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The current role of robotics in total hip arthroplasty

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- Robotic total hip arthroplasty (THA) improves accuracy in achieving the planned acetabular cup positioning compared to conventional manual THA.
- Robotic THA improves precision and reduces outliers in restoring the planned centre of hip rotation compared to conventional manual THA.
- Improved accuracy in restoring hip biomechanics and acetabular cup positioning in robotic THA have not translated to any differences in early functional outcomes, correction of leg-length discrepancy, or postoperative complications compared to conventional manual THA.
- Limitations of robotic THA include substantive installation costs, additional radiation exposure, steep learning curves for gaining surgical proficiency, and compatibility of the robotic technology with a limited number of implant designs.
- Further higher quality studies are required to compare differences in conventional versus robotic THA in relation to long-term functional outcomes, implant survivorship, time to revision surgery, and cost-effectiveness.

Keywords: functional outcomes; hip biomechanics; implant positioning; robotics; total hip arthroplasty/replacement

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Introduction

The surgical treatment of symptomatic end-stage hip osteoarthritis has evolved over the last three hundred years from rudimentary excision surgery to modern robotic total hip arthroplasty (THA).[1] Prior to the advent of modern anaesthesia, surgical treatment of hip osteoarthritis included proximal femoral resection or limb amputation.[1,2] Increasing functional demands of patients and developments in general anaesthesia led to the creation of interposition arthroplasty in which skin, fascia lata, or submucosa from porcine bladder were placed between the articulating surfaces of the hip joint.[1] Further advancements in the understanding of hip anatomy and joint biomechanics led to partial arthroplasties of the femoral head or native acetabulum with alloys of chromium, cobalt, and molybdenum.[2] These procedures were associated with high risk of failure owing to poor implant designs and suboptimal mechanical properties of the metal components.[2,3] In 1971, Charnley revolutionized THA through the introduction of low-friction arthroplasty, and his subsequent developments of acrylic cement to fix implants to living bone and high-density polyethylene as a bearing material.[1] Analysis of these implants, using revision of either component as the endpoint, found implant survivorship of 77–82% at 20 years follow-up, and led to many surgeons heralding THA as the 'operation of the century'.[1,2]

Since Charnley's low-friction arthroplasty, there have been several further advancements in implant design and material for THA including cementless technology to promote bone ingrowth, modular femoral components to restore native hip kinematics, larger femoral heads to reduce impingement-related wear, and improvements in bearing surfaces such as highly cross-linked polyethylene and modern ceramics.[4–17] Robotic technology is routinely used in general surgery, cardiothoracic surgery, gynaecology, and urology to improve surgical precision, reduce iatrogenic soft tissue injury, and enhance postoperative functional rehabilitation. Over the last decade, robotic THA has gained momentum as an avenue for reducing surgical error and improving the accuracy of implant positioning compared to conventional manual THA.[18,19] Conceptually, improved accuracy of implant positioning and greater precision in restoring hip biomechanics with robotic THA will translate to further improvements in

functional outcomes and implant survivorship. However, despite the recent surge in publications on robotic THA, many surgeons remain sceptical about introducing this unproven and costly technology to improve an already highly successful and cost-efficient manual THA procedure. Implant survivorship with conventional manual THA is now over 90% at 10 years follow-up and over 80% at 25 years follow-up.[4] This article discusses the current role of robotic technology in THA, provides an overview of how this technology affects functional and radiological outcomes, and explores the limitations of robotic THA compared to conventional manual THA.

Conventional manual techniques for THA

Accurate implant positioning and restoration of native hip biomechanics are important surgeon-controlled factors that influence postoperative acetabular bone stock, abductor function, joint stability, soft tissue injury, impingement, bearing surface wear, and long-term implant survival.[20–23] Conventional manual techniques for THA use radiographic templating, surgical alignment guides, and intraoperative landmarks such as the transverse acetabular ligament, acetabular notch, and anterior superior iliac spine with the sciatic notch to help guide acetabular reaming and implant positioning in THA. However, only 38–47% of acetabular components are within the desired safe ranges of anteversion and inclination using these manual handheld techniques, and low surgeon volume has been identified as a risk factor for errors in implant positioning.[23–26] Patients with hip osteoarthritis and/or spinal deformities also often have abnormal spinopelvic alignment or sagittal imbalances, which lead to patient-specific changes in the relationship of the pelvis, femur, and spine with functional activities of daily living. Conventional preoperative two-dimensional (2D) templating of the pelvis with the patient in the standing position may therefore not account for patient-specific safe zones for implant positioning.[27] Suboptimal implant positioning in THA leads to increased risk of hip instability, accelerated wear of the bearing surface, and reduced long-term implant survivorship.[22–24]

