Review Article

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Robotic-assisted Total Hip Arthroplasty and Spinopelvic Parameters: A Review

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Total hip arthroplasty (THA) is an effective treatment for osteoarthritis, and the popularity of the direct anterior approach has increased due to more rapid recovery and increased stability. Instability, commonly caused by component malposition, remains a significant concern. The dynamic relationship between the pelvis and lumbar spine, deemed spinopelvic motion, is considered an important factor in stability. Various parameters are used in evaluating spinopelvic motion. Understanding spinopelvic motion is critical, and executing a precise plan for positioning the implant can be difficult with manual instrumentation. Robotic and/or navigation systems have been developed in the effort to enhance THA outcomes and for implementing spinopelvic parameters. These systems can be classified into three categories: X-ray/fluoroscopy-based, imageless, and computed tomography (CT)-based. Each system has advantages and limitations. When using CT-based systems, preoperative CT scans are used to assist with preoperative planning and intraoperative execution, providing feedback on implant position and restoration of hip biomechanics within a functional safe zone developed according to each patient's specific spinopelvic parameters. Several studies have demonstrated the accuracy and reproducibility of robotic systems with regard to implant positioning and leg length discrepancy. Some studies have reported better radiographic and clinical outcomes with use of robotic-assisted THA. However, clinical outcomes comparable to those for manual THA have also been reported. Robotic systems offer advantages in terms of accuracy, precision, and potentially reduced rates of dislocation. Additional research, including conduct of randomized controlled trials, will be required in order to evaluate the long-term outcomes and cost-effectiveness of robotic-assisted THA.

Keywords: Total hip arthroplasty, Osteoarthritis, Robotic-assisted surgery, Spinopelvic parameters

INTRODUCTION

Total hip arthroplasty (THA) is a reliable treatment for osteoarthritis and patient reported outcomes have demonstrated this success. Clinically significant improvement of pain has been reported for upwards of 90%-95% of patients compared to preoperative[1]. The recent resurgence in popularity of the anterior approach has resulted in faster recovery compared with the more commonly used posterior approach. This difference was demonstrated at six weeks postoperative but had diminished by the three month follow-up[2]. Reduced risk of dislocation ranging from 0.6%-1.5% has been reported with use of the anterior approach[3-5]. Some studies that contradict this finding have demonstrated that there was no difference in dislocation rates or functional outcome when using a posterior approach compared to an anterior approach[6]. Many surgeons have adapted the use of techniques designed to decrease the risk of dislocation including the use of soft tissue repair, high offset stems, and dual mobility articulations. Despite these efforts, instability remains a primary diagnosis for revision THA. In the 1970s, the importance of implant position was demonstrated by

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Lewinnek et al.[7], who defined the Lewinnek safe zones. Approximately 40% of revision THA procedures are performed for malpositioned components, most commonly the acetabular implant[8]. Different methods, including fluoroscopy and navigation, have been utilized intraoperatively to confirm implant position. Despite these efforts, anteversion of the acetabular component cannot be reliably reproduced with use of fluoroscopy[9]. In addition, Abdel et al.[10] previously reported that the majority of unstable hips had components located within the Lewinnek safe zones. Although implant position is important in regard to stability in THA, it has not resolved the issue.

SPINOPELVIC PARAMETERS

A recent popular topic regarding instability in THA refers to the dynamic relationship between the pelvis and lumbar spine, termed spinopelvic motion[11]. This is still an evolving topic, and multiple contradicting studies have been reported[12]. In evaluation of the spinopelvic relationship in patients with THA instability, abnormal spinopelvic imbalance was detected in upwards of 75% of cases[13-15]. According to a recent review, the clinical implications of spinopelvic imbalance and spinal fusion surgery can be regarded as the single strongest predictor of hip instability[12]. The length of the fusion construct, lumbosacral fusion, type of lumbar surgery, and timing of fusion are variables of lumbar spine surgery that can affect hip instability[12]. Sagittal alignment and flexibility of the lumbar spine can also be affected by osteoarthritis and other degenerative conditions of the spine[12].

During normal spinopelvic motion, our focus is on two distinct positions: standing and sitting. Lateral radiographs of the lumbar spine and pelvis extending from the L3 vertebra to the proximal femur are obtained for evaluation of the parameters in these positions. These X-rays are taken with the patient in a standing position, followed by a sitting position (Fig. 1). Sacral slope (SS), anterior pelvic plane (APP), pelvic tilt (PT), pelvic incidence (PI), anteinclination, pelvic-femoral angle, and lumbar lordosis (LL) are measured on the lateral radiograph[12] (Table 1). Interpretation of spinopelvic motion can rapidly become confusing during measurement of these parameters. For simplicity and reproducibility, clinicians and researchers focus primarily on SS, LL, and the APP. SS is an angle formed by the S1 endplate and a horizontal line. LL is the angle formed by the proximal L1 vertebral body and the distal L5 vertebral body. The APP is formed by the anterior-superior iliac spine and pubic symphysis. PI, which is often referenced as well, is measured between a line perpendicular to the S1 endplate and the center of the femoral head (Fig. 2)[12].

