Evaluating Surgeon Estimation of Cup Position in Total Hip Arthroplasty: A Cadaver Study

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Abstract

Inaccurate placement of components during total hip arthroplasty (THA) can lead to significant postoperative complications including revision surgery. Traditionally, surgeons grossly estimate component positioning intraoperatively using anatomical landmarks; however, evidence indicates that this surgeon assessment may not be reliable. The purpose of this study was to determine the accuracy of surgeon estimates of component position as compared with imaging (radiographs and computed tomography [CT] scan) and a new surgical navigation system. Three board-certified orthopaedic surgeons each performed four THA procedures on six cadavers (12 hips). Radiographs and CT scans were obtained postoperatively. The "gold standard" measurements of implanted cup anteversion and inclination were derived from three-dimensional renderings created from postoperative CTs. A reference value for cup position was created by aligning the anterior pelvic plane in each rendering coplanar with the CT table. Following each procedure, surgeons provided their estimate of acetabular cup component orientation. Surgeon estimates were compared with data gathered from postoperative radiographs, CT scans, and the navigation device. Surgeon estimates of anteversion and inclination were within 10 degrees of reference values in 64% (7/11) and 82% (9/11) of cases, respectively. Surgeon estimates of anteversion differed from reference values by a mean of 7.6 ± 5 degrees, whereas inclination differed from reference values by a mean of 6.1 ± 5.1 degrees (all means absolute). Radiographic measurements differed from reference values by 7.8 ± 4.3 degrees ($p > 0.05$) and 2.7 ± 2.3 degrees ($p = 0.06$) for anteversion and inclination, respectively, whereas CT values differed by 2.5 ± 1.6 degrees ($p = 0.004$) and 2.3 ± 2.1 degrees ($p = 0.04$). The navigation system differed from reference values by 4 ± 4 degrees ($p = 0.08$) and 4.2 ± 3.2 degrees ($p = 0.31$). Surgeons underestimated anteversion and inclination by 7.7 ± 4.8 degrees and 6.9 ± 4.8 degrees,

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respectively. Surgeon underestimation was observed in 8/11 (73%) cases, with anteversion underestimated by > 5 degrees in 5/8 (62%) cases and inclination underestimated by > 5 degrees in 4/8 (50%) cases. Our findings suggest that surgeons tend to underestimate both anteversion and inclination and that the accuracy of their estimates is similar to that of radiographs. CT scans and the navigation system were able to provide more accurate measurements of cup position.

Inaccurate positioning of components during total hip arthroplasty (THA) can lead to potentially significant complications ranging from impingement to dislocation and revision surgery.[1–5] Surgeons traditionally rely on anatomical landmarks and experience when positioning the acetabular cup and femoral components during THA; however, devices ranging from simple calipers to sophisticated navigation systems are available to assist the surgeon with component placement. While usage of these tools among surgeons is growing, the majority of orthopaedic surgeons continue to manually place THA components without assistance.[6,7] Postoperatively, most surgeons use anteroposterior (AP) and cross-table lateral radiographs to evaluate final component positioning, but as these images are often taken hours to weeks after surgery, they do not assist in confirming component position intraoperatively. Furthermore, even if intraoperative AP radiographs are obtained, regardless of the surgical approach used, the inaccuracy associated with measuring component version from radiographs limits their usefulness as an intraoperative tool.[8,9] As such, surgeon perception of component position is an integral portion of THA and contributes to the stability of the construct in both the short and long terms.

Several studies have investigated the accuracy of surgeon estimates of cup position, comparing surgeon assessments with imaging measurements and subsequently estimating the likelihood that cups would be placed in Lewinnek's "safe zone" (40 ± 10 degrees inclination and 15 ± 10 degrees anteversion[10]).[11–14] Cup position reportedly falls within this safe zone in 45 to 85% of cases.[13,14] Patient-specific factors such as body mass index (BMI), gender, and age have been found to have no demonstrable impact on the accuracy of surgeon estimates, and while experience has been found to play a minor role,[15] the consensus remains that accurate intraoperative estimations of acetabular cup position are inherently difficult and that "freehand" placement of components is not a reliable method.[13,15]

A significant barrier to improving component positioning and decreasing the reliance on surgeon perception of cup position is the lack of suitable methods of providing intraoperative data.[16] Sophisticated computer-assisted navigation devices provide detailed intraoperative information but are used only sparingly due to their substantial costs and cumbersome nature.[6,7] The current reliance on postoperative imaging for confirmation also presents numerous challenges, from the inability to provide intraoperative data to the inaccuracies associated with radiographs.[17,18] A new surgical navigation system that provides real-time data on cup position and changes in leg length has been shown in clinical studies to accurately measure these parameters and may offer an alternative method for intraoperative monitoring.[19,20]