Computer-navigated versus robotic THA

Computer-navigated THA refers to the use of computer systems that provide the operating surgeon with information on patient anatomy and implant position during surgery.[28] This anatomical information may be obtained using preoperative CT scans (imaged-based navigation) or intraoperative mapping of osseous anatomical landmarks on a generic model of the pelvis (non-image-based navigation). Computer navigation provides patient-specific anatomical data with recommendations for bone resection and optimal implant positioning, but the computer system does not actively control or restrain the motor function of the operating surgeon. Robotic THA uses computer software to convert anatomical information into a virtual patient-specific three-dimensional (3D) reconstruction of the pelvis, which the operating surgeon uses to calculate and plan optimal implant positioning. An intraoperative robotic device helps to execute this preoperative patient-specific plan with a high level of accuracy.[29–31] Depending on the degree of control that the robotic device provides the operating surgeon, robotic systems are classified as either fully active or semi-active assistants.

Fully active versus semi-active THA systems

Fully active robotic assistants work autonomously to execute the planned bone resection and implant position during THA.[31] The surgeon oversees the surgical procedure and may activate an emergency shut-off switch if required. An example of a fully active robotic system is ROBODOC (Curexo Technology Corporation, Fremont, California), which has been shown to improve the accuracy, alignment, and fit of the femoral stem during THA.[32,33] However, fully active robotic THA systems have been associated with inadvertent soft tissue injury to the abductor mechanism and femoral fractures, which have led to several lawsuits against the manufacturers and resistance to the uptake of this technology for THA.[31] Furthermore, this technology has not been established for acetabular reaming or acetabular cup placement and its impact on achieving the planned combined version or inclination remains unknown.

Semi-active robotic systems enable the surgeon to maintain overall control over bone resection and implant positioning, but provide live intraoperative feedback to limit deviation from the preoperative surgical plan.[34] The Mako Robotic Arm Interactive Orthopaedic System (Stryker Ltd, Kalamazoo, Michigan, USA) is an example of a semi-active robotic system used to perform robotic THA. Acetabular reaming is confined to a haptic tunnel with stereotactic boundaries and the robotic arm has tactile, audio, and visual feedback, which help the surgeon to control the force and direction of acetabular reaming to execute the preoperative plan with a high level of accuracy.[34,35] Femoral osteotomy site and angle may also be marked prior to femoral bone resection and stem preparation, and live onscreen changes in bone coverage, implant position, offset, and leg length are checked prior to definitive implant selection and positioning.

Stages of robotic THA

Robotic THA uses four distinct stages for accurate execution of the patient-specific surgical plan. First, preoperative

Fig. 1 Intraoperative photograph showing osseous landmarks for registration and verification using the patient-specific virtual three-dimensional pelvic reconstruction.

CT scans of the pelvis and proximal femur are used to create a patient-specific virtual 3D model of the native hip anatomy. This model accounts for pelvic orientation in the axial, sagittal, and coronal planes, which enables accurate assessment and planning for restoration of hip biomechanics.[35] Second, the surgeon uses this virtual 3D reconstruction to template the optimal implant positions and sizes for achieving the desired bone coverage, restoration of hip biomechanics, component version, component inclination, and leg-length correction. Computer software calculates the depth of acetabular bone resection, femoral osteotomy site and angle, and component positioning for accurate execution of this surgical plan. Third, the surgeon intraoperatively maps the osseous anatomy of the acetabulum and proximal femur to establish bone geometry and confirm pelvic position prior to bone resection (Fig. 1). Fourth, a robotic device is used to execute the planned bone resection and guide final implant positioning with live onscreen changes in bone coverage, implant inclination, implant version, offset, and leg-length correction displayed throughout the procedure (Figs. 2–5).