NORMAL SPINOPELVIC MOTION

In patients with normal spinopelvic motion, in a standing position the hips are extended, the pelvis is tilted anteriorly, and the lumbar spine is lordotic (Fig. 2), enabling balance of the trunk over the pelvis with the

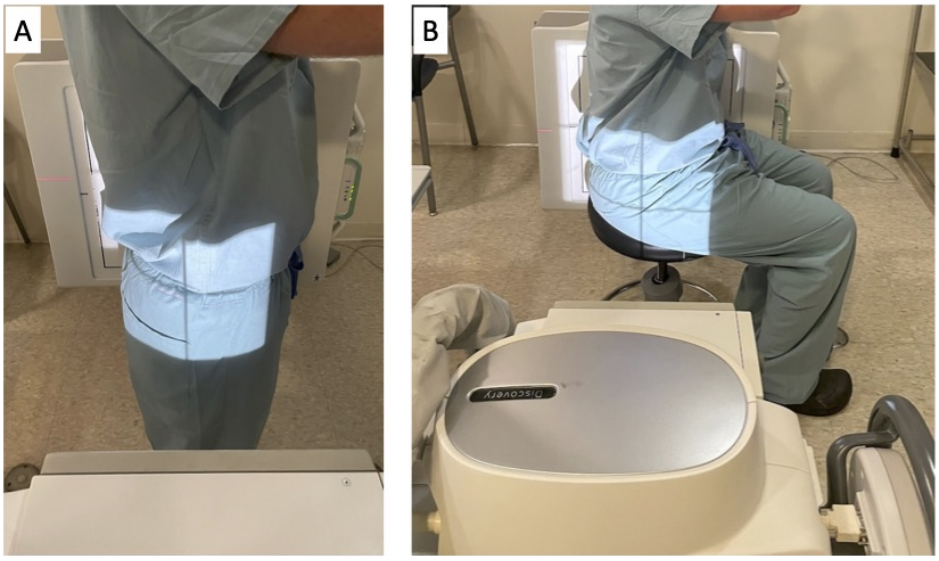

Fig. 1. Patient positioned for standing lateral radiograph (A) and sitting lateral radiograph (B).

Table 1. Spinopelvic Measurements

Name	Definition	Application
Lumbar lordosis angle (LL)	Angle formed by the proximal L1 vertebral body and the distal L5 vertebral body.	Used for sagittal alignment assessment and compared with PI. A patient has sagittal imbalance when the PI-LL is >10°.
Sacral slope (SS)	Angle formed by the S1 endplate and a horizontal line.	Used to measure pelvic motion, comparing the difference in values between two different postural positions.
Pelvic tilt (PT)	Angle formed by a line from the S1 endplate to the center of the femoral head and a second vertical line.	Used to describe the standing orientation of the pelvis.
Pelvic incidence (PI)	Angle formed by a line perpendicular to the S1 endplate and a second line from the midpoint of S1 to the center of the femoral head.	Used to describe the anterior-to posterior dimension of the pelvis and used to define the expected LL. A patient has sagittal imbalance when the PI-LL is >10°.
Anterior pelvic plane (APP)	Plane formed by the anterior superior iliac spines and the pubic symphysis.	Used to determine whether the standing position of the pelvis is posteriorly or anteriorly tilted. The standing APP should be vertical in patients with neutral alignment.
Anteinclination (AI)	Angle formed by a line through the long axis of the acetabulum and a horizontal line measured on lateral radiographs.	Used to measure the lateral orientation of the acetabular implant and to assess the risk of impingement.
Pelvic-femoral angle (PFA)	Angle formed by a line from the midpoint of S1 to the center of the femoral head and a second line parallel to the femoral diaphysis.	Used to measure femoral motion measuring the difference in PFA values between two different postural positions.

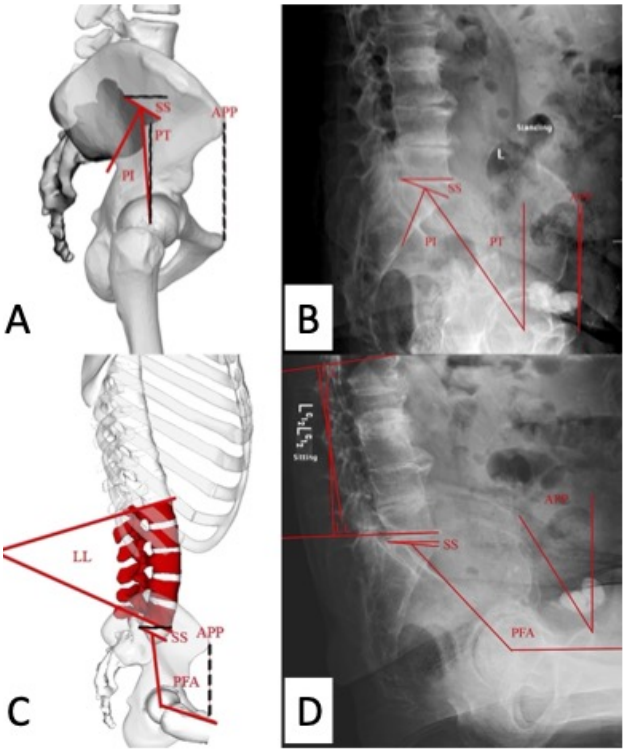

Fig. 2. (A) Spinopelvic parameters on standing illustration. (B) Standing radiograph. (C) Spinopelvic parameters on sitting illustration. (D) Sitting radiograph. SS: sacral slope, PT: pelvic tilt, PI: pelvic incidence, APP: anterior pelvic plane, LL: lumbar lordosis angle, PFA: pelvic-femoral angle.

acetabulum covering the femoral head without impinging. During transition to a sitting position with flexion of the hips, the lumbar spine flattens with less lordosis causing posterior tilting of the pelvis, resulting in 0.8° greater anteversion of the acetabulum for every 1° of posterior PT[16,17] (Fig. 2). The mean increase in acetabular anteversion from standing to sitting is approximately 15°[18]. This increase in anteversion enables maximal flexion of the hip without anterior impingement[12,14].

