

General

Technology in Total Hip Arthroplasty: Recent Advancements

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Technology in total hip arthroplasty (THA) encompasses various navigational and robotic devices employed to increase the accuracy of prosthetic placement during operations. Many such devices exist on the market today, attracting interest from both physicians and patients alike. This paper summarizes the main classes of navigation and robotic technologies employed during total hip arthroplasty, highlights the literature on the outcomes of their use, and discusses the pros and cons of using such technology in operations.

INTRODUCTION

Total hip arthroplasty (THA) is among the most performed surgeries in the field of orthopaedics. Despite high rates of success and overall excellent long-term implant survivorship,¹ patient dissatisfaction due to complications related to surgery occurs in approximately 7-10% of cases.²⁻⁴ These complications most commonly include component malposition, instability, infection, aseptic loosening, and periprosthetic fractures.⁵ The case volume of THA is expected to increase 176% by 2040,⁶ with more than 50% of THAs expected to occur in patients aged 65 or younger.⁷ Among this younger cohort of patients undergoing THA, desired patient outcomes include restoring a higher level of function and ability to engage in day-to-day activities pain free.⁸ While many factors affect patient satisfaction after surgery, the ability to achieve a favorable outcome is certainly influenced by optimal implant positioning with improper acetabular version or femoral component malrotation implicated in instability or dislocation.⁹⁻¹¹

Computer-navigated and robotic-assisted surgery has become prevalent in orthopaedics, and existing literature has demonstrated improvements in implant placement and patient-reported outcome measures in total knee arthroplasty (TKA).¹²⁻¹⁴ Systematic reviews and meta-analyses have concluded that robotic-assisted TKA leads to improved precision in prosthetic placement as measured by femoral and coronal alignment between the femur and tibia.^{15,16} When compared to conventional TKA, robotic TKA led to lower postoperative pain scores, shorter time to perform a straight leg raise, and larger ROM on discharge.¹⁷ A study by Todesca et. al found statistically significant increases in ROM and KOOS function scores when comparing computer-navigated TKA to conventional TKA at a median follow-up of 6.4 years.¹⁸ While computer navigation and robotics are becoming more prevalent in THA, conventional THA remains the dominant operation performed,¹⁹ with only 4% of patients receiving technology-assisted THA

by 2018.²⁰ This may be attributed to the learning curve and training required to use this technology, skepticism surrounding whether long-term patient outcomes in THA are improved by technology, as well as concerns about the financial burden associated with obtaining these systems.

We aim to assist orthopaedic surgeons in their decision to pursue the use of technology in THA by reviewing the types of technology available, as well as their potential benefits and drawbacks. This will also assist surgeons in having informed conversations with patients who frequently inquire about the use of technology in THA.

METHODS

A search was conducted of the PubMed database for literature including the terms “computer navigated, navigation, computer-assisted, robotic, robotic-assisted” in conjunction with “total hip arthroplasty” to find commonly used examples of technology employed in total hip arthroplasty. An analysis of the literature was performed to summarize the clinical outcomes and to develop a list of the pros and cons of each class of technology.

NAVIGATION IN THA

Navigation in total hip arthroplasty refers to any technology or software intended to aid the surgeon in visualizing the patient's anatomy and any movement from their original position, as well as the placement and orientation of the implant. Navigation is broken down into three main categories: (1) Intra-operative x-ray-based navigation systems (2) handheld navigation systems (3) mixed reality systems. In general, navigation technology employs either pre-operative or intra-operative imaging, and/or a bone-mounted tracking system to provide the patient's spatial information to the surgeon. In certain technologies, this is paired with a “bone registration” step where the technology-generated

render of the patient's anatomy and position is matched to their true anatomical landmarks by the surgeon, thus confirming the validity of the navigation. The navigation tool can then serve as an accurate reference of the patient in real time, allowing for changes in their resting position to be detected and accounted for, and implanted prosthetics to be compared against the planned position and orientation, among other functions.

X-RAY BASED NAVIGATION

X-ray-based technology employs intraoperative radiography or fluoroscopy to aid in the placement and positioning of implants during total hip arthroplasty. Using fluoroscopic or radiographic images of the patient's anatomy, such technologies provide real-time information on the patient and allow for accurate referencing to a pre-planned surgical outline created by the surgeon. Capabilities include providing accurate measurements of leg-length discrepancies (LLD), trialing variations in acetabular cup and femoral implants, and guiding the proper placement and orientation of implants, among others.

