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Accuracy of Component Positioning in 1980 Total Hip Arthroplasties: A Comparative Analysis by Surgical Technique and Mode of Guidance

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ABSTRACT

The purpose of this multi-surgeon study was to assess and compare the accuracy of acetabular component placement, leg length discrepancy (LLD), and global offset difference (GOD) between six different surgical techniques and modes of guidance in total hip arthroplasty (THA). A total of 1980 THAs met inclusion criteria. Robotic- and navigation-guided techniques were more consistent than other techniques in placing the acetabular cup into Lewinnek's safe zone ($P<0.005$ and $P<0.05$, respectively). Robotic-guided surgery was more consistent than other techniques in placing the acetabular component within Callanan's safe zone ($P<0.005$). No statistically significant differences were found between groups in the frequency of patients with excessive LLD. Clinically significant differences between groups were not found in the frequency of patients with excessive GOD. Level of Evidence: IV

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Performing a functional hip arthroplasty is challenging, as it depends on the surgical technique used, method of guidance, and patient characteristics [1–9]. Accurate restoration of hip biomechanics in THA requires proper implantation of the cup, as well as appropriate leg length (LL) and global offset (GO) in relation to the patient's parameters [10–12]. Improper component position is associated with higher rates of complications, such as accelerated weight-bearing surface wear [1–13], hip dislocations [3–5,14–16], and LLD [17–19], which may resulting in hip instability [10,20].

Many methods and guidelines have been used to gauge the accuracy of component positioning. Some of the most common, although not without critics, are the safe zones described by Callanan et al [4] and Lewinnek et al [5]. The term "safe-zone" was introduced by Lewinnek et al in 1978 based on the clinical observation that less dislocation occurred when the acetabular cup was placed within 30° to 50° of abduction and 5° to 25° of anteversion [5].

Dislocation is the primary indication reported for 22.5% of revision THAs and 33% of acetabular revisions [21]. LLD is one of the most common causes of medical litigation in orthopedic surgery in the United States [22–24] and may contribute to back pain [25–27], limping [12,28], and dislocation [3–6,14–16,28]. Furthermore, failure to restore GO may contribute to gait disorders, increased wear, and pain [1,2,13,29,30].

Multiple guidance modalities have been developed to improve the accuracy and consistency of component placement in THA, and multiple surgical techniques have been successfully employed [6,31–40]. Guidance modalities include robotic guidance, navigation guidance and intraoperative fluoroscopy. All have been developed with the goal of improving the acetabular component position, as well as maintaining adequate LL and GO [6,31–40]. The purpose of this multi-surgeon study was to assess the accuracy of acetabular component placement, LLD, and GOD in THA and to perform a comparative analysis by surgical approach and mode of guidance. As the study methodology was a retrospective review of acetabular cup placement, our study does not provide an assessment of patient-reported outcomes.

One or more of the authors of this paper have disclosed potential or pertinent conflicts of interest, which may include receipt of payment, either direct or indirect, institutional support, or association with an entity in the biomedical field which may be perceived to have potential conflict of interest with this work. For full disclosure statements refer to http://dx.doi.org/10.1016/j.arth.2015.06.059.

All nine authors were vital for this manuscript as this was a collaborative effort of several surgeons. Dr. Benjamin Domb headed the study at his institute and was response for both writing and revision, as well as the initial study idea. Dr. Carlos Suarez-Ahedo was vital for preparation of the manuscript, analysis of the data, and revision of the manuscript. Dr. Redmond assisted in creating the idea and writing the manuscript as well as revision. Dr. Louis, Dr. Alden, Dr. Daley, and Dr. LaReau were involved with the idea for the manuscript, data collection (as they performed many of the surgeries in the paper) and for revision of the final manuscript. Ms. Petrakos and Mr. Gui did extensive data analysis and data collection, as well as revision of the manuscript. All authors played a major role in this paper.

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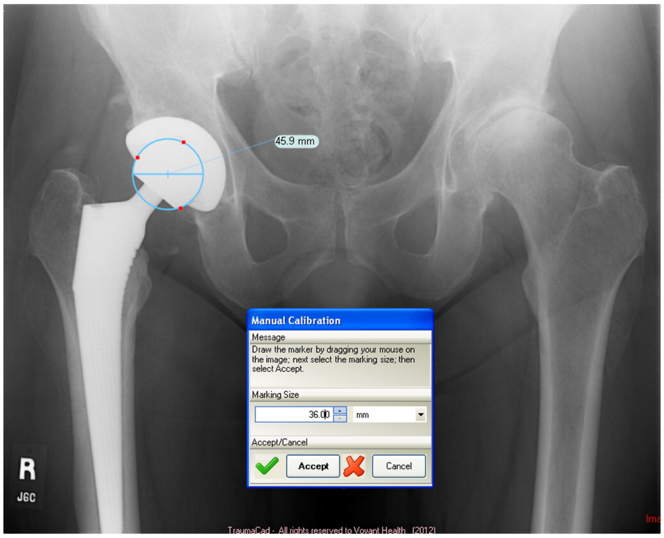

Manual Calibration

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Fig. 1. Calibration of the AP pelvis view radiographs.

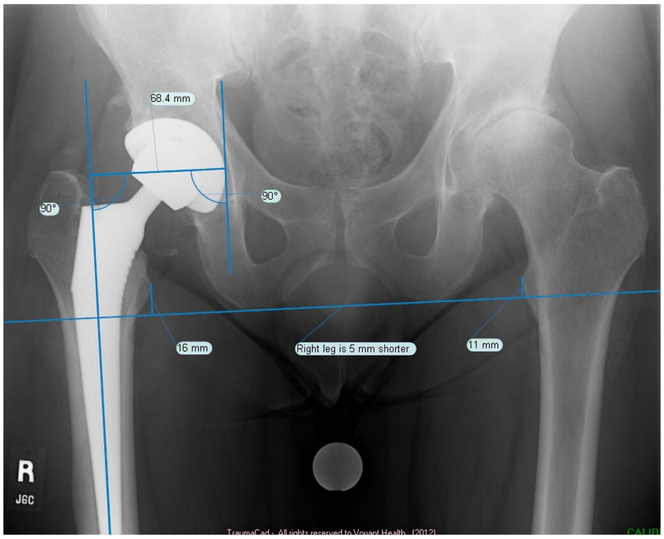

Fig. 3. Leg length discrepancy (LLD) and global offset (GO) measurements.