THE STIFF SPINE

When posterior tilt of the pelvis during sitting is decreased, anteversion of the acetabulum is not possible, which can lead to anterior impingement, which can cause a posterior dislocation. The lumbar spine can become imbalanced, rigid, or both after spinal surgery or in cases of lumbar degenerative arthritis. LL is subtracted from PI for measurement of imbalance of the lumbar spine and should be less than 10° (PI-LL ≤10°)[19]. Another method of measuring spinopelvic imbalance utilizes SS and APP, which do not require extension of the radiographs proximal to L1. SS, which can be easily measured on a lateral pelvic radiograph, is used when interpreting stiffness of the spinopelvic junction. Normal SS ranges from 20°-40°, with a higher slope while standing. For calculation of this value, SS is measured in both standing and sitting positions. The calculated difference (ΔSS) should be ≥10° in normal spinopelvic motion. ΔSS <10° indicates a stiff spine and places the patient at high risk for instability. Measurement of the

APP should then be performed in order to determine whether the patient's pelvis is also lacking compensatory motion. In the case of an APP that is neutral or tilted anteriorly, the patient is categorized as "stuck standing" and would be at risk of anterior impingement leading to posterior instability due to lack of acetabular anteversion while sitting (Fig. 3). In the case of an APP that is tilted posteriorly ≥10°, the patient is categorized as "stuck sitting" and would be at risk of posterior impingement with hip extension and anterior instability while standing, although this situation is less common[12,19]. To add to the controversy, a recent publication questioned the widespread adaption of SS as a surrogate for spinal imbalance/rigidity[20].

The risk of dislocation is higher for patients who have undergone lumbar spine arthrodesis prior to THA. To compensate for the loss of motion in the lumbar spine and the abnormal PT, the hip must reach a more extreme range of motion during performance of activities of daily living. In a retrospective case-control-matched study, Grammatopoulos et al.[21] reported that patients with a previous spinal arthrodesis were five times more likely to exhibit abnormal change in PT between standing and sitting. Their findings also showed a higher range of motion in the hip joint to compensate for lack of spinopelvic motion. Therefore, patients who are not able to achieve this increased range of motion of the hips due to factors such as impingement are at an increased risk for dislocation. In this matched analysis, abnormal PT was the only parameter showing association with inferior patient reported outcome (Oxford hip score, 35 vs. 40); however, this difference did not reach Minimal Clinically Important Difference (MCID) of 6-8[21,22].

SPINOPELVIC HYPERMOBILITY

On the other end of the mobility spectrum are patients with posterior spinopelvic hypermobility defined as a change in SS greater than 35° from standing to relaxed-seat position. Patients with this condition reach an extreme range of motion that can lead to impingement[12,22,23]. Sculco et al.[23] reported that resolution of this hypermobility occurs after THA in 93% of cases, implicating hip flexion contractures as the culprit responsible for increased posterior PT. Severe osteoarthritis in the contralateral hip was the only significant predictor of persistent spinopelvic hypermobility postoperatively[23]. Restricted range of hip motion necessitates increased pelvic compensation in the sagittal plane[23].

CLINICAL IMPLICATIONS OF SPINOPELVIC PARAMETERS

Clinical application of this knowledge remains controversial. When examining general trends, slightly increasing the acetabular anteversion by 5°-10° can be

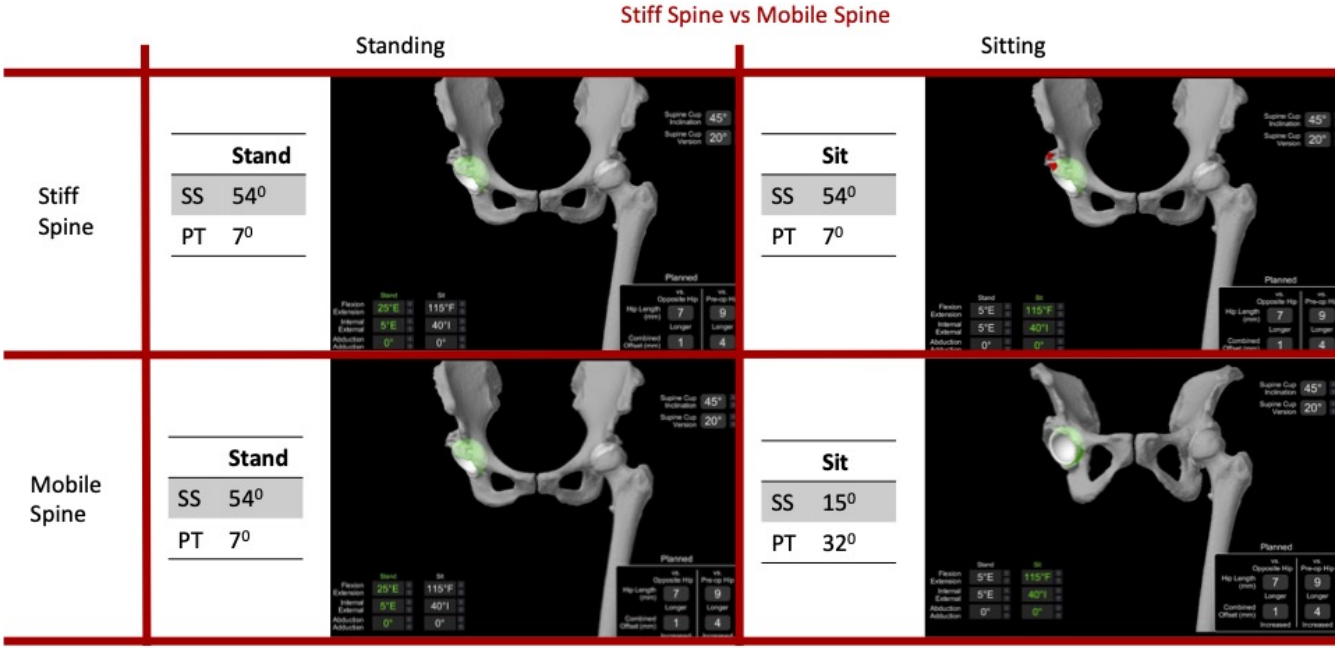

Fig. 3. Preoperative planning with spinopelvic parameters. Red indicates bone-bone or implant impingement. SS: sacral slope, PT: pelvic tilt.

