Robotic surgery in hip and knee arthroplasty

ABSTRACT

This article provides an overview of current use of robotics in hip and knee arthroplasty. Several studies have reported radiographic improvements in joint alignment using robotic-assisted arthroplasty surgery. The economic case made for introducing robotics in joint arthroplasty largely focuses on the hypothesis of reduced hospital stay and reduction in the rate of revisions. This awaits robust data from long-term studies along with the documentation of clinical benefits that will follow the larger implementation of robotic-assisted surgery. However, modern robotic systems offer an opportunity for reproducible implementation of a preoperative plan, with low complication rates. Growing clinical use may in future present robust data demonstrating an appreciable clinical benefit that justifies the large scale clinical use of robotic technology.

The techniques and technology of hip and knee arthroplasty have evolved over the years. The focus of arthroplasty surgery has advanced from pain relief to improving patients' quality of life. Today the patient, the surgeon and governing bodies are seeking patient-specific solutions that are well executed, cost effective and offer long-term solutions.

The technology of robotic-assisted hip and knee arthroplasty is now available to the orthopaedic surgeon and may be a solution to some of the drawbacks of current arthroplasty techniques. Robotic surgery allows the surgeon to translate preoperative planning to intraoperative execution with surgical accuracy and precision (Cobb et al, 2006; Lang et al, 2011). Whether this translates to the desired outcomes to the patient, the surgeon and the governing bodies needs further scientific proof. This article reviews current thinking and evidence around robotic-assisted hip and knee arthroplasty.

Shortcomings of current strategies in hip and knee arthroplasty

In 2015, there were 98 211 hip and 104 695 knee arthroplasties recorded in England, Wales, North Ireland and the Isle of Man (National Joint Registry, 2016). This number is projected to rise to approximately 95 877–439 097 total hip arthroplasties and 118 666–1 219 326 total knee arthroplasties annually in the UK by 2035 (Culliford et al, 2015).

Advances in hip and knee arthroplasty have the potential to increase efficiency and be of significant benefit to society. Patients undergoing arthroplasty have a range of expectations related to their age and preoperative activity level (Krushell et al, 2016); failure to meet these expectations combined with preoperative pain and postoperative complications are all possible risk factors for patient dissatisfaction (Bourne et al, 2010).

Along with the return to premorbid function, pain relief is an aim of arthroplasty. Currently, it is estimated that up to 19% of patients undergoing total knee arthroplasty may not be satisfied with the outcome (Bourne et al, 2010). In a follow-up period ranging from 3 months to 5 years, Beswick et al (2012) found that 7–23% of patients experienced unfavourable pain outcomes after total hip arthroplasty and 10–34% after total knee arthroplasty. They also noted that even in studies reporting good patient satisfaction from arthroplasty, an unfavourable pain outcome was reported in 9% of patients after total hip arthroplasty and around 20% of patients after total knee arthroplasty.

As well as patient outcomes, the ultimate shortcoming of an arthroplasty is the need for revision. A major factor affecting the rate of unicompartmental knee arthroplasty failure is tibiofemoral alignment; any intervention that improves this has the potential to improve implant life expectancy (Kim et al, 2012). Revision of joint arthroplasty increases load on the health-care system and also incurs significant costs, with a revision total knee arthroplasty estimated to cost between £10 893 and £21 937 depending on complexity and indication (Vanhegan et al, 2012). Therefore, there is an economic, as well as clinical, case for maximizing outcomes from primary arthroplasties. Robotic technology that claims to improve the outcome of primary arthroplasty could recoup the initial costs of installation within 2 years if their predictions on revision rates are correct (Swank et al, 2009).

Further shortcomings of existing strategies are inter-surgeon variability and variation in quality of outcomes. There is a lack of precise reproducibility of surgeon experience, and most procedures have a relatively steep learning curve. Rees et al (2004) showed that the outcomes of a surgeon's first ten unicompartmental knee arthroplasty operations are significantly worse than the subsequent ten.

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Figure 1. Computed tomography-based preoperative planning for robotic-assisted total hip arthroplasty. Leg length, offset and the position of components can be precisely planned.