Radlink GPS with Surgeon's Checklist Hip software from Radlink is a fluoroscopy-based system providing tools for accurate measurement of limb length, offset, pelvic tilt, cup anteversion and abduction, component sizing, and other metrics. Existing studies demonstrate this system's capability for accurate placement of components within the targeted abduction and anteversion measurements²¹ as well as meeting desired leg length adjustments^{22,23} and offset values.²³ Surgeon's Checklist Hip has additionally demonstrated potential in identifying mispositioning of components, allowing for immediate, real-time correction.²⁴ Recently, Radlink3D Hip was released as the potential successor to the Surgeon's Checklist Hip system. Coupling pre-operative MRI or CT scans with a single intra-operative X-ray, Radlink3D uses AI to generate a 3D mesh representation of the patient's anatomy. This representation can be directly manipulated to trial acetabular cup positions, limb length, and offset values, and serves as an intraoperative reference for navigation. The use of Radlink3D resulted in non-significant differences between true postoperative radiographs and intraoperative measurements of LLD, anteversion, and inclination generated by the Radlink3D system, whereas there were significant differences in intraoperative and final measurements of the aforementioned variables when using C-arm fluoroscopy and non-3D image analysis technology.²⁵

Velys Hip Navigation, or Joint Point, is an x-ray-based navigation software provided by DePuy Synthes. Beginning with preoperative x-rays, Velys Hip Navigation allows for the creation of a preoperative template and allows the surgeon to digitally trial different sizes of the femoral component, as well as inclination and anteversion values of the acetabular cup. The use of Velys Hip Navigation in clinical studies resulted in lower radiation dosage as compared to traditional radiograph overlay methods of assessing LLD as well as shorter operative durations.²⁶ There were also lower rates of readmission compared to THA performed without x-ray navigation assistance at 90 and 365 days postop,²⁷

and lower rates of overlengthening compared to standard fluoroscopy.²⁸

Hipgrid DRONE and PhantomMSK are produced by Orthogrid, now a Zimmer Biomet subsidiary. This system provides both a manual gridding system (MGS) and a digital gridding system (DGS) to account for S-distortion, which may affect the accuracy of fluoroscopic readings, while assisting with cup placement and leg-length adjustments. In a study comparing the two gridding systems in THA, Hip-Grid was able to simultaneously meet all desired criteria for global hip offset, leg length discrepancy, and cup abduction angle in 93.5% of cases using DGS and 97.6% of cases using an MGS.²⁹ Orthogrid has since released Orthogrid Hip AI, a system similar to DRONE and PhantomMSK now incorporating AI to automatically perform landmark detection, teardrop identification, and pelvic plane tracking. A clinical study comparing outcomes of patients undergoing primary THA with landmark identification performed either manually by an experienced human operator or automatically with Orthogrid Hip's built-in AI found no significant difference between the two groups.³⁰ In the group with automated navigation by the AI, 95% of cups were placed in the Lewinnek safe zone and 98% of final LLDs were within 5mm of intraoperatively calculated LLDs, demonstrating the potential of AI assistance in navigation to achieve satisfactory results.³⁰

Real Intelligence (RI) Hip Navigation software from Smith and Nephew expands the CORI surgical system's capabilities to assess pelvic tilt and leg length as well as predict postoperative X-ray outcomes. This system incorporates aspects of Brainlab 6.0 Hip Navigation, acquired by Smith and Nephew, which does not require registration of the anterior pelvic plane and resulted in shorter operative durations compared to previous iterations³¹ with 94% of navigation-predicted leg lengths within 5mm of postoperative radiographs.³² Currently, there are insufficient clinical studies on the use of RI Hip Navigation software along with CORI in total hip arthroplasty.

ADVANTAGES

The main advantage of x-ray-based navigation tools is increased accuracy and precision in the implantation of prosthetics. Clinical studies have demonstrated the ability of such tools to improve rates of meeting desired implantation criteria^{21,22,28,29} and reduce the variability of implant outcomes.²⁵ The use of x-ray-based computer navigation compared to traditional operative techniques leads to reductions in radiation exposure by around 38% by reducing the required number of radiographs taken throughout the operation²⁶ or eliminating the need for additional preoperative imaging.

