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Direct Anterior Approach Total Hip Arthroplasty Revisited

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Abstract

» In total hip arthroplasty, the advantages of the direct anterior approach (DAA) compared with the direct lateral and posterior approaches include a true intermuscular approach that spares the abductor musculature, protects the soft tissues surrounding the hip, and thus maintains hip joint stability.

» The disadvantages of the DAA compared with the direct lateral and posterior approaches include a steep learning curve; intraoperative radiation exposure; injury to the nerves, vessels, and muscles; and intraoperative and early postoperative complications including blood loss, wound-healing problems, increased time under anesthesia, proximal femoral fractures and dislocations, complex femoral exposure and bone preparation, and sagittal malalignment of the stem leading to loosening and an increased revision rate.

» Stem implantation in flexed sagittal position and early femoral-stem failures are more common with the DAA compared with the direct lateral and posterior approaches.

Total hip arthroplasty (THA) is currently a very successful orthopaedic procedure with a major evolution in surgical approaches and techniques since the original design and refinement[1-6]. Initially, indications for THA were limited to elderly and frail patients and patients with locomotor limitations and comorbidities[1]. Patients undergoing THA currently prefer the use of acclaimed, high-performance hip implants that will satisfy postoperative needs[1,7,8]. In financial terms, the global market for THA was approximately $4.8 billion in 2014, with an estimated forecast of $5.9 billion by 2020[8].

Traditional surgical approaches for THA include the posterolateral and mini-posterior approaches, the lateral approach, and the anterolateral approach; the posterior approach is the most commonly used worldwide and has stood the test of time[9-11]. Recently, there has been a trend toward minimally invasive surgical procedures for rapid recovery; in this regard, the direct anterior approach (DAA) has attracted much attention by orthopaedic surgeons and patients all over the world[9,11-34]. The popularity of this approach has been attributed primarily to claims of less surgical trauma and hemorrhage, shorter time of recovery, and faster rehabilitation and better outcome for the patients, with optimal orientation of the prostheses and a low rate of dislocation[12,14,18,27,32,35-45]. However, despite the extended literature regarding the DAA and the standard approaches for primary THA, the debate regarding the most effective or preferable technique continues, and controversy exists[9,11-34].

In contrast to the standard approaches for THA, the DAA has been in quasi-general use for only a short time, so a review of the current literature is going to include

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the results of many studies in which the investigators were working on a learning curve. Compared with the standard approaches for THA, the number of studies on DAA are lower; however, even with the less numbers, DAA has been associated with pitfalls and complications, which are summarized and discussed in the present article.

The Merits of DAA

Orthopaedic surgeons are increasingly exposed to the DAA during their training. Industry-sponsored seminars and courses, and surgeon mentorships and online discussions, have popularized and led to adoption of this surgical approach, especially among experienced professionals who were already adept at THA with other approaches, and who aimed to improve the outcome and decrease the surgical cost for their patients[46]. Currently, DAA THA is performed by many surgeons, with or without a specific orthopaedic table or intraoperative fluoroscopy. In the hands of experienced surgeons, exposure of the acetabulum and femur are at least as good as with any other surgical approach for THA.

Based on the approach described by Hueter, the DAA enters the hip joint through the intermuscular interval between the tensor fasciae latae and gluteus medius muscles laterally and the sartorius muscle and rectus fascia medially[9,47]. Compared with the posterior approach, the DAA is considered to be a true intermuscular approach that preserves the soft tissues around the hip joint, thereby preserving the stability of the joint with a lower risk of complications[9,12,17]. Compared with the mini-posterior approach, both approaches provide rapid recovery with a low risk of complications. Patients who undergo THA with a DAA experienced a slightly more rapid recovery, as measured by metrics of function and activity; however, the differences were not significant at 2 months[11]. Because the DAA is the less studied approach, longer-term complications may occur that will be important to quantify and may counterbalance the early benefits of the approach[11].

Speed of recovery and improved early clinical results are potential advantages of the DAA and are the typical reasons for patients choosing the approach[38,39,48-50]. The patients are mobilized the day of the operation without any necessary postoperative precautionary measures. Postoperative use of narcotic painkillers is often considerably less compared with other surgical approaches for THA[38]. The length of hospitalization following DAA THA is shorter, and the patients are more frequently discharged to home instead of to postoperative patient care facilities[39,49]. Recovery of motor function is faster[50], and the time to discontinue ambulatory assistance devices is shorter with the DAA compared with the standard approaches; the average time to discontinue the use of canes or a walker was 21 days, with 80% of patients ceasing ambulatory assistance devices by 7.6 days[48].

Another potential advantage of the DAA relative to the other approaches is that the abductor musculature is spared[22,36,51-53]. Additionally, because the patient is positioned supine, the use of intraoperative fluoroscopy that often accompanies the DAA may lead to improved component positioning and optimal leg length and hip-offset restoration[14,22,54-56]. Consistency and accuracy of the acetabular cup position are better with the DAA; intraoperative fluoroscopy allows for more exact cup insertion and less variance in cup angle compared with the posterior approach[56,57]. Although there is a tendency to insert the acetabular cup in a more anteverted position in DAA THA[58], rates of revision procedures for early acetabular cup failures (i.e., periprosthetic fractures or loosening of the acetabular component) or THA instability are lower in DAA compared with the posterior approach[59].

In general, there is considerable marketing and promotion of the DAA within the orthopaedic industry, as implant manufacturers sponsor courses and hospitals and surgeons have worked to popularize the procedure, playing a substantial role in the adoption of the approach[1,60-62].

The Demerits of DAA

Scientific data providing evidence of the safety and efficacy of DAA THA are conflicting and equivocal, and there is doubt that patients and surgeons find value in this method[59,61-96]. These findings involve a steep learning curve; injury to the nerves, vessels, and muscles; and intraoperative and early postoperative complications including radiation exposure, blood loss, wound-healing problems, increased time under anesthesia, postoperative pain, length of hospital stay, functional limitations, proximal femoral fractures and dislocations, complex femoral exposure and bone preparation, and sagittal malalignment of the stem leading to loosening and an increased revision rate (Table I)[1,33,59,63-68,72,77,78]. Moreover, although not substantial, in fluoroscopy-assisted DAA, there is intraoperative radiation exposure to the patient and the surgeons[73].

Learning Curve

The learning curve defines the progress of a person in gaining experience or new skills. In surgery, the learning curve refers to the number of cases that are necessary to attain a constant state of outcomes. In THA, the learning curve may depend on and be influenced by many variables, such as the skill and experience of the surgeon, type of implants and surgical approach, operating room team, and facilities[73]. De Steiger et al.[74] defined the learning curve as 50 to 100 cases, and Masonis et al.[66] defined it as 100 cases for a reduction in operating and fluoroscopy times[66].

Stone et al.[65] reported the results of 1,000 consecutive DAA THAs; in comparison to the posterior approach, the total time of the procedure (the time interval between the first incision to the complete closure of the wound) and the total time in the operating room (the interval from the time the patient enters

TABLE I Pitfalls of the DAA THA

Study Pitfalls and Complications	Comments
Learning curve	
Stone et al., 2018[65]	Transitioning from the posterior approach to the DAA, surgeons will likely experience a decrease in efficiency, with longer procedure times and total operative time
Masonis et al., 2008[66]	DAA THA showed a reduction in operative and fluoroscopy time after the initial 100 cases
de Steiger et al., 2015[74]	The cumulative revision rate at 4 years for the first 15 cases was 6%, which dropped to 2% for >100 operations
Radiation exposure	
McNabb et al., 2017[73]	DAA THA at many institutions is performed with fluoroscopic guidance throughout the procedure
Kaplan et al., 2016[77]	Whenever using fluoroscopy, it is important to remember the principle of ALARA (as low as reasonably achievable)—not only for the patient but for everyone in the operating room
Muscle inflammation	
Bergin et al., 2011[82]	The similar inflammatory profiles suggest that, although may be clinically important, it is difficult to claim that the DAA is less invasive
Wound complications	
Christensen et al., 2014[71]	A significantly greater number of DAA THAs required a revision procedure as a result of wound complications (1.4% versus 0.2%; $p = 0.007$)
Watts et al., 2015[83]	Female and obese patients (particularly those with body mass index $\geq$40 kg/m^2) were at increased risk of wound complications following DAA THA, with a large proportion of wound complications requiring a revision procedure
Vascular injury (circumflex vessels)	
Barton and Kim, 2009[67]	When the circumflex vessels are not properly identified and ligated, excessive bleeding during and after the procedure can occur
Cadossi et al., 2017[86]	Usually, the circumflex pedicle can be detected and ligated between the distal and middle thirds of the approach
Lateral femoral cutaneous nerve injury	
Rudin et al., 2016[87]	In approximately one-third of patients in whom a DAA is used, a certain amount of injury to the lateral femoral cutaneous nerve cannot be avoided
Superior gluteal nerve injury	
Grob et al., 2015[70]	The proximal part of the tensor fasciae latae, where the DAA occurs, is a vulnerable area for potential iatrogenic injury to its nerve supply
Stem sagittal alignment	
Abe et al., 2015[72]	Flexed-stem sagittal malalignment was more frequent with the DAA than with the posterolateral approach
Early femoral failure	
Meneghini et al., 2017[59]	The DAA may be a risk factor for early femoral and acetabular component failure as a result of aseptic loosening after THA

the operating room to the time the patient leaves the operating room) was similar or shorter after 500 DAA cases and 14% shorter after 850 DAA cases. However, the total operating room time was similar to the posterior approach after 900 cases because of the learning curve of the DAA for the whole surgical team, including the nursing staff, surgical and radiology technologists, anesthesia staff, sterile processing staff, and environmental service staff[65]. Additionally, there was the need for a trained assistant to position the patient safely and to perform intraoperative maneuvers for dislocation and relocation of the hip in DAA THA in order to avoid patient injuries, specifically ankle fractures because of improper positioning[14,65].

Woolson et al. considered that the DAA may not be safe in the hands of non-formally and extensively trained surgeons and that the complication rate associated with the approach may be excessively high for surgeons who otherwise may have low rates of complications with the standard approaches[68]. These authors suggested that the risk of a major fracture intraoperatively is higher with less experienced surgeons as most of the fractures of the greater trochanter and femoral shaft occurred within the first year of the practice of the surgeon and reduced considerably afterward[68]. The reduction in the incidence of femoral fractures in DAA THA was attributed to the more frequent release of the short external rotators during femoral exposure[68].

Furthermore, the revisions rate seems to be related to the experience of the surgeon and consequently to the learning curve. According to de Steiger et al., the 4-year cumulative revision rate of surgeons with ≤15 procedures was 6%, whereas the revision rate of surgeons with >100 procedures was 2%[74]. Lastly, although a correlation between intraoperative fractures and difficulty in exposure and elevation of the femur during femoral-stem preparation has been reported[75], other studies reported that early complications should not be considered a result of the learning curve but rather as inherent complications of the DAA[43,76].

Radiation Exposure

As with any medical procedure, when the use of radiation is necessary, the lowest dose possible is used[77]. DAA THA is performed in most centers with fluoroscopic guidance throughout the procedure[73]. The use of fluoroscopy, however, does not come without a potential risk to both the patient and the surgeon, especially when the hip and lumbar spine are involved[73,78,79]. McNabb et al. reported a mean patient radiation exposure of 178 mrem (range, 54 to 526 mrem) during a DAA THA, which is below the dose of a standard pelvic radiograph (600 mrem) and well below the maximum annual limit to the thyroid (15,000 mrem) and the annual gonadal limits (2,000 mrem)[73].

With the radiation dose to which the surgeons are exposed during DAA, one would need to perform between 300,000 and 450,000 DAA THAs to reach levels of radiation that cause concern for cataracts[80]. Similarly, the thyroid exposure of the surgeon after 51 DAA THAs over a 4-month period was 10 mrem, which is also well below the annual exposure limit[81]. Therefore, although it is a low dose, patients and surgeons are exposed directly to ionizing radiation during DAA THA[73].

To our knowledge, there are no available studies that evaluate the cost of the radiology technician and intraoperative imaging in DAA THA; for most operating theaters, the radiology technician is part of the surgical staff. However, the increased operating room traffic from the radiology technician and intraoperative imaging apparatus should definitely be considered an additional risk factor for complications related to the DAA, namely infection[71,83,85].

Muscle Inflammation and Injury

A minimally invasive procedure is defined differently by different surgeons on the basis of various criteria, including the length of the skin incision, the speed of recovery, and the details of surgical dissection[82]. When the comparison between DAA and the posterior approach is made on the basis of inflammation markers, the results indicate greater values of inflammation than the posterior approach, emphasizing that the DAA may not be as minimally invasive as it has been thought to be[82]. Bergin et al. reported higher creatine kinase levels with the posterior approach, which implicates greater muscle damage, and the remaining inflammatory profile was similar between the 2 approaches, which suggests that the inflammatory cascade associated with THA is not substantially influenced by the surgical approach per se but by bone osteotomies and prostheses implantation[82].

Wound Complications

Christensen et al. reported that the number of DAA THAs that required a revision procedure because of wound-related complications was significantly higher compared with THAs performed with a posterior approach (7 of 505 DAA THAs [1.4%] compared with 3 of 1,288 posterior-approach THAs [0.2%]; $p = 0.007$)[71]. The rate of wound complications that required a reoperation in the study by Christensen et al. (1.4%) was similar to that reported in other studies (1.3%[76] to 1.6%[84]). Although the overall rate of wound-related complications (infected and noninfected hematomas, and delayed wound healing) that required a revision procedure was higher for the DAA THA compared with the posterior approach, a particular type of wound complication that was more often in that group of patients was not recorded[71].

Wound complications reported following DAA THA include infected and noninfected hematomas, delayed wound-healing or formation of incision eschar, and periprosthetic joint infection[71]. Age, operative time, learning curve, surgeon skill and experience, and comorbidities (including diabetes mellitus and rheumatoid arthritis) were not found to be important predictors of wound-related complications following DAA THA[71,76,83].

Hallert et al. reported that the number of early complications with the DAA was not related to the learning curve associated with the new technique because there was no difference in the rate of complications after a surgeon had completed 10 or >100 DAA THAs[76]. Therefore, the learning curve does not have an effect on the rate of wound complication in DAA THA[71,76].

Watts et al. reported that female and obese patients, especially those with a body mass index of ≥40 kg/m^2, had an increased risk of wound complications following DAA THA, with most complications requiring a revision procedure[83]. In obese muscular patients, the space available to place the femoral and acetabular components may be limited, and to achieve enough exposure to implant the prostheses accurately requires considerable knowledge and experience regarding retractors and leg positioning. A straight impactor that attaches to the acetabular component often impinges against the large muscular thigh distally, which may lead to insertion of the acetabular cup in a more vertical and anteverted position. An offset inserter is helpful in such a situation[38]. These findings and aspects should be considered when selecting patients and preoperatively planning for a DAA THA, especially in morbidly obese patients because of the increased risk of wound complications in these patients[38,83].

Vascular Injury

During a DAA THA, the pedicle of the circumflex artery should be identified and ligated in the space between the middle and distal third of the incision[86]. Specifically, the procedure involves exposure and ligation of the ascending branches of the lateral femoral circumflex vessels that lie in the interval between the sartorius and the tensor fascia latae muscles underneath the deep fascial layer[67].

Routine electrocauterization usually provides adequate hemostasis of these vessels; however, in cases of improper identification and ligation, excessive hemorrhage may occur during and after the procedure, which may lead to an increased risk of postoperative hematoma formation[67].

Nerve Injuries

The lateral femoral cutaneous and superior gluteal nerves are at risk during DAA THA. The lateral femoral cutaneous nerve is a purely sensory nerve, the nerve fibers of which derive from the second and third lumbar nerves. The lateral femoral cutaneous nerve arises from the lateral border of the psoas major muscle, crosses the iliacus muscle obliquely in the pelvis, and runs toward and below the anterior superior iliac spine[87]. Rudin et al. observed 3 branching patterns of this nerve, including the sartorius type (36%), the posterior type (32%), and the fan type (32%)[87].

The rate of injury to the lateral femoral cutaneous nerve associated with DAA THA is highly variable between studies, with the reported rates ranging from 0.1% to 81%[12,32,87-89]. Although injury to the lateral femoral cutaneous nerve does not lead to a major neurological deficit, patients may report numbness or a sensation of burning in the anterolateral region of the thigh and, at worst, dysesthesia[87]. Rudin et al. reported 2 factors that may be associated with the potential risk of injury to the lateral femoral cutaneous nerve: (1) the specific distribution pattern of the nerve in the proximal aspect of the thigh and (2) the surgical technique and skin incision used for the DAA[87]. According to the authors, some degree of injury to the lateral femoral cutaneous nerve cannot be avoided in approximately one-third of patients who underwent hip procedures with an anterior approach[87].

Several cases of superior gluteal nerve injury have been reported following THA with the lateral approach described by Hardinge and the anterolateral approach described by Watson-Jones; however, an association between the DAA and superior gluteal nerve injury has not been documented[70]. The superior gluteal nerve is a motor nerve that originates from the posterior branches of the ventral rami of the fourth and fifth lumbar and the first sacral spinal nerves. This nerve innervates the gluteus medius and gluteus minimus muscles and the tensor fasciae latae; it exits superior to the piriformis muscle and divides into its superior and inferior branches[70,90]. The terminal branches of the inferior branch run anteriorly and supply the tensor fasciae latae muscle[91].

Meneghini et al.[36] compared the extent of damage to the tensor fasciae latae muscle between the minimally invasive anterior approach and the minimally invasive posterior approach in a cadaveric study; the authors reported damage to the tensor fasciae latae in all specimens that received the anterior approach. The tensor fasciae latae muscle surface was frequently damaged in the midsubstance of the muscle, where the superior gluteal nerve enters the muscle[36].

Grob et al.[70] reported that the terminal branch of the inferior division of the superior gluteal nerve enters the tensor fasciae latae in its proximal half; in 90% of cases, 1 to 2 terminal nerve branches enter the tensor fasciae latae muscle within 10 mm above the entry point of the ascending branch of the lateral circumflex femoral artery, which is always proximal to this point. Therefore, this artery can be a reliable intraoperative landmark to protect these nerve branches[70]. However, the area at the proximal part of the tensor fasciae latae muscle may become vulnerable to nerve injuries because the DAA travels exactly in this region. To avoid hemorrhage, the surgeon proceeds to clamping, coagulation, ligation, and transection of the ascending branch of the lateral circumflex femoral artery close to the muscle belly; in this regard, the surgeon may cause iatrogenic injury to the terminal branch of the superior gluteal nerve and atrophy of the tensor fasciae latae muscle[70]. Alternatively, the nerve branches may be injured in this area by excessive use of retractors during broaching of the femur or by incorrect proximal extension of the anterior approach[36,70]. One method to protect the surrounding tissues seems to be intracapsular rather than extracapsular placement of the retractors[14].

Injury to the superior gluteal nerve causes paralysis of the gluteus medius and minimus muscles and the tensor fasciae latae, leading to abductor weakness and a positive Trendelenburg sign[70]. However, injuries to the terminal nerve branches of the superior gluteal nerve are possibly underdiagnosed because usually the patients are asymptomatic; these patients usually have excellent clinical results and function without a cosmetic difference[70].

Early Femoral Failure

Recently, the reported rates of early THA failure have increased, ranging from 24% to 50% within 5 years after the index procedure secondary to early femoral or acetabular periprosthetic fracture, femoral stem and/or acetabular component malalignment and/or loosening, and instability[59,72,92-96]. In a study of 342 THAs with early failure, Meneghini et al.[59] reported that early femoral periprosthetic fractures and femoral component loosening were significantly more common with the DAA (57 of 112 THAs; 50.9%) compared with the direct lateral (39 of 112 THAs; 34.8%) and posterior (16 of 112 THAs; 14.3%; $p = 0.001$) approaches. Early femoral component loosening was significantly more common with the DAA (34 of 72 THAs; 47.2%) and the direct

lateral approach (31 of 72 THAs; 43.1%) compared with the posterior approach (7 of 72 THAs; 9.7%; p = 0.005). Although the differences were not significant, early femoral periprosthetic fractures were more common with the DAA (23 of 40 THAs; 57.5%) compared with the posterior (9 of 40 THAs; 22.5%) and direct lateral (8 of 40 THAs; 20.0%; p = 0.118) approaches[59].

Malalignment of the acetabular cup and/or the femoral stem in THA has been reported to cause impingement and related complications, including dislocation, early wear or breakage of the bearing, and loosening of the acetabular component[97-99]. Femoral stem alignment and acetabular component anteversion may vary among surgical approaches. It is reportedly more difficult to implant the femoral stem in the neutral position in the sagittal plane through the anterolateral approach compared with the posterolateral approach; this increased difficulty was attributed to the need to elevate the proximal aspect of the femur in the anterolateral approach[72,92], which may also be true in the DAA[72]. There is also a tendency to insert the acetabular cup in a more anteverted orientation in DAA THA[58], and femoral stem anteversion may be controlled more accurately through the posterolateral approach[72].

Abe et al. reported that the surgical approach was not related to the postoperative change in femoral anteversion, but that the approach did affect the sagittal alignment of the stem; the authors utilized an anatomical femoral stem and reported that stem implantation in flexed sagittal malalignment was more common with the DAA compared with the posterolateral approach[72]. Although Renkawitz e al. reported that stem sagittal alignment affected postoperative anteversion[93], Abe et al. reported that preoperative anteversion of the femur was the only factor related to the postoperative change in femoral anteversion[72]. However, this discrepancy might be attributed to different definitions used in the anteversion measurements by these surgeons[72]. Therefore, although the surgical approach does not seem to affect the postoperative change in femoral anteversion, it does affect the sagittal alignment of the stem, which may further affect the postoperative anteversion when an anatomical stem is used[72], as well as the width of the safe zone for acetabular cup placement when implanting the stem before the acetabulum component and utilizing a tapered stem[72,93].

Meneghini et al. reported that revision procedures for early acetabular cup failure (i.e., periprosthetic fractures or loosening of the acetabular component, or THA instability) were significantly less frequent in the DAA compared with the posterior approach[59]. Revision procedures for periprosthetic acetabular cup failures were more common with the posterior approach (43.3%) compared with the DAA (36.7%) and the direct lateral approach (20%). Similarly, revision procedures for instability were more common with the posterior (47.5%) compared with the DAA (37.5%) and the direct lateral approach (15%). The authors also noted that early revision procedures were significantly more likely to result from THA performed with the DAA or the direct lateral approach compared with the posterior approach[59].