applied in treatment of most patients with decreased spinopelvic motion (ΔSS ≤10° between sitting and standing). The caveat to this rule is the rare patient who is "stuck sitting". Patients in this cohort already have increased functional anteversion due to the posterior tilt of the APP; thus, excessive anteversion beyond 25° should be avoided[24]. Manual instrumentation of the acetabular component does not reliably enable such accurate positioning by the surgeon[25]. Some surgeons elect to use fluoroscopy for cup positioning; however, a lack of reliability for adjusting anteversion has been demonstrated[9]. In addition to restoring length and offset, some surgeons have considered the use of other techniques in the effort to improve stability, such as high offset stems or dual mobility bearings that allow for use of a head with a larger diameter[12]. A dual mobility bearing can be regarded as a useful option in treatment of patients with spinopelvic hypermobility (ΔSS ≥35° between sitting and standing).

NAVIGATION AND ROBOTICS IN TOTAL HIP ARTHROPLASTY

There are three main categories for THA navigation or robotic assistance: imageless, X-ray or fluoroscopy-based, and computed tomography (CT)-based (Table 2). Some of these simply provide an intraoperative evaluation of the position of the acetabular component, while others provide haptic feedback. X-ray or fluoroscopy-based systems utilize software intraoperatively for uploading images and calculating the cup orientation using an algorithm, similar to previously described methods[26]. Imageless systems require placement of pelvic arrays in the iliac crest allowing input of data regarding anatomic landmarks by the surgeon. Reliability can be skewed by human error during the data input phase, therefore meticulous input of landmarks is required. Anatomic landmarks are also required for reference when using the CT-based robotic arm system; however, these are designated on the preoperative CT scan and confirmed intraoperatively. In cases where the intraoperative osseous registration differs from the preoperative CT landmarks by more than 0.5 mm the system will require reregistration before proceeding. Haptic feedback is utilized intraoperatively to ensure that the preoperative plan is executed as accurately as possible. The haptic boundary allows a 15° cone of variation from the plan in each plane to ensure achievement of a concentric hemispherical ream. A three-dimensional (3D) model of the pelvis will illustrate the planned bone resection and which regions may require further reaming. The model will appear as red when reaming more than 1 mm past the plan and the haptic feedback will prevent reaming beyond 2.3 mm. Deviation beyond the stereotactic boundaries by the surgeon will cause activation of the fail-safe stop mechanism[27].

HISTORY OF ROBOTICS IN TOTAL HIP ARTHROPLASTY

The evolution of robotics in THA began with the introduction of the ROBODOC system in the late 1980s. ROBODOC, which was developed by Dr. William Bargar, his veterinarian partner, Dr. Howard Paul, and Integrated Surgical Systems, was the first active robotic system designed specifically for use in the field of orthopedic surgery. It utilized a computer-guided robotic arm to assist in preparation of femoral bone and implant placement during performance of THA, and

Table 2. Robotic and Navigation Systems

Type of guidance	Platform (company)	Features
X-ray/fluoroscopy	• Velys (DePuy) • ROSA (Zimmer-Biomet)	• Fluoroscopy: Yes • Pelvic arrays: No • Haptic feedback: No
Imageless	• Intellijoint (Intellijoint Surgical) • NaviPro Hip (Kinamed) • Real Intelligence Hip Navigation (Smith & Nephew) • NaviSwiss (NaviSwiss) • HipAlign (OrthAlign) • OrthoMap (Stryker)	• Fluoroscopy: No • Pelvic arrays: Yes • Haptic feedback: No
CT-based	• MAKO (Stryker)	• Fluoroscopy: No • Pelvic arrays: Yes • Haptic feedback: Yes

improved accuracy and precision were demonstrated in both laboratory and canine models prior to testing in human trials[28]. In the early 2000s, CASPAR (Computer Assisted Surgical Planning and Robotics) was introduced as another active robotic system for use in performance of THA. Similar to ROBODOC, this system integrated preoperative planning and intraoperative navigation for enhancement of femoral implant positioning. CASPAR showed variable precision and poor postoperative outcomes, demonstrating the challenges associated with use of early robotic systems[29].

ACROBOT (Active Constraint Robotic System), which was introduced in the mid-2000s as a semi-active robotic system for THA, utilized a combination of computer-guided navigation, anatomic registration, and a surgeon-guided robotic arm for optimization of implant stability and joint range of motion. Unlike its predecessors, ACROBOT provided real-time haptic feedback to surgeons during performance of implant positioning, resulting in similar accuracy and precision by comparison without significant time delay. An open platform was used, meaning that it can be utilized across multiple different implant companies. It was purchased by MAKO in 2013 due to patent infringement[30].

The MAKO robotic system has recently gained considerable popularity in performance of THA. As a semi-active robotic system, MAKO employs a robotic arm and a haptic guidance system to assist surgeons in preparation of acetabular and femoral bone as well as implant placement. It enables precise 3D modeling of the patient's anatomy, facilitating personalized sizing of components and restoration of hip biomechanics, bone coverage, component positioning, and correction of leg-length[31]. It provides intraoperative real-time assessment of leg length and hip offset, so that the surgeon can make decisions based on the desired changes in regard to these parameters and hip stability.