The purpose of this cadaveric study was to determine the accuracy of surgeon estimates of component position during THA. We further sought to compare surgeon estimate accuracy with measurements from a novel mini-navigation system and to postoperative measurements of inclination and anteversion measured on AP radiographs and computed tomography (CT) scan. Our hypothesis was that surgeons' estimates of inclination and version would be significantly different than measurements of postoperative component position obtained from CT scans. We further hypothesized that the mini-navigation system measurements would be more accurate than those obtained from radiographs and similar to those calculated from the postoperative CT scans.

Materials and Methods

This study was a cadaver study using six torso-to-toe, fresh frozen cadavers (12 hips). Three board-certified orthopaedic surgeons each performed four THA procedures using a posterior approach with the assistance of a navigation system. Participating surgeons are fellowship-trained, high-volume specialists in joint reconstruction at academic medical centers.

Procedure

The use of the Intellijoint HIP (Intellijoint Surgical, Inc.) surgical navigation tool has been described previously.[21] The device consists of two components: a camera and an optical tracker. The camera is fixed temporarily to the iliac crest through two surgical screws that are inserted into the ipsilateral crest through stab incisions. A platform is fixed to the screws, upon which the camera is magnetically attached. The camera is connected to a computer workstation, which remains outside of the sterile field but within the field of view of the surgeon, who controls the workstation through buttons on the camera. The camera captures the movements and position of the optical tracker, which can be magnetically attached to various objects during surgery. For example, to measure changes in leg length and offset, a small platform is temporarily fixed to the greater trochanter (using the primary incision for access) to which the tracker is attached. The tracker can also be magnetically fixed to the impactor to provide cup position measurements or other objects such as a surgical probe to provide specific positional data (►**Fig. 1**).

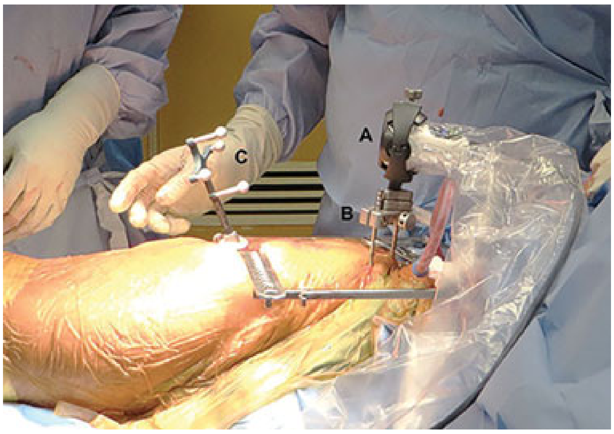

Fig. 1 The Intellijoint HIP surgical navigation system comprises a camera (**A**), which is magnetically attached to a platform (**B**) fixed to the iliac crest with two surgical screws. Movements of a tracker (**C**) are captured by the camera and relayed to a workstation outside of the sterile field.

In this cadaver study, the probe feature of the device was used to provide detailed positional data. Prior to primary incision, three fiducial screws were inserted bilaterally into the pelvis of each specimen (►**Fig. 2**). Fiducial screws were inserted at the anterior superior iliac spine (ASIS), inferior to the iliac crest, and superior to the acetabulum. These screws allowed for the creation of a common reference plane, both in situ and on subsequent CT images. During surgery, surgeons used the probe and tracker to probe each of the fiducial screws, plus several other landmarks, including the bilateral ASIS and the symphysis pubis (demarcating the anterior pelvic plane [APP]) and three points on the face of the implanted cups. Probing of the screws and boney landmarks