Conclusions

The DAA for THA was established as an internervous and intermuscular surgical approach[100] with claimed advantages such as less surgical trauma and hemorrhage, shorter recovery time, faster rehabilitation, and better outcomes with a low dislocation rate and more accurate placement of the prosthesis. Marketing has produced biased claims of superiority without the support of peer-reviewed literature; however, the DAA has inherent pitfalls that may even be considered complications of the approach. Therefore, the usefulness and early and long-term advantages of the DAA should be questioned.

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Comparison of Outcomes After Robotic-Assisted or Conventional Total Hip Arthroplasty at a Minimum 2-Year Follow-up

A Systematic Review

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Abstract

Background: This systematic review aimed to present an updated analysis of the evidence comparing outcomes between robotic-assisted total hip arthroplasty (robotic THA) and conventional manual total hip arthroplasty (manual THA).

Methods: A PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) systematic review was performed using the Cochrane Database of Systematic Reviews, Cochrane Central Register of Controlled Trials, PubMed, MEDLINE, and Embase. Controlled studies comparing primary robotic THA and manual THA utilizing patient-reported outcome measures (PROMs) at a minimum follow-up of 2 years were included. We also compared radiographic outcomes, dislocation rates, and revision surgical procedures between groups. The ROBINS-I (Risk of Bias in Non-Randomized Studies - of Interventions) and Cochrane Risk of Bias 2.0 tools were used to assess study quality and risk of bias.

Results: Of 765 studies identified, 7 articles comparing robotic THA with manual THA met inclusion criteria. A total of 658 patients were assessed, 335 of whom underwent robotic THA. The majority of studies found no significant differences ($p > 0.05$) in PROMs between the 2 techniques. Two low-quality studies (Level III) found significantly better postoperative PROMs favoring robotic THA at 2 years. When assessing radiographic outcomes, 6 studies showed that robotic THA resulted in more consistent and accurate component placement. No differences in postoperative dislocations, complications, or revision rates were found between groups except in 1 study, which found significantly more dislocations and revisions in the robotic THA cohort. Reported operative times were a mean of 12 to 25 minutes longer when using robotic THA.

Conclusions: The existing literature comparing robotic THA and manual THA is scarce and low-quality, with findings limited by methodological flaws in study design. Although evidence exists to support increased accuracy and reproducibility of THA component placement with robotic THA, this has not been shown to reduce postoperative dislocation and revision rates. Based on the available evidence, functional outcomes are comparable between techniques, and robotic THA appears to be associated with longer operative times. To fully evaluate the utility of

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robotic THA, additional well-designed, prospective controlled studies with continuous long-term monitoring are required.

Level of Evidence: Therapeutic Level III. See Instructions for Authors for a complete description of levels of evidence.

Total hip arthroplasty (THA) is a cost-effective and highly successful treatment for hip osteoarthritis[1-3] and can improve patient quality of life and function more than any other elective surgical procedure[1,4,5]. The demand for primary and revision THA is projected to grow. Between 2005 and 2030, the number of primary THAs performed annually is estimated to grow 174% and the number of revision THAs performed annually is estimated to grow 137%, resulting in a projected 4 million individuals in the United States who will have undergone a THA[6,7]. Despite the success of THA, complications such as component malpositioning, instability, and aseptic loosening still occur[8,9]. Concomitant with advances in technology, there has been an increased interest in the use of computer navigation and robotic technology as potential methods to decrease postoperative complications in THA.

Over the last several years, there has been a surge of publications showing early outcomes for robotic-assisted arthroplasty, most with regard to robotic-assisted total knee arthroplasty (TKA). To date, research on robotic-assisted THA (robotic THA) has primarily concentrated on component positioning, with evidence suggesting that robotic THA improves the accuracy of implant placement[10,11]. However, the use of robotic THA incurs substantial costs, which must be justified by demonstrating clinically important improvements over conventional manual THA, for which the bar of success is set high[12]. Additionally, objective precision of implant placement does not necessarily correlate with improved patient-reported outcome measures (PROMs). PROMs are increasingly being utilized to track outcomes and value in orthopaedic surgery, where many procedures are elective and performed to improve patient function and quality of life, and are thus essential in evaluating the benefits of an intervention.

Two prior systematic reviews have attempted to compare robotic THA and manual THA[13,14]; however, these reviews were equally broad in scope and not generalizable. Neither had strict minimum follow-up criteria or specifically examined PROMs. Furthermore, the increasing number of publications on robotic-assisted joint arthroplasty calls for an updated review of the evidence.

The purpose of this study was to systematically review the full body of clinical evidence comparing robotic THA and manual THA with a minimum 2-year postoperative follow-up on all patients. Specifically, we aimed to identify whether robotic THA resulted in improved PROMs, decreased dislocation and complication rates, or improved clinical outcomes and fewer revisions compared with manual THA.

Materials and Methods

Article Identification and Inclusion Criteria

This study was conducted in accordance with the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) guidelines (Fig. 1)[15]. Databases searched included PubMed, MEDLINE, Embase, the Cochrane Database of Systematic Reviews, and the Cochrane Central Register of Controlled Trials. The literature search strategy included the following keywords and all combinations thereof: "robotic," "robotic-assist*," "arthroplasty," "hip," and "conventional." These keywords were combined in the search using the Boolean operators "AND" or "OR." There were no publication period restrictions. The queries were performed in March 2020.

We included all controlled studies (prospective and retrospective) comparing robotic-assisted and conventional manual primary THA showing at least 1 PROM of satisfaction, quality of life, pain, or function at a minimum follow-up of 2 years. Case reports, conference abstracts, expert opinions, surgical technique articles, cadaveric studies, and articles published in languages other than English were excluded. Studies performed utilizing non-robotic, image-based, or imageless navigation were excluded. Furthermore, studies without a manual THA control group or studies showing outcomes for revision THA were excluded. There were no restrictions with regard to the surgical approach utilized. If a duplicate study population was encountered, the article with the longer mean follow-up was included to avoid overlap.

Two independent reviewers (M.C.S. and G.J.B.) manually screened titles and abstracts from all identified articles for eligibility. Full-text articles were obtained for additional review if necessary in accordance with our inclusion criteria. Manual electronic searches of Google Scholar and the reference lists from all eligible studies were reviewed to ensure that no relevant articles were missed. Additionally, implant manufacturer websites were searched to ensure that evidence was not overlooked. Any discrepancies between the 2 reviewers were reconciled by discussion and mutual agreement. Systematic review registration was performed a priori in March 2020 with the International Prospective Register of Systematic Reviews (PROSPERO), registration CRD42020175072.

Data Collection

The level of evidence of the studies included was assigned according to the classification system specified by Marx et al.[16]. Data were abstracted from the

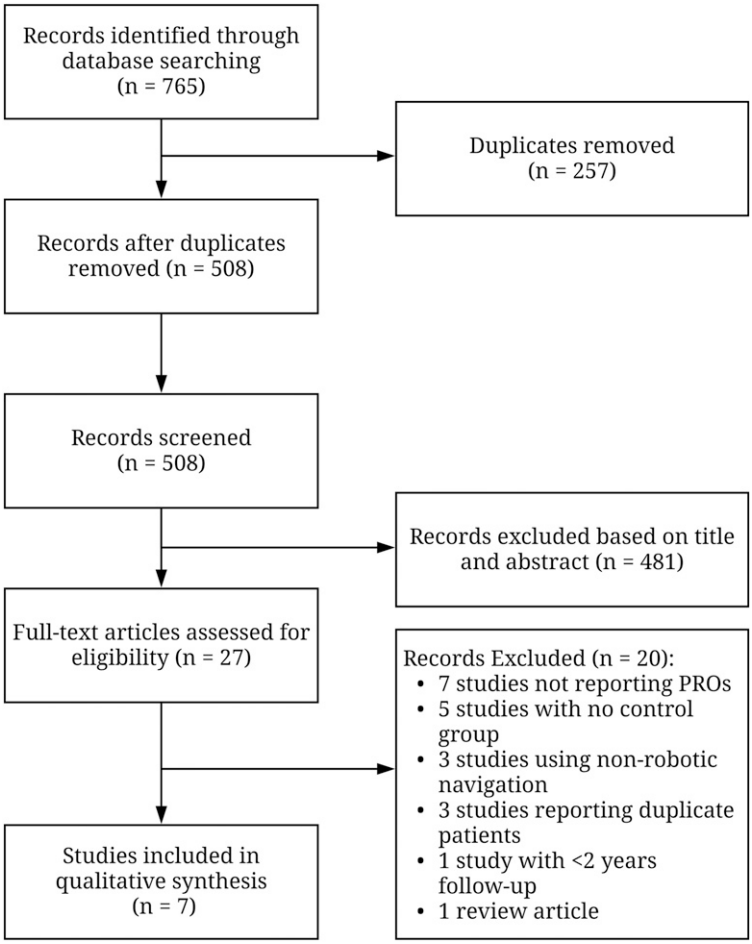

Fig. 1

Study search strategy according to PRISMA guidelines. PROs = patient-reported outcomes.

full text of all eligible articles into a custom, protected spreadsheet using a modified information extraction table[17,18]. During the initial review of the data, the following information was abstracted and recorded: patient demographic characteristics, robotic system utilized, surgical approach, follow-up duration, implant manufacturer, radiographic outcomes, perioperative complications, dislocations, reoperations, and revisions.

Based on a preliminary survey of the most common PROMs utilized, the following outcomes scores were recorded: Harris hip score (HHS), Merle d'Aubigne score, and the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC). If none of these scales were used, results were documented for the primary outcome measures used in the study. Given the overall lack of Level-I evidence and heterogeneity between eligible studies, data pooling (meta-analysis) was not appropriate and, thus, not performed.

Quality Assessment

The methodological quality and risk of bias in nonrandomized studies were assessed using the Risk of Bias in Non-Randomized Studies - of Interventions (ROBINS-I) assessment tool[19]. For randomized studies, the Cochrane Risk of Bias 2.0 (RoB 2.0) tool was used[20]. These tools assess study quality and risk of bias across the following domains: confounding, participant selection, classification of interventions, deviation from intended intervention, missing data, outcome measurement, selection of reported results, and randomization. Two reviewers (M.C.S. and G.J.B.) independently assessed study quality, with disagreements resolved by discussion and mutual agreement.

Results

Study Selection

The systematic search performed using the previously mentioned keywords identified 765 articles. After duplicate articles were identified and removed, 508 articles remained for further review. Based on the predetermined inclusion and exclusion criteria, 27 full-text articles were assessed for eligibility.

Three of the studies identified were published by the same group of authors and were noted to present updated results from the same patient cohort[21-23]. Two of these articles were excluded as individual studies because of risk of bias and duplicate patients[21,22], but all versions were considered for maximum data extraction. In their article, Bargar et al.[24] reported long-term follow-up of patients from 2 separate studies, a prospective randomized clinical trial (RCT)[23] and unpublished data

TABLE I Characteristics of Included Studies*

Study	Country	LOE	Study Design	Robot Used	Surgical Approach	Robotic Component Placed	Implant Used	Sample Size	
								Robotic THA†	Manual THA†
Domb[29] (2020)	United States	III	Retrospective cohort	Mako	Direct anterior or posterior	Cup	NR	66	66
Nakamura[27] (2018)	Japan	II	Prospective cohort	ROBODOC	Posterolateral	Stem	VersSys FMT stem, Trilogy cup (Zimmer)	59 (64)	56 (64)
Banchetti[30] (2018)	Italy	III	Retrospective cohort	Mako	Posterolateral	Cup	Fitmore/CLS (Zimmer), manual THA group; Corin/Accolade II (Corin/Stryker), robotic THA group	56	51
Bargar[24] (2018)	United States	III	Mixed cohort‡	ROBODOC	Posterolateral	Stem	DePuy AML, Howmedica Osteolock, Zimmer VerSys FMT stems	40 (45)	21 (22)
Lim[25] (2015)	South Korea	I	RCT	ROBODOC	NR	Stem	Tri-Lock Bone Preservation Stem (DePuy)	24 (24)	25 (25)
Hananouchi[28] (2007)	Japan	II	Prospective cohort	ROBODOC	NR	Stem	VersSys FMT stem, Trilogy cup (Zimmer)	29 (31)	24 (27)
Honl[26] (2003)	Germany	I	RCT	ROBODOC	Anterolateral	Stem	Modular S-ROM (DePuy); ESKA Implants cup	61	80

*LOE = Level of Evidence, and NR = not reported. †The values are given as the number of patients, with or without the number of hips in parentheses. ‡This article included patients from 2 previous randomized clinical studies.

from a later randomized trial after multiple updates to the robotic system were implemented. The previously published trial[23] was excluded as it represented the same patient cohort. The remaining 7 studies included 2 RCTs (Level I)[25,26], 2 prospective cohort studies (Level II)[27,28], 2 retrospective cohort studies (Level III)[29,30], and 1 mixed cohort study (Level III)[24], and all met inclusion criteria (Fig. 1).

Study Characteristics and Quality

The characteristics of the included studies are presented in Tables I through IV. The 7 studies included in the analysis comprised a total of 658 patients, among whom 248 (37.7%) were male. One study included only female patients undergoing THA for osteoarthritis[28]. The robotic THA group comprised 335 patients (40.9% of whom were male), whereas 323 patients (34.4% of whom were male) underwent manual THA. Importantly, 5 studies used the ROBODOC system (THINK Surgical) for femoral canal preparation, and 2 studies used the Mako system (Stryker) for acetabular reaming and cup placement.

Using the ROBINS-I tool, studies were at moderate to critical risk of bias due to their retrospective, observational nature and inherent risk of confounding by differences between treatment groups

TABLE II Patient Characteristics*

Study	Follow-up *(yr)*		Age *(yr)*		Male Sex	
	Minimum	Mean†	Robotic THA Group†	Manual THA Group†	Robotic THA Group‡	Manual THA Group‡
Domb[29] (2020)	5	NR	59.01 ± 8.16	57.77 ± 10.50	24 (36.4%)	25 (37.9%)
Nakamura[27] (2018)	10	11.3 (10 to 12.7)	57 ± 9	57 ± 9	12 (18.8%)	11 (17.2%)
Banchetti[30] (2018)	2	NR	66.2 ± 11.1 (42 to 83)	69.8 ± 10.2 (42 to 86)	31 (55.3%)	26 (50.9%)
Bargar[24] (2018)	NR	13.8 ± 3.2 (robotic THA), 14.2 ± 4.7 (manual THA)	59.1 ± 8.2	59.8 ± 9.4	35 (77.8%)	12 (54.5%)
Lim[25] (2015)	2	NR	51.2 (19 to 67)	45.6 (21 to 65)	11 (45.8%)	13 (52.0%)
Hananouchi[28] (2007)	2	NR	56.7 ± 9.2	57.4 ± 7.1	0§	0§
Honl[26] (2003)	2	NR	71.5 ± 7.1	70.7 ± 8.3	24 (39.3%)	24 (30.0%)

*NR = not reported. †The values are given as the mean, with or without the standard deviation, and with or without the range in parentheses. ‡The values are given as the number of patients, with the percentage in parentheses. §This study included only female patients.

TABLE III Summary of Quality Assessment of Included Non-RCTs: Methodological Assessment According to 7 Domains of Potential Bias (ROBINS-I)

Study	Bias Due to Confounding	Bias in Selection of Participants	Bias in Measurement of Interventions	Bias Due to Deviations from Intended Intervention	Bias Due to Missing Data	Bias in Measurement of Outcomes	Bias in Selection of the Reported Result	Overall Risk of Bias
Domb[29] (2020)	Moderate	Moderate	Low	Low	Low	Moderate	Moderate	Moderate
Nakamura[27] (2018)	Serious	Moderate	Low	Low	Low	Moderate	Moderate	Serious
Banchetti[30] (2018)	Serious	Moderate	Low	Low	Low	Moderate	Moderate	Serious
Bargar[24] (2018)	Serious	Serious	Low	Low	Serious	No information	Moderate	Serious
Hananouchi[28] (2007)	Serious	Critical	Serious	Low	Low	Serious	Moderate	Critical

(Tables III and IV). Only 1 of the nonrandomized studies attempted to adjust for confounders[29], although others advocated that there were no demographic differences between groups[27,28,30]. Most articles included an adequate description of the surgical protocol and indications for THA; however, few discussed surgeon experience using the robotic system. The 2 randomized studies were assessed to have some concerns over risk of bias. Participants were not adequately blinded in any of the included studies, reflecting the difficulty and impracticality of blinding surgical interventions.

Functional Outcomes

Thirteen different PROMs were reported in the 7 studies, of which the most commonly used were the HHS (5 studies)[24-26,29,30] and the WOMAC score (3 studies)[24,25,30]. Although there were discrepancies between outcomes scores utilized between studies, the majority of the evidence found no significant differences in postoperative PROMs between the robotic THA group and the manual THA group. Three of 7 studies showed a significant difference in PROMs favoring robotic THA during at least 1 postoperative assessment[24,26,29]. Honl et al.[26] reported significantly higher Mayo, HHS, and Merle d'Aubigne scores ($p < 0.05$) in the robotic THA group at several time points up to 12 months postoperatively; however, there were no differences between groups at 24 months for any measure (Table V). Domb et al.[29] reported significant differences ($p < 0.05$) in the HHS, Forgotten Joint Score-12 (FJS-12), Veteran RAND-12 (VR-12) Physical, and Short Form Health Survey-12 (SF-12) physical scores favoring the robotic THA group at a minimum 5-year postoperative follow-up. Bargar et al.[24] reported significantly higher scores ($p < 0.05$) for Health Status Questionnaire (HSQ) pain, Harris pain, and WOMAC scores in the robotic THA group. Of the 5 studies utilizing the HHS, 1 study showed a significant difference ($p < 0.001$) favoring the robotic THA group at 2 years postoperatively[29], and 4 studies[24-26,30] found no significant difference. All other PROMs are shown in Table V.

Operative Times

Three studies compared operative times between robotic THA and manual THA[25-27]. Honl et al.[26] reported significantly longer operative times ($p < 0.001$) in the robotic THA group (mean and standard deviation, 107.1 ± 29.1 minutes) compared with the manual THA group (82.4 ± 23.4 minutes). Nakamura et al.[27] reported longer operative times ($p = 0.06$) in the robotic THA group (120 ± 27 minutes) compared with the manual THA group (108 ± 38 minutes). Lim et al.[25] reported significantly longer operative times ($p = 0.012$) in the robotic THA group (103 minutes) compared with the manual THA group (78 minutes).

Radiographic Outcomes

Radiographic outcomes were reported in 6 studies[24-29]. Leg-length discrepancy was evaluated postoperatively in 4 studies[25-27,29]. Domb et al.[29] reported a

TABLE IV Summary of Quality Assessment of Included RCTs: Methodological Assessment According to 5 Domains of Potential Bias (RoB 2.0)

Study	Randomization Process	Deviations from Intended Intervention	Missing Outcome Data	Measurement of the Outcome	Selection of the Reported Result	Overall Risk of Bias
Lim[25] (2015)	Low	Low	Low	Some concerns	Some concerns	Some concerns
Honl[26] (2003)	Low	Low	Low	Some concerns	Low	Some concerns

TABLE V Outcome Measures Assessed

Study	Outcome Measures*	Robotic THA†	Manual THA†	P Value
Domb[29]‡ (2020)	HHS	90.57 ± 13.46	84.62 ± 14.45	<0.001§
	FJS-12	82.69 ± 21.53	70.61 ± 26.74	0.002§
	VAS pain score	1.27 ± 2.20	1.07 ± 1.87	0.45
	Satisfaction	8.91 ± 2.00	8.52 ± 2.62	0.35
	VR-12 Mental	60.76 ± 5.94	58.97 ± 6.93	0.17
	VR-12 Physical	50.30 ± 8.83	45.92 ± 9.44	0.002§
	SF-12 Mental	56.59 ± 5.60	56.20 ± 6.62	0.81
	SF-12 Physical	48.97 ± 9.21	44.01 ± 10.26	0.001§
Nakamura[27] (2018)	JOA Score			
	Preoperative	48 ± 11	52 ± 15	0.07
	10 years	97 ± 5	96 ± 7	0.159
Banchetti[30] (2018)	HHS			
	Preoperative	44.3 ± 13.8	46 ± 8.7	0.4386
	24 months	85.6 ± 8.1	85.15 ± 7.7	0.7276
	WOMAC			
	Preoperative	70.1 ± 14.8	68.9 ± 11.2	0.6256
	24 months	6.8 ± 11.1	6.9 ± 10.2	0.9536
	NRS			
	Preoperative	8.6 ± 1.2	8 ± 1.1	0.084
	24 months	0.82 ± 1.5	0.84 ± 1.5	0.9377
Bargar[24]‡ (2018)	VAS pain score	4.69 ± 10.15	6.42 ± 10.89	0.112
	HSQ Pain	83.75 ± 20.40	72.65 ± 16.31	0.019§
	HSQ Role Physical	81.39 ± 28.25	70.88 ± 35.23	0.317
	HSQ Physical Functioning	84.26 ± 26.71	75.49 ± 26.43	0.102
	Total HSQ 12	683.52 ± 113.09	637.16 ± 104.53	0.087
	Harris pain score	41.81 ± 5.05	39.09 ± 7.37	0.025§
	Total Harris score	93.49 ± 8.77	89.50 ± 12.03	0.089
	UCLA score	6.09 ± 1.86	5.71 ± 1.45	0.417
	WOMAC	8.44 ± 11.48	11.32 ± 11.92	0.034§
Lim[25] (2015)	HHS			
	Preoperative	52 (37 to 61)	55 (41 to 60)	0.155
	24 months	93 (85 to 100)	95 (89 to 100)	0.512
	WOMAC			
	Preoperative	60 (44 to 85)	61 (45 to 89)	0.517
	24 months	11 (6 to 17)	12 (5 to 15)	0.301
Hananouchi[28] (2007)	Merle d'Aubigne score			
	Preoperative	9.5 ± 2.7	9.9 ± 2.3	0.67
	24 months	17.8 ± 0.6	17.7 ± 0.7	0.83
Honl[26] (2003)	Mayo score			
	Preoperative	27.7 ± 15.6	28.1 ± 11.5	0.39
	24 months	73.1 ± 7.3	65.5 ± 9.1	0.07
	HHS			
	Preoperative	44.4 ± 12.9	47.6 ± 11.5	0.87
	24 months	85.9 ± 12.0	83.6 ± 11.9	0.06
	Merle d'Aubigne score			
	Preoperative	9.7 ± 2.1	10.1 ± 1.9	0.37
	24 months	15.7 ± 2.2	14.9 ± 2.1	0.06

*VAS = visual analog scale, JOA = Japanese Orthopaedic Association, NRS = Numerical Pain Rating Scale, HSQ = Health Status Questionnaire, and UCLA = University of California Los Angeles. †The values are given as the mean and the standard deviation, except for the Lim study, in which the values are given as the mean, with the range in parentheses. ‡No preoperative outcomes scores were reported. §Significant.