TSolution One, another advanced active robotic system utilized in performance of THA, combines technology designed for ROBODOC with modern advances, including preoperative planning, intraoperative navigation, and a robotic arm for optimizing implant placement of the acetabular and femoral components. TSolution One has received U.S. Food and Drug Administration (FDA) approval; however, its effectiveness has not been determined due to a lack of available studies[32].

X-RAY AND FLUOROSCOPY BASED NAVIGATION

The Velys Hip Navigation (DePuy) system, which provides intraoperative feedback via fluoroscopy, utilizes preoperative plain radiographs and intraoperative fluoroscopy to overlay the images and provide feedback regarding acetabular anteversion/inclination, leg length discrepancy (LLD), and offset. The recent addition of Cuptimize Hip-Spine Analysis software enables preoperative surgical planning while addressing the spinopelvic relationship. This system utilizes preoperative plain radiographs to input the spinopelvic parameters and provides a dynamic functional safe zone. This target safe zone is then recreated intraoperatively to the best of the surgeon's ability while using fluoroscopy. Because the system is based solely on fluoroscopy, there are no arrays or pins, which prevents the surgeon from utilizing live feedback for positioning of the implant. No literature regarding the use of Velys Hip Navigation is currently available.

The ROSA Hip System (Zimmer-Biomet) is another image-based system that only utilizes plain radiographs and fluoroscopy. Preoperative planning enables input of spinopelvic parameters for creation of a targeted safe zone. This system does not use arrays but requires intraoperative fluoroscopy for providing feedback. These fluoroscopic images are uploaded to the ROSA system during performance of surgery in order to obtain feedback regarding cup anteversion/inclination, offset, and LLD. No information regarding hip center of rotation (COR) and no haptic feedback is provided. The ROSA Hip System does not provide live feedback while reaming is being performed; however, it does provide feedback during final positioning of the implant to assist with placement of the acetabular component within the predetermined safe zone. Because it relies on fluoroscopy, this system has only been approved for use via an anterior approach, and it can only be used with Zimmer-Biomet implants.

ACCURACY AND REPRODUCIBILITY OF X-RAY BASED NAVIGATION

Although no randomized controlled trials utilizing X-ray based systems have been conducted, the findings of a matched-pair cadaveric study showed improved accuracy with regard to cup inclination and LLD when

compared with manual THA (mTHA) performed by 14 high-volume arthroplasty surgeons. No statistical difference in cup anteversion was observed between the ROSA Hip System and mTHA performed using fluoroscopy. Use of the ROSA system enabled placement of the cup in the Lewinnek safe zone 100% of the time compared to 73% for mTHA using fluoroscopy[33].

IMAGELESS NAVIGATION

Intellijoint (Intellijoint Surgical), an imageless system that utilizes arrays attached to the pelvis for creation of a three-dimensional model, requires anatomic landmarks designated by the surgeon intraoperatively for development of the surgical plan. It enables intraoperative feedback with regard to cup position, hip COR, LLD, and offset. This feedback can be used during reaming and final positioning of the implant. It does feature the option of inputting spinopelvic information preoperatively using plain radiographs, which provides a functional component position for intraoperative targeting by the surgeon. Calculation of both the SS and APP can be performed using this system, providing more information for use by the surgeon. It can be utilized when using either an anterior or posterior approach, and it can be used with any implant. It does not provide haptic feedback but does provide live information regarding the position of the acetabular component to assist the surgeon in replicating the preoperatively determined functional safe zone. Other imageless systems, including NaviPro Hip (Kinamed), Real Intelligence Hip Navigation (Smith & Nephew), NaviSwiss (NaviSwiss), HipAlign (OrthAlign), and OrthoMap (Stryker) function in a similar manner.

ACCURACY AND REPRODUCIBILITY OF IMAGELESS NAVIGATION

A meta-analysis was conducted for comparison of conventional THA with THA performed using imageless navigation. The analysis included 21 studies consisting of 10 randomized control trials, three prospective cohort trials, and eight retrospective cohort trials. No differences were observed between cup anteversion or inclination. Significantly less LLD was observed in the navigation group[34].

CLINICAL IMPLICATIONS WITH IMAGELESS NAVIGATION

A meta-analysis conducted by Migliorini et al.[34] for comparison of imageless navigation with mTHA reported that there were no differences between surgical duration, postoperative Harris hip score (HHS), and dislocation rate. A retrospective database review comparing traditional THA with THA performed using imageless navigation was published in March 2023. The main outcomes analyzed were 90-day adverse events and incidence of revision or dislocation after five years. The authors observed no improvement in clinical outcomes when using the imageless navigation system. A higher five-year rate of revision was observed in the navigation cohort (4.4% vs. 3.6%) and no difference in dislocation rates were observed at five years postoperatively. A secondary analysis reported significantly higher rates of wound dehiscence within 90 days in the imageless navigation cohort[35].

CT-BASED NAVIGATION

MAKO (Stryker), the most utilized FDA-approved CT-based navigation system, consists of a semi-active robotic arm that uses a preoperative CT scan to provide feedback to the surgeon both preoperatively and intraoperatively. Preoperatively, the CT images are uploaded to the MAKO Hip software and anatomic landmarks enable assessment of leg length, offset, 3D templating for cup size, anteversion, inclination, hip COR, and cup coverage/uncoverage. Preoperative lateral radiographs of the pelvis are used for inputting the spinopelvic parameters. Measurement of either the SS or PT can be performed by the surgeon, and calculation of the opposite will be performed by the software. This enables performance of a dynamic preoperative exam allowing the surgeon to take the hip through a virtual range of motion while applying the patient's spinopelvic parameters and assessing possible impingement (Fig. 3).