Materials and Methods

Between June 2008 and April 2014, THAs were performed by six surgeons at a single institution. The six modes of guidance were conventional posterior THA (CP-THA), intraoperative x-ray guided posterior THA (XP-THA), fluoroscopy-guided anterior THA (FA-THA), navigation-guided anterior THA (NA-THA), robotic-guided posterior THA (RP-THA), and robotic-guided anterior THA (RA-THA). Radiographic images from all patients were retrospectively measured using the TraumaCad® software for cup placement, LLD, and GOD. Cases with inadequate radiographic images were excluded from the study cohort. For a subset of one hundred cases, radiographic measurements were performed by two different blinded observers. Intraobserver and interobserver correlation and reliability were calculated ($r > 0.82$ and $P < 0.001$).

Patients were excluded if appropriately centered anteroposterior radiographic images of the pelvis were not of adequate quality. Specifically, we excluded patients whose post-operative AP pelvis radiographs were rotated, indicated a tilted pelvis, or where at least one lesser trochanter was hard to define.

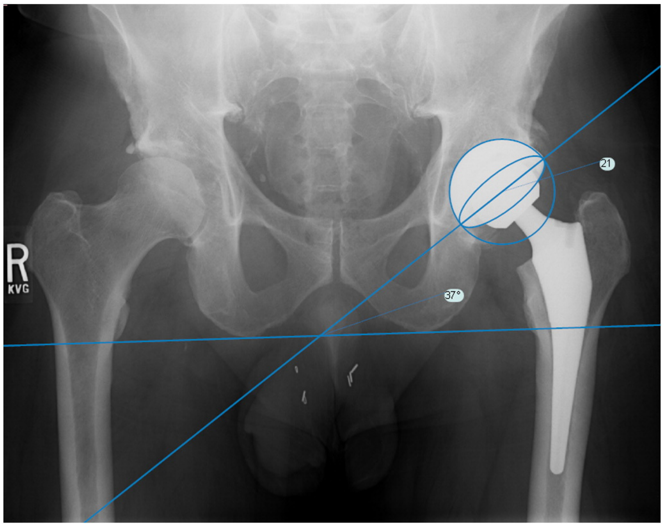

Fig. 2. Cup anteversion and inclination measurements.

Radiographic Measurements

The Trauma-Cad™ software (build number 2.2.535.0, Voyant Health®, 2012) was used to perform the radiographic measurements including acetabular cup inclination and version, LLD and GO on the AP view of the pelvis. All radiographs were calibrated using this software before performing any measurements. All patients underwent preoperative radiographs to plan component position and sizes, level of the neck cut, and amount of LL and GO. The use of this software in measuring parameters on radiographs has been validated in several studies [41–43] (Fig. 1).

For acetabular cup version and inclination, the software created a horizontal reference line along the inferior aspect of the pelvic inter-ischial line. The system also created a complex of lines comprising a sphere, a concentric ellipse, and a bisecting line that bisected the ellipse along its long axis. The lines that make up this complex could be manipulated individually, but their relation to each other remained unchanged. The sphere was then manipulated to fit the circumference of the acetabular cup, and the ellipse to fit the opening of the cup. The relative ratio of the axes of the ellipse gave the version angle of the cup. The angle formed by the bisecting line and the inter-ischial reference line shows the inclination angle of the cup (Fig. 2).

For LLD measurements, the program created a complex of three lines: one horizontal line and two vertical lines each perpendicular to that horizontal line. All three lines were connected in a way to ensure

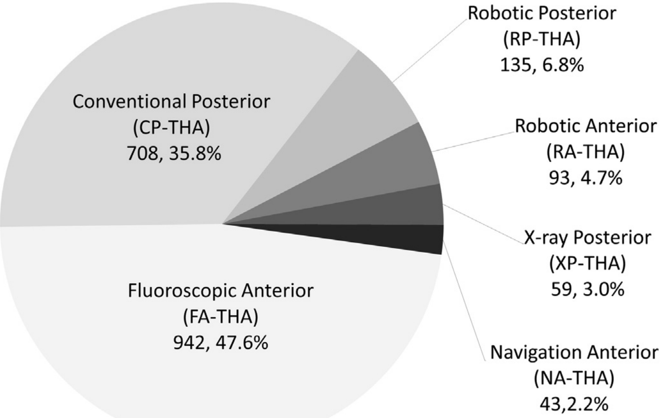

Fig. 4. Number of patients in each treatment group.

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Table 1
Age of Patients (Years) for Each Surgical Modality.

	Conventional (CP-THA)	X-ray (XP-THA)	Fluoroscopic (FA-THA)	Navigation (NA-THA)	Robotic Posterior (RP-THA)	Robotic Anterior (RA-THA)	All
Mean	64.75	67.45	63.86	64.72	58.68	59.60	63.76
SD	11.99	16.34	12.13	11.47	10.82	10.98	12.22
Min.	−16.17	−9.84	−16.83	46.16	25.63	0.09	−16.83
Max.	109.23	90.26	114.12	83.89	90.54	84.85	114.12
Count	708	59	942	43	135	93	1980
ANOVA *P*-value:				1.5×10^{-8}			

that the two vertical lines were always perpendicular to the horizontal line. The horizontal line was positioned along the inferior border of the pelvic ischia, and the tip of each vertical line placed at the level of the most supero-medial point of the two lesser trochanters. The LLD was measured as the difference in lengths from the horizontal line to the lesser trochanter of the operative side and to the lesser trochanter of the non-operative side (Fig. 3).

For the GO measurements, a vertical line through the middle of the femoral canal of the ipsilateral hip was formed. Another line, parallel to the femoral canal line, was formed and placed tangent to teardrop on the ipsilateral side. The distance between those two lines, crossing the center of the femoral, was the GO of the hip [23] (Fig. 3). GOD was defined as the difference (absolute value) in GO of the operative and non-operative sides.

This system could not differentiate between anteversion and retroversion. For version measurement, the cross-table lateral radiographs of all patients were reviewed using the Woo and Morrey [44] technique to ensure they were anteverted. Radiographic data for LLD, GOD, and cup anteversion and inclination were collected in a blinded fashion.

Surgical Techniques

In all surgical modes, the surgeons aimed to place the acetabular component at 40° of inclination and 20° of version.

Conventional Posterior THA (CP-THA)

CP-THA is performed using the standard posterior approach with the patient in lateral decubitus position [45]. The acetabular components are placed using an alignment guide, which provides an estimate of inclination and anteversion. The transverse ligament of the acetabulum, anterior walls, and posterior acetabular walls are used in conjunction with the alignment guide to help assess the acetabular cup position.