DISADVANTAGES

The use of X-ray navigation has been associated with increased time spent in surgery in certain studies,²⁷ however, other literature shows no significant increase³³ or even reductions²² in intraoperative time, suggesting that surgeon training and skill are integral to optimally utilizing X-ray

navigation. The costs of obtaining such technologies, along with specialized imaging required in the case of systems such as Radlink3D, must be considered given the unclear impact of such technologies on long-term patient outcomes. Additionally, there are some limitations in the accuracy of X-ray-based measurements due to fluoroscopic distortion or parallax when obtaining radiographs.³⁴

HANDHELD NAVIGATION

Handheld navigation encompasses a range of navigation technologies characterized by a small operative room footprint and often employing minimally invasive pin arrays for tracking purposes. In contrast to larger console navigation systems, handheld navigation features a reduced learning curve and tends to integrate into the workflow more smoothly due to its similarity to conventional alignment jigs.³⁵

HipAlign, manufactured by OrthAlign, uses pins to mount an array system directly into the iliac crest. Using an accelerometer and laser probe, the array can collect and display information regarding leg length and rotation as well as acetabular cup version and abduction in real time, allowing for accurate and repeatable implantation of components.³⁶ Clinical studies using HipAlign in THA resulted in lower postoperative leg-length discrepancies compared to unassisted THA³⁷ as well as a higher rate of hips installed within the Lewinnek safe zone compared to non-navigated THA.³⁸ Kolodychuk et. al found that using HipAlign led to significant reductions in LLD and deviations in cup placement and offset compared to standard fluoroscopic assistance.³⁹

NAVISWISS Hip is another handheld imageless navigation system, produced by NAVISWISS. This system uses a series of minimally invasive pin-mounted trackers placed on the iliac crest and greater trochanter with a handheld camera to determine the functional pelvic plane and baseline leg length. NAVISWISS can accurately determine the current version and abduction of the acetabular cup by assessing the angle of the impactor relative to the implanted trackers, as well as changes in leg length by measuring the distance between the iliac crest and greater trochanter-mounted trackers. NAVISWISS Hip has demonstrated sufficient accuracy of implantation to meet acceptable clinical recommendations for acetabular cup placement⁴⁰ and achieve a difference in component placement within 5 degrees for both acetabular inclination and anteversion compared to postoperative CT scan measurements,⁴¹ and a clinical study performed by Hasegawa et. al demonstrated lower mean errors compared to unnavigated THA in anteversion and inclination when comparing postoperative radiographs to planned positioning.⁴²

Navbit Sprint INS is a disposable inertia-based navigation system manufactured by Navbit. Packaged as a sterile unit, the system is first mounted to the iliac crest as a reference, and tracks inclination and version of the acetabular cup through changes in the center of gravity when attached to the impactor. The mean error of measurements made using this device under controlled settings is approximately 1.21 degrees,⁴³ and a prospective clinical study of

THA using Navbit Sprint INS resulted in mean differences between intraoperative and postoperative measurements of 2.8 degrees for cup abduction and 3.9 degrees for cup anteversion,⁴⁴ demonstrating sufficient accuracy. Angle measurements for cup anteversion were significantly more accurate than goniometer-produced measurements; however, there was no significant difference when assessing abduction.⁴⁴

Intellijoint Hip from Intellijoint Surgical relies on an iliac crest-mounted camera together with probe-based registration to capture information regarding the patient's intraoperative movements, current pelvic orientation, as well as the angle and resulting leg length of the implant. This system is usable in direct anterior, lateral, and posterior approaches of THA, with clinical studies demonstrating excellent accuracy of implant positioning. Assessing the accuracy of Intellijoint Hip using benchtop phantoms simulating a leg in a neutral position as well as 15 degrees of flexion, abduction, or external rotation as a reference obtained mean differences in measurements within 0.66 degrees for cup anteversion and inclination, 0.77mm for leg length, and 0.85mm for offset.⁴⁵ Cadaveric studies have demonstrated accuracy of measurements on average within one degree for anteversion and inclination, 0.27mm for leg length, and 1.75mm for offset compared to postoperative CT scans.⁴⁶

ADVANTAGES

The main advantages of handheld navigation include increased accuracy of implant placement^{38-40,42} and intraoperative measurements made relative to final radiographic measurements taken postoperatively,^{37,39,42-44} while smoothly integrating into surgical workflows. These systems also feature a reduced OR footprint compared to larger navigation systems and require less intraoperative imaging resulting in lowered radiation exposure for both the patient and surgeon.³⁹

Handheld navigation can improve surgical outcomes in patients with obesity. In a study of patients with a BMI greater than 35 kg/m², THA performed with Intellijoint navigation compared to non-navigated THA resulted in statistically significant reductions in leg length discrepancy and increases in component implantation within the safe zone as designated by the surgeon performing the procedure.⁴⁷

DISADVANTAGES

The use of handheld navigation in THA often involves increased surgical time^{39,43} and may be associated with a significant learning curve before improved accuracy is observed. Kolodychuk et. al's study found that significant improvements in acetabular cup version and LLD were only observed with HipAlign after the 31-35 case learning curve specified by the researchers.³⁹

While accuracy of implant placement and measurements were improved in many studies, there is insufficient evidence to conclude if the improved accuracy conferred by handheld navigation results in improved health outcomes

for patients. Lourens et. al's study assessing survivorship of THA with Intellijoint navigation compared to non-navigated THA with revision as an endpoint indicated no significant differences between the two categories.⁴⁸ In lieu of this, consideration must be made to assess if the benefits of handheld navigation justify the cost of using this technology.

