, and accelerated wear of the liner.^{20–23}

An early cadaveric study by Nawabi et al.²⁴ found that acetabular components implanted with MAKO in 6 hips were significantly more accurate than 6 contralateral manually implanted cups. In a match-controlled study of 100 THAs, Domb et al.²⁵ found that cups placed by the MAKO robotic arm were statistically more likely to fall within both the Lewinnek and the Callanan safe zones, with 100% and 92% respectively. A study on robotic-assisted THA by Illgen et al.²⁶ similarly found that cups placed using MAKO were significantly more likely to be within the Lewinnek safe zone than manual THA. This constituted a 71% increase in accuracy and resulted in a lower dislocation rate in the MAKO patients. Notably, a study of THA in obese patients by Gupta et al.²⁷ found that MAKO effectively produced safe zones for version and inclination in this more challenging patient population. Domb et al.²⁸ performed a retrospective review of 1980 cases, finding that THAs performed with computer navigation and robotic assistance had more consistent placement of the cup within the Lewinnek and Callanan safe zones. Kamara et al.²⁹ analysed the first 100 robotic-assisted THAs performed by a single surgeon and found that they were significantly more likely to fall within the safe zone compared to both fluoroscopic guidance and manual THA, suggesting that robotic assistance improves precision of implantation even when considering the learning curve discussed below.

It is worth noting that recent evidence has suggested that the safe zone concept may belie the biomechanical influence of spinopelvic mobility on cup positioning and THA stability.³⁰ Newer navigation systems such as the Optimized Positioning System (Corin Group; Cirencester, UK) use patient-specific instruments that can address such concerns, and have demonstrated significantly improved anteversion accuracy.³¹ As this navigation technology develops, its integration with robotic assistance systems is a promising outlook for THA outcomes.

Thus, there is evidence that robotic assistance improves the accuracy and precision of implant positioning in THA.

Surgical robotic systems have been developed to guide placement of both femoral stem and acetabular cup components. By ensuring proper implantation, robotic assistance has the capability to reduce instability and impingement, extending THA durability and minimising postoperative complications.

Leg-length discrepancy

Leg-length discrepancy is another key reason for the importance of correct implant positioning. Differences in limb length are a common problem following THA and result in inferior outcomes and patient dissatisfaction, being the leading cause of litigation brought against orthopaedic surgeons.³² Thus, a critical obligation of robotic-assisted THA is maintenance or improvement of leg-length equality.

The first prospective study on ROBODOC by Honl et al.⁵ found that leg-length discrepancy was significantly lower with robotic assistance (1.8 ± 3.0 mm) compared to manual implantation (9.6 ± 9.3 mm). Nakamura et al.³⁰ followed 146 primary THAs for a minimum of 5 years and concluded that using ROBODOC resulted in significantly less variance of leg length.

The MAKO computer navigation software directly measures changes in leg length as well as combined offset. The cadaveric study by Nawabi et al.²⁴ found that the root mean square error for leg-length discrepancy was within 1 mm. Jerabek et al.³¹ presented results showing that performing THA with MAKO assistance led to more desirable leg length and offset. Domb et al.²⁵ compared leg-length discrepancy between THA with MAKO, fluoroscopy-guided anterior approach THA, and posterior approach THA. They found that the study groups had similar leg length discrepancies and rates of outliers and concluded that robotic-assisted THA was accurate in this regard.

Bone stock preservation

An important consideration in THA is preservation of bone stock. As the incidence of revision hip arthroplasty rises, it is advantageous to preserve as much femoral and acetabular bone stock as possible while maintaining stability. Shorter stem implants have been used as a potential solution to this issue, offering an option which are less invasive of bone with evidence of favourable results.^{33,34} ROBODOC was shown to be effective when used with short metaphyseal-anchored stem implants. In a cadaveric study, Lim et al.³⁵ found that ROBODOC resulted in significantly better and more precise anteroposterior alignment and vertical seating with short stems, suggesting that robotic milling improves implant fit and reduces the risk of fracture. A subsequent prospective clinical study concluded that patients that had short stems implanted with ROBODOC had more accurate implantation than those that underwent manual THA with short stems.³⁶

A recent study by Suarez-Ahedo et al.³⁷ compared 57 THAs performed with MAKO assistance to 57 match-controlled THAs performed with the conventional technique. This study found that the MAKO THAs had significantly smaller cup sizes, both relative to femoral head diameters and measured as the difference between cup and femoral head diameters. Using cup size as a measure of bone loss during THA, the authors concluded that MAKO assistance may improve intraoperative bone preservation.