TABLE VI Complications, Dislocations, and Revisions*

Study	Complications		Conclusions	
	Robotic THA	Manual THA	Dislocations	Revisions
Domb[29] (2020)	Superficial infections: 2, deep vein thrombosis: 1	"Minor numbness in thigh": 3, sciatic nerve palsy: 1	No significant difference	No significant difference
Nakamura[27] (2018)	Heterotopic ossification: 19 (30%), conversion to manual THA: 2†	Heterotopic ossification: 12 (19%), intraoperative femoral fracture: 5 (7%)	No significant difference	No significant difference
Banchetti[30] (2018)	NR	NR	NR	NR
Bargar[24] (2018)	NR	NR	No significant difference	No significant difference
Lim[25] (2015)	0	Intraoperative femoral fracture: 2	No significant difference	NR
Hananouchi[28] (2007)	Heterotopic ossification, 1	Heterotopic ossification: 1, intraoperative femoral fracture: 2 (7.4%)	NR	No significant difference
Honl[26] (2003)	Heterotopic ossification: 6 (10%), sciatic nerve palsy: 4 (7%), prolonged wound-healing: 4 (7%), deep vein thrombosis: 3 (5%), conversion to manual THA: 13 (18%)†	Heterotopic ossification: 8 (10%), femoral nerve palsy: 1 (1%), prolonged wound-healing: 3 (4%), deep vein thrombosis: 3 (4%)	Significantly more dislocations in robotic THA group	Significantly more revisions in robotic THA group

*NR = not reported. †The conversion from robotic THA to manual THA occurred intraoperatively because of technical problems with the robotic system.

smaller absolute leg-length discrepancy in the robotic THA group (4.35 ± 3.53 mm compared with 5.54 ± 4.10 mm; $p = 0.091$). Nakamura et al.[27] reported no significant difference in the mean absolute leg-length discrepancy (5 ± 3 mm compared with 6 ± 6 mm; $p = 0.2$) between groups; however, significantly less variance was noted in leg-length discrepancy in the robotic THA group compared with the manual THA group (F-test, $p = 0.004$). Lim et al.[25] reported significantly smaller leg-length discrepancy ($p = 0.011$) in the robotic THA group (1.9 mm) compared with the manual THA group (4.9 mm). Similarly, Honl et al.[26] demonstrated significantly less mean leg-length discrepancy in the robotic THA group (0.18 ± 0.30 cm compared with 0.96 ± 0.93 cm; $p < 0.001$).

Acetabular component placement was assessed radiographically in 1 of the 2 studies using the Mako system. Domb et al.[29] measured acetabular cup inclination and version, leg-length discrepancy, and global offset on postoperative radiographs and assessed cup position compared with the safe zones as described by Lewinnek et al.[31] and Callanan et al.[32]. Of the 66 hips that underwent robotic THA, 97% of acetabular components were placed within the Lewinnek safe zone and 90.9% were placed within the Callanan safe zone, whereas of the 66 hips that underwent manual THA, 73.8% were within the Lewinnek safe zone and 56.9% were within the Callanan safe zone[29]. However, the only dislocation reported in this study occurred in a patient who underwent robotic THA, whose cup was placed within the aforementioned safe zones.

Femoral component alignment was assessed in all 5 studies using the ROBODOC system[24-28], although the methods of radiographic measurements were highly variable between studies. All studies showed superior radiographic stem alignment in the robotic THA group compared with the manual THA group. Hananouchi et al.[28] evaluated postoperative femoral periprosthetic bone remodeling using dual x-ray absorptiometry (DXA) scans. They reported significantly better proximal medial stem fit and stem alignment, as well as significantly less bone loss in proximal periprosthetic areas in the robotic THA group at 2 years postoperatively. Nakamura et al.[27] reported significantly less stress-shielding in the proximal part of the femur in the robotic THA group compared with the manual THA group at both 2 and 5 years postoperatively. However, all studies showed no substantial radiographic loosening in either group at the final follow-up.

Complications, Revisions, and Reoperation Rates

Two studies showed at least 1 aborted robotic THA due to technical complications, resulting in completion of the case by manual preparation[26,27]. Honl et al.[26] reported 13 intraoperative failures (18%) during robotic THA due to system errors during the reaming process. Nakamura et al.[27] reported 2

robotic THA cases requiring conversion to manual THA due to a video board problem and to locator pin loosening. These patients were excluded from the final analysis in both studies.

Revision rates were reported in 5 of 7 studies (Table VI). Two studies showed no revisions in either group at the final follow-up[27,28]. Bargar et al.[24] reported 1 revision in each group for periprosthetic fractures at 2 years postoperatively for the robotic THA group and 3 years postoperatively for the manual THA group. Additionally, Bargar et al.[24] reported 3 reoperations in the robotic THA group and 5 reoperations in the manual THA group, all for head and liner exchange due to polyethylene wear. Honl et al.[26] reported 9 revisions (15%) in the robotic THA group: 1 for grade-3 heterotopic ossification, and 8 for a pronounced Trendelenburg sign associated with recurrent dislocation in 5 hips. In the same study, 2 patients (3%) in the manual THA group required a revision surgical procedure for infection ($p = 0.007$). Domb et al.[29] reported, at a 5-year follow-up, 3 revisions in the robotic THA group and 6 revisions in the manual THA group; however, this difference was not significant ($p = 0.479$). The indications for a revision surgical procedure were not reported in this study.

Postoperative dislocations were discussed in 5 of 7 studies (Table VI). Two studies showed no dislocations in either the manual THA group or the robotic THA group[24,25]. Of the 3 studies showing at least 1 postoperative dislocation in either group, there was a higher percentage of dislocations noted in patients who underwent robotic THA[26,27,29]. However, this difference was significant ($p < 0.001$) in only 1 study, which showed dislocation rates of 18% in the robotic THA group and 4% in the manual THA group[26].

Discussion

The most important finding of this systematic review is that there is a paucity of high-quality evidence comparing robotic THA and manual THA. To our knowledge, no studies have systematically compared robotic THA outcomes with manual THA outcomes over short-term to intermediate-term follow-up. As a result of technological advances, resurgence of interest in robotics and navigation in THA, and evolving dynamics in the robotic arthroplasty market, we aimed to assess the current evidence comparing robotic THA and manual THA.

In this review, we found comparable PROMs whether THA was performed with or without robotic assistance at a minimum 2-year follow-up. Two of 7 studies showed long-term PROMs favoring robotic THA[24,29]. However, as these 2 studies utilized separate robotic systems and neither reported preoperative PROMs, the clinical importance of these results is unclear. Additionally, in 1 of these studies, approximately half of all patients were lost to follow-up[24]; in the other study, patients were not randomized[29]. The remaining studies failed to show a meaningful advantage of robotic THA over manual THA in postoperative PROMs.

The proponents of robotic THA have hypothesized that improved accuracy of implant placement may translate into fewer postoperative dislocations and complications related to technical factors. All studies included in this review showed more consistent and accurate placement of THA components within the desired range of radiographic parameters with robotic THA, consistent with previous reports[11,33,34]. Interestingly, more precise implant placement did not result in fewer postoperative dislocations or revisions in the included studies. There were more postoperative dislocations in the robotic THA group found in all studies showing this outcome[26,27,29], although this difference was significant in only 1 study[26]. This finding further substantiates the complexity of THA stability, which is dependent on multiple variables; the optimal component position for many patients may lie outside of the described safe zones[35-37]. Domb et al.[29] reported more revisions in the manual THA group at a minimum postoperative follow-up of 5 years; however, this difference was not significant. On the contrary, Honl et al.[26] reported significantly more revisions in patients undergoing robotic THA at a minimum follow-up of 2 years. Considering that these studies were published 17 years apart and used different robotic systems, among other important differences, caution is needed when interpreting these results. We concluded that there was insufficient evidence to suggest that robotic THA lowers the risk of THA dislocation and revision surgical procedures.

Robotic technology has been increasingly adopted in total joint replacement surgical procedures, with the majority of the current literature evaluating robotic-assisted TKA and unicompartmental knee arthroplasty[10-12,33,34,38-40]. In a recent review of the National Inpatient Sample (NIS), Hsiue et al.[41] reported a 30-fold increase in the incidence of technology-assisted THAs performed in the United States, from 0.1% in 2005 to 3.0% in 2014. Boylan et al.[42] reported similar trends using a New York database, with the number of THA cases utilizing technology assistance increasing from 0.5% to 5.2% between 2008 and 2015. Orthopaedic surgeons will undoubtedly encounter technology and robotics in their practices in the years to come, which is emphasized by several recently published reviews discussing the growth of the orthopaedic robotic market[11,34,43].

There are currently 2 commercially available robotic systems approved by the U.S. Food & Drug Administration (FDA) for THA: ROBODOC and Mako. ROBODOC received U.S. FDA clearance in 2008 and remains the only fully active robotic system granted FDA approval[24]. Mako is a semi-active robotic system that provides haptic feedback to the surgeon and received FDA approval for use in THA in 2015[43]. It is worth noting that these robots are substantially different, both in

terms of their function and current utilization. ROBODOC is used for active femoral canal milling, with reported utilization in just 17,000 THAs since 1994[24]. Technology from ROBODOC has been updated for use in the new TSolution One system (THINK Surgical), which assists with acetabular cup implantation in addition to femoral canal preparation; however, there are few published data on this system, as it is new to the market[44]. Mako utilizes computed tomographic (CT)-guided navigation to assist in acetabular reaming and cup placement, femoral neck osteotomy, and reproduction of leg length and offset and has achieved more widespread market penetration and adoption by orthopaedic surgeons in the United States. Several studies have validated the accuracy and precision of acetabular component placement with the Mako system[45-59], and few have shown outcomes[50,52].

In an era of value-based health care, widespread acceptance of robotic technology will ultimately depend on the cost-effectiveness and value added to a total joint arthroplasty over an already cost-efficient manual THA[12,60]. The specific disadvantages of robotic-assisted arthroplasty include increased cost, longer operative time, the learning curve, and preoperative radiation exposure. Incorporating the robot into a practice incurs several costs: the upfront capital investment of purchasing the robot, which can exceed $1 million[44,61,62]; annual maintenance and servicing fees; software upgrades; disposable equipment; and preoperative CT scans. A complete financial analysis of robotic THA is outside the scope of this article, as pricing agreements are often negotiated at the institutional level, contracts are highly variable, and return on investment analyses are complex. Furthermore, longer operative times have been associated with increased expenses and risk of surgical site infection[63]. Although only 3 studies included in this review showed operative times[25-27], each of these 3 studies found operative times longer by a mean 12 to 25 minutes per case when performed with robotic assistance. These limitations must be considered when justifying the use of robotic THA.

We acknowledge several limitations to the present study. First, this review was limited by the quality of the included studies, of which only 2 showed Level-I evidence. Due to the paucity of Level-I studies, we decided against excluding studies based on study design and eliminating potentially useful data from this review. Second, although we excluded several studies that explicitly showed that they used the same patient cohorts, it is possible that a small number of patients were included in more than 1 article. Third, there was important clinical and methodological heterogeneity between studies in terms of the intervention, study design, outcome measures used, surgical approach, surgeon experience, follow-up period, and setting. Due to inherent biases and low quality of the included studies, as well as the aforementioned heterogeneity, a meta-analysis was not performed. Fourth, there were obvious differences between the ROBODOC and Mako systems in terms of their technology and role in THA component placement. Fifth, the Mako system is more widely used today, which reduces the relevance of our results in the context of current practice. Unfortunately, existing robotic THA literature has primarily reported on the ROBODOC system. Sixth, the more recent FDA approval of the Mako system may have resulted in the exclusion of studies with <2-year follow-up or studies in the data collection phase. Seventh, there was variation in follow-up between studies. This is an inherent challenge when evaluating long-term outcomes of technology-assisted arthroplasty, as the evolution of technology may render long-term data obsolete by the time that they become available. Finally, an additional limitation is the potential for commercial bias in many of the studies, including financial conflicts of interest that authors may have with the companies described. Nevertheless, we believe that the current review provides a valuable, updated synthesis of the current robotic THA literature and, more importantly, highlights the critical need for higher-quality studies to delineate the role and utility of robotics in THA.

In conclusion, although an exciting and promising technology, our understanding of robotic THA is currently in its infancy. This review found that, based on the available evidence, postoperative PROMs for patients undergoing robotic THA or manual THA are comparable. Currently, there is evidence to support more accurate and predictable component placement with robotic THA. However, there is little evidence to indicate that this results in fewer postoperative complications or revision surgical procedures. Only low-quality data exist in the literature, highlighting the need for high-quality, prospective RCTs before a firm recommendation claiming superiority for robotic THA or manual THA can be made. As technology continues to evolve, orthopaedic surgeons must continue to critically assess the impact of this technology on patient outcomes and ensure that it is supported by robust evidence.

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Current Concepts Review

Robotic Technology in Orthopaedic Surgery

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- Robotic technology used in orthopaedics can be classified on the basis of direct and indirect action and according to the mechanism of cutting, including autonomous, haptic, and boundary control.
- Robotics have been used in multiple orthopaedic subspecialties including spine, total joint arthroplasty, trauma, shoulder, and foot and ankle.
- Advantages of using robotic technology in orthopaedics include the possibility of improving implant placement (e.g., reducing outliers), accessing certain anatomic areas, reducing complications, decreasing fluoroscopy use, and performing remote surgery.
- Disadvantages of using robotics in orthopaedics include increased costs, the need for updated software, the surgeon learning curve and increased operative time, imaging for preoperative templating, potential incorrect placement of implants with poor input of data from the surgeon, and possibly no difference in long-term outcomes.

Robotic technology has been utilized in manufacturing for decades, but the technology has permeated the medical field only more recently. In 1985, the use of a PUMA (Programmable Universal Manipulation Arm; Nokia) 260 robot during a neurosurgical biopsy marked, to our knowledge, the first use of robotic technology during surgery[1]. Since then, its implementation as a surgical aid has steadily increased. In 2012, 85% of prostatectomies in the U.S. were performed with robotic assistance[2], and it was estimated that the global market for medical robotics would surpass $1.5 billion by 2018[3].

Early medical robotic systems focused largely on laparoscopic procedures[4-13]; however, they are applicable to orthopaedic surgery. The static nature of skeletal anatomy simplifies preoperative imaging, enhances the precision of intraoperative computer registration and navigation, and eliminates the need for advanced sense-response algorithms that are necessary in more dynamic surgical environments, such as soft tissues with variable 3-dimensional (3D) structures[14]. Robotics are now being used in multiple orthopaedic subspecialties, given the potential advantages of improved accuracy and reproducibility of hardware placement, which may reduce outliers and improve clinical outcomes. Disadvantages associated with robotic use include increased cost, additional imaging, and potentially increased surgical time. This overview encompasses the use of robotics in orthopaedics in a variety of subspecialties, including potential advantages and disadvantages along with reported results.

Types of Robots Used in Orthopaedic Surgery

There are different categorizations of robotic systems used throughout surgery. The historical categorization of robots includes passive, semi-active, and active systems. Passive systems guide surgeons, but robotic instrumentation must be directed by a surgeon to perform a task. Examples of passive systems include the OMNIBotics (OMNI) and the da Vinci surgical system (Intuitive Surgical), which is commonly used in urologic and gynecological surgical procedures and has also been used in arthroscopic shoulder surgery[15]. In semi-active systems, robots constrain surgical manipulation through feedback to restrict what can be done surgically. An early example of this system is the Acrobot (Active Constraint Robot; Stanmore Implants Worldwide), which is no longer in use, and a current example is Mako Robotic-Arm Assisted Surgery (Stryker)[16-18]. Finally, active systems are capable of independently performing tasks without direct human manipulation through the use of preprogrammed algorithms and defined

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parameters for bone resection. The first active robotic system used in orthopaedics was the ROBODOC Surgical System (Think Surgical)[19], which allowed surgeons to initiate and stop a robot's activity, but the surgeon did not have continuous control of the robot and could not modify the robot's actions intraoperatively. Newer systems, such as the TSolution One (Think Surgical), may be fully autonomous, which allows robots to autonomously mill the bone without the physical guidance of a surgeon.

Robots should, by definition, play some active role in surgery to be classed as robots, and they can be described by 2 key attributes in orthopaedics. Robots can act directly, when they cut the bone to the final desired shape, or indirectly, when they machine features in the bone to allow placement of cutting jigs or hold cutting jigs. Furthermore, methods of robotic cutting can be divided into 3 main areas: (1) autonomous—the robot cuts bone with no controlling human hand; (2) haptic—human interaction is required to move the robot to cut, but the robot's movement is constrained by a border[20]; and (3) boundary control—human interaction is required to move the robot, but cutting is deactivated or prevented by some means if it travels beyond a boundary even though it is free to move anywhere in space.

According to these principles, robotic systems in orthopaedics can be classified as follows:

1. Direct and autonomous: Robots cut bone according to a plan with no direct human guidance.
2. Direct and haptic: Robots cut bone under the guidance of a human hand within a haptic boundary.
3. Direct and boundary control: Robots machine bone under the guidance of a human hand and shut off when boundaries are exceeded.
4. Indirect: Robots do not touch bone, but they hold cutting jigs.
5. Indirect and haptic: Robots machine features into bone to receive cutting jigs within a haptic boundary.
6. Indirect and boundary control. Robots machine features into bone to receive cutting jigs.

The classification system can be applied to orthopaedic robots that are currently available on the market (Table I).

TABLE I Cutting Robotic Systems Used in Orthopaedics

System*	Application†	Cutting Type	Cutting Control
TSolution One	TKA	Direct	Autonomous
Mako	UKA	Direct	Haptic
Mako	TKA	Direct	Haptic
Mako	THA	Direct	Haptic
NAVIO	UKA	Direct	Boundary control
NAVIO	TKA	Indirect	Boundary control
OMNIBotics	TKA	Indirect	Cutting guide
SpineAssist	Pedicle screw	Indirect	Cutting guide
Globus	Pedicle screw	Indirect	Cutting guide

*TSolution One is manufactured by Think Surgical; Mako, by Stryker; NAVIO, by Smith & Nephew; OMNIBotics, by OMNI; SpineAssist, by MAZOR Robotics; and Globus, by Excelsius Medical. †THA = total hip arthroplasty, TKA = total knee arthroplasty, and UKA = unicondylar knee arthroplasty.

Total Hip Arthroplasty

Total hip arthroplasty is one of the more commonly performed orthopaedic procedures[21]. However, reasons for total hip arthroplasty revision include dislocation, infection, implant loosening, and periprosthetic fractures[22]. Thus, improvements in implant positioning, restoration of hip offset, and implant sizing may be important for decreasing complications such as dislocation and implant loosening, which may be achieved with robotics in total hip arthroplasty[23].

Advantages of Robotics in Total Hip Arthroplasty

Radiographs are most commonly used when planning and templating for total hip arthroplasty. However, it is difficult to control magnification and obtain perfect images, especially in patients with joint contractures or with obesity. By using 3D image-based systems, one can improve the accuracy of preoperative surgical planning and achieve precise placement of components[24]. When the acetabulum is being templated, accurate visualization of osseous landmarks can permit component sizing changes, enable placement of the acetabular component in the target anteversion and abduction, provide full component coverage, and minimize bone compromise such as in the medial wall[25,26]. Robotic use in total hip arthroplasty for the acetabulum in semi-active systems allows the surgeon to control the robotic arm to ream the acetabulum to a specified depth and size, without having to sequentially ream larger acetabular sizes. After reaming, the acetabular cup is placed at the end of the robotic arm, and the surgeon applies direct pressure to strike the cup into the preplanned position, without being allowed to overmedialize the cup. Accurate acetabular component placement can reduce the likelihood of dislocation, leading to fewer revision procedures[27]. In a follow-up study combining 2 randomized clinical studies comparing 45 patients having robotic total hip arthroplasty and 22 control subjects having total hip arthroplasty, long-term follow-up at 14 years demonstrated no stem-loosening failures, less pain, and lower Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) scores in the robotic total hip arthroplasty group, with similar complications and reoperations for polyethylene wear[28].

For the femur, 3D imaging can account for femoral offset and implant length and size. Imaging software can also take limb length into account, by assessing the distance from the top of the lesser trochanter to the center of the femoral head, or the distance from the proximal aspect of the lesser trochanter to the neck cut or the calcar. Automated robots have been used to mill the femur, with improved leg-length equality, decreased intraoperative femoral fractures, and improved stem alignment[29]. Restoration of offset and limb lengths may further reduce complications associated with total hip arthroplasty. The results of robotic total hip arthroplasty versus manual total hip arthroplasty are summarized in Table II[26-36].

TABLE II Robotic Compared with Manual Total Hip Arthroplasty (THA)

Study	Level of Evidence	Country	No. of Procedures	Main Finding
Lim et al.[29] (2015)	I	Korea	Conventional = 25; robotic = 24	The use of ROBODOC for THA resulted in longer operative times, with greater limb-length equality and fewer intraoperative femoral fractures.
Siebel and Käfer[33] (2005)	II	Germany	Conventional = 35; robotic = 36	There were longer surgical durations when the CASPAR robot was used for THA compared with manual instrumentation, with similar complications and Harris hip scores.
Nakamura et al.[36] (2010)	II	Japan	Conventional = 71; robotic = 75	The use of ROBODOC for THA resulted in more precise implant positioning, less limb-length inequality, and less stress-shielding of the proximal part of the femur.
Domb et al.[26] (2014)	III	United States	Conventional = 62; robotic = 69	Using the MAKO robot in THA allowed for improvement in placement of the acetabular cup in abduction and anteversion.
El Bitar et al.[32] (2015)	III	United States	Conventional = 59; fluoroscopic = 29; robotic = 67	All 3 approaches achieved similar limb-length discrepancies.
Bukowski et al.[30] (2016)	III	United States	Conventional = 100; robotic = 100	Robotic THA had longer operative times, less blood loss, higher activity scores, and higher patient-reported outcomes, with similar complications, compared with manual THA.
Tsai et al.[34] (2016)	III	United States	Conventional = 14; robotic = 12	Neither manual nor robotic THA was able to fully restore native hip anatomy, but there was less variation in component orientation in robotic-assisted THA.
Bargar et al.[28] (2018)	III	United States	Conventional = 22; robotic = 45	Long-term follow-up at 14 years demonstrated no stem loosening failures, less pain, and lower Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) scores in the robotic THA group (ROBODOC), with similar complication rates and reoperation for polyethylene wear.
Illgen et al.[27] (2017)	III	United States	Conventional = 200; robotic = 100	The use of robotic THA (MAKO) resulted in improved component positioning within Lewinnek safe zone compared with manual THA. There were no dislocations in the robotic THA group, compared with 3% in later manual THA cases, and 5% in early manual THA cases.
Suarez-Ahedo et al.[35] (2017)	III	United States	Conventional = 57; robotic = 57	The acetabular cup size used in robotic THA cases was more often smaller than the femoral head compared with conventional THA, indicating preservation of acetabular bone.
Domb et al.[31] (2015)	IV	United States	Conventional = 708; radiographic = 59; fluoroscopic = 942; navigation = 43; robotic = 228	Robotic and computer navigation-guided techniques utilizing multiple systems more consistently placed the acetabular component in the Callanan and Lewinnek safe zones.