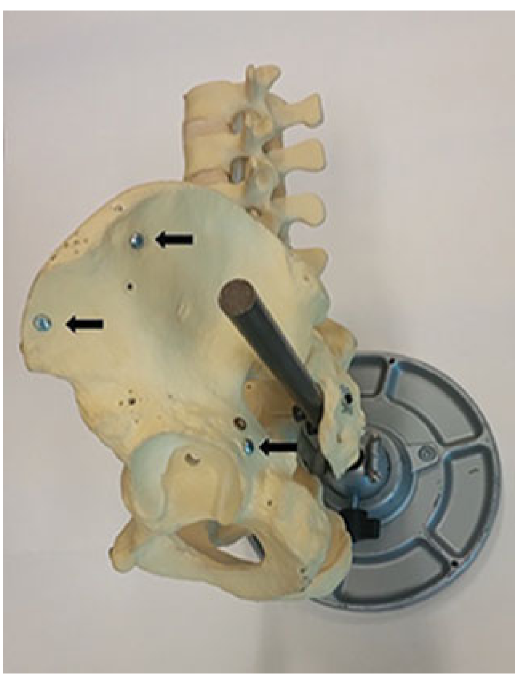

Fig. 2 Prior to each procedure, three fiducial screws (arrows) were inserted into the pelvis to provide a reference plane for comparison of image-based measurements with device measurements.

Table 1 Target values for implantation of hip arthroplasty components

	Inclination	Anteversion	Leg length change	Offset change
Hip 1	45	20	+0 mm	+0 mm
Hip 2	45	10	+3 mm	+0 mm
Hip 3	35	20	+6 mm	+0 mm
Hip 4	35	10	+9 mm	+0 mm

was performed at the beginning of each procedure and again after implantation of the acetabular cup component.

Surgeons were asked to perform the procedure per their normal surgical workflow but, prior to commencing, were randomly provided one of four targets for anteversion and inclination (►**Table 1**). The four target orientations were determined a priori to represent variations within Lewinnek's safe zone and were distributed in an order determined by a random number generator such that each surgeon was provided the same four targets but in random order. Once the camera and tracker were in place, the workstation was turned away from the surgeon to blind them to the positioning data. Following surgery, surgeons were asked for their assessment of the final cup position and provided their estimate of anteversion and inclination. Final cup position data were shown to the surgeon only upon completion of the procedure and their assessment of cup position.

Imaging

Radiographic and CT imaging were used in this study. AP plain radiographs were obtained using a Viztek portable radiographic unit (Konica Minolta). Radiographs were obtained pre- and postoperatively and were analyzed by a licensed health care practitioner not involved in the surgical procedure and blinded to the system data. Prior to the preoperative radiograph, the specimen was positioned in the lateral decubitus position and secured with standard surgical bolsters. Specimen position was recorded using the navigation device, which recorded the position of the lower limbs, the pelvis, and the radiographic cassette. Prior to postoperative images, specimen position was reoriented to match the initial position to ensure consistency between the pre- and postoperative images. Radiographic images were analyzed using TraumaCad (Brainlab), through the interischial line method.[22–24]

CT scans were obtained postoperatively using a GE Lightspeed 16 imager (GE Healthcare; image parameters: 140 kV, 600 mA at 0.8-second revolution time and 0.625-mm slice thickness). CTs were analyzed by two board-certified radiologists blinded to system measurements and not participants in the surgical procedures. Prior to analysis, Mimics and 3-Matic software (Materialise) was used to create three-dimensional renderings of each pelvis (►**Fig. 3**).[25,26] The radiologists were asked to identify several points on the renderings, including the fiducial screws bilaterally, the bilateral ASIS, the symphysis pubis, and three points on the face of each acetabular cup. Each landmark was defined in triplicate, and the results averaged to