Disadvantages

Financial cost

The robotic assistance systems used for THA are associated with high front-end costs due to the investments necessary to develop the computer navigation and robotic arm technology. The ROBODOC system was first offered in Europe in the 1990s at a price of \$635,000, and some users have paid as much as \$1.5 million for the system.³⁸ There are further costs for routine operation of the system, such as the pins and arrays used for intraoperative registration, as well as maintenance. The navigation software for robotic systems also requires a preoperative CT scan, which imposes an additional cost as well as patient exposure to radiation. These financial considerations are in addition to those that would be involved in a manually performed THA, such as staffing, trays, and the implants themselves. Thus, robotic assistance can be a marked financial burden on the healthcare system.

It is worth noting, however, that there are a number of potential financial advantages that could be associated with robotic-assisted THA. For example, the possibility of reducing the rate of complications and reoperations after THA is a potential source of savings, as well as an improvement for patient outcomes. In addition, reducing the number of trays required for operation, and thus the costs of sterilisation services, could be another way by which robotic assistance begins to pay for itself. This is an area that calls for study so that healthcare systems can accurately assess the value of these systems.

As the field of robotic-assisted THA advances, the procedures can be expected to become more cost-effective. Robotic-assisted THA is still relatively uncommon and remains a developing market. As demand rises, the costs of robotic systems will trend down significantly due to increasing returns to scale. In other words, as production of the systems increases, efficiency of production will increase in turn, lowering costs. The economists Solow and Swan independently developed a model demonstrating the positive impact of technology on economic growth.^{39,40} In fact, technological progress was identified as the only definitive way of achieving growth and increases in productivity in the long term. The Solow-Swan model has been found to match well to empirical economic data.⁴¹ Thus, despite the initial financial hurdles

of using robotic assistance in THA, it can be expected to ultimately be of economic benefit to the industry.

Operative time and learning curve

Naturally, the introduction of new techniques and technology in THA can lead to increased operative times. The initial Bargar et al.⁴ clinical trial found that patients that underwent THA with ROBODOC had significantly longer procedures, 258 minutes on average compared to 134 minutes in the control group, as well as greater blood loss. In the later study by Honl et al.,⁵ mean operative time for ROBODOC procedures was 107 minutes, although still significantly longer than 82 minutes for the control patients. Siebel et al.¹⁰ reported higher operative times and blood loss in cases using CASPAR. The Lim et al.³⁵ cadaveric study on short stems found that using ROBODOC took 27 minutes longer on average than the manual procedure. The subsequent outcomes study by Lim et al.³⁶ calculated that ROBODOC required 8.9 minutes for registration and 11.2 minutes for the automated milling itself. In the study comparing robotic-assisted and manual cup implantation, Domb et al.²⁵ found that MAKO procedures had higher mean time of 110 minutes compared to 102 minutes in a difference that approached significance ($p=0.08$).

Much of this difference in operative times may be attributable to the learning curve as surgeons become accustomed to using robotic systems. Nakamura et al.³⁰ reported a mean time of 120 minutes with ROBODOC and 108 minutes for manual THA. They calculated a Pearson product-moment correlation coefficient of the consecutive ROBODOC operative times and found that times decreased by 17 seconds each case from the initial time of 140 minutes ($r^2=0.054$), demonstrating significant involvement of a learning curve.

Redmond et al.⁴² analysed the first 105 robotic-assisted THAs performed by a single surgeon and found that both improper cup implantation and operative times decreased significantly with accumulating experience. Given the effect suggested by these results, it is likely that the issues of operative time and related considerations such as blood loss and infection will resolve as surgeon proficiency with robotic systems improves.

Another point of discussion that has yet to be studied in the literature is the specialised staff in the operating room and their learning curve.

Complications

A major concern about the use of robotics in THA is the potential for perioperative complications. Schulz et al.⁴³ reported that 9 of 97 ROBODOC cases (9.3%) had technical complications directly involving the robotic arm system. Honl et al.⁵ reported that in 13 of 74 (18%) of cases, the ROBODOC system failed and implantation had to proceed manually. They also found that the ROBODOC group

had a dislocation rate of 18%, significantly more than the control group. The study by Siebel et al.¹⁰ on the early CASPAR system found a higher rate of heterotopic ossification compared to the control group. Furthermore, the CASPAR patients had statistically poorer abductor function and Trendelenburg's sign at follow-up. Nakamura et al.³⁰ also reported a higher rate of heterotopic ossification in ROBODOC cases, although the difference was not statistically significant.