Intraoperative X-Ray Guided Posterior THA (XP-THA)

XP-THA was performed with the same conventional posterior approach. Intraoperative x-ray was performed after component placement.

Fluoroscopic-Guided Anterior THA (FA-THA)

FA-THA is performed with patients in the supine position on a radiolucent operating table as described by Matta et al [46]. After exposure and femoral cut, the acetabulum is exposed and reaming begins. The acetabular cup is positioned with fluoroscopic guidance. On the femoral side, fluoroscopy is used to ensure the broaches are centralized. A trial reduction is done. The fluoroscope is used to assess LL and GO. Then the final components are placed.

Table 2
Significant and Non-Significant Differences in Age Among the Surgical Modalities, Calculated Using Tukey–Kramer Post-Hoc Test, With Significance Defined as $P < 0.05$.

	Conventional (CP–THA)	X–ray (XP–THA)	Fluoroscopic (FA–THA)	Navigation (NA–THA)	Robotic posterior (RP–THA)	Robotic anterior (RA–THA)
Conventional		>0.05	>0.05	>0.05	<0.05	<0.05
X–ray	>0.05		>0.05	>0.05	<0.05	<0.05
Fluoroscopic	>0.05	>0.05		>0.05	<0.05	<0.05
Navigation	>0.05	>0.05	>0.05		<0.05	>0.05*
Robotic posterior	<0.05	<0.05	<0.05	<0.05		>0.05*
Robotic anterior	<0.05	<0.05	<0.05	>0.05*	>0.05*	

*Indicates power ≥0.8 for comparisons that do not show significant differences.

Navigation-Guided Anterior THA (NA-THA)

NA-THA is performed through an anterior approach with patients in the supine position. Computer tomography (CT) guided component placement was performed the CT-based module of the VectorVision Hip 3.0 system (BrainLAB, Heimstetten, Germany). Only one image-free navigation system was used (BrainLAB).

Robotic-Guided Posterior THA (RP-THA)

RP-THA was performed with the MAKOplasty® Total Hip Application (MAKO Surgical Corp.®, Fort Lauderdale, FL, USA). It is based on a three-dimensional model of the patient's hip, reconstructed from CT.

The first step in RP-THA is to place three pelvic threaded pins into the thickest portion of the ipsilateral iliac crest to hold the pelvic array. The array allows the robot camera to visualize the exact 3D orientation of the pelvis.

RP-THA is performed with patients in the lateral position using the standard posterior approach, as described by Domb et al [6]. After exposure, femoral registration is performed and verified by the system. A registration error of more than 1 mm indicates that the verification process failed and the femur must be re-registered. Once the femoral neck cut is completed, registration and verification are performed and the acetabulum is reamed for cup placement. A haptic robotic arm guided acetabular reaming and cup placement, stem version, LL, and GO.

Robotic-Guided Anterior THA (RA-THA)

RA-THA is performed with patients in the supine position in a special radiolucent fracture table using the anterior approach described by Matta et al [46]. RA-THA requires three pelvic threaded pins to be placed in the thickest portion of the contralateral iliac crest to hold the pelvic arrays. The femoral registration and verification is performed, and if the system does not detect errors in the registration, the surgeon proceeds to make the femoral neck cut based on the registration and verification of the acetabulum.

Statistical Analysis

Mean inclination and version angles, LLD, and GO were calculated for the six modalities. We calculated the number of hips in each group that were in the safe zones described by Lewinnek et al (30°–50° inclination and 5°–25° version) and Callanan et al (30°–45° inclination and 5°–25° version). We also calculated the number of hips in each group with LLD and GOD ≤10 mm. Categorical data, such as the number of hips in the safe zones, were compared among groups using χ^2 test, with the Yates correction for small sample size, where applicable. Continuous data, such as LLD and GOD, were compared among groups using ANOVA and the Tukey–Kramer post-hoc test. Differences in variance between groups were assessed using Levene's test. Uncertainties were reported as standard deviations. We consider *P*-values less than 0.05 to be significant. Institutional review board approval was received for this study.

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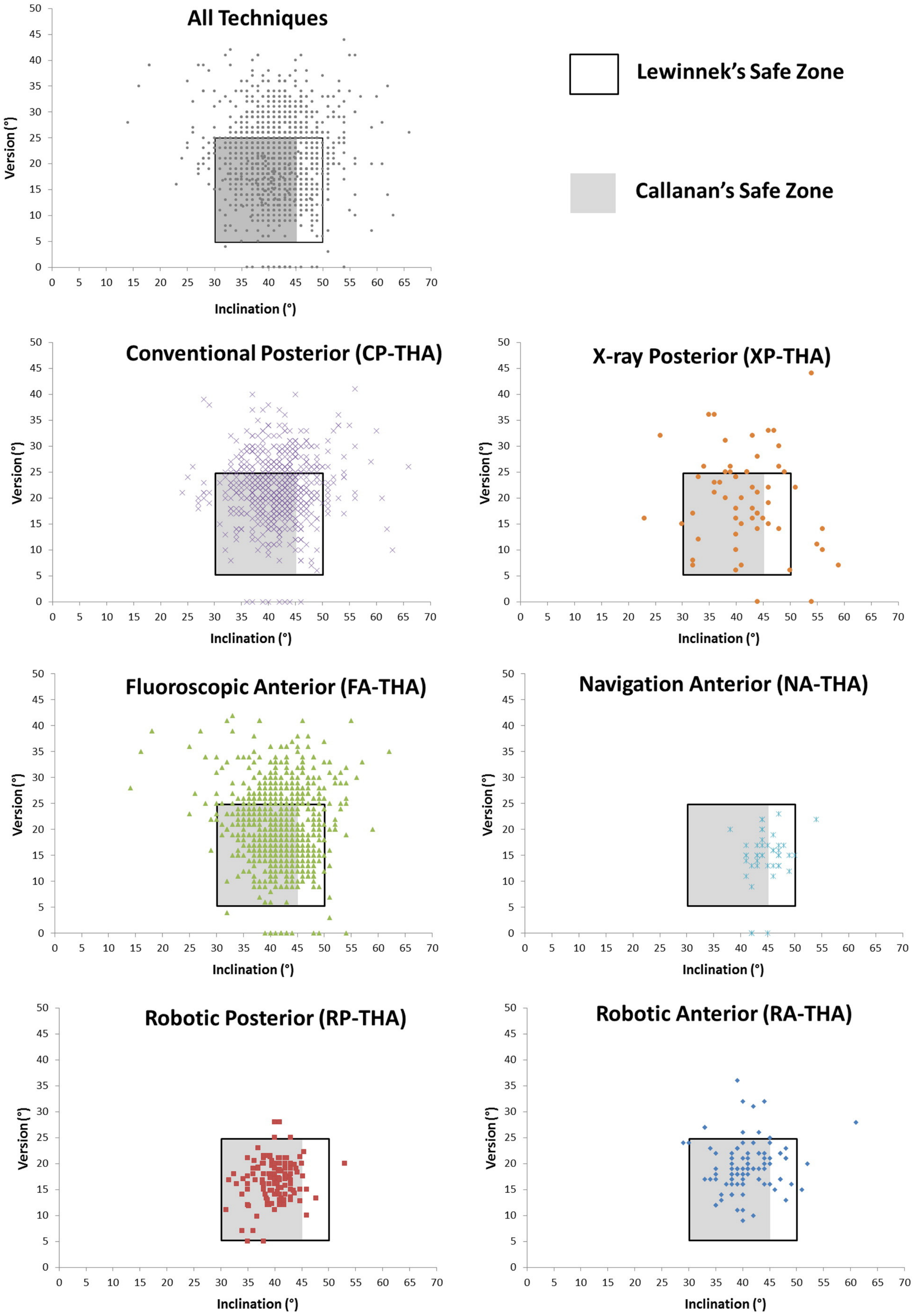