Accuracy of implant positioning

Data from the National Joint Registry for England, Wales, Northern Ireland and the Isle of Man has shown that instability is the leading complication in both primary and revision THA within the first after year of surgery.[4] To minimize

Fig. 2 Intraoperative photograph showing robotic-arm-assisted acetabular reaming.

the risk of instability and its associated problems, many surgeons use predefined safe zones, such as those of Lewinnek et al (5–25° anteversion, 30–50° inclination) to guide acetabular cup positioning during THA.[24] However, achieving implant positioning within these safe zones is challenging owing to intraoperative pelvic tilt, distorted anatomical landmarks, and limited accuracy and reproducibility of the alignment guides.[24,25] Robotic THA uses intraoperative mapping of osseous landmarks with fixed femoral and acetabular registration pins to confirm hip anatomy and establish pelvic tilt, which helps to reduce manual subjective errors in achieving the planned implant positioning. El Bitar et al followed 61 patients undergoing robotic THA and reported overall mean acetabular cup inclination of 38.9° ± 3.2° and anteversion of 20.3° ± 2.8°.[29]

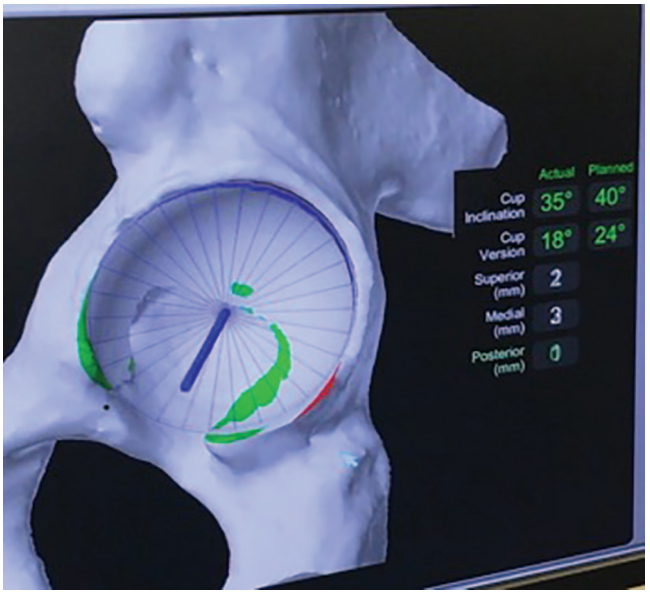

Fig. 3 Intraoperative photograph showing acetabular reaming through the predefined haptic tunnel (displayed in green).

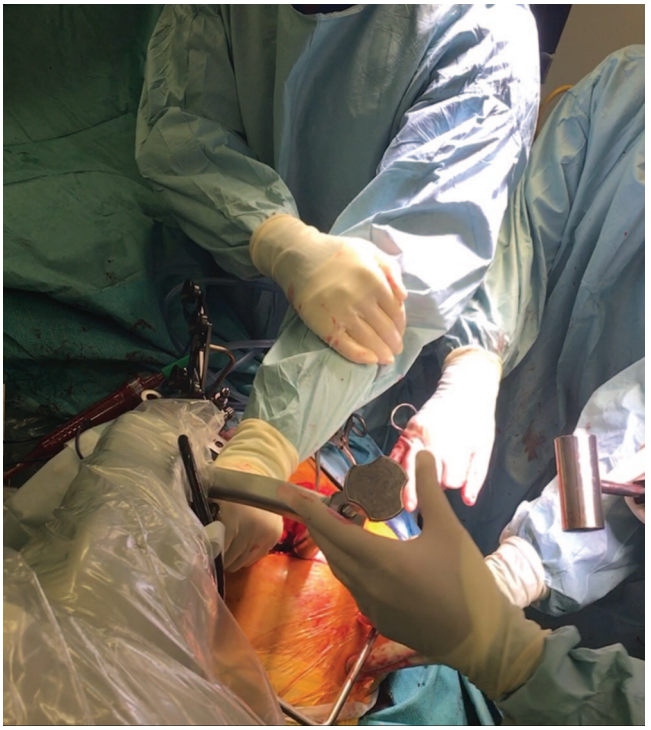

Fig. 4 Intraoperative photograph showing the robotic arm positioning the acetabular cup into the desired position prior to manual implantation.