Navigation in orthopaedics involving pin-mounted trackers may increase the risk of postoperative complications in the form of pin-site infections or fractures.^{49,50}

MIXED REALITY NAVIGATION

Mixed reality navigation is a novel class of navigation technology relying on pre-operative imaging to generate a 3D representation of a patient for surgical planning, which is then holographically projected onto the patient intraoperatively allowing surgeons to receive real-time guidance. This is often accomplished through a head-mounted device for surgeons coupled with the registration of anatomic landmarks either through marker pins or a probe.

HipInsight is a CT-based system augmented reality system assisting surgeons through the generation of a 3D surgical plan. Utilizing a preop CT and a mixed reality headset, the system provides intraoperative holographic navigation utilizing anchors at predetermined anatomical landmarks and holographically projects the correct position of the impactor to achieve the desired angles of version and abduction of the acetabular cup. While no clinical studies currently exist for this technology, a retrospective study using its predecessor HipXpert for acetabular cup placement resulted in implantation within 10 degrees of targeted inclination and anteversion measurements simultaneously in all patients, and within 5 degrees in 30 of 47 patients, with mean absolute error between preoperative and postoperative measurements of 2.66 degrees for inclination and 3.68 degrees for anteversion.⁵¹

ADVANTAGES

The advantage of a mixed reality navigation system is the ability for surgeons to see anatomy beyond the standard surgical view utilizing preop CT 3D individualized planning in real time. This may allow surgeons to improve anatomic placement of components and to individualize planning for surgery before the surgery utilizing the precision of a preoperative CT scan.

DISADVANTAGES

The disadvantage of a mixed reality navigation system is the requirement of intra-operative landmarking and/or pin placement in the pelvis. Inaccurate registration of bony landmarks may lead to some inconsistency, and any movement of these arrays may lead to inaccurate guidance or prosthetic placement.

ROBOTICS

Robotic technologies in THA are commonly subdivided into classes based on the level of autonomy afforded to the robot: passive, semi-active, and active. Passive robots refer to systems where the surgeon performs bone cuts independent of a robot-mounted saw but receives support or guidance by other means. Semi-active robots represent the most used class today, featuring surgeon-guided cuts with robotic arms aimed at increasing precision and accuracy. Active or fully autonomous robots perform operations independent of the surgeon's direction, although surgeons frequently supervise the robot's actions and can intervene as necessary. Further classification of surgical robots in THA includes "open" versus "closed" systems, with "open" surgical systems accepting a variety of implant types and designs, whereas "closed" systems accommodate only specific implants.

Prior to or during the operation, robotic-assisted THA is further aided through either imaging and/or an array system. In the case of imaging, CT scans or MRIs are commonly employed to better visualize the patient's anatomy and plan the operation. Typically, a system of pin-mounted arrays can be inserted at various anatomical landmarks, usually including the iliac crest and greater trochanter, and serve as a reference for both the positioning of the patient and planned bone resection.

The MAKO surgical system from Stryker is a closed semi-active system available for direct anterior, posterolateral, and anterolateral approaches of hip arthroplasty. Using a preoperative CT scan, MAKO generates a 3D representation of the patient used to plan implant size and positioning. MAKO's robotic arm can then be employed to assist in reaming, with built-in guidance to prevent excessive bone removal, and impaction of the acetabular cup with the desired inclination and version. Matched pair studies comparing MAKO-THA with conventional non-robotic THA found significant improvements in the rate of placement within both the Lewinnek and Callanan safe zones, with 100% of MAKO-THA within the Lewinnek safe zone and 92% within the Callanan safe zone as opposed to 80% and 62% for traditional non-robotic arthroplasty, respectively.⁵² MAKO has also demonstrated good results in complicated patients, with usage in orthopaedic oncology patients and patients with developmental dysplasia yielding favorable results.^{53,54}