Fig. 5. Distribution of cup inclination and version in relation to Lewinnek's and Callanan's safe zones, for each treatment group.

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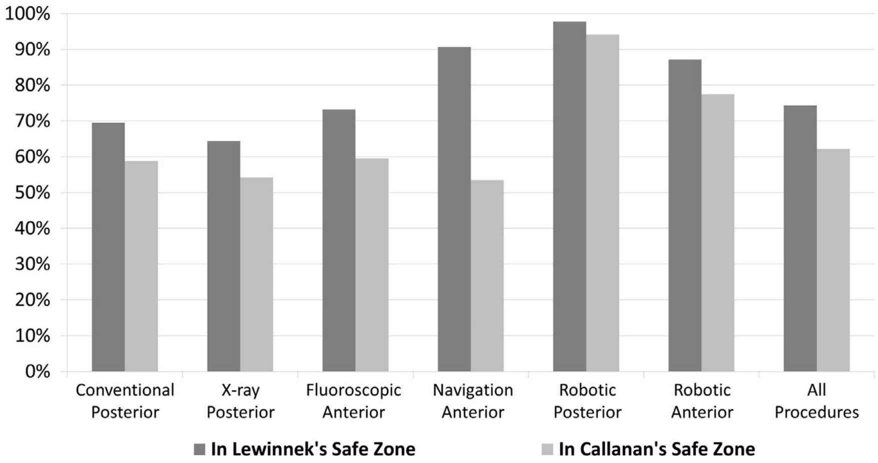

Fig. 6. Percentage of patients in each treatment group with cup position in Lewinnek's and Callanan's safe zones. Corresponding *P*-values for comparisons between groups are reported in Tables 4 and 5.

Table 3
Number of Cases for Each Surgical Modality With Acetabular Cup Placement in Lewinnek's and Callanan's Safe Zones.

	Conventional (CP-THA)	X-ray (XP-THA)	Fluoroscopic (FA-THA)	Navigation (NA-THA)	Robotic Posterior (RP-THA)	Robotic Anterior (RA-THA)	All
Total	708	59	942	43	135	93	1980
In Lewinnek's safe zone	492 (69.49%)	38 (64.41%)	689 (73.14%)	39 (90.70%)	132 (97.78%)	81 (87.10%)	1471 (74.29%)
In Callanan's safe zone	416 (58.76%)	32 (54.24%)	561 (59.55%)	23 (53.49%)	127 (94.07%)	72 (77.42%)	1231 (62.17%)

Table 4
P-values Indicating Significant and Non-Significant Differences Among the Surgical Modalities in Percentage of Cases With Cup Placement in Lewinnek's Safe Zone.

	Conventional (CP-THA)	X-ray (XP-THA)	Fluoroscopic (FA-THA)	Navigation (NA-THA)	Robotic Posterior (RP-THA)	Robotic Anterior (RA-THA)
Conventional		0.42*	0.10*	0.005	<0.0001	0.0004
X-ray	0.42*		0.14*	0.002	<0.0001	0.0009
Fluoroscopic	0.10*	0.14*		0.01	<0.0001	0.003
Navigation	0.005	0.002	0.01		0.10*	0.54
Robotic posterior	<0.0001	<0.0001	<0.0001	0.10*		0.001
Robotic anterior	0.0004	0.0009	0.003	0.54	0.001	

* Indicate power ≥0.8 for comparisons that do not show significant differences.

Results

After evaluating 2330 radiographs from THAs performed during the study period, 1980 patients constituted our cohort, and 350 were excluded due to inadequate radiographic images. The procedures listed from most frequent to least frequent were: FA-THA (942, 47.5%), CP-THA (708, 35.7%), RP-THA (135, 6.8%), RA-THA (93, 4.69%), XP-THA (59, 2.97%), and NA-THA (32, 2.17%) (Fig. 4).

ANOVA indicated significant differences in age between groups ($P < 0.0001$) (Table 1). The mean age of patients with RP-THA and RA-THA was four to six years lower than the age of patients treated without robotic guidance ($P < 0.05$, except RA-THA versus NA-THA) (Tables 1 and 2).

Postoperative inclination and version were evaluated in terms of the safe zones described by Lewinnek et al and Callanan et al (Figs. 5 and 6). RP-THA and RA-THA resulted in a significantly greater percentage of cups placed in Lewinnek's safe zone than FA-THA, CP-THA, XP-THA ($P < 0.005$) (Tables 3 and 4). RP-THA and RA-THA also resulted in a significantly greater percentage of patients in Callanan's safe zone than all other groups ($P < 0.0005$) (Tables 3 and 5). The frequency of cups placed in Callanan's and Lewinnek's safe zones was significantly greater for RP-THA compared to RA-THA ($P < 0.005$) (Tables 3, 4, and 5). The frequency of cups placed in Lewinnek's safe zone was significantly greater for NA-THA compared to FA-THA, CP-THA, or XP-THA ($P < 0.05$) (Tables 3 and 4). ANOVA indicated significant differences in both inclination and version between treatment groups ($P < 0.0001$) (Tables 6 and 7).

The mean inclination and version of the overall cohort were 42° and 20°, respectively (Figs. 7 and 8). We compared the standard deviations of inclination and version between groups (Tables 8 and 9; Fig. 9).