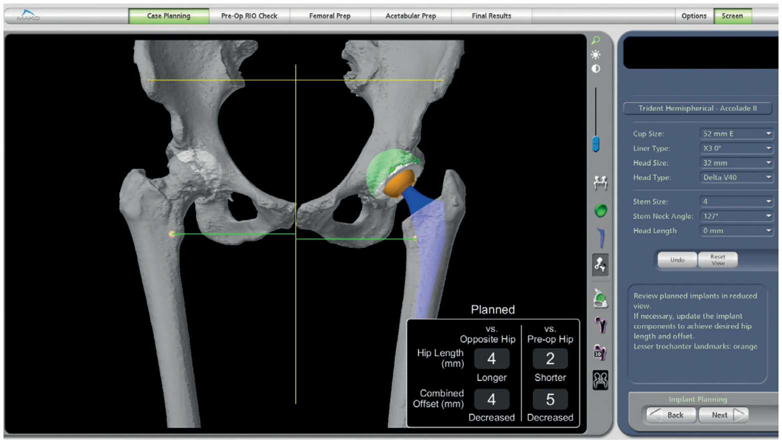
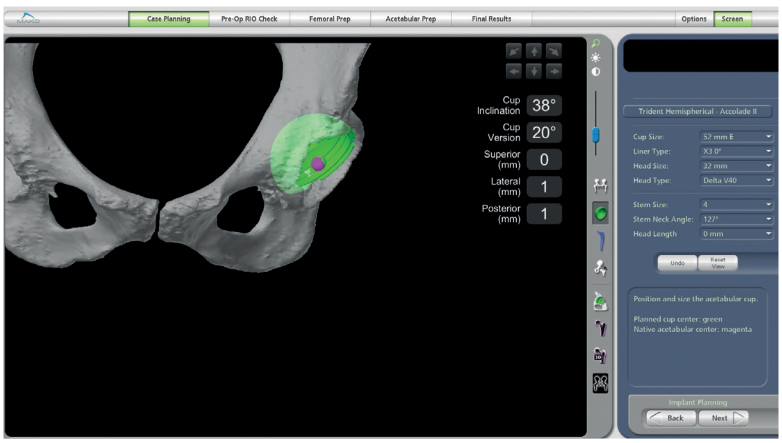


Figure 2. Preoperative planning of the position for robotic-assisted placement of the acetabular shell using computed tomography. This is then translated on-table with precision by the robotic-assisted arm.



What is the clinical problem that robotics is trying to solve?

The primary aim of robotics in arthroplasty is precise reproduction of the surgeon's preoperative plan during surgery. Studies have shown that robotic systems are able to improve the alignment and positioning of implants in both total hip arthroplasty and total knee arthroplasty (Nishihara et al, 2006; Park and Lee, 2007). It is hypothesized that more accurate implant placement will translate to better clinical outcomes, although the current data supporting improved patient satisfaction are conflicting (Honl et al, 2003).

Robotics offers several other potential advantages. The ability to create a preoperative plan and accurately execute it during surgery using intraoperative feedback reduces variation in component placement (Bell et al, 2016). This benefit may also be true for less experienced surgeons as demonstrated in unicompartmental knee arthroplasty on dry bone models. Junior surgeons were able to place components with greater accuracy with robotic assistance compared to conventional methods (Karia et al, 2013). *Figure 1* illustrates computed tomography-based preoperative planning for robotic-assisted total hip arthroplasty (Mako, Stryker, Mahwah NJ). This process allows precise planning of offset length and centre of rotation, which can then be reproduced intraoperatively using the robotic arm. *Figure 2* illustrates the preoperative planning of robotic-assisted placement of the acetabular shell position using computed tomography. The precise placement of acetabular shell has long been a subject of debate.

Robotic surgery also attempts to minimize the rate of complications during surgery. Modifications in instrumentation of the medullary canal are suggested to help reduce the incidence of pulmonary embolism during total hip arthroplasty when the ROBODOC system (Curexo Technology Corporation, Fremont, CA) is used (Hagio et al, 2003).

The concept of robotic surgery

Robotic surgery has been developing since its first application in 1985 improving the precision of neurosurgical biopsies (Davies, 2000). In orthopaedic surgery, the bony landmarks used to orientate the robot do not deform, allowing a preoperative plan to be carried out with precision, provided the robot can correctly register its location and proceed (Jacofsky and Allen, 2016).