Disadvantages of Robotics in Total Hip Arthroplasty

As with all use of robotics in surgery, the addition of extra capital expenditure increases costs with no guarantee that there will be a return of the investment, such as decreasing complications or hospital readmission[29]. Simply purchasing a robot may not necessarily improve surgical outcomes, such as differences in limb length, dislocations, or patient-reported outcomes, and there may be increased surgical time per case[29,32]. When imageless robotic surgery is performed, the identification of osseous landmarks is paramount for ensuring correct performance of the procedure. Finally, surgeons must also be trained to use this equipment prior to implementation, which often involves bone models and cadaver sessions with surgical observation, and must undergo a learning curve involving at least 35 cases to reduce operative time when instituting robotic total hip arthroplasty[37].

Partial and Total Knee Arthroplasty

Robotics have been used to perform unicondylar knee arthroplasty (Table III), patellofemoral arthroplasty[38], and total knee arthroplasty (Table IV). The use of robotics in partial and total knee arthroplasty started with the ROBODOC Surgical System, which was first used in total hip arthroplasty to perform femoral canal reaming for placement of cementless femoral implants. Clinical studies in total knee arthroplasty have demonstrated better gap balancing and implant alignment using the ROBODOC system compared with conventional techniques[39-44]. While the ROBODOC system is no longer in use, the newest autonomous robotic system, TSolution One, is used clinically[45].

Two other robotic systems emerged after the ROBODOC. Functionally, the CASPAR robot (URS Ortho) was very similar to the ROBODOC, and results from early studies using this system

TABLE III Robotic Compared with Manual Unicondylar Knee Arthroplasty (UKA)

Study	Level of Evidence	Country	No. of Procedures	Main Finding
Bell et al.[61] (2016)	I	United Kingdom	Conventional = 58; robotic = 62	Robotic UKA (Robotic Interactive Orthopaedic Arm [RIO]) had a higher proportion of patients within 2° of the target position compared with manual UKA with respect to femoral component axial position, femoral component coronal position, femoral component sagittal position, tibial component axial position, and tibial component sagittal position.
Blyth et al.[53] (2017)	I	United Kingdom	Conventional = 69; robotic = 70	Robotic UKA (MAKO) had lower pain and higher functional scores than manual UKA at 3 months, but there was no difference at 1 year.
Cobb et al.[49] (2006)	III	United Kingdom	Conventional = 14; robotic = 13	Robotic UKAs (Acrobot) all achieved planned tibiofemoral alignment with longer-duration surgical procedures compared with manual UKA.
Lonner et al.[50] (2010)	III	United States	Conventional = 31; robotic = 27	Robotic UKA (Tactile Guidance System) had improved posterior tibial slope, less variance, and less varus in the coronal plane compared with manual UKA.
Hansen et al.[63] (2014)	III	United States	Conventional = 32; robotic = 30	Robotic UKA (RIO) had longer operative times with minimal clinical and radiographic differences compared with manual UKA.
Ponzio and Lonner[52] (2016)	III	United States	Conventional = 27,989; robotic = 8,421	Robotic UKA (Blue Belt and MAKO) had thinner tibial polyethylene inserts and smaller tibial resections compared with manual UKA.
Herry et al.[60] (2017)	III	France	Conventional = 40; robotic = 40	Robotic UKA (Blue Belt) restored joint-line height better than manual UKA using 2 different measuring methods.

for total knee arthroplasty have demonstrated improved implant alignment compared with traditional total knee arthroplasty. Siebert et al. found an average tibiofemoral alignment (and standard deviation) of 0.8° ± 1.0° (range, 0.0° to 4.1°) in the robotic group compared with 2.6° ± 2.2° (range, 0.0° to 7.0°) in the manual total knee arthroplasty group[46], with other studies showing similar results[47]. The CASPAR robot has since been removed from the market, as the cost for the robot was high and complications such as cut collateral ligaments occurred.

On the other hand, the Acrobot was designed to function as an "intelligent tool" controlled by the physician, rather than an autonomous system, with an active constraint system. Using a control lever, the surgeon could initiate and terminate resection and could continuously control the speed and plunge

TABLE IV Robotic Compared with Manual Total Knee Arthroplasty (TKA)

Study	Level of Evidence	Country	No. of Procedures	Main Finding
Park and Lee[40] (2007)	I	Korea	Conventional = 30; robotic = 32	Robotic TKA (ROBODOC) had improved implant alignment but a higher complication rate due to smaller skin incisions and array placement compared with manual TKA.
Song et al.[41] (2011)	I	Korea	Conventional = 30; robotic = 30	Robotic TKA (ROBODOC) had less outliers and less postoperative bleeding, but longer operative times and incisions compared with manual TKA.
Song et al.[39] (2013)	I	Korea	Conventional = 50; robotic = 50	Robotic TKA (ROBODOC) had no mechanical axis outliers with less flexion-extension mismatch and less postoperative bleeding. However, these robotic cases had longer operative times, but no differences in patient outcomes and complications compared with manual TKA.
Liow et al.[43] (2014)	I	Singapore	Conventional = 29; robotic = 31	Robotic TKA (ROBODOC) had no mechanical axis outliers, no notching, and less joint-line outliers compared with manual TKA.
Liow et al.[42] (2017)	II	Singapore	Conventional = 29; robotic = 31	Robotic TKA (ROBODOC) had higher quality-of-life patient outcome measurements and higher complications compared with manual TKA. Objective scores were similar between groups.
Yang et al.[44] (2017)	III	Korea	Conventional = 42; robotic = 71	Robotic TKA (ROBODOC) had less alignment outliers and fewer radiolucent lines compared with manual TKA, with similar clinical outcomes and survival rates.

depth of the cutting instrument on the basis of situational factors. Clinical results from this system showed improved implant alignment compared with manual total knee arthroplasty without the inconveniences that plagued early autonomous platforms[48,49]. However, the Acrobot has also been removed from the market, as Mako Surgical purchased all Acrobot patents and technology.

On the basis of the early success of semiautonomous systems, their use was expanded into unicondylar knee arthroplasty, first with the Acrobot, then with the Mako RoboticArm Assisted Surgery system (Stryker). This system utilized preoperative computed tomography (CT) images of the lower extremity to develop a preoperative plan and to guide intraoperative navigation. Then, a 6-mm cutting burr affixed to a robotic arm was used to complete the procedure by using haptic feedback to restrict bone resection to the desired bounds by stopping the equipment when the boundaries had been reached. Previous studies have demonstrated a higher proportion of ideal radiographic alignment of prosthetic implants when using robotics in unicondylar knee arthroplasty compared with manual unicondylar knee arthroplasty[50,51]. This robotic unicondylar knee arthroplasty system also utilized a thinner tibial polyethylene insert and conserved tibial bone, while also resulting in lower pain and higher functional scores at 3 months compared with manual unicondylar knee arthroplasty[52,53]. The use of this system has since been expanded to total knee arthroplasty, with the added benefit of using a saw blade for osseous resection instead of a burr. Basic-science studies have shown that this robotic-assisted total knee arthroplasty system produced accurate cuts with minimal disruption to the surrounding soft tissue[54,55]. Preliminary clinical studies demonstrated that use of this robotic-assisted total knee arthroplasty system compared with conventional total knee arthroplasty resulted in increased patient satisfaction, decreased short-term pain, and improved physical function, as measured by the WOMAC score[56]. On further evaluation of the learning curve in robotic total knee arthroplasty, 20 robotic total knee arthroplasty cases are needed to reduce operative time to equal that for manual total knee arthroplasty cases[57].

Subsequently, the NAVIO Surgical system with robotic-assisted technology (Smith & Nephew) was developed for use in unicondylar knee arthroplasty, patellofemoral arthroplasty, and femoroacetabular impingement (FAI). In addition, it utilizes optical tracking trays affixed to registration pins rather than preoperative CT scans to assess the mechanical and rotational axes of the joint and surrounding structures. This system utilizes a 5 or 6-mm handheld cutting burr and performs with "exposure control," which limits resection volume by modulating exposure of the cutting burr outside its protective sheath, or "speed control," which limits the speed of the burr as it nears the established cutting boundaries, eventually stopping as the boundary is met. Some studies have demonstrated excellent precision, improved restoration of the joint-line height, smaller incisions, less blood loss, and more precise anatomic alignment using robotic unicondylar knee arthroplasty compared with manual unicondylar knee arthroplasty[58-62]. However, a study with conflicting results found that there were minimal clinical and radiographic differences between robotic and manual unicondylar knee arthroplasty[63].

As with total hip arthroplasty, the use of robotics in unicondylar knee arthroplasty, patellofemoral arthroplasty, and total knee arthroplasty increases costs, as there are hardware and software updates[62]. Data that are incorrectly entered into the system may result in inaccurate osseous cuts, leading to suboptimal outcomes. There is often the need for additional imaging, such as CT scans, which can increase the amount of radiation exposure[64]. While initial outcomes have been promising with the use of robotics in partial and total knee arthroplasty, further studies are needed to determine if longer-term clinical outcomes and survivorship improve with the use of robotics.

Spine

Spine surgery has improved over the past decades with respect to operative techniques, implants, and biologics[65]. In addition, the application of robotics has facilitated screw placement in spinal fusion procedures and has assisted surgical resection of the spinal column and intradural tumors, revision procedures, and deformity cases.

In the early 2000s, miniature navigation systems that attached directly to osseous landmarks were introduced to assist with pedicle screw placement[66]. The first use of robotics in the spine was done with the SpineAssist/Renaissance robot (MAZOR Robotics), which is a semi-active system that provides surgical tool guidance while allowing the surgeon to perform surgical procedures, such as drilling[67]. The robot can be attached directly to an anatomic landmark (e.g., spinous process) or to a frame triangulated by a percutaneously placed guidewire. The system allows for 6 degrees of freedom of motion when positioning spinal instruments. In 1 large multicenter study, the use of the SpineAssist robot yielded acceptable placement of 98.3% of 3,271 pedicle screws in the safe zone (89.3% within the pedicle and 9.0% breaching <2 mm of the pedicle) based on postoperative CT scans[68]. The robot has been shown to be useful when correcting complex spinal deformity and/or in patients with abnormal anatomic landmarks[69]. ROSA (Medtech) is another robot used in spine surgery that is combined with an intraoperative imaging system that assists with the placement of pedicle screws and performance of transforaminal lumbar interbody fusions[70-73].

Another reported advantage of robotic systems in spinal procedures is reduced radiation exposure. In a comparative retrospective study, Kantelhardt et al. investigated the accuracy of pedicle screw insertion between the SpineAssist robot (250 screws) and the conventional technique (286 screws)[74]. The authors found that the robotic group achieved more accurate placement, less patient analgesic requirements postoperatively, and less intraoperative radiation exposure for the surgeon and patient. On the contrary, 1 prospective study demonstrated no benefits of the SpineAssist robot (64 screws) with regard to screw placement accuracy or radiation exposure

compared with the conventional method (64 screws)[75]. Furthermore, in a prospective randomized study of 60 patients (298 pedicle screws), Ringel et al. compared a freehand technique with fluoroscopy assistance and the SpineAssist robot in placing lumbar and sacral pedicle screws and found that the overall operative and radiation times were not significantly different between groups[76]. Additionally, the authors noted that the freehand technique resulted in shorter pedicle screw insertion time with better accuracy compared with the robotic technique. The authors attributed these inferior results in the robotic group to the technical challenges related to the robot reference system using fixation to the bone and skidding of the cannula that was intended to hold and maintain the screw trajectory. In a systematic review, Marcus et al. found insufficient evidence to recommend robotic pedicle screw placement versus the conventional technique[77]. The findings of these studies may explain the slow adoption of robotics in spinal surgery[78], while improved robotic techniques and higher-quality studies are required to justify the high cost of robotics and demonstrate its utility in spinal surgery.

Orthopaedic Trauma

Robotic technology has been applied in orthopaedic trauma, by utilizing robots to assist with closed fracture reduction and reconstruction and in performing surgery remotely. Utilizing preoperative 3D technology can assist with planning fracture reduction and allow for intraoperative modification of the preplanned reduction and immediate evaluation of the reduction results using intraoperative 3D imaging. Based on preoperative imaging, robotic-assisted fracture reduction may enable accurate intra-articular fracture reduction in minimally invasive ways. Other advantages in fracture care include using robotics to guide precise antegrade femoral nails and easily insert distal interlocking screws or bolts[79,80].

There have been experimental developments that assist with fracture reduction in the lower extremities. Dagnino et al. developed a system that provided 3D intraoperative guidance to assist with reducing intra-articular fractures using a robotic system at the Bristol Robotics Laboratory[81,82]. The surgeon can virtually reduce the fracture preoperatively and then the robot performs the physical fracture reduction after pin registration of bone fragments. In their experiment, the reduction accuracy was a mean of 1.0 ± 0.2 mm (translation) and a mean of 1.56° ± 0.1° (rotation) when the robot reduced the fracture. Hung and Lee designed a robot that mounted onto the operating-room fracture table and assisted the surgeon in performing closed reduction through motor control rather than the manual conventional technique[83]. An experiment on 6 volunteer subjects showed good correlation in knee flexion angle between the robot and the subjects; in addition, steady traction could be applied with an appropriate increase of limb length in the distal and proximal segment of tested lower extremities[83]. Although these experimental studies provided promising results, the drawbacks of using robotic-assisted technology in actual patients remain unknown. Challenges to using robotics in orthopaedic trauma cases include proving the intraoperative safety of the technology with regard to soft-tissue management, reducing operative time, and identifying soft-tissue landmarks in patients with obesity.

Additionally, robotic techniques in the military sphere have been developed[84]. Robotic systems, either autonomously or in a telemedicine mode, can be used to perform critical acute surgical procedures and medical stabilization of soldiers on the battlefield, where immediate assistance may not be available[84]. Robotic arms can also be used as a scrub technologist or nurse in war zones, where there may not be enough assistance in the operating room on the battlefield. These technological advances may eventually translate from the battlefield to standard operating rooms in the future.

TABLE V Grades of Recommendation*

Recommendation	Grade
Use of robotics in total hip arthroplasty provides more predictable component positioning.	A
Use of robotics in total knee arthroplasty decreases soft-tissue disruption.	A
Use of robotics in partial knee arthroplasty improves radiographic alignment and results in less tibial bone resection.	A
Use of robotics in spine surgery improves pedicle screw placement and reduces radiation exposure.	A
Use of robotics in orthopaedic trauma surgery assists with closed fracture reduction and remote surgery.	I
Use of robotics in shoulder surgery may improve access to difficult anatomic areas.	I
Use of robotics in foot and ankle surgery may improve foot and ankle joint infiltrations.	I

*According to Wright[96], grade A indicates good evidence (Level-I studies with consistent findings) for or against recommending intervention; grade B, fair evidence (Level-II or III studies with consistent findings) for or against recommending intervention; grade C, poor-quality evidence (Level-IV or V studies with consistent findings) for or against recommending intervention; and grade I, insufficient or conflicting evidence not allowing a recommendation for or against intervention.

Shoulder

Use of robotics in shoulder surgery may offer technical advantages in arthroscopic shoulder surgery and total shoulder arthroplasty by making difficult anatomic areas more easily accessible. There is currently only 1 study in the literature, to our knowledge, in which the use of robotics in shoulder surgery is cited, as other studies have focused on navigation-assisted placement of the glenoid component in total shoulder arthroplasty[85,86]. In 1 cadaveric study, Bozkurt et al. used a 4-armed da Vinci surgical system to gain arthroscopic control of various anatomic structures by utilizing the robot in both the beach-chair and lateral decubitus shoulder positions[87]. This technology may be beneficial for patients with difficult anatomic considerations, such as those with obesity, as it may facilitate easier access to specific

anatomic structures. Further advances are needed in this field to determine if robotic assistance can be utilized in clinical scenarios to improve shoulder arthroscopy and total shoulder arthroplasty.

Foot and Ankle

Most studies in foot and ankle surgery have centered around passive navigation, as computer-assisted navigation has been used for tibial preparation in total ankle arthroplasty[88,89], fusion of the ankle and subtalar joints using intramedullary nails[90,91], screw and plate fusion of the midfoot and tarsometatarsal joints[92], and subtalar fusion using 2 screws[93]. Only 1 study in the literature, as far as we know, has evaluated passive robotic assistance for placement of foot and ankle joint infiltrations[94]. The authors used an Innomotion assistance device (Innomedic) on a multislice CT scanner to infiltrate 16 patients who were referred for midfoot and hindfoot diagnostic joint infiltrations. While all 16 patients had successful joint injections as defined by the CT localization of contrast media in the target joint, no comparison group was available. Given the similarities between total knee arthroplasty and total ankle arthroplasty, future applications of robotics in foot and ankle surgery may include component placement in total ankle arthroplasty to optimize long-term outcomes.

Future Use of Robotic Surgery in Orthopaedics

Until now, much of the technology implemented in orthopaedics has utilized computer-aided navigation, and adaptation of this technology rose and fell in some subspecialties, such as total joint arthroplasty in the United States. In other fields, such as anterior cruciate ligament reconstruction and foot and ankle surgery, computer navigation continues to be used to help with steps such as tunnel placement and joint fusion. Use of robotics in orthopaedics will most likely increase over time, as technology utilization trends have increased since 2008 and more robotic systems are being introduced to the market[95].

In the future, robotic systems are more likely to be autonomous, as some currently available robotic systems can independently perform tasks, but they have constraints to allow for surgeon guidance. This may reduce the role of the surgeon; however, it may also remove variability associated with different surgical techniques. As more robotic systems enter the market and further clinical research trials are conducted, data will demonstrate whether the use of robotics can improve patient clinical outcomes after orthopaedic procedures. On the basis of currently available data, there is no specific robotic system that performs better than others and there is no consensus as to the best robotic systems available. Patient outcomes will drive the era of robotic use in orthopaedics; if outcomes improve, the use of robotics in orthopaedics will increase. If there is minimal clinical improvement, the era of robotic use in orthopaedics may be short-lived.

Overview

Robotics systems in orthopaedics assist surgeons in allowing for more accurate placement of implants, they enable surgeons to perform surgery remotely, and they may ultimately improve patient outcomes. The levels of evidence for the research in this field of orthopaedics vary (Table V). Continued innovation and future studies with long-term outcomes are needed to better evaluate the role of robotics in orthopaedics. ■

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Navigation and Robotics in Total Hip Arthroplasty

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Abstract

» Navigation provides information about patient anatomy and the relative positioning of the implants to guide the surgeon.

» Some systems use a robotic arm that assists with specific parts of the procedure on the basis of anatomical information provided to the navigation system. Currently, all total hip arthroplasty robotic systems require preoperative imaging.

» Imageless systems rely only on intraoperative landmarks identified by the surgeon and provide feedback about limb alignment and component positioning.

» The primary benefits of navigation are a reduction in outliers during acetabular cup positioning and improved accuracy when quantifying limb-length and offset measurements. It remains to be seen whether these benefits translate into meaningful improvements in clinical outcomes.

Although standard total hip arthroplasty (THA) techniques involving modern components yield excellent results in terms of overall survivorship and durability, hip instability and mechanical loosening are common causes for revision[1]. Navigation systems convert qualitative human judgments into calculated surgical decisions that are supported by patient-specific anatomical data, with the potential to improve the accuracy and reproducibility of implant positioning. *Navigation* refers to a tool that provides information about patient anatomy and the relative positioning of the implants to guide the surgeon. *Robots* are computerized instruments that carry out specific parts of the procedure on the basis of anatomical information that is provided to them.

Navigation systems register anatomical landmarks with sensors that are placed on the patient intraoperatively. The static reference frame typically is mounted on the ipsilateral iliac crest and is kept in the same position throughout the procedure. Instruments are marked with trackers called *dynamic reference frames,* which can be moved throughout the procedure to allow the computer to calculate spatial relationships between anatomical structures and implants. Navigation systems can be classified according to whether they require preoperative imaging and whether they involve a robotic assistant.

Navigation Concept and Technique

Procedures involving computed tomography (CT)-based and robotic navigation systems generally involve 4 main steps: (1) digital modeling based on preoperative imaging, (2) preoperative implant templating, (3) intraoperative bone registration, and (4) component positioning and

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implantation[2]. Procedures performed with use of imageless and fluoroscopy-based navigation systems do not involve preoperative imaging and therefore omit Steps 1 and 2.

(1) **Digital modeling.** The navigation software creates a patient-specific digital model on the basis of preoperative CT imaging, accounting for orientation in the coronal, sagittal, and axial planes. Preoperative limb lengths and offset are calculated.

(2) **Preoperative templating.** Component size and positioning are planned with templating software. CT-based templating accounts for anteroposterior acetabular wall bone stock, which is difficult to appreciate using traditional templating on anteroposterior pelvic radiographs. The software then calculates expected changes in limb length and combined offset on the basis of the templating plan.

(3) **Intraoperative bone registration.** During surgery, a static reference frame is placed on the iliac crest to define the pelvic plane and to account for patient positioning. Additional pelvic and femoral landmarks are registered and mapped onto the patient-specific virtual model (for CT-based systems) or a generic simulated model (for imageless systems).