Table 5
P-Values Indicating Significant and Non-Significant Differences Among the Surgical Modalities in Percentage of Cases With Cup Placement in Callanan's Safe Zone.

	Conventional (CP-THA)	X-ray (XP-THA)	Fluoroscopic (FA-THA)	Navigation (NA-THA)	Robotic Posterior (RP-THA)	Robotic Anterior (RA-THA)
Conventional		0.50	0.74	0.50*	<0.0001	0.0005
X-ray	0.50		0.42*	0.94	<0.0001	0.003
Fluoroscopic	0.74	0.42*		0.43*	<0.0001	0.0007
Navigation	0.50*	0.94	0.43*		<0.0001	0.005
Robotic posterior	<0.0001	<0.0001	<0.0001	<0.0001		0.0002
Robotic anterior	0.0005	0.003	0.0007	0.005	0.0002	

* Indicates power ≥0.8 for comparisons that do not show significant differences.

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Table 6
Inclination of Hips (°) for Each Surgical Modality.

	Conventional (CP-THA)	X-ray (XP-THA)	Fluoroscopic (FA-THA)	Navigation (NA-THA)	Robotic Posterior (RP-THA)	Robotic Anterior (RA-THA)	All
Mean	41.72	41.93	41.95	44.70	40.13	40.78	41.74
SD	5.27	7.29	5.07	2.93	3.33	4.88	5.12
Min.	24.00	23.00	14.00	38.00	31.00	29.00	14.00
Max.	66.00	59.00	62.00	54.00	53.00	61.00	66.00
Count	708	59	942	43	135	93	1981
ANOVA *P*-value:				4.1×10^{-6}			

Table 7
Version of Hips (°) for Each Surgical Modality.

	Conventional (CP-THA)	X-ray (XP-THA)	Fluoroscopic (FA-THA)	Navigation (NA-THA)	Robotic Posterior (RP-THA)	Robotic Anterior (RA-THA)	All
Mean	21.83	19.63	20.35	14.77	16.91	19.44	20.46
SD	6.09	9.04	7.18	5.09	3.87	4.81	6.72
Min.	0.00	0.00	0.00	0.00	5.00	9.00	0.00
Max.	41.00	44.00	42.00	23.00	28.00	36.00	44.00
Count	708	59	942	43	135	93	1981
ANOVA *P*-value:				9.7×10^{-21}			

XP-THA had significantly greater standard deviations of inclination and version than all other groups ($P < 0.01$) (Tables 8 and 9). RP-THA and NA-THA had a significantly smaller standard deviation of inclination than all other groups ($P < 0.02$) (Table 8). NA-THA, RP-THA, and RA-THA had significantly smaller standard deviation of version than all other groups ($P < 0.05$) (Table 9).

Over 97% of cases had postoperative LLD ≤10 mm (Table 10; Fig. 10). There were no significant differences in the frequency of cases with LLD ≤ 10 mm between groups (Table 11). However, ANOVA did reveal significant differences in mean LLD among groups ($P < 0.0001$) (Table 12). FA-THA and NA-THA had significantly smaller LLD than CP-THA, XP-THA, and RA-THA ($P < 0.05$) (Tables 12 and 13).

Over 85% of cases had postoperative GOD ≤10 mm (Table 14; Fig. 10). RP-THA had significantly fewer cases with GOD ≤10 mm than FA-THA, NA-THA, or RA-THA ($P < 0.05$) (Table 15). FA-THA had significantly more cases with GOD ≥10 mm than CP-THA. Although ANOVA indicated significant differences in mean GOD among groups ($P < 0.0001$), there were only two instances of slightly significant differences: the mean GOD for CP-THA was significantly greater than the mean GOD for FA-THA and NA-THA (Tables 16 and 17).

We performed post-hoc power analyses to determine whether we had sufficient power to show a lack of significant difference when comparing treatment groups. Results demonstrating sufficient power are indicated by asterisks in Tables 2, 4, 5, 11, 15, 17, 18, and 19. Some comparisons did not have sufficient power, especially those with relative small sample sizes and very similar outcome measures.

Discussion

Robotic guidance resulted in a significantly greater percentage of components placed in Lewinnek's and Callanan's safe zones than all other modalities except navigation ($P < 0.005$). Navigation had a higher frequency of cups within Lewinnek's safe zone than all other modalities except for robotic guidance ($P < 0.05$). Forty-six (2.3%) of our cases had an LLD greater than 10 mm, with XP-THA having the highest incidence (5.1%) ($P < 0.05$). Few significant differences in GOD were found when comparing the groups. Patients treated with robotic guidance were significantly younger ($P < 0.05$).

Placing the cup outside the established safe zones has been associated with complications, including dislocation, instability, LLD, and revision surgery. De Palma et al [47], analyzed the financial impact of a dislocated THA in patients with primary hemiarthroplasty (HA), THA, and revision surgery (RTHA), finding that 87 cases (18 HA, 44 THA, and 25 RTHA) dislocated within six weeks of the primary operation. An early dislocation increased the cost of HA, THA, and RTHA by 472%, 342%, and 352%, respectively. An average of 22.5% of revision THAs are secondary to instability of the primary implant [21].

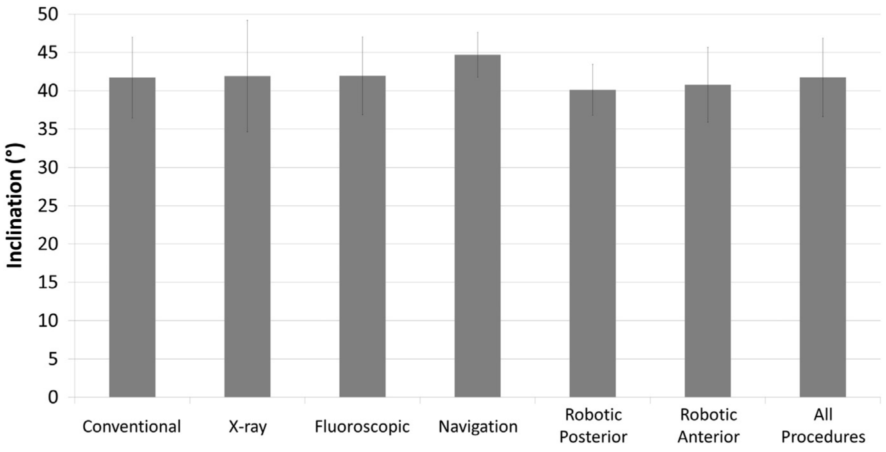

Fig. 7. Mean inclination for each treatment group. Error bars represent standard deviations. Corresponding *P*-values for comparisons between groups are reported in Table 18.