Illgen et al reviewed outcomes in 200 consecutive conventional manual THAs followed by 100 consecutive robotic THAs, and found robotic THA was associated with an additional 71% improvement in the accuracy of acetabular implant positioning compared with manual THA in the first year of use.[35] Acetabular implant positioning within Lewinnek's safe zones was achieved in 30% of the first 100 consecutive conventional THAs, 45% of the last 100 consecutive conventional THAs, and 77% in the first 100 consecutive robotic-arm-assisted THAs. Nawabi et al showed manual THA was associated with root mean square error values that were five times higher for cup inclination and 3.4 times higher for cup anteversion compared to robotic THA.[30]

Accuracy of restoring hip biomechanics

Robotic THA uses the preoperative CT scan and virtual 3D reconstruction to calculate the optimal femoral and acetabular bone resection levels for accurate execution of the surgical plan. Semi-active robotic devices enable the femoral resection site to be marked prior to femoral osteotomy with a manual saw blade whilst fully active robotic devices autonomously resect at the planned femoral osteotomy level. Acetabular reaming is controlled by the robotic device to ensure the desired depth is reached for accurate restoration of the hip offset and centre of rotation.[18,19] Adverse outcomes have been reported in THA in which the centre of rotation is shifted medially by more than 5 mm or superiorly by greater than 3 mm.[23] Nawabi et al conducted a cadaveric study in which six conventional manual THAs were performed on one side and six robotic THAs on the contralateral side.[30] Robotic THA reduced root mean square error values in achieving both planned horizontal (1.5 mm vs. 2.0 mm respectively), anteroposterior (1.2 mm vs. 2.8 mm respectively) and vertical (1.9 mm vs. 2.2 mm respectively) centres of rotation compared to conventional THA.[30] Tsai et al reviewed radiological outcomes in 14 conventional THA versus 12 robotic THA, and found robotic technology improved the accuracy of achieving the planned vertical centre of rotation (0.7 mm ± 4.4 mm vs. 4.0 mm ± 4.7 mm respectively) compared to conventional manual THA.[34] Nodzo et al followed 20 patients undergoing robotic THA, and reported intraoperative robotic measurement of the hip centre of rotation had a mean mediolateral error of 1.0 mm ± 0.79 mm, anteroposterior error of 1.2 mm ± 0.8 mm, and superoinferior error of 1.6 mm ± 0.8 mm in planned acetabular component position compared to postoperative CT-measured values.[18] The authors also showed that there was no significant difference in the postoperatively measured mean change in hip offset compared to the preoperatively planned mean change in hip offset (0.5 mm ± 3.0 mm vs. 1.4 mm ± 4.0 mm respectively).

Lewinnek's safe zones provide the most commonly adopted range of angles for acceptable acetabular component positioning. Acetabular cup angles that stray

Fig. 5 Intraoperative photograph showing live on-screen inclination and version of the acetabular cup during implantation.

outside of these safe ranges may lead to increased risk of dislocation, liner fracture, impingement, edge-loading, and wear.[22–24] There are several factors that may influence cup positioning within these predefined safe zones. Callanan et al reviewed outcomes in 1,823 THAs and found that only 917 (50%) were within Lewinnek's safe ranges for both inclination and version.[36] Factors correlated to malpositioned cups included minimally invasive surgical approach, low surgeon volume, and obesity (BMI > 30 Kg/m^2). Esposito et al reviewed implant positioning in 147 patients that had dislocation within six months of primary THA, and found no differences in radiographic zones (± 5°, ± 10°, ± 15° boundaries) within the dislocated hips.[37] The authors concluded that acetabular component position alone did not predict instability. More recently, patient-specific safe zones based on preoperative assessments of pelvic kinematics have gathered momentum as a route for improving stability and reducing complications in THA. Pierrepont et al assessed pelvic tilt in 1,517 patients undergoing THA in the supine, standing, and flexed-seated positions, and found mean pelvic tilt was 4.2° (range: –20.5° to 24.5°), –1.3° (range: –30.2° to 27.9°) and 0.6° (range: –42.0° to 41.3°) respectively in the three positions.[38] Mean sagittal pelvic rotation from supine to standing was –5.5° (range: –21.8° to 8.4°), from supine to flexed seated was –3.7° (range: 48.3° to 38.6°) and from standing to flexed seated was 1.8° (range: –51.8° to 39.5°). Preoperative spinopelvic radiographs or CT scans to assess individualized pelvic kinematics during functional activities could help to determine patient-specific safe zones for implant positioning. Robotic technology may offer an avenue for executing implant positioning into these patient-specific safe zones with a high level of accuracy.