The ROSA surgical system from Zimmer Biomet is another closed semi-active system. This robotic system features a main robotic unit mounting an arm for directly assisting procedures, guided by fluoroscopy, and an optional secondary optical unit. Optimized for the direct anterior approach, fluoroscopy is used to create a 3D representation of the patient before anatomical landmarks are used to determine the reference axis, preoperative leg length, and offset to plan the operation. Intraoperatively, ROSA's arm can assist in the placement of the acetabular cup component at desired values of anteversion and offset. THA using ROSA led to 100% of cups installed within the Callanan safe zone, a statistically significant increase over the 73% observed in

manual THA in matched pairs of cadaveric knees.⁵⁵ Clinical studies comparing ROSA and MAKO-assisted THA yielded comparable precision and accuracy regarding the implantation of components within the Lewinnek safe zone and meeting desired anteversion and inclination.⁵⁶ When compared to manual THA, clinical studies have shown ROSA assistance leads to improved accuracy of final acetabular anteversion compared to the planned position of the implant and higher rates of implantation within the Lewinnek safe zone.⁵⁷ Similar improvements were observed when assessing THA in patients with obesity, with ROSA's accuracy relatively undiminished by obesity in comparison to the statistically significant decrease in placement within the Lewinnek safe zone and increased cup inclination angles in obese patients undergoing manual THA.⁵⁸

TSolution-One is an open, fully active robotic system for THA manufactured by THINK Surgical. Using preoperative CT scans to generate the operation plan in conjunction with the acting surgeon, TSolution-One is capable of autonomously milling out the femur to accept the planned implant and providing navigation to the surgeon during the implantation of the acetabular component, which is performed manually. Insufficient clinical studies currently exist for this iteration of the system.

ADVANTAGES

Robotic THA has been demonstrated in numerous studies to increase the accuracy of component placement for THA^{52,53,57,58} which is retained even in complicated patients.^{53,55,58} This accuracy has been associated with improved patient outcomes, with rates of dislocation for robotic-assisted THA observed to be significantly lower than rates of dislocation for manual THA in some reports.⁵⁹ Robotic assistance may allow junior surgeons to achieve surgical outcomes comparable to experienced surgeons by several metrics. A study by Kolodychuk et. al found no significant differences in complication rates and differences from planned leg length discrepancy between junior surgeons with robotic THA in both the anterior and posterior approach compared to experienced surgeons, with junior surgeons displaying increased accuracy of acetabular component placement in the posterior approach.⁶⁰ Complete parity was not achieved, however, with the experienced surgeons achieving comparable radiographic outcomes but with higher Harris Hip Scores in the anterior approach.⁶⁰

DISADVANTAGES

Robotic-assisted THA often requires a high initial investment.⁶¹ While studies demonstrate significant improvements in the accuracy of implant placement, there is no consensus on whether this results in significant long-term benefits for patient outcomes. Additionally, robotic-as-

sisted THA does not improve the accuracy of femoral sizing during THA, which can contribute to poor outcomes if chosen improperly. Systematic reviews comparing outcomes of robotic-assisted and manual THA found that manual THA resulted in fewer postoperative complications and similar functional scores⁶² with only statistically insignificant improvement in the forgotten joint score for MAKO.⁶³ A retrospective study by Singh et. al comparing outcomes between robotic-assisted THA and conventional THA found that patients undergoing robotic-assisted THA had significantly higher odds of periprosthetic fractures.⁶⁴ Further studies investigating long-term effects on patient outcomes are essential to determining the benefits or drawbacks of employing robotics in THA.

The surgical experience and outcomes of robotic-assisted THA remain heavily dependent on surgeon skill and training. A study by Kayani et. al found that surgeons required on average 12 operations for robotic-assisted THA to achieve an operative time comparable to manual THA.⁶⁵ Moreover, robotic outcomes are inherently constrained by the limitations of the operation or patient. Despite the use of MAKO in a study to install a single wedge, straight, uncemented stem in THA, the stem was placed in the desired range of anteversion in only 48% of patients as a result of inherent low femoral neck version in the patients involved.⁶⁶

SUMMARY

Currently, a plethora of navigation and robotic technologies are available to aid surgeons during THA. Clinical evidence for X-ray-based, handheld navigation, mixed reality navigation, and surgical robots generally suggest that these technologies are associated with increased accuracy of component placement compared to traditional manual THA. Despite this, many studies demonstrate no significant differences in revision rates or functionality compared to manual unassisted THA. Additionally, the use of these technologies often involves a steep learning curve and has significant acquisition and maintenance costs.

Further studies investigating the long-term effects of technology use on patient outcomes are necessary to fully understand the benefits these systems bring, and their role in the surgical environment. Regardless, it is evident that proper component positioning and placement is critical to patient satisfaction after total hip arthroplasty and there are multiple technologies available on the market to aid surgeons in achieving this level of accuracy.

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