(4) **Component positioning and implantation.** The acetabulum and femur are prepared with computer guidance. The computer displays measurements of cup inclination and anteversion angles, femoral and/or combined offset, and limb lengths to guide final implant positioning. The final implants are impacted with or without robot guidance, and the final measurements are recorded. Both semi-active and fully active robotic systems assist with this step.

Imageless Navigation (Non-Robotic)

Non-robotic navigation systems can be categorized according to whether or not they require preoperative imaging. Imageless navigation relies only on intraoperative registration of osseous landmarks to create a virtual 3-dimensional (3D) model of patient anatomy, accounting for positioning. Whereas image-based navigation systems can generate patient-specific 3D reconstructions of the actual patient anatomy, imageless systems map landmarks that are identified by the surgeon onto a generic pelvic model. The anterior pelvic plane is defined by securing a reference array to the iliac crest and probing landmarks such as the anterior superior iliac spines and pubic tubercles. The femoral reference plane is determined by probing landmarks on the femur such as the greater trochanter or femoral head, or by performing a hip motion maneuver, which the computer uses to estimate the center of rotation and alignment of the femur. After registering landmarks on the femur and pelvis intraoperatively, the software provides live values for acetabular cup anteversion and inclination, limb length, and femoral offset, allowing the surgeon to adjust in real time to match the preoperative plan. Because these systems are merely providing information about the relative positioning of the femoral and acetabular implants and rely primarily on osseous landmarks, imageless navigation systems are compatible with implants from all companies.

Intellijoint HIP (Intellijoint Surgical) is a miniature smart tool that provides surgeons with real-time, intraoperative measurements to facilitate the positioning of orthopaedic implants during THA. Intellijoint HIP is made up of a patient-mounted miniature camera and tracker that quickly and efficiently provide the surgeon with measurements for cup position, limb length, offset, and new hip center of rotation, all while accounting for intraoperative patient movement (Figs. 1-A and 1-B). Because the optical localizer is placed within the surgical field, Intellijoint has fewer line-of-sight disruptions than systems relying on nonsterile consoles. This system can be controlled entirely by the surgeon from the sterile field and is compatible with implants from all companies and most surgical techniques and approaches.

The Brainlab imageless navigation system (Brainlab) is used for >40,000 orthopaedic operations annually. This system includes software to guide cup position as well as to restore limb length and offset. Advantages include simple registration steps that can be performed with the patient in the supine or lateral position, without patient repositioning, and universal instrumentation that is compatible with implants from all companies.

OrthAlign (OrthAlign) is an accelerometer-based device consisting of a disposable computer display unit and a reference sensor. This system aims to combine the accuracy of large-console computer navigation systems with the convenience of conventional alignment techniques and is compatible with all hip and knee arthroplasty systems[3]. In lieu of traditional registration, the surgeon registers specific intraoperative landmarks and moves the limb in specific patterns, which are captured by the accelerometer and are used to calculate the mechanical axis of the limb. The device is then mounted on jigs and provides real-time feedback for the surgeon to perform reaming and component positioning[3]. Some groups have harnessed accelerometer-based smartphone applications such as level indicators and digital protractors to guide cup positioning, with outcomes similar to those associated with other imageless navigation systems[4].

Advantages

Compared with robotic navigation, imageless navigation requires less capital investment, spares the patient radiation exposure and the expense of preoperative imaging, and requires only minimal setup for each procedure. Most imageless navigation systems do not disrupt preexisting surgeon workflow and do not add substantial time to the surgical procedure.

Imageless navigation systems are generally precise and reliable. In one

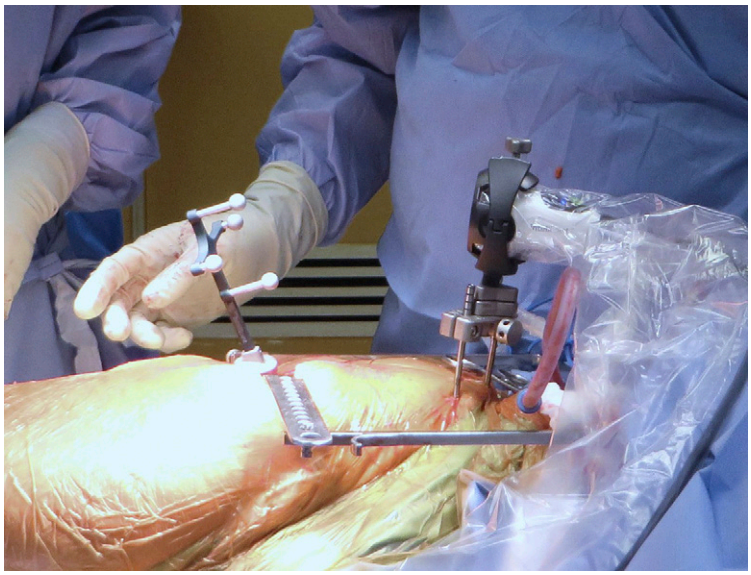

Fig. 1-A

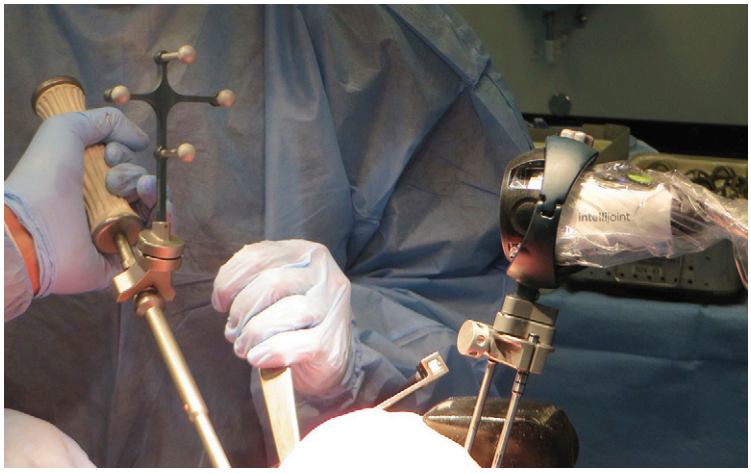

Fig. 1-B

Figs. 1-A and 1-B Photographs made during a THA performed with use of the Intellijoint imageless navigation system. A patient-mounted optical sensor on the surgical field provides limb-length and offset information by detecting arrays attached to femoral component instrumentation (**Fig. 1-A**) and acetabular cup instrumentation (**Fig. 1-B**).

study, imageless navigation yielded precise and reproducible acetabular cup positioning within 5° for both inclination and abduction, compared with 12° and 13°, respectively, for cups placed manually by experienced surgeons[5]. Similarly, a separate group demonstrated that >97% of cups that were placed with imageless navigation were within the safe zone of ±10° for both inclination and anteversion[6].

As described below for robotic THA, a primary benefit of computer navigation is a reduction in the number of acetabular cups placed far outside the acceptable safe zone[7]. A prospective randomized controlled trial (RCT) in which conventional THA was compared with the ORTHOsoft imageless navigation system (Zimmer) demonstrated no difference in cup abduction angles but showed that the final cup anteversion deviated significantly less from the planned angle of 15° in the navigation group[8].

Imageless navigation also can facilitate the restoration of limb length. In a randomized comparison of imageless navigation and intraoperative fluoroscopy (without navigation), limb-length restoration and femoral offset did not differ between groups, but the navigation group had fewer outliers that were >5 mm outside the target zone, accounting for both limb length and femoral offset[9]. Other groups have also restored limb length to within 6 mm of that on the contralateral side in >95% of cases using navigation[10], although there is currently no clear evidence that imageless navigation restores limb length better than conventional THA does.

Multiple groups have reported good clinical outcomes with imageless

navigation, although it is not yet clear if clinical outcomes for imageless navigation exceed those for THA without navigation. In an RCT comparing conventional THA to a femur-first technique using the Brainlab imageless navigation system, both groups had >87% osseous surface contact with the cup, but more patients in the navigation group achieved maximal impingement-free hip motion (84% compared with 65%)[11]. Harris hip scores were higher in the navigation group at 6 weeks, but the difference was clinically unimportant, and by 1 year there were no differences in patient satisfaction, clinical outcomes, and manual range-of-motion testing. Retrospective comparisons of imageless navigation and conventional THA found no differences in Harris hip scores, periprosthetic bone mineral density, range of motion, or polyethylene wear at 5 to 7 years postoperatively[7]. An RCT comparing THA via an anterolateral approach with imageless navigation to conventional THA with the same approach demonstrated no difference in clinical scores or polyethylene wear at 10 years[12].

Disadvantages

Although operative time decreases with experience, it can be lengthened by 12 to 18 minutes as a result of additional registration steps when using imageless navigation[8,9,11].

In contrast to image-based and robotic navigation, the virtual model displayed by an imageless navigation system is based on a generic image used for all patients and therefore may not reflect anatomical abnormalities unique to a specific patient. Surgeons must be mindful of this generic model, especially during complex cases in which the patient has abnormal anatomy such as hip dysplasia or posttraumatic deformities. Furthermore, the accuracy of imageless navigation depends on the surgeon's registration technique; poorly identified osseous landmarks result in poorly placed components, an issue termed "garbage in, garbage out."[13] Imageless navigation is especially susceptible to this issue because it requires identifying landmarks through soft tissue and because the computer is mapping onto a generic model. Obesity is associated with decreased accuracy of acetabular cup positioning during THA procedures performed with imageless navigation systems[14]. In addition, when the pelvic coordinates are defined by the anterior pelvic plane, functional pelvic tilt and sagittal imbalances cannot be taken into account[15].

Image-Based Navigation (Non-Robotic)

Image-based navigation involves the use of preoperative CT or magnetic resonance imaging (MRI) or intraoperative fluoroscopy to facilitate surgical planning and execution. CT-guided navigation is the most common form of image-based navigation. Preoperative planning for non-robotic CT-based systems is essentially the same as that for CT-based robotic systems. Intraoperatively, the surgeon registers osseous landmarks and instruments, which are mapped onto the patient-specific model generated from the preoperative imaging. Unlike robotic THA, the surgeon executes the entire procedure without any robotic assistant. The absence of a robot gives the surgeon more freedom to alter the preoperative plan on the basis of intraoperative findings, but it also allows the surgeon to err or to place the components outside the recommended zone.

Fluoroscopic navigation is similar to imageless navigation because neither method involves the use of advanced preoperative imaging. Instead, the surgeon registers each landmark intraoperatively with use of fluoroscopy. For example, Radlink GPS (Radlink) is a digital radiography system that includes a system to compare intraoperative fluoroscopy and preoperative radiographs side by side, without any reference pins or optical arrays.

Other image-based navigation systems include newer technologies such as patient-specific templates (PSTs), many of which are still in development and have not been thoroughly studied. PSTs are created on the basis of preoperative CT scans and are applied to the bone surface to achieve the planned osseous resection. The Corin OPS system (Corin Group), which is available in Australia and South Africa and was approved by the Food and Drug Administration (FDA) in the United States in June 2016, is used to account for variations in patient-specific anatomy and relative positions of the pelvis and femur during daily activities. Preoperative CT scans are obtained and patient-specific anatomy is recorded while the patient performs 3 poses mimicking functional positioning for activities of daily living. These simulations are then used to calculate the optimal cup position for the specific patient anatomy and function, balancing impingement and wear/contact pressure, and to generate a patient-specific acetabular guide for cup orientation. This system may be useful for patients with spinal deformity and sagittal imbalance, which can alter the optimal cup version.

HipXpert (Surgical Planning Associates) is a CT-based system that enables a simple mechanical device to dock to the pelvis and guide cup orientation. Steppacher et al. reported that cup anteversion and inclination were more accurate when the cup was placed with use of HipXpert than when it was placed with traditional CT-based navigation[16]. An acetabular implant from any vendor can be used with image-based non-robotic navigation systems.

Advantages

CT-based navigation systems permit accurate intraoperative measurements of cup alignment, resulting in fewer cup-positioning outliers than occur with conventional THA[17-19]. One retrospective review of 180 THAs performed with navigation and 120 manual THAs demonstrated fewer cups placed outside the safe zone (0% compared with 26%) and fewer postoperative dislocations (0% compared with 8%) in the navigation group, although the 13-year implant survival rate was not different

between the groups[20]. A systematic review involving 400 patients revealed no significant difference in mean cup inclination or anteversion between conventional THA and navigation-assisted THA, but variability in cup position and the risk of placing the cup outside the safe zone were significantly reduced in the navigation group (risk ratio [RR] = 0.21, 95% confidence interval [CI] = 0.13 to 0.32)[21].

When both the femoral and acetabular components are inserted using navigation, CT-based systems enable surgeons to measure and modify cup position, limb length, combined anteversion, and combined offset. Image-based navigation can improve the accuracy of minimally invasive approaches, which traditionally have been associated with an increased risk of component malpositioning[22].

Disadvantages

CT-based navigation is associated with increased cost and radiation from the preoperative CT as well as increased time for preoperative planning and computer modeling. Patient-specific templates take 3 to 6 weeks to produce, although lag times are decreasing. Fluoroscopy-based navigation exposes the surgeon to radiation, although the dose is similar to that typically associated with an anterior-approach THA.

Fully Active Robotic Navigation

Currently, all THA robotic navigation systems require preoperative imaging to match the patient anatomy and position in space during surgery. Preoperative imaging data and templating are transferred to a robotic surgical assistant with an articulating arm that attaches to the surgical instrument or implant, such as the acetabular reamer or cup (Figs. 2-A and 2-B). Robotic assistants may be fully active or semi-active, depending on the degree to which they permit the surgeon to retain some control over the task.

Fully active systems like ROBODOC (formerly produced by Integrated Surgical Systems), the first robotic assistant created for THAs, can perform femoral canal preparation and can aid in positioning of the final implants autonomously; the surgeon oversees the robot and can activate an emergency stop button but does not directly control the robot[23-25]. The ROBODOC system completes femoral preparation autonomously without additional instruments. Fully active robots can only be used with certain implant systems whose models have been incorporated into the robotic system's software.

Advantages

The initial randomized multicenter feasibility study for ROBODOC, which involved the use of a posterior approach, demonstrated significant improvements in terms of fit, fill, and alignment of femoral stems compared with non-robotic THA ($p < 0.05$ for all), and no patient in the ROBODOC group sustained an intraoperative fracture[26,27]. An RCT comparing ROBODOC and conventional THA demonstrated significantly less proximal femoral stress-shielding in the ROBODOC group at 2 years ($p = 0.03$) and 5 years ($p = 0.002$)[28]. Similarly, proximal medial femoral spot-welding was more prevalent (48% compared with 11%) and stress-shielding was less prevalent (17% compared with 31%) in the ROBODOC group than in the traditional THA group at 24 months postoperatively[29], although all components were well fixed without signs of loosening. Nakamura et al. found no significant difference in terms of average limb-length inequality ($p = 0.2$), but the ROBODOC group had significantly less variance in limb-length inequality than did the conventional THA group ($p = 0.004$)[28].

Disadvantages

Despite evidence indicating that robotic THA is associated with improved accuracy and fewer outliers in component positioning, it is not yet clear whether these radiographic benefits translate into improved clinical outcomes. Although some authors have reported better clinical scores after short-term follow-up among patients managed with robotic THA, these improvements do not persist over time. Harris hip scores in the original ROBODOC trial were no different between groups at 2 years[30] or at 5 to 7 years postoperatively[7]. Nakamura et al. reported a 2-point greater improvement (on a 100-point scale) in terms of Japanese Orthopaedic Association (JOA) clinical scores for the robotic group at 2 and 3 years, but the difference was not clinically meaningful and the scores did not differ at 5 years[28]. In an RCT comparing ROBODOC and conventional THA performed through an anterolateral approach, Honl et al. reported better Mayo clinical and Harris hip scores at 12 months but no difference by 24 months[31].

In some studies, ROBODOC has been associated with increased perioperative complications. Honl et al. reported that robotic THA was associated with higher rates of dislocation (18% [11 of 61] compared with 4% [3 of 80]; $p < 0.001$) and revision for reasons other than infection (15% [9 of 61] compared with 0% [0 of 78]; $p < 0.001$), which the authors attributed to abductor damage during robotic milling[31]. Nakamura et al. found that the rate of heterotopic ossification was higher among patients managed with robotic THA than among controls (27% [20 of 75] compared with 15% [11 of 71]), although the difference was not significant ($p = 0.1$)[28]. Other technical complications included femoral shaft fractures requiring cerclage wiring and milling defects in the acetabulum and greater trochanter[32,33]. The rate of conversion of robotic procedures to manual procedures has been reported to be as high as 18% (13 of 74); reasons for conversion have included electronic failure or software crashes, the inability to accurately register landmarks, or the surgeon's perception that the cup position recommended by the robot was clearly outside the safe zone[30,33,34]. Surgical time has been consistently

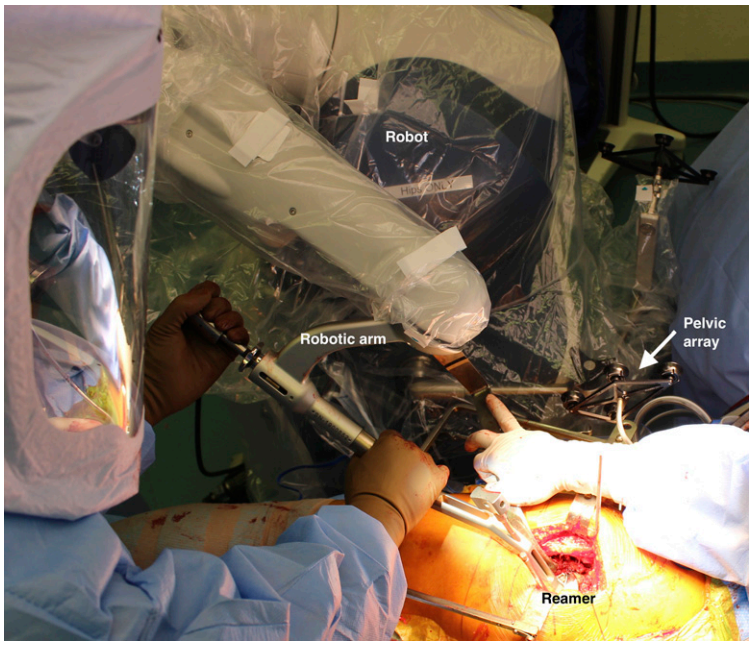

Fig. 2-A

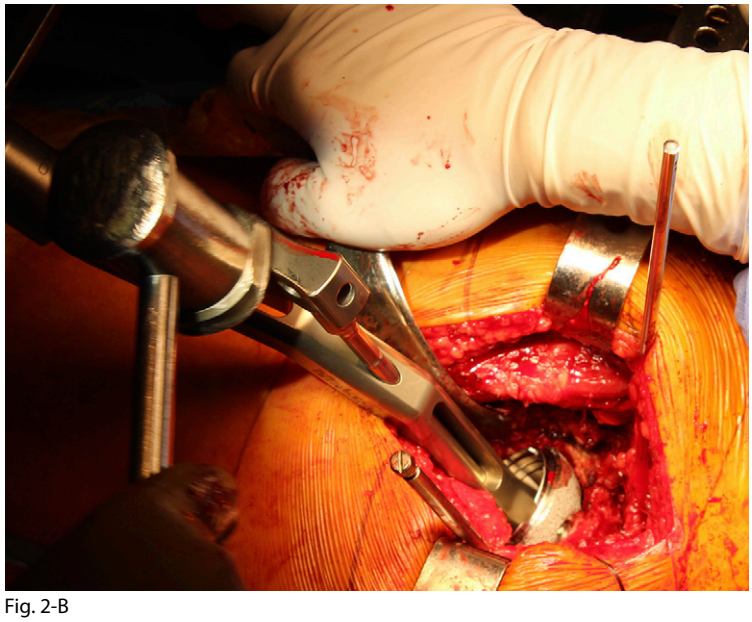

Fig. 2-B

Figs. 2-A and 2-B Photographs made during a THA performed with use of the MAKO semi-active robotic navigation system. **Fig. 2-A** During acetabular reaming, the pelvic reference array provides spatial data to the robot, which then guides the surgeon to ensure that reaming occurs within the planned zone. **Fig. 2-B** During cup impaction, the robotic arm positions and stabilizes the acetabular implant while the surgeon impacts the cup.

increased in association with ROBODOC THA, ranging from 12 to 120 additional minutes[28,30,31].

After some patients who had experienced complications following ROBODOC surgery filed a class-action lawsuit against Integrated Surgical Systems in Germany in 2004, the company became financially unstable and ceased its operations in 2005. The intellectual property for ROBODOC was acquired by Curexo Technology, which later became THINK Surgical. The company has received 510(k) FDA clearance for its next-generation active robotic system, TSolution One.

Semi-Active Robotic Navigation

Alternatively, so-called semi-active robotic systems provide auditory or tactile feedback to constrain the surgeon to a preplanned boundary, while still permitting the surgeon to maintain control over executing the procedure. Semi-active robots like the MAKO Robotic Arm

Interactive Orthopedic (RIO) System (Stryker) use haptic feedback, which permits the surgeon to slightly adjust reamer orientation but ensures that the reamer stays within a few degrees of the planned cup position. The software measures changes in limb length and combined offset relative to both the contralateral limb and the preoperative status of the ipsilateral limb.

Semi-active robotic systems can be used with a standard surgical approach, although they require an additional small incision over the iliac crest for the pelvic reference frame. Robots permit single-stage acetabular reaming because they can easily overcome torque generated by larger reamers. However, the robotic system must be designed to accommodate each specific implant; therefore, only certain implant brands are compatible with each robotic system.

Advantages

The primary benefit of navigation for THA is a reduction in acetabular component positioning outliers. Cups implanted outside the Lewinnek safe zone (5° to 25° of anteversion, 30° to 50° of abduction) are at increased risk for instability, dislocation, and accelerated polyethylene wear[35-37]. However, retrospective studies have shown that only 60% to 85% of manually placed cups are within this acceptable window[22,38,39]; Callanan et al. demonstrated that only 50% (917) of 1,823 cups were within the acceptable window for both inclination and version[22]. Domb et al. found that all 50 of 50 robotic MAKO THA cups were within the Lewinnek safe zone, compared with only 40 (80%) of 50 conventionally placed cups[34]. Similarly, Elson et al. reported that 114 (95%) of 120 cups were placed within 3.5° of the intended position with use of the MAKO system[40]. Domb et al., in a retrospective review of 1,980 THAs, showed that cups placed with robotic- and navigation-guided techniques were significantly ($p < 0.005$) more likely to be within the safe zone than manually placed cups[41]. Femoral component size and positioning also contribute to the combined anteversion and limb length, which in turn affect hip stability, gait mechanics, and patient satisfaction. Robotic THA has been shown to achieve limb-length equality[28].