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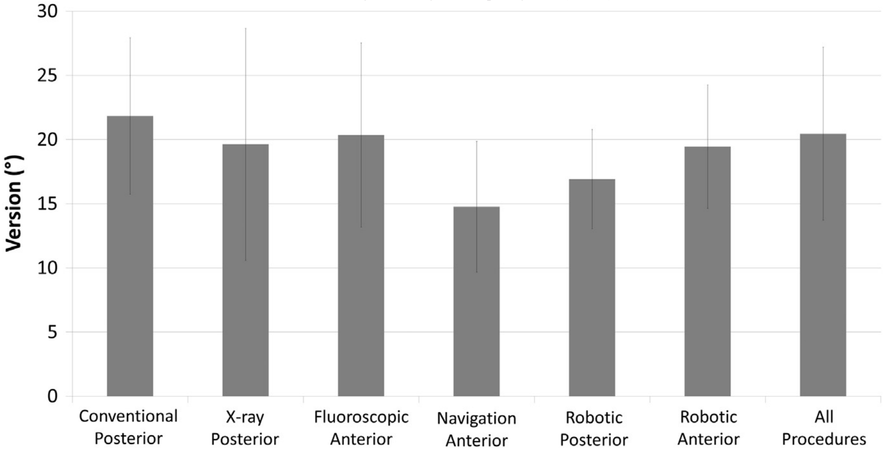

Fig. 8. Mean version for each treatment group. Error bars represent standard deviations. Corresponding *P*-values for comparisons between groups are reported in Table 18.

Table 8
P-Values From Levene's Test Indicating Significant Differences in Variance of Inclination Among the Surgical Modalities.

	Conventional (CP-THA)	X-ray (XP-THA)	Fluoroscopic (FA-THA)	Navigation (NA-THA)	Robotic Posterior (RP-THA)	Robotic Anterior (RA-THA)
Conventional		0.0006	0.35	0.003	<0.0001	0.46
X-ray	0.0006		<0.0001	<0.0001	<0.0001	0.003
Fluoroscopic	0.35	<0.0001		0.005	<0.0001	0.73
Navigation	0.003	<0.0001	0.005		0.53	0.01
Robotic posterior	<0.0001	<0.0001	<0.0001	0.53		0.002
Robotic anterior	0.46	0.003	0.73	0.01	0.002	

Table 9
P-Values From Levene's Test Indicating Significant Differences in Variance of Version Among the Surgical Modalities.

	Conventional (CP-THA)	X-ray (XP-THA)	Fluoroscopic (FA-THA)	Navigation (NA-THA)	Robotic Posterior (RP-THA)	Robotic Anterior (RA-THA)
Conventional		<0.0001	<0.0001	0.05	<0.0001	0.02
X-ray	<0.0001		0.007	<0.0001	<0.0001	<0.0001
Fluoroscopic	<0.0001	0.007		0.0009	<0.0001	<0.0001
Navigation	0.05	<0.0001	0.0009		0.44	0.68
Robotic posterior	<0.0001	<0.0001	<0.0001	0.44		0.09
Robotic anterior	0.02	<0.0001	<0.0001	0.68	0.09	

Lewinnek et al [5] were the first to describe a “safe zone” for acetabular component positioning between 30° and 50° of inclination and 5° and 25° of anteversion. In their series, the hip dislocation rate was 1.5% when acetabular components were placed within the safe zone, and 6.1% when acetabular components were placed outside the safe zone. Biedermann et al [3] showed similar results in their series of 127 dislocations. Recently, Callanan et al [4] suggested a “modified safe zone” of 30° to 45° of inclination and 5° to 25° of version, based on the study by Leslie et al [48]. Rathod et al [45] found that FA-THA resulted in a higher percentage of cups in their safe zone compared to CP-THA.

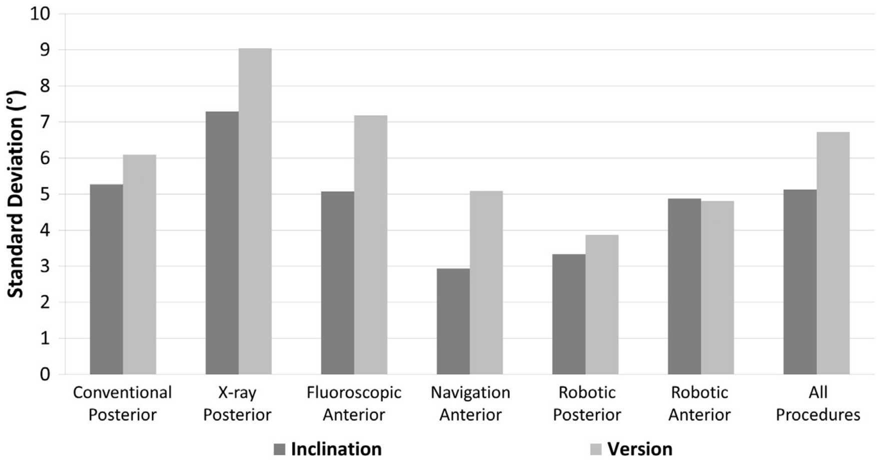

Fig. 9. Standard deviation of inclination and version for treatment groups. Corresponding *P*-values for comparisons between groups are reported in Tables 8 and 9.

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Table 10
Number of Cases for Each Surgical Modality in Which Postoperative Leg Length Discrepancy (LLD) Was Less Than or Equal to 10 mm.

	Conventional (CP-THA)	X-ray (XP-THA)	Fluoroscopic (FA-THA)	Navigation (NA-THA)	Robotic Posterior (RP-THA)	Robotic Anterior (RA-THA)	All
Total cases	708	59	942	43	135	93	1980
LLD ≤ 10 mm	688 (97.18%)	56 (94.92%)	925 (98.20%)	43 (100.00%)	133 (98.52%)	89 (95.70%)	1934 (97.68%)

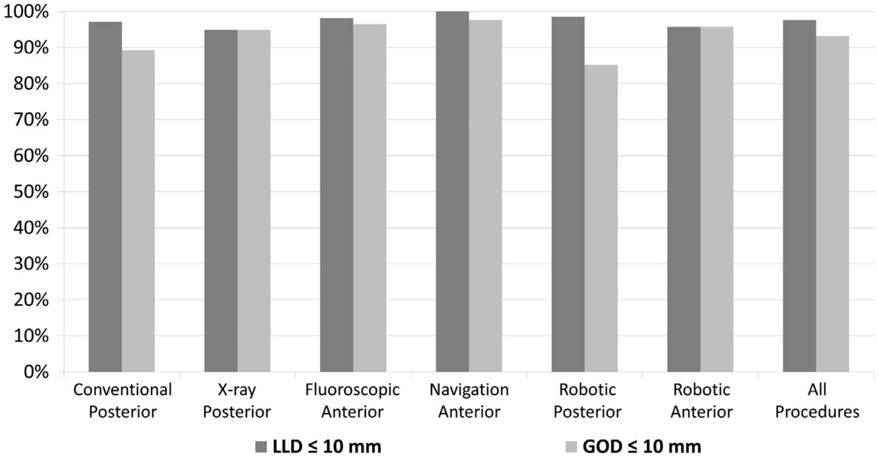

Fig. 10. Percentage of patients in each treatment group with leg-length discrepancy or global offset discrepancy less than or equal to 10 mm. Corresponding *P*-values for comparisons between groups are reported in Tables 11 and 15.