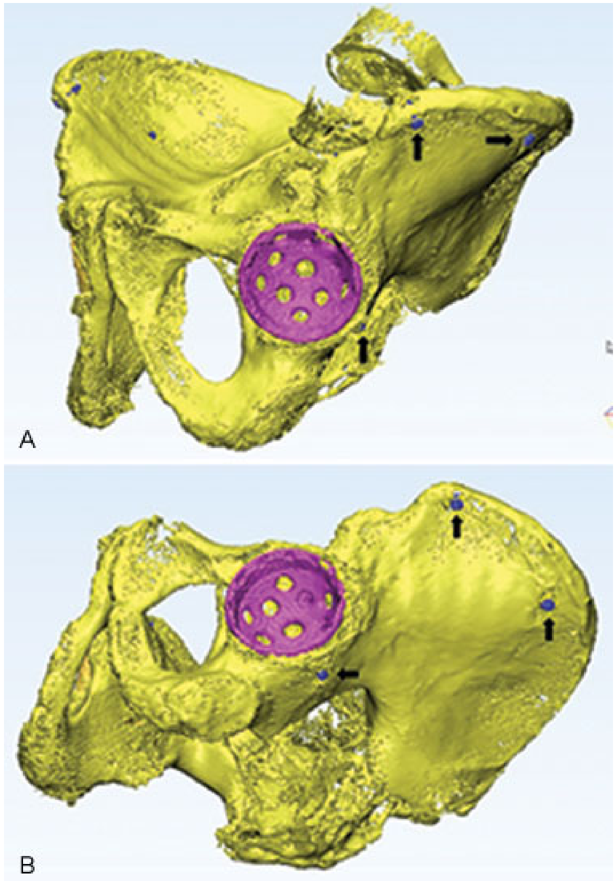

Fig. 3 Three-dimensional renderings (**A**,**B**) were created from computed tomography (CT) scans. Fiducial screws (arrows) were marked during analysis, as was the cup face for each acetabular cup component (purple).

provide final coordinate data. MATLABS software (MathWorks) was used to create coordinate data from the marked renderings.

Determination of Reference Values

CT scans were performed postoperatively with the specimen lying supine on the CT table. The long axis of the specimen was aligned with the long axis of the table, but no other positional correction was made prior to image capture. Postprocessing of coordinate data allowed for creation of a corrected CT scan, where the orientation of the APP was corrected such that it was aligned coplanar with the CT table. This corrected CT image served as the "gold standard" for the study. Cup position data derived from this corrected image were used as the reference value and represented the true measurement of the cup position free of distortion from rotation or deflection. Cup position derived from the uncorrected CT scan was considered to mimic the standard of care for CTs. All comparisons of cup position were made relative to the corrected reference value.

Statistical Analysis

For all statistical comparisons, α was set a priori at 0.05. Means were compared using independent or dependent samples *t*-tests and/or single-factor analysis of variance and are presented as mean (standard deviation [SD]; range). All statistical analyses were completed by an independent statistician not involved in the radiographic/CT image analysis or the surgical procedures.

Results

One hip was excluded from the analysis due to errors associated with postprocessing of the CT images.

Accuracy of Surgeon Estimate

Anteversion

The mean differences between surgeon estimates of cup position and reference values are summarized in ►**Table 2**. As expected, surgeon estimates of anteversion were significantly different than those measured from the postoperative CT ($p = 0.004$). Surgeon postoperative estimates of anteversion differed from the reference value by an absolute mean of 7.6 ± 5 degrees. More specifically, surgeons underestimated anteversion in 73% (8/11) cases by an average of 7.7 ± 4.8 degrees. Surgeon estimates of anteversion were within 5 degrees of reference values in 36% (4/11) cases and within 10 degrees of reference values in 64% (7/11) of cases (►**Table 3**), with estimate error ranging from 1 to 16 degrees. Anteversion was underestimated by < 5 degrees in 38% (3/8) cases, by 5 to 10 degrees in 25% (2/8) cases, and by > 10 degrees in the remaining 38% (3/8) cases.

Table 2 Summary of mean difference between cup position and reference values based on method of measurement or estimation of cup position

Measurement method	Anteversion (degrees)			Inclination (degrees)		
	Actual Δ[a]	Absolute Δ[a]	*p*-Value[b]	Actual Δ[a]	Absolute Δ[a]	*p*-Value[b]
Surgeon estimate	−3.7 ± 8.5	7.6 ± 5.0	–	−4.0 ± 7.0	6.1 ± 5.1	–
Radiographs	−7.8 ± 4.3	7.8 ± 4.3	0.91	−1.7 ± 3.2	2.7 ± 2.3	0.06
Navigation	−3.5 ± 4.5	4.0 ± 4.0	0.08	−1.9 ± 5.0	4.2 ± 3.2	0.31
CT	−0.9 ± 2.9	2.5 ± 1.6	0.004	−0.4 ± 3.2	2.3 ± 2.1	0.04

Abbreviation: CT, computed tomography.
[a]When compared with reference values for anteversion and inclination.
[b]Versus surgeon estimate using absolute values.

Table 3 Proportion analysis of relative ability to accurately estimate or measure cup position when compared with reference cup position values

	Anteversion		Inclination	
	< 5 degrees (*n*/*N*, %)	< 10 degrees (*n*/*N*, %)	< 5 degrees (*n*/*N*, %)	< 10 degrees (*n*/*N*, %)
Surgeon	4/11[a], 36%	7/11, 64%	6/11, 55%	9/11, 82%
Radiograph	4/11, 36%	6/11, 55%	9/11, 82%	11/11, 100%
Navigation	7/11, 64%	10/11, 91%	7/11, 64%	11/11, 100%
CT	11/11, 100%	11/11, 100%	10/11, 91%	11/11, 100%

Abbreviation: CT, computed tomography.
[a]One hip was excluded from analysis due to errors associated with postprocessing of the CT images.