Disadvantages

Robotic systems require substantial upfront financial investment for the robot and software in addition to annual maintenance and disposables for each case. Compared with the ROBODOC system, the MAKO semi-active robot has a more modest learning curve, but total operative time is still increased relative to non-robotic THA. In the study by Redmond et al., average total operative time decreased from 80 minutes for the surgeon's first 35 cases to 69 minutes after the surgeon had completed at least 70 cases[42]. Robotic THA is also subject to the disadvantages of CT-based systems, including increased cost and radiation exposure associated with the scan and longer time devoted to preoperative planning.

Summary

Computer navigation and robotic assistance represent new surgical tools with the potential to minimize outliers in component positioning and to assist in challenging cases involving patients with irregular anatomy. Semi-active robotic systems offer the most accurate patient-specific preoperative planning tools and ensure that the plan is executed accurately during surgery. However, robotic systems can add considerable cost and radiation and have a steep learning curve. Imageless navigation systems aid the surgeon by ensuring accurate component positioning and limb alignment intraoperatively, with comparatively less expense and radiation and simpler intraoperative techniques.

Current evidence demonstrates equivalent outcomes when computer navigation has been compared with traditional THA techniques, with the potential benefit of decreasing complications such as hip instability. One challenge of evaluating the outcomes and efficacy of navigation systems is that computer technology changes so rapidly that it is obsolete by the time long-term clinical data are available. Therefore, studies evaluating outcomes for patients who underwent navigation-assisted THA 10 years ago may not accurately reflect current navigation technology. Despite little evidence of a clinical benefit to navigated THA in the published literature to date, there may be meaningful benefits in the future as technology changes.

We hypothesize that THA navigation may increase the confidence of surgeons who perform only a few arthroplasty procedures each month. It also may be a useful tool for experienced arthroplasty surgeons when performing revision or challenging primary THAs. However, we urge caution in relying on navigation. Achieving the desired clinical objective for each patient still requires mastery of the biomechanical principles, preoperative templating, and surgical techniques, with or without the added tool of navigation.

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Techniques for Optimizing Acetabular Component Positioning in Total Hip Arthroplasty

Defining a Patient-Specific Functional Safe Zone

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Abstract

» Proper acetabular component positioning is dependent on multiple factors.

» Proper preoperative templating is of utmost importance, and the surgeon must take care to determine acetabular position and location, orientation (anteversion and inclination), and size, while also focusing on limb length and offset.

» Patient positioning on the operative table, whether in the supine or lateral position, can affect final acetabular component position.

» Intraoperative execution with use of appropriate tools and techniques (e.g., anatomical landmarks, mechanical alignment guides, and computer-assisted or robotic navigation) allows for component positioning consistent with the preoperative plan.

» It is important to understand the benefits and limitations of each tool, recognizing how to identify and remove the possibility of error.

Defining an ideal and accurate acetabular component position during total hip arthroplasty remains a challenge for the orthopaedic surgeon. Even for the experienced hip surgeon, only 50% to 61% of acetabular cup placement falls within the Lewinnek abduction and anteversion "safe zones."[1-5] Moreover, despite the appeal of a universal safe zone, the majority of dislocations continue to occur in hips in which the cup is inserted within this range, leading many to question its validity and applicability[6,7]. Poor component positioning is an important risk factor for a myriad of other suboptimal total hip arthroplasty outcomes, including hip instability, early and excessive liner wear, impingement, liner dissociation, limb-length discrepancies, limited range of motion, osteolysis, and implant squeaking in ceramic-bearing hips[4,8-14]. Taken together, proper acetabular component alignment is integral for ensuring the success of total hip arthroplasty. In the present review, we describe a variety of techniques and tools that can enhance the surgical accuracy and reproducibility of acetabular component positioning. More importantly, we introduce the concept of the "functional safe zone," an acetabular positioning parameter specific to each patient, which is determined as part of a

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standard comprehensive preoperative examination.

Standardized Terminology

It is important to establish common verbiage when describing the orientation of the pelvis. In doing so, surgeons can better understand and communicate the dynamic relationship between pelvic orientation and functional acetabular positioning (Figs. 1-A and 1-B).

Planes

The *anterior pelvic plane* is defined by 3 anatomical landmarks: the 2 anterior superior iliac spines and the midpoint between the pubic tubercles[3].

The *functional pelvic plane* passes through the pubic tubercle and remains parallel to the coronal plane of the body when the patient is standing or supine[15].

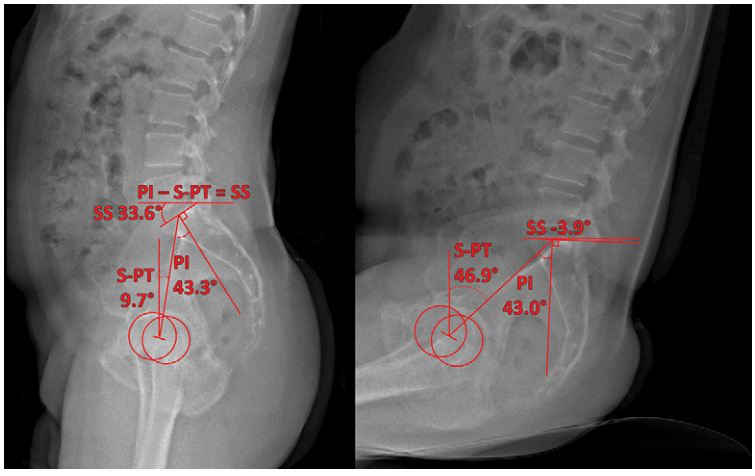

Fig. 1-A

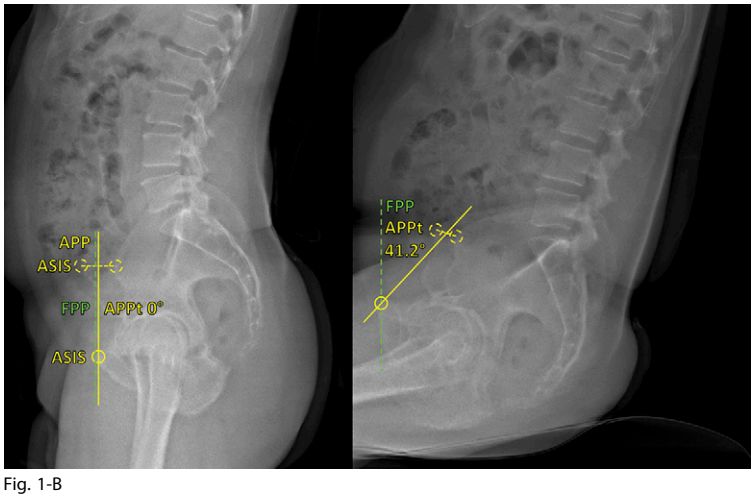

Fig. 1-B

Figs. 1-A and 1-B Stereoradiographic images showing the spinopelvic planes and angles during standing and sitting. **Fig. 1-A** Stereoradiographic image, made with the patient standing, showing the spinopelvic parameters, including sacral slope (SS), spinopelvic pelvic tilt (S-PT), pelvic incidence (PI), and pelvic tilt (PT). The relationship between spinopelvic parameters can be mathematically derived with the formula PI – S-PT = SS. **Fig. 1-B** Stereoradiographic image, made with the patient sitting, showing the functional pelvic plane (FPP) in green and the anterior pelvic plane (APP) in yellow. Anterior pelvic plane pelvic tilt (APPt) is derived from the angle between the functional pelvic plane and the anterior pelvic plane. ASIS = anterior superior iliac spine.

Angles and Alignment

The terms *spinopelvic tilt* and *pelvic tilt of the anterior pelvic plane* have been used interchangeably to describe "pelvic tilt," but their relationships with pelvic orientation are drastically different[16,17]. *Spinopelvic tilt,* as seen on a lateral radiograph, is the angle between the vertical axis and a line drawn from the center of the superior aspect of the first sacral end plate to the center of the femoral heads. *Anterior pelvic plane pelvic tilt* is the angle between the anterior pelvic plane and the functional pelvic plane.

Sacral slope is the angle between a horizontal reference line and a line parallel to the superior end plate of S1.

Pelvic incidence is the angle between a line connecting the midpoint of the bicoxofemoral axis and a line centered on and perpendicular to the upper plate of S1[16].

Lumbar lordosis is the Cobb angle derived from the angle between an upper line drawn at the superior end plate of L1 and a lower line drawn at the superior end plate of S1.

Sagittal balance is an assessment of the postural displacement of the patient's center of gravity relative to the sacrum. Sagittal balance is typically determined on the basis of the sagittal vertical axis, which is the anteroposterior displacement of the C7 plumbline from the posterosuperior corner of the S1 end plate.

Techniques for Optimal Acetabular Component Positioning

Templating

Preoperative templating is regarded by many surgeons as an essential step in preparing for total hip arthroplasty[9]. Although no studies to date have investigated the direct effects of templating on improvement in acetabular positioning when compared with no templating, 60% to 97% of implanted cup sizes can be correctly estimated within a size range of ±2 mm[18,19]. The ability to estimate the implanted cup size is improved with the use of computer-assisted and computed tomography (CT)-based digital

templating[20]. Templating allows surgeons to preoperatively select an appropriately sized component inventory, reducing surgical idle time. Additionally, templating encourages the surgeon to think 3-dimensionally, allowing for the anticipation of complex anatomy and potential intraoperative complications[21]. Here, we review the major variables to be accounted for during the preoperative phase of total hip arthroplasty, including positioning of the acetabular cup center of rotation, cup orientation, and combined parameters such as limb length and offset.

Acetabular Cup Center of Rotation Positioning

One of the aims of total hip arthroplasty is to restore the hip center of rotation to the extent allowed by patient's native anatomy. Classically, the cup is medialized to the Kohler line and is placed at the inferior margin at the level of the teardrop. However, optimal acetabular cup placement should be conceptualized into 3-dimensional planes: anterior-posterior, medial-lateral (depth), and superior-inferior (height). Changes in these axes alter the hip center of rotation, which in turn alters the joint reaction force, the maximum force produced by the hip abductors (F_{max}), and the minimum forces required by the hip abductors to maintain a stable pelvis during normal gait (F_{req})[22,23]. In a biomechanical computer modeling study by Heller et al., lateralization of the hip center of rotation resulted in the most drastic alteration in the joint reaction force, with each 10-mm shift resulting in an 8% increase in the joint reaction force, compared with the 1% increase in joint reaction force with superior shifts[23]. Lateral shifts in the center of rotation should also be avoided due to their prominent increase in F_{req}, potentially contributing to postoperative abductor lurch or Trendelenburg gait[22].

Although superior translation of the hip center of rotation is also unfavorable, the resultant effects of increased joint reaction force, increased F_{req}, and reduced F_{max} appear clinically nominal. In the study by Nawabi and colleagues, patients with Crowe type-II and III hip dysplasia demonstrated a 97% all-cause revision survival rate at 12 years when the hip center of rotation was medialized and placed superiorly to improve osseous purchase[24]. When those patients were compared with patients with Crowe type-I dysplasia and an anatomically placed center of rotation, patient-reported outcomes, acetabular loosening, and wear rates were equivalent. For patients with considerable acetabular dysplasia and a superiorly migrated center of rotation, the trade-off of anatomical superior-inferior acetabular positioning for satisfactory osseous coverage is warranted.

Medialization of the acetabular cup has been well established to reduce the rate of liner wear and, in turn, to improve the survivability of the implant[23]. However, the benefits of medialization must be balanced against the accompanying disadvantages associated with reduced bone stock and decreased offset, which increases the risk of osseous impingement and reduced range of motion. Medialization of the hip also requires restoration of the hip's global offset with use of extended-offset femoral heads or acetabular liners. Failure to do so can result in increased head-liner microseparation due to poor abductor tensioning, potentially accelerating liner wear[10]. In a study of staged bilateral hip replacement, Sakalkale et al. reported that lateral-offset femoral stems reduced annual liner wear rates by 52.4% in comparison with contralaterally implanted standard-offset stems[25]. It must also be noted that extended-offset acetabular liners nullify the benefits afforded by acetabular medialization and increase the rate of aseptic loosening due to altered torsional forces at the bone-cup interface[26,27].

Acetabular Cup Orientation

Lewinnek et al., in a retrospective study that was published in 1978, observed a reduced dislocation rate when the acetabular cup was positioned within 30° to 50° of abduction and 5° to 25° of anteversion relative to the anterior pelvic plane[3]. Despite analyzing only 113 radiographs, of which only 9 demonstrated hip dislocations, the study gained widespread acceptance within the orthopaedic community as describing a "safe zone" for the prevention of dislocation[3,6]. The notion of a universal acetabular safe zone has been substantiated by recent studies such as the one by Biedermann et al., who observed a distinct U-shaped distribution for dislocations as acetabular anteversion angles deviated from 15°[28]. More importantly, patients with $<4°$ or $>24°$ of anteversion were found to be at a 7-times greater risk for posterior and anterior dislocations, respectively. However, more recent studies have questioned the utility of this all-encompassing safe zone[6,7].

By referencing measurements off the static anterior pelvic plane, the Lewinnek safe zone fails to account for the effects of global pelvic orientation on functional acetabular positioning[16,29]. The variability in iliac wing morphology and anterior pelvic plane offset from the center of hip rotation demonstrates the imprecise nature of the anterior pelvic plane pelvic tilt as an indicator of true pelvic tilt[16,29]. This is in in contrast to spinopelvic parameters, such as spinopelvic tilt and pelvic incidence, which take into account the relative positioning of the acetabulum[16,29].

To assess the clinical implications of a universal safe zone, Abdel et al. retrospectively evaluated the acetabular position in patients who had a dislocation after total hip arthroplasty[7]. The authors found that, of the hips that dislocated following a posterior-approach total hip arthroplasty, 92% and 73% fell within the Lewinnek abduction and anteversion safe zones, respectively. A lower but sizable 62% and 49% of hips that dislocated after an anterolateral approach were also within the respective safe zones. In total, 58% of all dislocated hips demonstrated appropriate acetabular component positioning in both safe zone parameters. Esposito et al. also found that the Lewinnek safe zone was

an unreliable predictor of hip dislocation but did report a trend toward increased dislocation risk ratios for more anatomically deviant cup placement[6], similar to the findings of Biedermann et al.[28].

With regard to acetabular cup abduction, several studies have indicated that an abduction angle of >45° accelerates the linear wear rate of ultra-high molecular weight cross-linked polyethylene liners by 40% and also may be correlated with an increased risk of hip squeaking in patients with ceramic-on-ceramic total hip replacements[13,14]. Similarly, metal-on-metal bearings with an excessive cup abduction angle are associated with increased edge wear, leading to elevated serum metal ion levels and the associated the risk of an adverse reaction to metal debris, including local tissue necrosis, lymphocytic infiltration, and, in rare cases, pseudotumors[10-12].

Taken together, the majority of dislocations following total hip arthroplasty occur in hips in which the acetabular cup was placed within the Lewinnek safe zone, but surgeons should remain cognizant of the increases in the risk for hip dislocations and contact forces along the acetabular component rim when the cup is placed outside of this safe zone[7]. Surgical factors such as bearing type, head size, spinopelvic malalignment, and developmental dysplasia of the hip also contribute to dislocation rates and therefore confound our understanding of optimal cup positioning[6]. Furthermore, commonly utilized 2-dimensional radiographic evaluations based on anteroposterior or lateral radiographs do not account for pelvic tilt and axial rotation and have limited utility outside of the research environment. In the study by Biedermann et al., only one-third of the 342 hips in the control group could be evaluated for cup anteversion with use of digital radiographs[28]. Additionally, these common methods fail to account for femoral anteversion, the version of the femoral neck relative to the femoral condyles. With the advent of new technologies, such as full-body, 3-dimensional radiographic imaging, orthopaedists can expect more refined guidelines in the future. In anticipation, we propose the concept of the "functional safe zone," a patient-specific safe zone that is defined preoperatively with a thorough evaluation of spinopelvic parameters and accounts for pelvic motion during sitting, standing, and supine positioning.

To assess spinopelvic motion and, thus, predicted acetabular component position in the standing and sitting positions, we propose a standardized preoperative imaging evaluation (Fig. 2). This

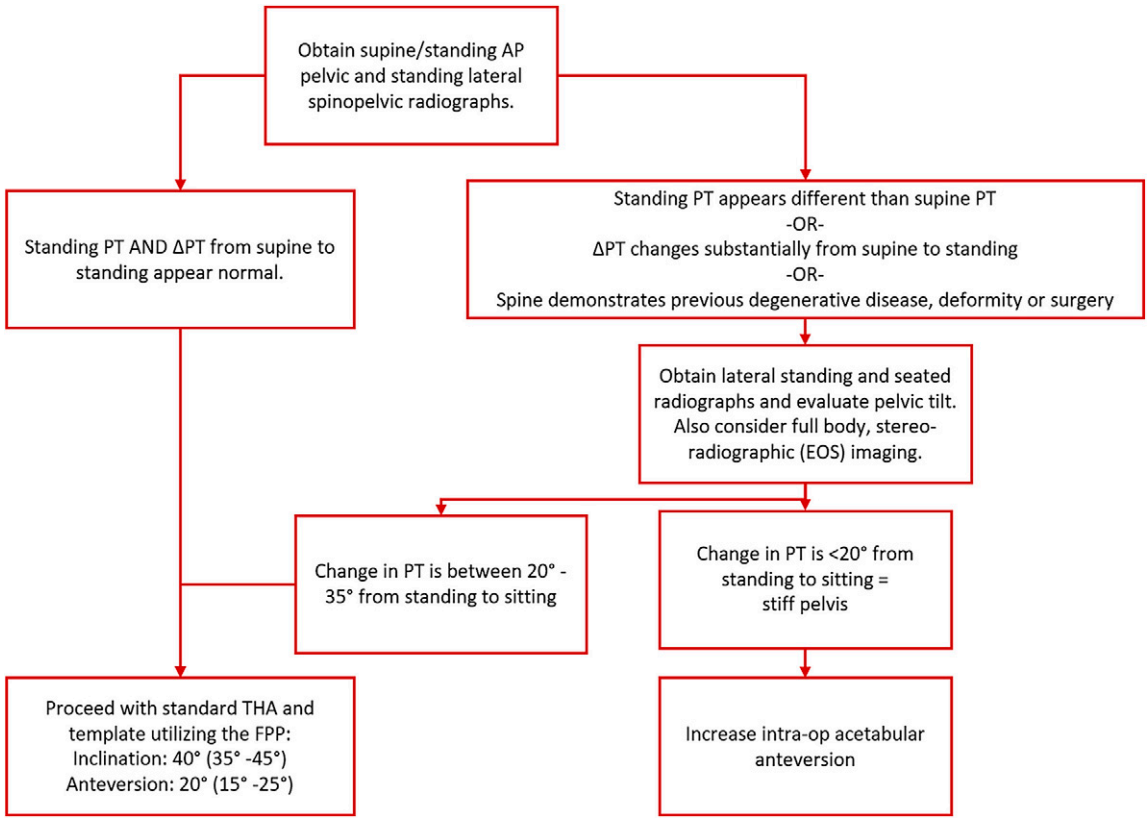

Fig. 2

Proposed flowchart for evaluating acetabular positioning. Current evidence indicates that patients with <20° of pelvic tilt in the anterior pelvic plane from standing to sitting require increased anteversion[68]. AP = anteroposterior, PT = pelvic tilt, THA = total hip arthroplasty, and FPP = functional pelvic plane.

imaging allows the surgeon to assess the change in spinopelvic tilt between the supine and standing positions and quantifies the change in spinopelvic tilt at the extremes of motion (standing and sitting). While parameters regarding compensatory anteversion have not been described in the literature, to our knowledge, several early studies have used 3-dimensional reconstructions of normal and dysplastic hips, which demonstrated a change of approximately ±4° of functional anteversion and ±2° of functional abduction with each ±5° change in spinopelvic tilt[16,30-32]. Interestingly, nearly 17% of patients from the general population undergoing total hip arthroplasty present with spinopelvic tilt of >10°[30]. Taken together, these functional changes serve as a potential basis for defining each patient's "functional safe zone."

Perioperative and Intraoperative Considerations

Patient Positioning

The position of the patient on the operative table is integral to optimum acetabular positioning, particularly in cases in which the acetabular cup is placed freehand or with the assistance of a mechanical guide. Ideally, for patients in the lateral decubitus position, the sagittal plane of the pelvis should be parallel with the floor while the coronal and transverse planes should be parallel with the walls of the room. Deviations in any of these parameters can substantially alter and distort the surgeon's sense of geometric orientation. Changes in pelvic obliquity will have a direct impact on the perceived acetabular inclination. Meanwhile, changes in pelvic tilt or rotation will impact perceived inclination and anteversion, respectively. These principles can be applied similarly to supine patients undergoing anteriorly based approaches.

In the study by Milone et al., rigid pelvic positioners were assessed for their reliability in securing patients undergoing total hip arthroplasty in the lateral decubitus position, and changes in position were confirmed with computer navigation[33]. When the surgeon's predicted anteversion angles were compared with the readout generated by the computer navigation system, the anteversion angles deviated by >5° in 41% of the cases and by >10° in 22%. Similarly, the surgeon's expected abduction angles also deviated from the computer-navigated abduction angles by >5° in 18% of the cases and >10° in 2%. These differences in orientation were likely due to patient positioning and positioner type used. Lower-extremity manipulation and dislocation also have been shown to introduce additional pelvic movement[34,35]. In the study by Nishihara et al., mean pelvic movement following posterior hip dislocation resulted in a mean (and standard deviation) of 12° ± 4° of posterior pelvic tilt, 2° ± 4.4° of pelvic abduction (coronal plane), and 7° ± 5° of pelvic internal rotation (axial plane)[35]. Those studies demonstrated the need for a reliable technique to assess 3-dimensional pelvic orientation intraoperatively that does not rely on the patient's positional relationship to the operating table and room[34,35].