There are active, semi-active (haptic) and passive robotic systems in existence. Active systems are autonomous and operate under supervision of the surgeon but without active input. Semi-active systems allow the surgeon to perform the burring or cutting procedure but will retract the cutting tool or provide alerts and feedback when the edges of a resection margin are reached. Passive systems are under continuous and direct control of the surgeon.

Robotic systems rely on having a defined operative plan and being orientated in space. This is achieved via imaging, for example using computed tomography data, or an imageless system where bony landmarks are recorded into the robotic software, allowing creation of a virtual reconstruction based on these parameters.

Evolution and modification in robotic concept

One of the earliest robots to be used in an orthopaedic clinical setting was the ROBODOC system, first designed in the late 1980s to improve success rates in total hip arthroplasty, and used on humans in 1992 (Paul et al, 1992). The current ROBODOC is a computed tomography-based, computer-aided robotic milling system that increases accuracy and consistency in prosthetic placement and allows the surgeon to see where the robot is milling in cavity preparation for total hip arthroplasty and surface preparation for total knee arthroplasty (Jacofsky and Allen, 2016).

Navio PFS (Blue Belt Technologies, Plymouth, MN), approved by the Food and Drug Administration in 2012 (Jacofsky and Allen, 2016), is a semiactive, handheld, imageless instrument developed for sculpting in unicondylar and patellofemoral knee arthroplasty. The end-cutting burr retracts as a safeguarding measure to remove only the planned bone. Currently, the Navio system is approved for use only in unicompartmental knee arthroplasty. Wallace et al (2014) reported a quick learning curve of eight procedures for surgeons performing robotic-assisted surgery, with a total procedure mean time of 64.9 minutes over the first four procedures.

The Robotic Arm Interactive Orthopaedic System (Rio; Mako Stryker, Fort Lauderdale, FL) is a haptic system that creates three-dimensional computerized models of the patient's knee or hip based on preoperative computed tomography images to determine sizing and positioning of components used in unicompartmental knee arthroplasty, total knee arthroplasty and total hip arthroplasty. Jinnah et al (2011) reported a learning curve of 13 cases for unicompartmental knee arthroplasty, with no detriment to the patient during this period.

Surgical tips and tricks

Coon (2009) described guidelines for integrating the Mako surgical robotic arm into the operating room. The set up of the device, including placement of the machine, sterile draping, registering the arm and positioning the patient by a team of trained theatre staff, can improve theatre efficiency. While the initial unicompartmental knee arthroplasties took 80–120 minutes, taking the aforementioned steps to improve efficiency resulted in a total tourniquet time of 40 minutes after 20 procedures.

Chun et al (2011) outlined criteria for aborting the surgery:

1. If the predicted time to recover from the obstacle was greater than 30 minutes
2. If there were four or more repetitive failures in the same step that could not be skipped
3. If there was real or potential damage of soft tissue.

These criteria may help to decide when to take over from the robot and avoid problems linked to the extra time required to fix the associated complications.

Results to date and unique complications

Knee

Robotic assistance during unicompartmental knee arthroplasty and total knee arthroplasty can improve the accuracy of implant placement and postoperative alignment compared to the conventional procedure. Cobb et al (2006) performed a prospective randomized controlled trial comparing the performance of the Acrobot system in unicompartmental knee arthroplasty with conventional surgery. While all of the subjects in the robotics group achieved tibiofemoral alignment angles on the coronal plane within the target zone of ±2°, only six of 15 conventional knees did. It was noted that the total operation time was longer (albeit not significant) in the robotic group; this did not influence the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) scores at 18 weeks.

“Robotic assistance during unicompartmental knee arthroplasty and total knee arthroplasty can improve the accuracy of implant placement and postoperative alignment compared to the conventional procedure.”