A preoperative plan involving calculation of native femoral version can be applied in specific cases for patients with abnormal proximal femoral pathology (i.e., previous slipped capital femoral epiphysis (SCFE)/fracture, dysplasia, Perthes, femoral acetabular impingement). For example, if there is an increase or decrease in the native femoral anteversion, the position of the

acetabular implant can be adjusted since a metaphyseal fitting stem can only safely adjust for 5°-10° of version[36]. If there is a significant increase (i.e., severe hip dysplasia) or decrease in the native femoral version, then the femoral implant can be addressed first and can be changed to a modular or cemented stem for control of version[37]. Numerous cases involving utilization of robotic-arm-assisted THA (rTHA) in complex THA such as developmental dysplasia of the hip, ankylosing spondylolysis, and post-traumatic arthritis have been reported. These reports have demonstrated excellent functional outcomes and improved positioning of the acetabular implant when compared with similar cases performed without navigation[38-43]. Fig. 4 shows an example of a complex case in a 17-year-old male with DiGeorge Syndrome and severe acetabular protrusio. The robotic arm can be used in performance of reverse reaming for impact grafting of the protrusio defect and for accurate recreation of the new medial wall.

Intraoperatively, MAKO utilizes pelvic arrays (Fig. 5) and does not require the use of fluoroscopy, thus it can be used with an anterior, anterolateral, or posterior approach. A probe is used for registration of bony landmarks, which enables the robotic arm to orient itself in space. It has only been FDA-approved for use with Stryker implants. Haptic feedback is utilized during reaming and cup impaction to ensure accurate execution of the preoperative plan. MAKO Hip also offers an option to assist with femoral preparation using Enhanced Femoral Workflow. The probe can be used in planning the neck cut and the femoral stem version can be tracked or adjusted during broaching.

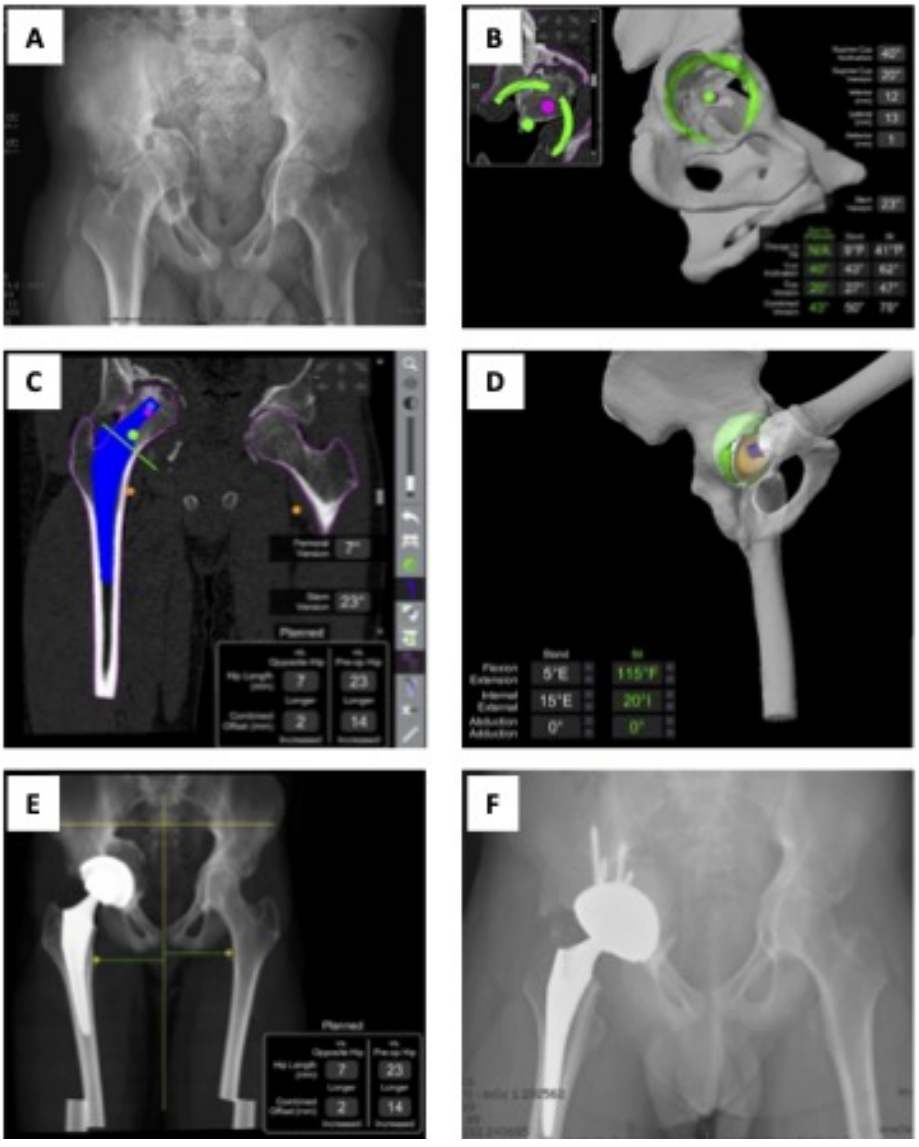

Fig. 4. Preoperative planning with postoperative radiograph. (A) Preoperative X-ray in a 17-year-old male with DiGeorge Syndrome. (B) Acetabular implant plan with planned impaction grafting of protrusio defect. (C) Femoral implant plan. (D) Virtual range of motion with impingement at 115° flexion and 20° internal rotation. (E) Virtual anteroposterior (AP) pelvis X-ray. (F) Clinical 6-week postoperative AP pelvis X-ray.