Conversely, no significant difference was observed in the socket anteversion measured by the mini-navigation compared with the reference values (mean difference: –3.5 ± 4.5 degrees; absolute mean difference: 4 ± 4 degrees; $p = 0.08$). While the mini-navigation improved the accuracy of component position measurement compared with surgeon estimates by 3.6 degrees, it only trended toward significance ($p = 0.08$). Further, the mini-navigation device measured anteversion to within 10 degrees in 91% (10/11) of THAs.

Radiographic measurement of cup anteversion was inaccurate and was similar in accuracy to surgeon estimates of cup anteversion. The mean difference between anteversion calculated from radiographs and reference anteversion was –7.8 ± 4.3 degrees (abs: 7.8 ± 4.3 degrees; $p = 0.91$ vs. surgeon estimate). Radiographs measured anteversion to within 10 degrees of reference values in only 55% (6/11) of cases.

Inclination

While surgeons were more accurate in estimating cup inclination than they were in estimating cup anteversion (►**Table 2**), surgeon estimates of cup inclination were significantly different than measurements obtained on the postoperative CT ($p = 0.04$). Surgeon estimates of inclination differed from reference inclination values by an average of –4 ± 7 degrees (abs: 6.1 ± 5.1 degrees; estimate error ranged from 0.05 to 16 degrees). Similar to cup anteversion, inclination was underestimated by surgeons in 73% (8/11) cases by an average of 6.9 ± 4.8 degrees. Inclination was underestimated by < 5 degrees in 50% (4/8) of cases, by 5 to 10 degrees in 38% (3/8) of cases, and by >10 degrees in 1 case. Overall, surgeons estimated inclination to within 5 degrees of reference values in 55% (6/11) of cases and to within 10 degrees in 82% (9/11) of cases (►**Table 3**); estimate error ranged from 0.05 to 16 degrees.

The mini-navigation device measured inclination to within a mean of –1.9 ± 5 degrees (abs: 4.2 ± 3.2 degrees) of reference values, which was better than, but still comparable to, surgeon estimates ($p = 0.31$). The mini-navigation system measured inclination to within 10 degrees of reference values in 100% of cases.

Radiographic measurement of inclination was of comparable accuracy to estimates from surgeons, differing from reference values by –1.7 ± 3.2 degrees (abs: 2.7 ± 2.3 degrees; $p = 0.06$). Radiographic measurements of inclination were within 10 degrees of reference values in 100% of cases and within 5 degrees in 82% (9/11) of cases.

Discussion

Despite the availability of computer-assisted navigation systems to assist during THA, surgeons primarily rely on their experience to estimate the position of implanted components, including the acetabular cup. Inaccurate positioning of the cup and other components can lead to instability, dislocation, and revision surgery, adding to the burden of an already stressed health care system. Evidence indicates that surgeon estimates of cup position may not be reliable, thus increasing the likelihood that the cup will be placed outside of Lewinnek's safe zone.[14,15] In a cadaver study, we compared surgeon estimates of cup position with measurements from radiographs, CT scans, and a novel navigation system for THA. We found that when compared with corrected CT scans, surgeon estimates were associated with error similar to that of radiographs, whereas standard CT scans and the navigation system offered more accurate measures of cup position.

Several studies have investigated the accuracy with which surgeons can estimate acetabular cup and femoral component position during THA. Studies specifically examining the accuracy of surgeon estimates of cup position have observed that surgeons tend to underestimate both anteversion and inclination.[13–15] Bosker et al[15] compared orthopaedic surgeons with residents in their ability to accurately estimate cup position and found that surgeons' estimates differed from the actual cup position by 4.1 degrees (SD: 3.9 degrees) for inclination and 5.2 degrees (SD: 4.5 degrees) for anteversion, versus 6.3 degrees (SD: 4.6 degrees) and 5.7 degrees (SD: 5 degrees), respectively, for residents. They noted that factors such as BMI, gender, type of fixation (cemented versus uncemented), and surgical approach (anterolateral versus posterolateral) were not influential and did not impact estimate accuracy. As such, in their study, estimate accuracy relied almost entirely on surgeon experience. Conversely, Woerner et al, in a similar study, found that surgeon experience had no impact on the accuracy of estimates of inclination, anteversion, or stem version.[13] These authors noted that gender, level of professional experience, Kellgren score, and length of incision had no impact on estimate accuracy. They noted a trend toward obesity being influential

($p = 0.06$) and found that cup size ($r = 0.384$; $p = 0.03$) and BMI ($r = 0.376$; $p = 0.008$) had statistically significant but not clinically relevant effects on anteversion and inclination, respectively.