Song et al (2011) performed a bilateral total knee arthroplasty with one knee replaced with robotic-assisted implantation and the other replaced by a conventional method. Postoperatively, 12 patients preferred the robotic-assisted total knee arthroplasty while six preferred the conventional leg; this was consistent with balanced flexion and extension gaps in 27 robotic-assisted knees compared to 23 conventional knees and a mean mechanical axis of 9.1° and 10.9° respectively. For an intermediate term follow up (minimum 3 years'), clinical outcomes after total knee arthroplasty were equivalent for robotic-assisted implantation and conventional groups, with no differences in postoperative range of movement, WOMAC and Hospital for Special Surgery knee scores (Song et al, 2013). The results show no mechanical axis outliers (> ±3° from neutral) in the robotics group, compared to 24% in the conventional group, and a higher rate of flexion-extension gap balance. Although the surgical time in robotic-assisted total knee arthroplasties was 25 minutes longer than the conventional operations, this was not associated with an increase in complications such as infection and resulted in less postoperative blood drainage.

In a comparison of robot-assisted and computer-assisted navigation systems in primary total knee arthroplasty, it was observed that robot-assisted navigation reduced navigation times by 9 minutes compared to computer-assisted navigation. There was no difference in mean tourniquet time between the groups (Clark and Schmidt, 2013). The robot-assisted navigation method also resulted in alignments on average 0.5° closer to the mechanical axis than the computer-assisted navigation group.

Hip

In a prospective study comparing robotic-assisted implantation of a total hip arthroplasty to conventional manual implantation, Honl et al (2003) found significantly more favourable limb length equality and varus-valgus stem orientation after the robotic implantations. The robotics group also demonstrated improved clinical outcomes, with a better Mayo Hip Score at 6 and 12 months and Harris Hip Score at 12 months. However, no difference between the robotics and conventional groups was found for either score at 24 months, making it difficult to draw conclusions about long-term advantages. The robotics-assisted procedures were significantly longer than the conventional method, and failure of the robotics system led to 18% of the 74 implantations being converted to manual technique.

> **For unicompartmental knee arthroplasty, the learning curve for robotic-assisted procedures averaged 13 cases; during this period, there was no additional risk to the patient.**

A long-term study with a minimum of 5 years' follow up indicated that robotic milling in cementless total hip arthroplasty achieved more precise positioning of the implant with reduced variance in limb length inequality and less stress shielding of the proximal femur 5 years postoperatively (Nakamura et al, 2010). Nevertheless, although the robotics group had better clinical outcomes indicated by a higher Japanese Orthopaedic Association score at 3 years, this difference was no longer significant at 5 years.

Complications

The use of a more recent generation of robots has not demonstrated a high complication rate but several authors have reported complications with earlier systems.

Intraoperative conversion to conventional technique was reported by several studies. Chun et al (2011) reported on a series of 100 robot-assisted hip and knee arthroplasties, of which 22 were prematurely aborted as a result of serious obstacles encountered during the procedure. In total knee arthroplasty, the two most common reasons for abortion were interruption of the patella tendon and repetitive failure in registration. The sole hip arthroplasty conversion was a result of limited motion in the hip joint. The conversion of a robotic-assisted procedure has implications in terms of time and money lost, as well as the need to manually continue from where the surgery was left.

In two of 75 cases of robotic-assisted cementless total hip arthroplasty, the procedure was abandoned as a result of intraoperative technical problems, and converted to the manual method (Nakamura et al, 2010). Honl et al (2003) also reported significant complications during robotic-assisted implantation of total hip arthroplasty. Revision surgery was indicated in eight of 61 patients in the robotics group compared to none in the 78 who underwent manual implantation.

While using the ROBODOC surgical assistant during total hip arthroplasty, surgical complications reported included breakage of a Kirschner wire, temporary lateral femoral cutaneal nerve damage, and excessively deep acetabular reaming. Technical complications such as damage to the acetabulum and re-registration occurred in 9.3% of cases (Schulz et al, 2007).

In a comparison of conventional manual implantation in total knee arthroplasty with a robotic-assisted method, Park and Lee (2007) reported a high rate of complications (six of 32 cases) among patients, including superficial infection, patellar dislocation, rupture of the patellar tendon, postoperative supracondylar fracture and peroneal injury in the early cases; a pattern that was no longer apparent beyond the learning curve. For unicompartmental knee arthroplasty, the learning curve for robotic-assisted procedures averaged 13 cases; during this period, there was no additional risk to the patient (Jinnah et al, 2011).