Recent studies have presented more promising results in terms of complications related to robotic assistance in THA. In the study on the later MAKO system by Domb et al.²⁵, there was only 1 technical complication in 50 cases performed with robotic assistance. Illgen et al.²⁶ reported a lower dislocation rate and similar infection rate for MAKO procedures compared to manual THA. Robotic assistance may help reduce the risk of intraoperative fracture during THA. Bargar et al.⁴ found a statistically significant difference with no femoral fractures in the ROBODOC group compared to 3 in the control group. Nakamura et al.³⁰ had no intraoperative complications or fractures in 75 cases performed with ROBODOC. In contrast to the Honl et al.⁵ study, they had a dislocation rate of 5.3%, which was not significantly more than the control group. The authors attributed this to better retraction and preservation of the abductor muscles. This illustrates the attention that must be paid to prevent complications even when using a fully-automated system in robotic-assisted THA. As the surgical technique and navigation and robotic technology are refined, the risk of complications in robotic-assisted THA will likely continue to decline.

Outcomes

When weighing these advantages and disadvantages of robotic-assisted THA, the critical question is how they translate into clinical outcomes. Given the aforementioned costs of these procedures, there must be clear benefit to the patient to justify its use. Currently, there are relatively little outcomes data available for robotic-assisted THA, and a conclusive clinical perspective has yet to be achieved.

The Bargar et al.⁴ ROBODOC clinical trial found no statistically significant differences in Harris Hip Score (HHS) at 1-year or 2-year follow-up. Honl et al.⁵ had significantly better Mayo score and HHS at 6-month and 1-year follow-up. However, these differences were not statistically significant at 2-year follow-up. The Schulz et al.⁴³ study used the Merle d'Aubigné-Postel score and concluded that ROBODOC had similar results as manual THA. Nakamura et al.³⁰ reported superior 2-year and 3-year Japanese Orthopaedic Association scores for ROBODOC, but no significant difference after 5 years. The Lim et al.³⁶ study using short stems found that HHS and Western Ontario and McMaster Universities index were similar between ROBODOC and control patients at

2-year follow-up. Bargar et al.⁴⁴ recently published a longer-term study with mean 14-year follow-up. They found that patients who underwent THA with ROBODOC assistance had significantly higher HHS and Health Status Questionnaire scores compared to manual THA, although Western Ontario and McMaster Universities index was lower. The only study reporting outcomes of CASPAR was by Siebel et al.,¹⁰ which found similar improvement of HHS compared to manually performed THA but significantly less improvement in Merle d'Aubigné-Postel score.

Perets et al.⁴⁵ recently published 1 of the first clinical outcomes study of THA using MAKO assistance, with minimum 2-year follow-up of 162 cases. At latest follow-up, they reported a mean HHS of 91.1 and a mean Forgotten Joint Score (FJS-12) of 83.1, as well as a mean pain score of 0.7 on a 0–10 visual analogue scale. They also found an intraoperative complication rate of 3.7% and a postoperative complication rate of 3.7%. In addition, no leg-length discrepancies >10 mm or dislocations were reported, concluding that short-term outcomes were favourable and did not demonstrate an increased complication rate. Investigation of the clinical outcomes of specific systems and techniques is warranted as they are developed and released to market.

Evaluating the clinical outcomes of robotic-assisted THA relative to the conventional technique is a challenging endeavor, because THA is generally a successful procedure. Thus, identifying differences where they exist requires a fine differentiation between “good” and “excellent” outcomes. Many of the tools commonly used to measure outcomes, such as HHS and Merle d'Aubigné-Postel score, are limited in this regard by high ceiling effects.^{46,47} This may explain the mixed and inconclusive results in the literature for ROBODOC. For these reasons, careful consideration of methodology is warranted as the study of robotic-assisted THA advances.

Discussion

This study has reviewed the available literature on robotic-assisted THA. Despite initial obstacles and setbacks, robotic arms guided by navigation systems tailored to the patient's individual anatomy is becoming increasingly recognised as an effective tool to improve the accuracy of implant placement in THA. As we can see, the older literature did not favor robotics much, but the newer literature does. The progressive replacement of the surgeon's intuition with computerised precision has the potential to minimise effects of human error, such as leg length discrepancy or over-resection of bone. On the other hand, the financial costs, increased operative time, and potential risks of introducing these systems to the operating room must be weighed when evaluating their net utility. It is foreseeable that as the technology and techniques advance, these concerns will be resolved.

The accuracy and reproducibility of the robotic-assisted THA is greater than that achievable by human hands alone. The goal now is to apply these advantages for the benefit of the patients. As in many fields, robotics may enhance human performance and quality of life in THA, but its full potential has yet to be realised. This review shows that available data has yet to definitively prove the benefits of robotic-assisted THA, and optimisation of the techniques remains a work in progress.

The ultimate determination will be made as clinical outcomes data become more prevalent, demonstrating the true effects of robotic-assisted THA for the patient. A new generation of robotic systems such as MAKO and TSolution One carry the promise of more advanced technology that could result in safer and more effective procedures. Like many industries, the field of THA is facing a potential revolution as it integrates computer and robotic technology. The physician's role will remain critical, both in the operating room and in investigating the impact of robotic assistance for the patient.

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