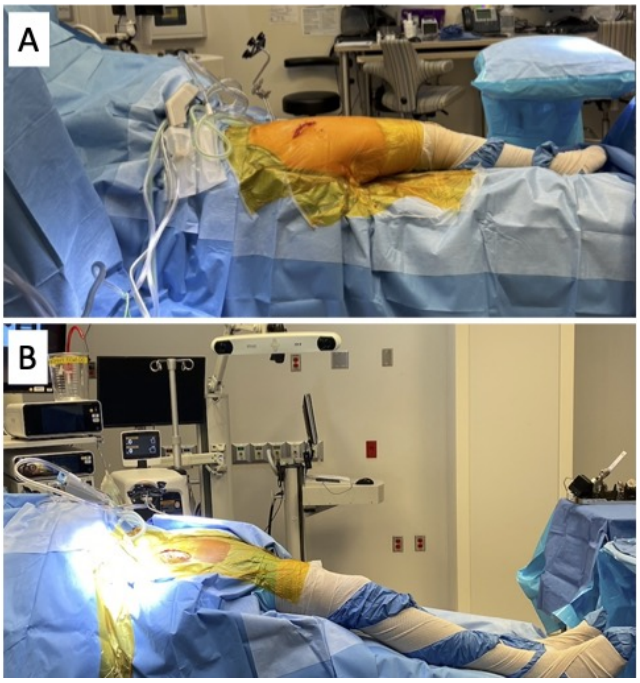

Fig. 5. Intraoperative set up for posterior total hip arthroplasty (THA) with patient in the lateral decubitus position (A) and anterior THA in the supine position (B).

ACCURACY AND REPRODUCIBILITY OF CT-BASED NAVIGATION

The accuracy of executing the preoperative plan has been demonstrated in multiple studies[44,45]. According to these articles, a significantly greater number of components were placed in the safe zone when compared with implants positioned using fluoroscopy or imageless navigation systems. In fact, 95% of the acetabular implants were placed within 3.5° of the planned position[46]. A separate study reported that use of the MAKO System enabled more consistent placement of the acetabular component within the Lewinnek safe zone (100% robotic vs. 80% manual) and Callanan safe zone (92% robotic vs. 62% manual)[25]. This difference is even more pronounced when comparing cases performed by a surgeon who is early in training. A retrospective cohort study evaluated the rate of acetabular component placement within the Lewinnek safe zones among the first 100 mTHAs, the last 100 mTHAs, and the first 100 rTHA performed by a single experienced surgeon. The authors reported that rTHA was the most successful, followed by the last 100 mTHAs and the first 100 mTHAs (77%, 45%, and 30%, respectively)[47]. The same accuracy has been demonstrated for hip COR, leg length, and offset[48] and remains consistent even in obese patients[49]. This precision and accuracy can even be achieved by less-experienced surgeons, which was demonstrated in a comparison of manual versus rTHA performed by orthopaedic surgery fellows. Significantly greater accuracy and precision in regard to version of the acetabular component, inclination, and LLD was demonstrated in these cadaveric studies[50].

CLINICAL IMPLICATIONS WITH CT-BASED NAVIGATION

In addition to implant position, other benefits of CT-based rTHA have also been described. Suarez-Ahedo et al.[51] used the acetabular cup size relative to the native femoral head size as a surrogate for measurement of acetabular bone resection in rTHA versus mTHA. They reported significantly smaller ratios in the robotic-arm-assisted cohort, indicating greater preservation of acetabular bone stock[51].

Opponents of rTHA often cite the potential for added surgical time, cost, and lack of clinical benefit. Regarding operative duration and learning curve, Redmond et al.[52] evaluated the first 105 rTHAs performed by a single surgeon. Operative time decreased after the first 35 cases (63 minutes vs. 80 minutes). There was no learning curve in regard to implant position, LLD, technical problems, or complications within this cohort[52]. This benefit of decreased operative time was also demonstrated by Heng et al.[53], who conducted a retrospective comparison of the last 45 mTHAs with the first 45 rTHAs performed by a single surgeon. The average surgical time was approximately 12 minutes longer in the rTHA cohort (96.7 minutes vs. 84.9 minutes); however, after 35 cases the average time in the rTHA cohort was reduced to 82.9 minutes[53]. Another study examining the learning curve with rTHA showed that a decrease of operative time started to occur after 14 cases; however, no improvement in operative time was observed beyond mTHA until after 85 cases[54]. A systematic review published in 2021 reported a learning curve for rTHA of 12-35 cases[55]. The improvements in operative time can likely be attributed to the single-ream system, where only the final size acetabular reamer is utilized instead of sequential reaming used in mTHA.

Multiple studies have reported on the clinical benefit of rTHA or the lack thereof. These studies are often

fraught with bias, including industry, confounding, selection, experience, etc. Bukowski et al.[56] reported higher HHS in a comparison of unmatched rTHA with mTHA (92 vs. 86, respectively); however, this result failed to meet MCID for the HHS, which is 16-18 in THA[56,57]. In a similar manner, the results of matched analyses have shown statistically significant improvements in the Forgotten Joint Score (FJS-12) for rTHA versus manual (80 vs. 69) without reaching MCID (17.5)[58,59]. This same cohort was followed for a minimum of five years, and although statistical significance was demonstrated, there was no clinically significant difference in the HHS, FJS-12, visual analog scale, satisfaction, Veterans RAND-12 (VR-12), or Short Form Health Qustionnaire-12 (SF-12). Similar revision rates were also observed[60]. A meta-analysis of comparative studies reported better radiographic outcomes and fewer intraoperative complications in rTHA compared to mTHA, but no difference in functional outcomes[61].