Lingering concerns with robotics and future prospects

Cost

One of the most commonly reported setbacks in the widespread use of robotics in orthopaedic surgery is the high cost associated with its implementation. In addition to the initial start-up cost, the ongoing calibrations and upgrades may be prohibitive (Lang et al, 2011). The Rio system produced by MAKO has a reported cost of $793 000 for the robotic platform (Lang et al, 2011). Honl et al (2003) reported an additional $700 per case for use of the robotics system in total hip arthroplasty. This should be considered in addition to the cost of extended operating room time especially when first converting to use of robotic systems. The true impact of cost may vary between countries and health-care models.

The added costs of using robotics can be justified by improved outcomes such as fewer complications, implant longevity with improving prosthetic alignment, better clinical outcomes and earlier hospital discharge (Davies et al, 2007; Song et al, 2011). Moschetti et al (2016) have shown that when more than 94 operations are performed annually robotic-assisted unicompartmental knee arthroplasty is cost-effective compared to manual surgery, failure rates are below 1.2% 2-year postoperatively, and total system costs are <$1.426 million. Low volume centres may take longer to demonstrate cost-effectiveness of introducing robotic surgery based on the available evidence.

Efficiency and safety

In order to optimize the efficiency of robotic systems, educating surgeons and staff may be necessary, potentially increasing operative time, especially in early cases.

The safety and reliability of robotic systems is variably reported in literature. Conversion rates during total hip arthroplasty have been reported to be as high as 18% (13 of 74 cases), and any potential impact on clinical outcomes is unclear (Honl et al, 2003). There is also concern over the usefulness of some robotics systems if the plan needs to be changed during surgery (Jacofsky and Allen, 2016). As the system itself cannot decide on a new plan, the surgeon may have to intervene to retract soft tissues that may become compromised should they get in the planned route. Error leading to incorrect registration could have disastrous results, and a surgeon's expertise and experience will be important in case of hardware or software failure (Jacofsky and Allen, 2016).

The possibility of a rise in litigation as a result of lesser involvement of the surgeon during the procedure was a concern that had arisen in a series of German hospitals which brought about the decline in the use of the ROBODOC system after it was alleged to be associated with higher rates of infection and nerve damage (Davies et al, 2007).

Paucity of long-term data

Although the advantages of robotics in improving accuracy are clear, multicentric long-term follow up is necessary to demonstrate their lasting effect on prosthesis survival.

Future prospects

Developments to simplify the robotic systems to reduce operative time and intraoperative complications continue to be pursued. The increased planning and on-table feedback provided by the robotic systems will play a key role in the understanding of joint balancing in the knee or restoring centre of rotation in the hip. This may then go on to improve our knowledge of what the optimum position of a hip or knee arthroplasty should be.

A key step forward with several surgeons adapting the new technology will be the greater attention to ergonomics in the use of instruments for the surgeon and theatre staff. The surgical workflow that has developed over the years with regards to reproducing the joint biomechanics may see some changes and a 'robotically aligned' joint arthroplasty may be in vogue in the future. Surgical instrumentation, retractors as well as assistance will see modifications and change of role as the technology advances.

Conclusions

Robotics have begun to establish themselves in the field of hip and knee arthroplasty and offer some tangible advantages in terms of improved accuracy in prosthetic joint positioning, reproducibility, and relative ease of use among less experienced surgeons. Several single surgeon series look promising with regards to ease of use, surgical times, reduced revisions, cost-effectiveness and patient outcomes. Long-term clinical outcomes from multicentre studies and different health models are awaited. Despite this, there have been rapid advances in robotic-assisted hip and knee arthroplasty over the preceding decade and this technology may well be here to stay. **BJHM**

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KEY POINTS

- Current strategies in hip and knee arthroplasty are limited by the need for revision and lack of reproducibility.
- Robotics offers the ability to execute a precise preoperative plan during surgery.
- Robotics systems increase the accuracy of implant placement in hip and knee arthroplasty.
- The efficiency of robotics systems is improved with the education and experience of surgeons and theatre staff.
- The high cost of robotics systems may be justified by the corresponding improvement in clinical outcomes.
- Long-term data reporting clinical outcomes are needed to draw conclusions regarding this technique over the conventional method.

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