Table 11
P-Values Indicating Differences Among the Surgical Modalities in the Percentage of Cases With Postoperative Leg Length Discrepancy (LLD) Less Than 10 mm.

	Conventional (CP-THA)	X-ray (XP-THA)	Fluoroscopic (FA-THA)	Navigation (NA-THA)	Robotic Posterior (RP-THA)	Robotic Anterior (RA-THA)
Conventional		0.56*	0.17	0.53*	0.55	0.64
X-ray	0.56*		0.21*	0.36	0.34	0.86
Fluoroscopic	0.17	0.21*		0.77*	0.93	0.21*
Navigation	0.53*	0.36	0.77*		0.98	0.4*
Robotic posterior	0.55	0.34	0.93	0.98		0.38*
Robotic anterior	0.64	0.86	0.21*	0.4*	0.38*	

No significant differences are observed.
* Indicates power ≥0.8 for comparisons that do not show significant differences.

Table 12
Postoperative Leg Length Discrepancy (LLD, in mm) for Each Surgical Modality.

	Conventional (CP-THA)	X-ray (XP-THA)	Fluoroscopic (FA-THA)	Navigation (NA-THA)	Robotic Posterior (RP-THA)	Robotic Anterior (RA-THA)	All
Mean	3.41	3.66	2.59	1.81	3.32	3.01	2.97
SD	3.00	2.94	2.45	1.19	2.54	2.64	2.70
Min.	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Max.	17.00	13.00	15.00	6.00	12.00	12.00	17.00
Count	706	58	941	43	132	93	1974
ANOVA *P*-value:				6.7×10^{-10}			

Table 13
Significant Differences in Leg Length Discrepancy Among the Surgical Modalities, Calculated Using Tukey–Kramer Post-Hoc Test, With Significance Defined as $P < 0.05$.

	Conventional (CP–THA)	X–ray (XP–THA)	Fluoroscopic (FA–THA)	Navigation (NA–THA)	Robotic posterior (RP–THA)	Robotic anterior (RA–THA)
Conventional		>0.05	<0.05	<0.05	>0.05*	>0.05*
X–ray	>0.05		<0.05	<0.05	>0.05	>0.05
Fluoroscopic	<0.05	<0.05		>0.05	<0.05	>0.05
Navigation	<0.05	<0.05	>0.05		<0.05	>0.05*
Robotic posterior	>0.05*	>0.05	<0.05	<0.05		>0.05
Robotic anterior	>0.05*	>0.05	>0.05	>0.05*	>0.05	

*Indicates power ≥0.8 for comparisons that do not show significant differences.

Domb et al [6], in a study assessing accuracy of cup placement in RP-THA, found that acetabular components were placed in Lewinnek's safe zone for inclination and anteversion in 100% of patients, and in the Callanan's safe zone in 92% of patients. This is compared to 80% of acetabular components placed within Lewinnek's safe zone, and 62% of acetabular components placed in Callanan's safe zone without the guidance technique. In the present study, robotic-guided THA was more accurate in the placement of the acetabular component within both safe zones compared to all other techniques (except navigation in the context of Lewinnek's safe zone).

The mean LLD in the literature varies from 1 to 15.9 mm [17,28]. Most patients perceived an LLD when shortening exceeds 10 mm and

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Table 14
Number of Cases for Each Surgical Modality in Which Postoperative Global Offset Difference (GOD) Was Less Than or Equal to 10 mm.

	Conventional (CP-THA)	X-ray (XP-THA)	Fluoroscopic (FA-THA)	Navigation (NA-THA)	Robotic Posterior (RP-THA)	Robotic Anterior (RA-THA)	All
Total cases	708	59	942	43	135	93	1980
GOD ≤10 mm	632 (89.27%)	56 (94.92%)	909 (96.50%)	42 (97.67%)	115 (85.19%)	89 (95.70%)	1844 93.13%

Table 15
P-Values Indicating Significant and Non-Significant Differences Among the Surgical Modalities in the Percentage of Cases With Postoperative Global Offset Difference (GOD) Less Than 10 mm.

	Conventional (CP-THA)	X-ray (XP-THA)	Fluoroscopic (FA-THA)	Navigation (NA-THA)	Robotic Posterior (RP-THA)	Robotic Anterior (RA-THA)
Conventional		0.17*	<0.0001	0.13*	0.17*	0.05*
X-ray	0.17*		0.79*	0.85	0.05*	0.86
Fluoroscopic	<0.0001	0.79*		0.99	<0.0001	0.92
Navigation	0.13*	0.85	0.99		0.03	0.94
Robotic posterior	0.17*	0.05*	<0.0001	0.03		0.01
Robotic anterior	0.05*	0.86	0.92	0.94	0.01	

* Indicates power ≥0.8 for comparisons that do not show significant differences.

Table 16
Postoperative Global Offset Difference (GOD, in mm) for Each Surgical Modality.

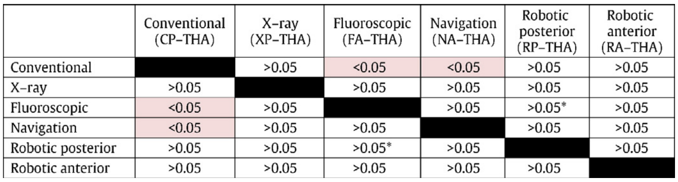
	Conventional (CP-THA)	X-ray (XP-THA)	Fluoroscopic (FA-THA)	Navigation (NA-THA)	Robotic Posterior (RP-THA)	Robotic Anterior (RA-THA)	All
Mean	4.74	3.91	3.54	3.08	4.26	3.93	4.04
SD	3.84	3.31	3.02	2.60	3.45	3.06	3.42
Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Max	24.70	17.00	21.60	10.20	16.40	16.20	24.70
Count	708	59	942	43	124	93	1970
ANOVA *P*-value:				1.8×10^{-10}			

lengthening exceeds 6 mm [28]. Our study showed that over 94% of patients in all treatment groups had LLD ≤ 10 mm, and the frequency of patients exceeding this value was not significantly different between groups ($P < 0.05$).