By contrast, a prospective matched study reported a difference at 12-months postoperative in FJS by 21 points in favor of the rTHA cohort, which reached MCID[62]. A large retrospective review of more than 13,000 patients comparing one-year revision rates among patients who underwent posterior THA performed using robotic navigation, imageless navigation, or manual instrumentation was recently published. Patients were matched using a propensity score based on age, gender, body mass index, femoral cementation, history of spine fusion, and Charlson comorbidity index. No difference in overall complication rates was observed among the groups. A lower re-operation rate for dislocation was observed in the rTHA group compared with mTHA (odds ratio [OR], 0.3). The OR for imageless navigation was 0.8 when compared with manual; however, OR was 3.0 when compared with rTHA. The mean operative time was shorter in the mTHA cohort compared with imageless navigation and rTHA (77 minutes, 85 minutes, 94 minutes, respectively)[63]. Another retrospective study using multivariate regression analysis reported similar findings with a lower rate of dislocation in the rTHA cohort compared with mTHA (0.6% and 2.5%, respectively), but no difference in patient reported outcomes or other early complications[64]. Illgen et al.[47] reported on the two-year outcomes of the first 100 mTHAs, the last 100 mTHAs, and the first consecutive 100 rTHAs performed by a single surgeon. Dislocation rates were 5% in the early mTHA group, 3% in the late THA group, and 0% in the rTHA group. No difference in infection rates was observed between groups[47]. The decreased risk of dislocation and potential improvement in patient reported outcomes is likely a result of change in cup position when accounting for spinopelvic motion and the functional safe zone for each patient.

While extensive study of the impact of rTHA on postoperative trochanteric bursitis has not been conducted, it can be inferred that improved restoration of hip biomechanics such as offset would lower the risk. King et al.[65], who compared rates of postoperative trochanteric bursitis among mTHA and rTHA, reported a decreased rate in rTHA (10.4% vs. 21%) and a decreased rate of trochanteric bursa injections postoperatively. This article reported on a consecutive cohort study of all mTHAs performed by a single surgeon using a posterior approach 12 months prior to the use of robotics compared to all rTHAs performed during the first 12 months after the complete conversion to rTHA[65].

COST ANALYSIS

The initial investment, maintenance, and disposables (pins, discs, markers, and drapes) are direct costs associated with rTHA. The cost of procuring a robot can range from $700,000 to $1.25 million and an annual service contract is often required[66,67]. Indirect costs include operative time, revision rates, complications, length of hospital stay, discharge disposition, and rehabilitation. A Medicare analysis of the 90-day episode of care comparing 938 rTHAs matched with 4,670 mTHAs reported that patients who underwent rTHA were significantly less likely to require admission to inpatient rehabilitation or skilled nursing facilities and used fewer home health agency visits. Total 90-day episode of care costs were $785 less than that for mTHA[68]. Multiple similar studies also demonstrating this benefit in the private payor and Medicare systems reported a decrease of $1,573-$1,810 and $945 for rTHA, respectively[69,70]. Perets et al.[58] reported that average post-index costs were 12% lower for rTHA compared with mTHA. Disposables represent a large portion of the cost of rTHA, however, these costs can be decreased, to a certain extent, on a surgeon-by-surgeon basis. For example, when utilizing MAKO in performance of rTHA, some of the screws and checkpoints can be omitted and a fixed point can instead be used on the pelvic array or proximal femur. The surgeon can also elect to use two pins for the pel-

vic array instead of three. The minimum disposables required for performance of a MAKO rTHA would include a drape for the robotic arm, two pins, and a package of sterile discs for the array. While these adaptions are off label, they allow the surgeon to cut costs significantly for every case, adding up over time.

IMPACT ON THE SURGICAL TEAM

Robotic THA can also benefit the surgeon in regard to ergonomics and workload demand. Cadaveric studies have demonstrated that there is less energy expenditure during performance of acetabular reaming and impaction when using Mako rTHA compared with mTHA. The surgeons in the study also reported less mental demand during reaming with rTHA[71]. For example, during performance of a posterior approach to the hip, the table can be tilted towards the surgeon, if standing behind the patient, so that the surgeon does not have to lean over during acetabular exposure, reaming, and implantation. In a similar manner, during performance of an anterior approach, the table can be tilted away from the surgeon resulting in less strain on the physician. The combination of CT-based guidance, pelvic arrays, and haptic feedback enables ergonomic positioning of the patient, allowing easier access for the surgeon.

CONCLUSION

Technology in the field of arthroplasty has been a recent endeavor in the effort to improve patient outcomes. There are many options for navigation that can be utilized in performance of THA, while only a small number of robotic platforms have been FDA-approved. Utilization of these tools in performance of THA in the operating room and during the perioperative period has met with some resistance due to increased cost, learning curves, and time constraints without clear-cut long-term evidence to support their outright adaption. The touted increased time requirement appears to become negligible after the learning curve has been surpassed, usually averaging around 35 cases. After reaching this threshold, procedures can be performed even more rapidly than with use of manual instrumentation. Costs can be mitigated by safely decreasing the number of disposables used and practicing efficiency in the operating room in order to save on indirect costs. Patient safety, which is of the utmost importance, does not appear to be compromised with the use of robotic navigation. Early data on rTHA showed a decreased risk of dislocation with noninferior patient-reported outcomes when compared with mTHA. It appears that patients with abnormal spinopelvic motion resulting from concomitant lumbar spine pathology receive the greatest benefit. Future studies should focus on conduct of randomized controlled trials and number-needed-to-treat analyses for rTHA in the effort to reduce the risk of dislocation.

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Conflict of Interest

One of the authors (H.H.L.) has a potential or pertinent conflict of interest and reports a consultancy with Stryker. No other potential conflict of interest relevant to this article was reported.

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