Intraoperative Execution: Transverse Acetabular Ligament

The transverse acetabular ligament, identified by Archbold et al., is an anatomical structure that has been proposed to reliably reapproximate the anteversion, height, and depth of the natural hip[8,36]. In the original study by Archbold et al., the transverse acetabular ligament was successfully identified intraoperatively during 99.7% of 1,000 consecutive total hip arthroplasty procedures, with only 0.6% of the hips dislocating after 8 to 41 months of follow-up[36]. These findings were confirmed in the randomized controlled study by Meermans et al., in which use of the transverse acetabular ligament for acetabular component anteversion resulted in significantly more accurate and less variable placement (mean angle of anteversion, 21° [range, 2° to 35°] in the freehand group, compared with 17° [range, 5° to 25°] in the transverse acetabular ligament group; p = 0.004)[37]. Furthermore, none of the acetabular components in the acetabular ligament group fell outside of the anteversion safe zone, whereas 22.5% of the components in the freehand group fell outside of that zone (p = 0.002). The study by Fujita et al. also demonstrated the viability of utilizing the transverse acetabular ligament in dysplastic hips, with only 1.9% (1) of 52 dysplastic hips falling outside of the acetabular cup anteversion safe zone, compared with 8.3% (5) of 60 non-dysplastic (control) hips[15]. More importantly, severe posterior pelvic tilt has been found to be a better predictor of component malpositioning than hip dysplasia is[15,38]. It should be noted that the cadaveric study by Hiddema et al. demonstrated that the transverse acetabular ligament also may be utilized to gauge acetabular cup abduction[39]. However, to our knowledge, no other studies have been performed to adequately evaluate this finding. Meermans et al. demonstrated a non-significant trend toward improved acetabular cup inclination positioning in the transverse acetabular ligament group as compared with the freehand group (with 80% and 62.5% of cups within the safe zone, respectively; p = 0.14), but these results remain difficult to interpret[37]. Additionally, Beverland et al. and Archbold et al. specifically reported that the transverse acetabular ligament did not help when optimizing abduction alignment[8,36].

Using the transverse acetabular ligament for acetabular positioning has several limitations. The transverse acetabular ligament is useful for identifying the native acetabular anatomy but does not account for pelvic tilt[15]. This limitation can become problematic in cases in which the native anteversion is excessive, as in select cases of developmental dysplasia of the hip and spinal abnormality. The most extreme example of this limitation is observed in patients with ankylosing spondylitis, in whom acetabular components that are placed solely on the basis of the transverse acetabular ligament frequently fall into excessive functional anteversion. Interobserver reliability in identifying the

transverse acetabular ligament is also variable[15,36,37,40]. As originally described by Archbold et al., in approximately 50% of surgical cases, soft tissue and osteophytes along the inferior border of the acetabulum must be sufficiently removed prior to proper exposure of the transverse acetabular ligament (Figs. 3-A and 3-B)[8,36]. It is therefore presumed that surgical experience plays a major role in reproducible identification of the transverse acetabular ligament; as demonstrated in the study by Epstein et al., the rate of successful identification of the transverse acetabular ligament differed by 31% (63% compared with 32%) between the 2 participating surgeons[40]. Additional information on identifying the transverse acetabular ligament was provided in the study by Beverland et al.[8].

Intraoperative Execution: Mechanical Guides

Mechanical guides, specifically A-frames, have been commonly used to improve acetabular component alignment. These guides are used during the impaction of the acetabular component and are inherently dependent on the patient's position relative to the surgical table. With the patient in the lateral decubitus position, the A-frame is placed in parallel relative to the operating room floor to orient the cup in approximately 45° of abduction. The guide is subsequently flexed, and the A-frame is brought in line with the patient's longitudinal axis to achieve approximately 20° of anteversion[41]. Of note, intraoperative flexion around the transverse plane axis is dissimilar from anatomical anteversion, which is achieved by rotating the cup along the axis of the coronal plane. Conversions between these 2 values can be achieved with normograms that are available in the literature[42].

Digioia et al. reported that, when compared with intraoperative computer-assisted navigation, A-frame-derived abduction nonsignificantly deviated from the expected abduction angle by a mean of −1° (range, −10° to 14°; p = 0.13)[41]. However, flexion angles significantly deviated by a mean of −19° (range, −46° to 13°; p < 0.001). Such large deviations in anteversion substantiate the findings of previous studies that pelvic positioning on the surgical table cannot be assumed to be neutral[33-35]. Other limitations of the A-frame include restricted abduction and anteversion angles, which are predetermined by the manufacturer, and its reliance on the anterior pelvic plane, making it a poor choice for patients with deviant spinopelvic tilt and abnormal sagittal balance.

Intraoperative Execution: Radiographic Imaging

With the growing popularity of the direct anterior approach, some surgeons have proposed that the use of intraoperative fluoroscopy can improve acetabular positioning. Several studies have

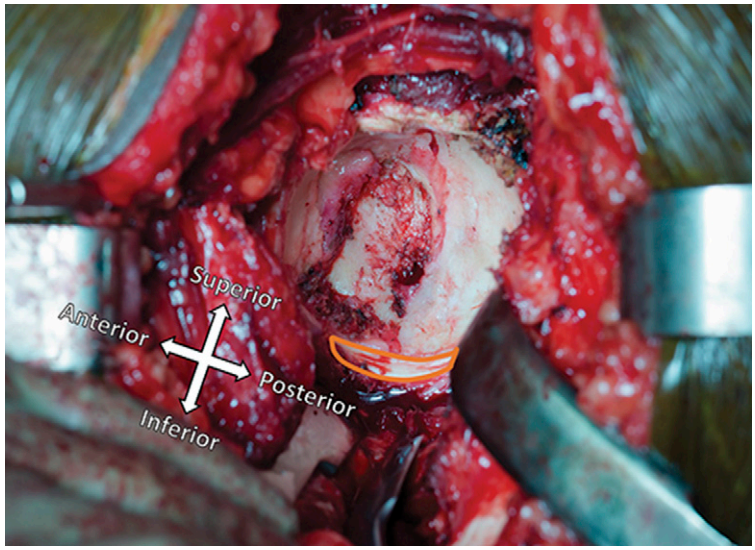

Fig. 3-A

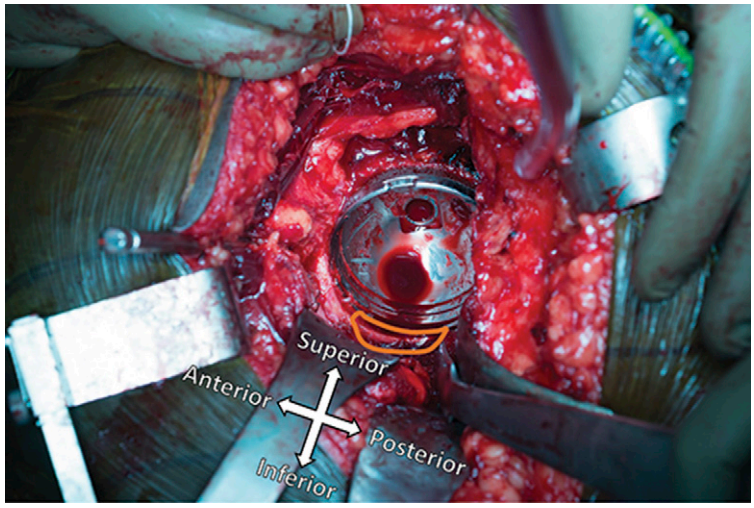

Fig. 3-B

Figs. 3-A and 3-B Intraoperative photographs showing the transverse acetabular ligament. **Fig. 3-A** The transverse acetabular ligament (outlined in orange) should be well exposed for optimal acetabular positioning. **Fig. 3-B** Subsequent cup placement should be parallel to the transverse acetabular ligament (outlined in orange) for optimal anteversion, and the ligament can also assist in assessing the most appropriate depth and height of the cup.

clearly demonstrated the benefits of using fluoroscopic guidance during the anterior approach[43,44]. When the direct anterior approach with use of fluoroscopy has been compared with a standard posterior approach, the results have been less clear. In the study by Leucht et al., in which the direct anterior approach with fluoroscopy was compared against the standard posterior approach without fluoroscopy, postoperative radiographs demonstrated that the direct anterior approach was associated with more anatomically appropriate levels of anteversion but significantly more variability (25.9° ± 8.2° compared with 35.3° ± 7.1°, respectively; $p < 0.0001$)[45]. In the study by Nam et al., direct anterior total hip arthroplasty with fluoroscopy and posterior total hip arthroplasty without fluoroscopy demonstrated similar outcomes, with 68.2% and 70% of acetabular cups falling within the Lewinnek safe zone, respectively[46]. However, posterior total hip arthroplasty with computer-assisted navigation was superior to both, with 90.9% of acetabular components falling within the targeted safe zone[46].

When using fluoroscopy, surgeons must be cognizant of the position of the patient and the orientation of the pelvis on the image[47]. Confirmatory intraoperative fluoroscopy should appear to be nearly identical to the preoperative radiograph. Alterations in the orientation of the pelvis due to patient positioning or the fluoroscopic beam can create a false profile of the cup.

Other Risk Factors

It should be noted that previous studies have identified 5 other major risk factors that increase the risk of component malpositioning: minimally invasive surgery (odds ratio [OR], 6.10), surgeon experience (OR, 2.30), surgical volume (OR, 2.07), anterolateral versus direct lateral approach (OR, 2.02), and obesity (OR, 1.35)[2,4]. While many of these variables are modifiable, some (e.g., surgical approach and volume) may be impractical to modify in an established orthopaedic practice. Instead, these risk factors should serve as reminders for more methodical planning during acetabular cup positioning.

Intraoperative Execution: Computer and Robotic-Assisted Total Hip Arthroplasty

With the rapid growth and adoption of technology in medicine, computer-navigated and robotic-assisted surgical tools have been developed to assist surgeons when positioning total hip arthroplasty components and thereby reduce the complications related to component malpositioning[28]. While these tools are designed to improve surgical accuracy and reproducibility, the approaches to achieve these goals are different[48]. Computer navigation systems provide surgeons with real-time, intraoperative positional information on surgical implants, limb-length discrepancy, and offset with use of an array of methods. Computer navigation systems can be further subdivided into imageless and image-based systems depending on their use of preoperative advanced imaging, such as CT scans (Table I)[49]. Conversely, robotic-assisted surgery systems can integrate data to produce a feedback response. This feedback response is demonstrated either through a safety-control mechanism, as in haptic and semi-active robotic-assisted surgery systems, or in conscious motions of the robotic system, as in active robotic-assisted surgery systems.

Patil et al. reported that acetabular component malpositioning was one of the most important factors in determining the risk of hip instability[14]. Combined with dislocation, acetabular component malpositioning is responsible for 22.5% of all total hip arthroplasty revisions and 33% of acetabular revisions[50]. Jolles et al., in a cadaveric study in which cup placement with use of computer-assisted systems was compared with the freehand method, computer navigation resulted in a mean error in alignment of 1.5° in abduction and 2.5° in anteversion, compared with 10° and 3.5°, respectively, for the freehand technique[51]. Similarly, Nam et al. retrospectively compared the success rate of acetabular component positioning with use of computer navigation versus mechanical guides[46]. When computer navigation was utilized, 91% of acetabular components fell within 40° ± 10° of abduction and 15° ± 10° of anteversion. Conversely, only 70% of components fell within their abduction and anteversion target zones when mechanical guides were used. Although computer navigation and robotic-assisted surgery reduce the variability in component positioning and potentially increase the range of motion, we are not aware of any study to date that has conclusively demonstrated clinical superiority[34,46,52-55]. However, the available literature on these systems has evaluated only short-term outcomes. It has been hypothesized that the benefits of these systems may only be apparent with longer-term follow-up[55]. Additionally, with the different varieties of technology-assisted systems, technological heterogeneity may obscure the results.

Despite offering less variability in component positioning, navigated systems have several limitations that may increase patient morbidity and the cost associated with total hip arthroplasty. Navigated systems are associated with an initial learning curve, which leads to increased surgical time, preventable systems errors, and, in scenarios of poor intraoperative landmark registration, component malpositioning[56,57]. Preliminary studies of knee arthroplasty have demonstrated this learning curve to be only 16 to 20 cases in the hands of the general orthopaedic surgeon[58,59]. Technology-assisted navigation is also variable in terms of the use of referencing planes, with select imageless and image-based navigation systems still dependent on the anterior pelvic plane or supine coronal plane, leading to poor cup placement relative to the patient's sagittal balance[29,32,60,61]. Most computer navigation and robotic systems also require advanced imaging prior to surgery, exposing patients to high radiation doses. Last, many systems require specific implants, software, instrumentation, and training, adding substantially

TABLE I Characteristics of Computer Navigation Systems

Type	Description	Advantages	Limitations	Systems
• Non-robotic navigation	—	• More freedom than robotic-assisted surgery to deviate from the preoperative plan based on intraoperative findings • Improved surgical accuracy and precision when placing acetabular cup	• Increased operative time • Relies on anterior pelvic plane	—
• Imageless	• Relies only on intraoperative registration of osseous landmarks	• Requires the least capital • Does not require preoperative CT, reducing radiation dosage • Compatible with implants from all companies • Minimally intrusive to the standard surgeon workflow • Does not add substantially to the surgical time	• Lengthens surgery by 8-12 min • Uses generic models and does not account for abnormal anatomy • Most sensitive to technical errors and poor surgeon technique • Acetabular cup positioning accuracy is decreased in obese patients • Does not account for functional pelvic tilt and sagittal imbalances	• Intellijoint HIP (Intelljoint Surgical, Waterloo, ON, Canada) • Brainlab (Brainlab AG, Munich, Germany) • Orthoalign (Brainlab AG, Munich, Germany)
• Image-based	• Combines preoperative CT or magnetic resonance imaging, or intraoperative fluoroscopy, with intraoperative registration of osseous landmarks	—	• Increased radiation exposure for CT-based navigation • Longer duration for creating patient-specific templates, but is currently down-trending	• HipXpert (Surgical Planning Associates, Medford, MA) • Radlink (Radlink, El Segundo, CA) (intraoperative fluoroscopy without osseous landmark registration)
• Robotic-assisted	• Improved accuracy of acetabular cup orientation with fewer outliers	—	• Increased radiation exposure for CT scan • Substantial financial investment • Substantially increases operative time	—
• Semiactive/ haptic	• Uses auditory or active feedback to constrain the surgeon to a preplanned boundary	• Surgeon maintains control over executing the procedure	• Modest learning curve in comparison to fully-active	• Mako Robotic Arm (Stryker, Mahwah, NJ)
• Active	• Only 1 system available, but can perform femoral canal preparation and assist in acetabular cup placement using preoperative CT and intraoperative osseous registration of landmarks	—	• Increased radiation exposure for CT scan • Increased perioperative complications • Possible increased dislocations • Revisions for reasons other than infection • High robotic-to-manual conversion rate • Currently used with certain implants only • Lengthens surgery by 12-120 min	• Robodoc (Think Surgical, Fremont, CA)

to the cost of a total hip arthroplasty without short-term clinical justification. In summary, it should be recognized that computer navigation and robotic-assisted total hip arthroplasty provide surgeons with reliable alternatives for the positioning of total hip arthroplasty components, particularly in complex cases in which freehand alignment techniques and anatomical landmarks may be less reliable.

Complex Total Hip Arthroplasty

As noted, complex total hip arthroplasties are less forgiving than routine primary procedures. Degenerative processes such as lumbar kyphosis and flatback syndrome, lumbar compression fractures, spondylolisthesis, and disc-space narrowing have been shown to increase posterior pelvic tilt and therefore cup abduction and anteversion, thereby placing the patient at higher risk of anterior dislocation, particularly while standing or lying in bed[38,61-63]. In addition, the risk of anterior impingement and posterior dislocation is increased during sitting. When a patient with normal spinopelvic motion is in the seated position, the pelvis rolls back around the femoral heads to accommodate the flexing proximal parts of the femora, thus preventing anterior impingement. The net effect of this movement is a decrease in sacral slope and an increase in posterior pelvic tilt. However, in a patient with pathological spinopelvic motion, there is limited ability to rotate the pelvis to allow for this accommodation, and the patient is at risk for early impingement while seated. The presence of spinal fusion further reduces pelvic motion, placing the patient at even greater risk for posterior hip dislocation[29,63-66]. Thus, these patients require increased anteversion and/or inclination to prevent anterior impingement and potential posterior dislocation while seated. Muscle weakness due to aging, lumbar degenerative diseases, and hip and knee flexion contractures can further contribute to an increase in posterior pelvic tilt[62].

In contrast to the influence of pelvic stiffness on acetabular orientation, the hypermobile pelvis experiences large changes when a patient moves from a standing to a sitting position[67]. Kanawade et al. recommend placing the acetabulum in 35° to 40° of abduction and in less anteversion than usual to accommodate for the large increase in anteversion in the seated position[67]. These patients also may benefit from the use of a dual-mobility acetabular component because of the implant's drastically increased range of motion and jump distance.

The presence of disrupted anatomy in complex cases further limits the surgeon's ability to align and position the acetabular component due to obscure landmarks (i.e., the transverse acetabular ligament, sourcil, and ilioischial and iliopubic lines). As computer navigation and robotic systems become more reliable and affordable, it is expected their indications will broaden to incorporate more complex total hip arthroplasties, improving the accuracy and outcomes of these challenging procedures.

Overview

Acetabular component positioning continues to be a challenge even for the experienced orthopaedic surgeon. With the growing demand for total hip arthroplasty, the incidence of suboptimal outcomes has become unacceptably large. While new technologies are being developed and refined, a comprehensive understanding of the patient "functional safe zone"—as well as of modern techniques, instruments, and their limitations—enhance outcomes for patients.

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Guest Editorial
What's New in Hip Replacement

Patrick Morgan, MD

Implant Design and Related Outcomes

Dual Mobility

In a recent study comparing dislocation mechanisms between dual-mobility, neutral, and constrained liners using a cadaveric model and a dual fluoroscopy system, Klemt et al. observed no increase in range of motion in the dual-mobility total hip arthroplasty (THA) construct when compared with a neutral THA construct, but did observe increased provocative anterior and posterior subluxation range of motion before dislocation[1]. The authors suggested that this may be the mechanism for previously observed lower dislocation rates.

According to a 2 to 10-year postoperative follow-up study[2], surgeons considering the use of some modular dual-mobility devices may want to include the potential for increased serum metal ion levels in their decision-making. Civinini et al. reported that 29.7% of patients had ion levels above the normal range.

Polyethylene

In a recent radiostereometric analysis study of wear rates of 2 different polyethylene liners and 2 sizes of cobalt-chromium femoral head[3], Kjærgaard et al. reported on 94 patients at a 5-year follow-up and found very low wear rates for all implants and no difference in wear rates between vitamin E polyethylene liners and conventional cross-linked polyethylene liners for both 32-mm and 36-mm heads.

Patient Factors in Relation to Outcomes

Young Patients

According to a study utilizing the New Zealand Joint Registry[4], surgeons may need an additional metric with which to counsel young patients considering THA. Nugent et al. recommended using the lifetime risk of revision. Although they found an overall, 10-year implant survival rate of 93.6%, this survival rate was lowest in the youngest age group (46 to 50 years), who had an estimated lifetime risk of a revision surgical procedure of 27.6% compared with 1.1% in those who were 90 to 95 years of age at the time of the primary surgical procedure.

Most young patients who present for the first time with early hip osteoarthritis will not require THA in the following 10 years, according to van Berkel et al.[5]. Following 588 participants at baseline and at 2, 5, 8, and 10 years, the authors observed that patients with early, symptomatic osteoarthritis progressed to THA in only 12% of cases. During the study, Kellgren and Lawrence scores worsened and the use of pain medication increased from 43% to 50% of participants. Despite this, all Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) subscales remained constant, on average, for patients who did not undergo arthroplasty.

Race and Ethnicity

Using the American College of Surgeons National Surgery Quality Improvement Program, Sheth et al. identified all African American patients in the database who underwent elective, primary THA between 2011 and 2017 (11,574 patients)[6]. Over the study period, the authors found an increase of 109% in THAs performed in this group as well as a reduction in the prevalence of osteonecrosis, anemia, and dyspnea. There were no changes in the rates of 30-day surgical complications, readmission, reoperations, and mortality. However, there was a decrease in the rate of postoperative medical complications, especially in the incidence of postoperative myocardial infarction. In another recent study of 1,041 African American patients undergoing THA and total knee arthroplasty (TKA), Chisari et al. reported that, when controlled for demographic characteristics and medical comorbidities, there were no differences in readmission or complication rates. However, African American patients had significantly lower preoperative Hip disability and Osteoarthritis Outcome Score (HOOS) and Knee disability and Osteoarthritis Outcome Score (KOOS) values at 33.5 points compared with Caucasian patients at 45.1 points ($p < 0.001$)[7].

Preoperative Opioid Usage

In a recent study, Vakharia et al. identified 42,097 Medicare patients who underwent primary THA between 2005 and 2014 and produced 2 matched cohorts of patients with and without opioid use disorder[8]. The authors found that patients with opioid use disorder had a higher risk of developing periprosthetic joint infections (relative risk, 1.32) and having 90-day readmissions (relative risk, 1.23) and higher 90-day costs compared with controls.

Disclosure: The **Disclosure of Potential Conflicts of Interest** form is provided with the online version of the article (http://links.lww.com/JBJS/G650).

What's New in Hip Replacement

Prior Hip Arthroscopy

Using the Swedish Hip Arthroplasty Registry, Lindman et al. compared 135 patients who had undergone failed ipsilateral hip arthroscopy and then underwent conversion to THA with 540 age-matched controls. The authors evaluated the patient-reported outcome measures obtained with the use of multiple questionnaires[9]. The mean interval between the arthroscopy and the THA was 27 months. The authors reported that, at the 1-year follow-up, there were no differences in hip pain or reported satisfaction between the 2 groups.

Body Mass Index (BMI)

Onggo et al. recently performed a meta-analysis and systematic review of 67 studies on the topic of obesity and THA outcomes that included 581,012 obese patients and 1,609,812 non-obese patients[10]. The authors found that obese patients had a higher risk of dislocations, reoperations, revisions, readmissions, all complications, deep infections, and superficial infections. In a subgroup analysis of morbidly obese patients (BMI ≥40 kg/m^2), the risks of all of these parameters were even greater.

In addition to a higher risk of complications, Katakam et al. found that obese class-III patients (BMI >40 kg/m^2) also had a higher risk of no improvement in their postoperative physical function[11]. The authors reported that the class-III obese patients had a nearly threefold increased risk of not achieving the minimal clinically important difference on the HOOS-Physical Function Short Form (HOOS-PS) at the 1-year follow-up. Also, the authors suggested that their data may be used for setting patient expectations.