Adequate GO is important for optimal function of the hip joint. Lowering the GO leads to a decrease in the lever arm across the hip joint and a reduction in abductor muscle power, which can result in limping and a Trendelenburg gait. Another consequence of decreased GO is an increase in the forces across the articular surfaces, resulting in increased wear. Furthermore, increased GO may result in an increased lever arm across the joint, which may lead to pain, increased wear, and LLD [1–13]. We found few significant differences in GOD between the six groups ($P < 0.0001$) (Fig. 10). Recently Weber et al [49] found the imageless navigation-guided THA resulted in smaller LLD, GOD, and femoral offset discrepancy compared to fluoroscopic-guided THA ($P < 0.001$), although they do not consider these differences clinically significant.

A strength of our study is that it contains the largest series in the literature assessed for the accuracy of component positioning in THA. A total of 2330 patients were considered initially, and 1980 patients were included after applying exclusion criteria. Furthermore, the study includes six guidance modalities, with surgeries performed by six surgeons over six years. Another strength of our study was that it compared the variance of cup inclination and version between different modes of guidance, showing that NA-THA, RA-THA and RP-THA resulted in less variance in these parameters than other modes of guidance. This analysis provides some measure of the precision of acetabular cup placement that is independent from the previous conventions established by Lewinnek et al and Callanan et al.

Table 17
Significant Differences in Global Offset Difference (GOD) Among the Surgical Modalities, Calculated Using Tukey–Kramer Post-Hoc Test, With Significance Defined as $P < 0.05$.



	Conventional (CP–THA)	X–ray (XP–THA)	Fluoroscopic (FA–THA)	Navigation (NA–THA)	Robotic posterior (RP–THA)	Robotic anterior (RA–THA)
Conventional		>0.05	<0.05	<0.05	>0.05	>0.05
X–ray	>0.05		>0.05	>0.05	>0.05	>0.05
Fluoroscopic	<0.05	>0.05		>0.05	>0.05*	>0.05
Navigation	<0.05	>0.05	>0.05		>0.05	>0.05
Robotic posterior	>0.05	>0.05	>0.05*	>0.05		>0.05
Robotic anterior	>0.05	>0.05	>0.05	>0.05	>0.05	

*Indicates power ≥0.8 for comparisons that do not show significant differences.

Limitations

One limitation is unequal sample sizes representing each of the six techniques. An additional challenge was that the study period included cases that may have been performed during individual surgeons' learning curves for the specific guidance modality. The study was unable to distinguish inaccuracies caused by the learning curve of specific surgical techniques. This study was a retrospective analysis focusing on radiographic evidence of component positioning, and did not assess or record the cohort's overall complication rate or clinical outcomes. Future studies must compare the clinical efficacy of the surgical techniques examined in this study, and assess the effects of component positioning on clinical outcomes.

Another limitation is that we did not have sufficient sample size in some treatment groups to have sufficient statistical power in all comparisons. We were not able to obtain sufficient sample sizes for all treatment groups due to the surgeons' differing preferences in surgical modality. However, we believe that the key results of this study are the significant differences shown between groups, which do not suffer from the problem of insufficient power.

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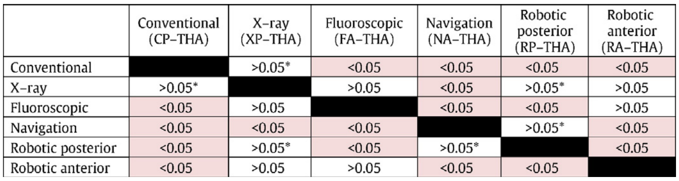
Table 18
Significant Differences in Inclination Among the Surgical Modalities, Calculated Using Tukey–Kramer Post-Hoc Test, With Significance Defined as $P < 0.05$.

	Conventional (CP-THA)	X-ray (XP-THA)	Fluoroscopic (FA-THA)	Navigation (NA-THA)	Robotic Posterior (RP-THA)	Robotic Anterior (RA-THA)
Conventional		>0.05	>0.05	<0.05	<0.05	>0.05
X-ray	>0.05		>0.05	>0.05	>0.05	>0.05
Fluoroscopic	>0.05	>0.05		<0.05	<0.05	>0.05*
Navigation	<0.05	>0.05	<0.05		<0.05	<0.05
Robotic posterior	<0.05	>0.05	<0.05	<0.05		>0.05
Robotic anterior	>0.05	>0.05	>0.05*	<0.05	>0.05	

* Indicates power ≥0.8 for comparisons that do not show significant differences.

Table 19
Significant Differences in Version Among the Surgical Modalities, Calculated Using Tukey–Kramer Post-Hoc Test, With Significance Defined as $P < 0.05$.



	Conventional (CP–THA)	X–ray (XP–THA)	Fluoroscopic (FA–THA)	Navigation (NA–THA)	Robotic posterior (RP–THA)	Robotic anterior (RA–THA)
Conventional		>0.05*	<0.05	<0.05	<0.05	<0.05
X–ray	>0.05*		>0.05	<0.05	>0.05*	>0.05
Fluoroscopic	<0.05	>0.05		<0.05	<0.05	>0.05
Navigation	<0.05	<0.05	<0.05		>0.05*	<0.05
Robotic posterior	<0.05	>0.05*	<0.05	>0.05*		<0.05
Robotic anterior	<0.05	>0.05	>0.05	<0.05	<0.05	

*Indicates power ≥0.8 for comparisons that do not show significant differences.

We were unable to address why each surgeon chose to use or discontinue a specific modes of treatment that they did as well the patient populations within each surgeon's practice. This could be based on several reasons, those may include personal abilities and preferences that cannot be separated from the more objective lessons that one might hope to derive.

Conclusion

Robotic-guided and navigation-guided techniques were more consistent than other techniques in placing the acetabular cup into Lewinnek's safe zone. Robotic-guided surgery was more consistent with respect to Callanan's safe zone. The frequency of excessive LLD was consistently low across all groups. Few differences in GOD were observed. Further studies are needed to investigate the long-term clinical outcomes, complications, and cost-effectiveness of various techniques and modes of guidance in THA.

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