In this study, we also observed that surgeons tended to underestimate cup position. Both cup anteversion and inclination were underestimated in 73% of cases. Anteversion was estimated to within 5 degrees of reference values in 36% of cases and to within 10 degrees in 64% of cases. Inclination was similarly underestimated in the majority of cases (8/11) but was within 5 degrees in 55% and within 10 degrees in 82% of cases. Despite the small sample size in our study, our findings approximate those of Bosker et al,[15] who observed surgeon estimates of cup position within 5 degrees in 61 and 64.5% for anteversion and inclination, respectively. Furthermore, our differences are reported as absolute values. Taken as signed values, our mean differences between estimates and actual values are -3.7 ± 8.5 degrees and -4 ± 7 degrees for anteversion and inclination, respectively, values that are less than those observed by Bosker et al. However, the maximum error associated with surgeon estimates in our study mirrors that of other authors. We reported maximum errors of 16 degrees in both anteversion and inclination, a finding that replicates that of Wines and McNicol, who noted surgeon estimates differing from actual cup position by as much as 16 degrees in anteversion.[14] The fact that our study was a cadaver study and therefore more controlled than live patient surgery could contribute to the improved accuracy of surgeon estimates. The three surgeons in our study, however, are all board-certified, experienced surgeons who have trained at and are currently on staff at high volume, arthroplasty-specific facilities. Their estimates of cup position are similar to those of the experienced surgeons in the study by Bosker et al,[15] suggesting that experience may in fact play a substantial role in the ability of the surgeon to estimate cup position.

Our study also compared surgeon estimates with other methods of measuring cup position, including radiographs, standard CT, and a novel navigation system. We noted that surgeons' estimates closely matched measurements from radiographs, with each tending to underestimate cup position to a similar degree. Surgeon estimates were less accurate than measurements from CTs or the navigation device, although they were significantly different than those from only CTs. Radiographs are known to be associated with significant error and distortion,[8,9,17,18] enough that some authors have suggested that surgeons should underestimate their final cup position by as much as 8 degrees to account for the error inherent in radiographs.[27] This degree of error, however, risks placing the final cup position near the edge of the safe zone, which may inadvertently increase the likelihood of dislocation in cups implanted with this approach. While CT offers the most accurate and reliable imaging-based measure of cup position, which was confirmed in our study, its use as a standard of care imaging modality is limited by increased costs and radiation exposure.[28–30] Furthermore, CT scanning is not a feasible solution for intraoperative monitoring. Given these limitations and those identified in other measurement methods in this study, the use of a navigation tool such as the one used in this study may be a viable alternative for many surgeons.

Our study has limitations. Primarily, the use of cadavers raises concerns that the specimens do not accurately represent clinical conditions or movements. In addition, in this study, we used specimens that comprised the torso and lower extremities only. As such, there was a chance that the positioning of our specimens during surgery did not accurately reflect patient positioning during THA. This potential risk was mitigated, however, by the use of surgical bolsters to secure the specimen in the appropriate position throughout surgery. Furthermore, the use of frozen cadavers has been suggested as a limitation, as frozen tissue may not adequately replicate health human tissue.[31] For this study, however, we allowed the specimens to fully thaw to allow their movement to closely mimic that of normal human tissue. In addition, the use of cadavers allowed us to use fiducial markers in the pelvis to create a reference plane for comparisons. In this way, the use of cadavers allowed us to increase the accuracy of measurements, adding to the strength of our conclusions.

Conclusion

Our study demonstrates that surgeons tend to underestimate anteversion and inclination during THA and that their estimates of cup position are similar in accuracy to that of plain radiographs. We further demonstrated that CT scans and a navigation system offer improved accuracy at measuring cup position when compared with radiographs or manual estimates. This study echoes the findings of others who have stated that surgeon estimates of cup position are potentially not as reliable as other methods and provides data to support the use of alternative measurement methods, including CT scans or the navigation system, both of which offered improved accuracy over that of radiographs or surgeon estimate. Future clinical studies comparing surgeon estimates with other measurement methods are warranted.

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