Functional outcomes

Improved accuracy of implant positioning and restoration of hip biomechanics in robotic THA has not translated to differences in short-term functional outcomes compared to conventional manual THA.[39-42] Perets et al followed 162 patients with hip osteoarthritis undergoing robotic THA and reported reduced pain, increased patient satisfaction, and improved functional outcomes as assessed using the Harris Hip Score and Forgotten Joint Score at minimum two years follow-up.[39] However, there was no control group undergoing conventional manual THA in this study. Siebel et al conducted a prospective randomized study on 36 robotic THAs versus 35 conventional manual THAs and found no difference in Harris Hip Scores between the two groups at an average of 18 months follow-up after surgery.[40] The authors reported that Merle d'Aubigné and Postel scores and hip abductor function were better in the conventional THA group compared to the robotic THA group at an average of 18 months follow-up. Bukowski et al compared outcomes in 100 conventional THAs versus 100 robotic THAs and found improved University of California Los Angeles (UCLA) scores in the robotic group but no difference in Short-Form 12 Health Survey (SF-12), Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) score, or postoperative complications at minimum one year after surgery.[31] Banchetti et al retrospectively reviewed outcomes in 56 robotic-arm-assisted THAs and 51 conventional manual THAs, and found no difference in the pain score on the numerical rating scale, WOMAC score, Harris Hip Scores, or postoperative complications between the two treatment groups at minimum 24 months follow-up.[42] Chen et al recently conducted a meta-analysis of 994 conventional manual THAs versus 522 robotic THAs and found no difference in functional outcomes, leg-length discrepancy, stress shielding, or rates of revision surgery between the two treatment techniques.[43] Karunaratne et al performed a meta-analysis of patient-reported outcome measures using data from seven studies reporting on 755 THAs, and found no differences in the modified Harris Hip Score, Harris Hip Score or Mayo Clinical Hip Scores between conventional and robotic THA at short-term follow-up.[44] At long-term follow-up, pooled estimates of function using the Merle d'Aubigne Score, and combined modified Harris Hip Score and Harris Hip Score showed no difference in outcomes between conventional and robotic THA, though the evidence levels of the studies used for analysis were classified as low-quality.

Limitations of robotic THA

Robotic THA is associated with substantive costs for installation of the robotic device, updating and servicing the computer software, and training the surgical team to become familiar with the new instruments and workflow. The robotic technology is also only compatible with a select number of implant designs from the manufacturer. There is a steep learning curve for the operating surgeon with additional operative times and surgical delays until surgical proficiency is reached.[19] Preoperative CT scans for surgical planning are associated with additional radiation exposure and extra time is required for segmenting and templating with the 3D virtual reconstruction. Complications reported with robotic THA include injury to soft tissues of the abductor mechanism, heterotrophic ossification, milling defects in the femur, and technical issues such as robotic device dysfunction.[30,34,40] Mechanical issues with the robotic device have led to conversion from fully active robotic THA to conventional manual THA in up to 18% of patients.[40] Patients with advanced osteoarthritis also often have abnormal spino-pelvic alignment or sagittal imbalances through the arc of flexion, which creates patient-specific safe zones for optimal implant positioning.[27] Robotic THA does not currently use dynamic preoperative imaging to assess the relationship of the pelvis, femur, and spine through these functional activities. However, if preoperative dynamic imaging were used to determine patient-specific safe zones for implant positioning then robotic technology could offer an avenue for executing this surgical plan with a high level of accuracy.[27]

Conclusion

Robotic THA uses preoperative imaging to create a patient-specific surgical plan and an intraoperative robotic device to execute this plan with a high level of accuracy. Preliminary studies have shown that robotic technology improves the accuracy of acetabular cup positioning within Lewinnek's safe zones and enables more precise restoration of the planned centre of hip rotation compared to conventional manual THA. However, improved radiological outcomes in robotic THA have not translated to differences in short-term functional outcomes, correction of leg-length discrepancy, or postoperative complications compared to conventional manual THA. Limitations of robotic THA include additional radiation exposure, substantive installation costs, and the lack of long-term data showing improved clinical outcomes or implant survival compared to manual techniques. The deficiency of long-term clinical and radiological data on robotic THA has restricted the uptake of this technology to routine arthroplasty practice. Robotic technology offers promise in the early stages but further studies reporting on long-term functional outcomes, implant survivorship, complications, and cost-effectiveness are required before this technique may be adopted into mainstream THA practice.

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