Spinal Pathology

Spinal pathology is increasingly understood as a risk factor for adverse events in the population undergoing THA. In a meta-analysis of 10 articles corresponding to 9 unique observational studies totaling 1,992,366 primary THAs, Wyatt et al. identified 32,945 cases of spinal fusion[12]. When comparing spinal fusion with no spinal fusion, the relative risk was 2.23 (95% confidence interval [CI], 1.81 to 2.74) for dislocation in 7 studies and 2.82 (95% CI, 1.37 to 5.80) for any complication in 3 studies.

The identification of patients without a history of spinal fusion but with a clinically relevant stiff lumbar spine remains a challenge. In a Level-II, diagnostic study, Innmann et al. reported that patient screening can be accomplished through a combination of physical examination and a standing lateral radiographic image of the spinopelvic complex taken using a biplanar, low-radiation-dose imaging system[13]. After calculating what they referred to as a "hip user index" by quantifying the percentage of sagittal hip movement compared with the overall movement between the standing and deep-flexed positions, the authors reported a sensitivity of 90% and specificity of 71% for identifying a patient with little spinal contribution to sagittal motion when the standing pelvic tilt was found to be ≥19°.

Previous Hip Surgical Procedures

Douglas et al. compared matched retrospective cohorts of 25,081 patients who underwent primary THA with 8,339 patients who had undergone at least 1 hip surgical procedure prior to THA[14]. The authors found that the patients who underwent conversion THA had significantly higher rates of complications (periprosthetic joint infections, hip dislocations, mechanical complications, and need for a revision surgical procedure within 90 days), higher transfusion rates, higher 30-day readmission rates, and higher median cost of care at 90 days compared with the patients who underwent primary THA.

Surgical Factors in Relation to Outcome

Surgical Approach

In a study of 30,098 patients who underwent THA between 2015 and 2018 in Ontario, Canada, Pincus et al. reported finding a small but significantly increased risk of major surgical complications among 2,993 propensity score-matched patients undergoing an anterior approach (61 patients [2%]) compared with 2,993 matched patients undergoing a posterior or lateral approach (29 patients [1%]); the absolute risk difference was 1.07% (95% CI, 0.46% to 1.69%), and the hazard ratio was 2.07 (95% CI, 1.48 to 2.88)[15].

In a similarly large study population, Charney et al. evaluated 38,399 THAs from the Kaiser Permanente's Total Joint Replacement Registry for the impact of the surgical approach on rates of dislocation, revision for instability, revision for periprosthetic fracture, and revision for aseptic loosening[16]. The authors found a slightly lower risk of dislocation in the direct anterior approach group compared with the posterior approach group (hazard ratio, 0.39 [95% CI, 0.29 to 0.53]). However, there was a higher risk of revision for aseptic loosening in the direct anterior approach group compared with the posterior approach group (hazard ratio, 2.26 [95% CI, 1.35 to 3.79]).

Implant Fixation

Utilizing the Norwegian Arthroplasty Register, Dale et al. evaluated the modes of fixation in primary THA and the influence of age and sex with regard to reported lower survivorship for, but increased use of, cementless THA in some populations[17]. Utilizing data from 2005 to 2017, the authors found a considerably higher rate of revision due to fracture and dislocation in female patients 55 to 75 years of age undergoing THA with all-uncemented designs (relative risk, 1.3 [95% CI, 1.0 to 1.7]). This was higher still in female patients older than 75 years of age (relative risk, 1.8 [95% CI, 1.2 to 2.7]). The authors recommended against using uncemented stems in THA in these patients.

Cement fixation was also endorsed by multiple investigators studying outcomes for displaced intracapsular hip fractures. In a prospective, double-blinded, randomized controlled trial (RCT), Clement et al. randomized 50 patients

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who were >60 years of age and had an intracapsular hip fracture to THA with either an uncemented design (n = 25) or a cemented design (n = 25)[18]. The study was terminated early after only one-quarter of the intended enrollment was reached because of the significantly higher rate of intraoperative complications (p = 0.004) in the uncemented group (8 patients). The authors endorsed the use of cemented components in these patients. In another publication, Nantha Kumar et al. performed a systematic review and meta-analysis of 2,819 hemiarthroplasties performed for intracapsular hip fractures[19]. They found no difference in the risk of mortality when comparing cemented and uncemented stems, but did find that uncemented implants had a substantially higher risk of periprosthetic fracture.

With regard to surgeons selectively using uncemented stems in elderly women with good bones, in a recent study of 2,635 THAs[20], Hopman et al. reported 18 revisions for early periprosthetic fracture in elderly female patients. These fractures were not correlated with BMI, osteoporosis, or Dorr classification. The authors estimated that the number needed to treat to avoid 1 revision, if assuming that the patients undergoing THA with no cement would have had no fractures with cement, was 48.

Complications

Surgeon Age as Risk Factor

The goal of identifying complication risk factors has extended to the age of the surgeon. In a study of 122,043 THAs performed by 298 surgeons, Matar et al. found that middle-aged surgeons (45 to 55 years of age) had the lowest complication rate and younger surgeons had a higher risk of composite complications, revision, and infection[21]. Excluding older low-volume surgeons (who also had a higher composite risk of complications), older surgeons had complications similar to those of middle-aged surgeons.

Dislocation

The variable rate of dislocation in the literature may be due to the difficulty in identifying all of the dislocations that are occurring, according to Hermansen et al.[22]. Utilizing the Danish Hip Arthroplasty Register, the authors attempted to identify the true rate of a dislocation for patients undergoing THA for osteoarthritis using what the authors described as a comprehensive, nationwide review of patient files of patients who underwent THA performed between 2010 and 2014. They reported that their final tally was 50% higher than the results from using their registry alone and cautioned that better algorithms integrating medical records may be required to use registries to monitor dislocation.

According to Huerfano et al., the dislocation rate, true or otherwise, does not seem to be influenced by the surgeon's choice of approach. In their recent meta-analysis of 25 studies (5 RCTs and 20 non-RCTs) of 7,172 THAs[23], the authors compared the posterolateral approach and the direct anterior approach and found no significant differences in dislocation rates between the approaches. Subgroup analyses indicated similar results with respect to posterior soft-tissue repair (p = 0.50) and the learning curve (p = 0.77). The authors concluded that the surgical approach had no influence on dislocation rate after THA.

Adverse Local Tissue Reactions

Kwon et al. reported on 89 consecutive patients managed for head-neck taper junction corrosion[24]. They found that the erythrocyte sedimentation rate (ESR) and C-reactive protein (CRP) remained useful in excluding infection. The suggested cutoffs were 57 mm/hr for ESR, with 57% sensitivity and 94% specificity, and 35 mg/L for CRP, with 93% sensitivity and 76% specificity. The authors observed no significant differences in metal ion levels between the infected and uninfected groups.

Even without infection, revision for adverse local tissue reaction in the hip can be challenging because of abductor insertion necrosis. Klemt et al. reported a decreased dislocation risk for these patients when managed with a dual-mobility implant[25]. In their cohort of 234 such patients, no dual-mobility implant had dislocated at a mean 4-year follow-up compared with 4.1% of patients treated with a constrained liner and 15.5% treated with a conventional articulation.

Technology

Virtual Clinic Visits

El Ashmawy et al. provided some insight into what many of our patients experienced during the COVID-19 pandemic. Reporting on 1,749 patients seen in a virtual visit between January 2017 and December 2018, the authors examined the effectiveness of and patient satisfaction with virtual visits[26]. They found that, for the 1-year postoperative visit and routine scheduled follow-up visits, only 7.22% of patients required a further in-person appointment. Patient satisfaction rates were similarly promising, with 89.29% reporting being satisfied or very satisfied with this mode of care.

Outcome Scores

Ackerman et al. examined the HOOS-12 and KOOS-12, shorter, 12-question versions of the 40-question HOOS and KOOS[27]. Using the Oxford Hip Scores, Oxford Knee Scores, and EuroQol-5 Dimensions-5 Levels (EQ-5D-5L) as comparators, the authors found good psychometric properties in the 12-question version in the joint replacement population, including excellent responsiveness, although they cautioned that ceiling effects may limit monitoring of postoperative improvement.

Robotic-Assisted THA

Does robotic-assisted THA improve patient outcomes? That is the question asked by Singh et al. in their study of 1,960 consecutive THAs, including 135 robotic-assisted THAs, 896 navigation-assisted THAs, and 929 THAs with conventionally

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placed implants[28]. They reported finding no clinically important differences in patient-reported outcome measures at 1 and 2 years. However, surgical time for the robotics group was significantly longer ($p < 0.001$) at 119.61 minutes than that for the navigation group (90.35 minutes) or the conventional group (95.35 minutes).

For those who do choose to utilize intraoperative robotics, the surgical approach and the patient's pelvic tilt may affect the accuracy of the technology. Hayashi et al. found that posterior pelvic tilt and an anterior surgical approach were significantly associated with postoperative inaccurate cup positioning in robotic-assisted THA[29].

Artificial Intelligence

In a recent study, Siebelt et al. examined machine learning models for the diagnosis of hip symptoms[30]. Using a digital questionnaire, the authors found that the Random Forest Model was most accurate; with the addition of Kellgren-Lawrence scores, a Support Vector Machine model was the most accurate. They concluded that machine learning algorithms trained with patient-reported outcome measures and radiographic scores can accurately differentiate diagnoses in patients with hip pain.

Current Trends and Debates

Lumbar Spinal Fusion or THA First

Yang et al. screened 85,595 patients who underwent THA and identified 1,356 patients who underwent THA before lumbar spinal fusion and 2,016 patients who underwent THA after spinal fusion[31]. The authors found that the patients who underwent THA first had an increased dislocation risk, higher rate of periprosthetic joint infection, surgical site complications, revision, and postoperative opioid use compared with those who underwent THA after lumbar spinal fusion.

Vigdorchik et al. have argued that patients undergoing both THA and spinal fusion may benefit from an extended-offset prosthesis[32]. Using a computed tomography (CT)-based computer software impingement modeling system, the authors assessed 50 consecutive patients with spinal stiffness for osseous or prosthetic impingement during simulated range of motion of virtually implanted prostheses. The stiff spine was identified by examining standing and relaxed-sitting lateral spinopelvic radiographs. Each patient model was run 5 times. Of the 51 dislocations seen, 96% had a standard-offset stem. They reported 5° of additional virtual range of motion before impingement for every 1 mm of offset increase.

Sport After THA

Patient counseling on return to sport after THA remains variable. In a Level-V study of surgeon opinion, Vu-Han et al. evaluated the return-to-sport recommendations of 300 German orthopaedic surgeons using a questionnaire[33]. Over 80% of surgeons were in favor of returning to sport after THA, but, with regard to high-impact sport, 51.5% believed that it was appropriate if the patient received adequate training and 34.3% recommended no high-impact sport at all.

Postoperative Opioid Use

The topic of pain management with opioids remains one of intense international interest. In a study of 507 patients who underwent either THA or TKA, Ruddell et al. evaluated the impact of initial postoperative prescriptions[34]. The authors noted a dose-dependent relationship between initial outpatient dosing and greater future quantities of opioids consumed. They found that 30% of patients required postoperative opioids between days 31 to 90 and each 1-morphine milligram equivalent (MME) increase in the initial outpatient prescription was associated with a 0.997-MME increase in the quantity filled during the prolonged period. Among the 14% requiring opioids between postoperative days 91 and 150, this increased to 1.678 MME. The authors recommended that providers should attempt to minimize early outpatient opioid utilization.

Such a reduction in opioids prescribed after THA is not associated with a decrease in patient satisfaction, according to Bloom et al.[35]. Using an opioid-sparse protocol published by Feng et al.[36], Bloom et al. reported a 73.8% reduction in mean opioids prescribed at discharge, with a mean prescription of 114 ± 156 MME in the final cohort, down from a previous level of 432 ± 298 MME ($p < 0.001$). They saw no associated decrease in patient satisfaction scores.

Perioperative Management

Prophylactic Antibiotics

In their AAHKS (American Association of Hip and Knee Surgeons) Clinical Research Award paper, Kheir et al. examined whether a 7-day postoperative course of oral antibiotics could reduce the risk of periprosthetic joint infection in patients identified as high-risk[37]. The study reviewed 3,855 consecutive THAs and TKAs performed between 2011 and 2019. Starting in 2015, high-risk patients were managed with an extended antibiotics protocol commencing after inpatient intravenous antibiotics were completed. High-risk patients with extended antibiotic prophylaxis had a significantly lower rate of periprosthetic joint infection (0.89%) than high-risk patients without extended antibiotic prophylaxis (2.64%). No difference in the infection rate was observed between high-risk patients who received the extended antibiotics and low-risk patients.

Intrawound Vancomycin

In their recent systematic review of the use of topical vancomycin to prevent periprosthetic joint infection in THA and TKA, Wong et al. called the practice into question[38]. The authors identified 9 studies, including 3,371 patients who received topical vancomycin and 2,884 patients who did not. The authors found no convincing evidence for the practice. They identified 6 studies in which overall complications could be compared and found no difference in overall complication

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risks with topical vancomycin, but warned that these studies were underpowered for detecting differences in uncommon complications associated with vancomycin use (e.g., ototoxicity, allergy, and nephrotoxicity). The authors concluded that, without a sufficiently large evidence base reporting on safety-related end points and in the absence of clear evidence of efficacy, topical vancomycin powder should not be used in routine primary THA and TKA.

Povidone-Iodine Irrigation

Kim et al. questioned the practice of povidone-iodine lavage in a systematic review and meta-analysis of 7 studies with 31,213 THA and TKA cases including 8,861 patients who received povidone-iodine lavage and 22,352 patients who did not[39]. The authors reported no detected difference in the overall postoperative infection rates between the groups with and without povidone-iodine lavage before wound closure in primary THAs and TKAs and aseptic revision arthroplasties at 3 or 12 months postoperatively in all studies in the subgroup analysis.

Anesthesia and Analgesia

Surgeons advocating for both spinal analgesia and operating room efficiency may be interested in a recent study by Ritz et al.[40]. The authors questioned if administration of spinal anesthesia for THA and TKA in the preoperative area, before entering the operating room, was safe and whether it would have positive effects on perioperative efficiency. They reported no adverse events when administering spinal anesthesia preoperatively before entering the operating room, and they recorded shorter anesthesia induction times, shorter operating room recovery times, and shorter post-anesthesia care unit recovery times. Turnover times were longer, negating these gains.

Tranexamic Acid (TXA)

In a meta-analysis of the use of intravenous TXA and its impact on wound complications, Sukeik et al. identified 25 clinical trials including 1,608 patients[41]. Although the authors found that TXA use did reduce blood loss and transfusion rates without an increase in thrombotic complications, there was no significant difference in the use of antibiotics or surgical intervention for wound problems. Levack et al. studied TXA use in the setting of periacetabular osteotomy using a placebo-controlled, double-blinded randomized trial[42]. The authors found that intravenous TXA reduced intraoperative blood loss by 293 mL and the frequency of allogenic transfusion by 73%.

Prophylaxis for Thromboembolism

Two studies have added to the growing body of data for aspirin prophylaxis for thromboembolism. The first study was a systematic review of the literature that included 45 studies. In that study, Azboy et al. suggested that low-dose aspirin for patients after total joint arthroplasty is not inferior to high-dose aspirin in preventing venous thromboembolism[43]. The second study was a systematic review and meta-analysis. In that study, Matharu et al. suggested that aspirin taken as venous thromboembolism prophylaxis after THA and TKA did not differ in clinical effectiveness in a significant way from other anticoagulants[44].

Laboratory Studies

To investigate the utility of preoperative laboratory studies, Ondeck et al. queried a national database from 2011 to 2015, identifying 92,093 patients[45]. The authors found that abnormal preoperative creatinine and sodium levels were associated with the occurrence of all studied adverse outcomes.

Sequeira et al. evaluated 98,681 patients with a preoperative diagnosis of iron deficiency anemia[46]. The authors found that patients with preoperative iron deficiency anemia who underwent THA, when compared with 386,724 matched controls, were at greater risk for experiencing early postoperative complications and had greater utilization of hospital resources, including increased risks of 30-day emergency department visits and 30-day readmission. Iron deficiency anemia was associated with major complications such as increased 1-year rates of periprosthetic joint infection, revision, dislocation, and fracture. In addition, it was significantly associated with an increased 90-day medical complication rate. Compared with the controls, patients with iron deficiency anemia accrued lower hospital reimbursement ($5,509.90 compared with $3,605.59) and higher hospital charges ($27,658.27 compared with $16,709.18).

With regard to postoperative laboratory studies, Wu et al. performed a retrospective study of 395 consecutive patients undergoing THA[47]. The authors sought to evaluate the utility of routine postoperative laboratory tests in an Asian population. The authors identified 6.8% of patients who received medical intervention that was directly related to postoperative abnormal laboratory values. The most frequent abnormalities observed were anemia and hypoalbuminemia, and the intervention rates for patients with abnormal postoperative creatinine, sodium, potassium, and calcium were deemed to be extremely low.

Postoperative Rehabilitation

Postoperative rehabilitation after THA in the United States is estimated to cost in excess of $180 million per year[48]. In a recent systematic review and meta-analysis, Saueressig et al. sought to explore the clinical outcomes associated with exercise training before and after THA[49]. Including 26 randomized clinical trials with 1,004 patients, the authors reported that, compared with usual intervention or no or minimal intervention, postoperative exercise training was not associated with improved self-reported physical function at 4 and 26 weeks postoperatively. Comparing preoperative exercise interventions with the control group revealed no

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association between exercise training and self-reported physical function at the 12-week and 1-year follow-ups. The authors suggested that routine preoperative exercise training may not be necessary, and recent guidelines have indicated that supervised postoperative training may only be needed in select subgroups, such as those with difficulty with activities of daily living and those with cognitive impairments.

Evidence-Based Orthopaedics

The editorial staff of *JBJS* reviewed a large number of recently published studies related to the musculoskeletal system that received a higher Level of Evidence grade. In addition to articles cited already in this update, 4 other articles relevant to hip surgery are appended to this review after the standard bibliography, with a brief commentary about each article to help guide your further reading, in an evidence-based fashion, in this subspecialty area.

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Evidence-Based Orthopaedics

Bergvinsson H, Sundberg M, Flivik G. Polyethylene wear with ceramic and metal femoral heads at 5 years: a randomized controlled trial with radiostereometric analysis. *J Arthroplasty.* 2020 Dec;35(12):3769-76. Epub 2020 Jun 23.

Using radiostereometric analysis, 50 patients with osteoarthritis undergoing THA were randomized to have either a cobalt-chromium femoral head or a ceramic femoral head and were followed at intervals. At the 5-year follow-up, both groups had very low wear rates (<0.01 mm/yr) and no differences in cup migration or clinical outcomes were observed. At a time when THA implants have been increasingly seen as a cost center for orthopaedic practices and hospitals, the age of patients undergoing THA has been decreasing. This has the potential to create conflicting motivations for implant contracting and selection. This study suggested that, at least in terms of wear rates, there was no advantage in choosing one femoral head material over another when the head is mated with a cross-linked polyethylene implant. This may be useful information when choosing implants.

Bober K, Kadado A, Charters M, Ayoola A, North T. Pain control after total hip arthroplasty: a randomized controlled trial determining efficacy of fascia iliaca compartment blocks in the immediate postoperative period. *J Arthroplasty.* 2020 Jun;35(6S):S241-S245. Epub 2020 Feb 14.

In this randomized placebo-controlled trial, 122 patients undergoing THA received either a fascia iliaca compartment block or a placebo block and were evaluated for pain and morphine equivalents used during the first 24 hours as well as distanced walked and get-up-and-go testing at the first physical therapy session. No differences were seen between the 2 groups in terms of pain measures, ambulation, or get-up-and-go times. In contrast, 22% of patients receiving the fascia iliaca block demonstrated quadriceps weakness, necessitating a change to their therapy protocol.

In a health-care environment that increasingly requires the cost savings realized with total joint arthroplasties performed in patients who are then discharged, on the same day of the surgical procedure, from the hospital either to home or to a non-medical setting with a nurse (at a hotel or a nearby site suite), the decreased quadriceps function demonstrated here may have implications for this intervention's appropriateness specifically for the ambulatory setting; the lack of demonstrated positive effect in any of the metrics evaluated calls into question the practice in general. The authors' conclusion that the fascia iliaca block cannot be recommended for patients undergoing THA appears justified and may prove to be useful when counseling patients considering this intervention.

Sershon RA, Fillingham YA, Abdel MP, Malkani AL, Schwarzkopf R, Padgett DE, Vail TP, Nam D, Nahhas C, Culvern C, Della Valle CJ; Hip Society Research Group. The optimal dosing regimen for tranexamic acid in revision total hip arthroplasty: a multicenter randomized clinical trial. *J Bone Joint Surg Am.* 2020 Nov 4;102(21):1883-90.

In this multicenter, randomized trial, 4 dosing regimens were compared for safety and efficacy: (1) a single 1-g dose of TXA administered intravenously prior to incision; (2) 1-g intravenous TXA administered prior to incision, followed by 1-g intravenous TXA administered at closure; (3) a combination of 1-g intravenous TXA administered prior to incision and 1-g intraoperative topical TXA; and (4) 3 oral TXA doses totaling 1,950 mg. Assuming that a >1-g/dL difference in hemoglobin reduction was clinically important, equivalence

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testing showed that all possible pairings were statistically equivalent. There was only 1 venous thromboembolism overall and no differences were found between groups.

Although the use of TXA in the management of patients undergoing THA has been notably positive since its widespread adoption, great variability in its administration and dosing has added a level of uncertainty, in part driven by practice site-specific protocols. The authors suggested that a wide range of practice may be appropriate in terms of efficacy and patient safety.

Tabori-Jensen S, Mosegaard SB, Hansen TB, Stilling M. Inferior stabilization of cementless compared with cemented dual-mobility cups in elderly osteoarthrosis patients: a randomized controlled radiostereometry study on 60 patients with 2 years' follow-up. *Acta Orthop.* 2020 Jun;91(3):246-53. Epub 2020 Feb 6.

In this patient-blinded, randomized trial of 60 patients undergoing THA for osteoarthritis, Tabori-Jensen et al. used radiostereometry to assess acetabular fixation in elderly patients. The authors found that cemented acetabular components ceased migration at 3 months and cementless implants in patients with low bone mineral density had not stabilized after 2 years. These data provide insight into the natural history of cementless acetabular components in the elderly population and may be of use in implant selection in this population. Taken with data on the increased periprosthetic femoral fracture risk in the elderly patient managed with a cementless device, this study may indicate that a role remains in modern practice for the THA performed with cemented components.

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