Predictive Value of Robotic-Assisted Total Hip Arthroplasty

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abstract

Acetabular cup positioning, leg-length discrepancy, and global offset are important parameters associated with outcomes following total hip arthroplasty (THA). Deviation from an accepted range of values can lead to significant complications, including dislocation, leg-length discrepancy, impingement, accelerated bearing surface wear, and revisions. The purpose of this study was to assess whether robotic-assisted THA was reliable in predicting radiographic measurements of cup inclination and anteversion, leg-length change, and global offset change. All 61 robotic-assisted THAs that met the inclusion and exclusion criteria were performed by a single surgeon through a mini-posterior approach. Data provided by the robot were collected prospectively, and radiographic data were collected retrospectively by 2 blinded independent reviewers. The cohort in this study consisted of 27 male and 34 female patients, with an average age of 60.5 years. A strong inter- and intraobserver correlation was found for the radiographic measurements of cup inclination, cup anteversion, leg-length discrepancy, and global offset ($r>0.8$ with $P<.001$ for all). Ninety-six point seven percent of robotic-measured inclination angles and 98.4% of robotic-measured anteversion angles were within 10° of radiographic measurements. One hundred percent of robotic-measured leg-length change and 91.8% of robotic-measured global offset change were within 10 mm of radiographic measurements. Robotic-assisted THA showed good predictive value for cup inclination and anteversion angles and measurements of leg-length change and global offset change done postoperatively on plain radiographs. Further refinement of the robotic system would make it more accurate in predicting the postoperative parameters mentioned. [*Orthopedics*. 2015; 38(1):e31-e37.]

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The overall burden of total joint arthroplasty is expected to increase significantly over the next 2 decades, with a projected 572,000 primary total hip arthroplasties (THAs) and 96,700 revision THAs in the year 2030.[1] Therefore, every effort should be directed at providing the best possible THA to avoid revisions and ensure a long-lasting prosthesis with good quality of life for patients with hip osteoarthritis. Acetabular cup positioning, leg-length discrepancy, and global offset are important parameters that play a significant role in the success and longevity of THA.

Proper acetabular cup placement is a critical step when performing THA, regardless of the approach used or the implant type. Placing the cup outside a safe zone of inclination and anteversion[2,3] can result in multiple complications, including dislocation,[2-4] leg-length discrepancy,[5] impingement,[6] accelerated bearing surface wear,[7] and revisions. Leg-length discrepancy is currently one of the most common orthopedic complications associated with medical litigation.[8] Leg-length discrepancy of more than 1 cm is considered a significant source of adverse clinical sequelae, including nerve palsies,[8,9] abnormal gait,[10] and low back pain.[11] Maintaining an adequate global offset is important for optimal mechanical function of the hip joint. Deviating from an acceptable range of global offset can result in several complications. Decreasing the global offset can lead to limping,[12,13] Trendelenburg gait,[12,13] and increased wear,[12,14] whereas an increase in global offset can result in increased wear,[14] pain,[15] and leg-length discrepancy.[16]

Computer-assisted surgery has been gaining significant popularity over the past few decades in the field of arthroplasty. The need to address individual variations in hip anatomy has led to the development of patient-specific surgeries.[17] These relatively new technologies allow for preoperative planning and intraoperative execution tailored to every patient's anatomy. Robotic-assisted THA,[18,19] image-assisted navigation,[20,21] and imageless navigation[22] have all been introduced into the field of THA for the purpose of decreasing technical errors intraoperatively.

The purpose of this study was to assess whether the use of the MAKOplasty Total Hip Application (MAKO Surgical Corp, Ft Lauderdale, Florida) was reliable in predicting postoperative radiographic measurements of cup inclination, cup anteversion, leg length, and global offset in THA.

Materials and Methods

All robotic-assisted THAs performed between June 2011 and December 2012 by the senior surgeon (B.G.D.) through a mini-posterior approach were reviewed. Patients with proper postoperative supine anteroposterior (AP) pelvis radiographs were included in the study. Excluded patients were those who had missing or improper postoperative radiographs (rotated or tilted pelvis)[23] or had radiographs with at least 1 lesser trochanter that was hard to define. Sixty-one cases of robotic-assisted THA met the inclusion and exclusion criteria. Investigational review board approval was obtained prior to initiation of this study.

Patients scheduled for robotic-assisted THA underwent preoperative computed tomography (CT) scan of the involved hip. The robotic system created a patient-specific virtual 3-dimensional (3-D) model of the pelvis and proximal femur that was used to guide surgery. Patient-specific landmarks were then defined and used intraoperatively to determine the position of the pelvis and proximal femur. This system involved a haptic robotic arm for acetabular reaming and cup placement and gave the surgeon real-time feedback regarding cup position, leg length, and global offset. The robotic system software took into consideration pelvic tilt and rotation in determining intraoperative measurements. These were calculated on the coronal (functional) plane of the body as described by Murray.[24]

The acetabular implant used in all 61 cases was the Restoris Trinity Cup (Corin Group PLC, Cirencester, United Kingdom). The femoral stem used was the MetaFix Hip Stem (Corin Group PLC) in 39 cases and the Anthology Stem (Smith & Nephew, London, United Kingdom) in 22 cases. Stem choice was based on preoperative templating to determine the best fit to the femur.

This was a radiographic study with no clinical outcomes measured and no long-term patient follow-up. Trauma-Cad software (Voyant Health, Petach-Tikva, Israel) was used for all radiographic measurements, including leg-length discrepancy, global offset, acetabular cup inclination, and version. The measurements were done on the AP pelvis view following the coronal plane of the body[24,25] (**Figure 1**) after calibration. Trauma-Cad software has been previously studied and its accuracy reported in the literature.[26,27] This software allows for the measurement of the version angle on the AP view of the pelvis but cannot differentiate between anteversion and retroversion. To determine the direction of version, the authors used the postoperative cross-table lateral radiographs of all patients, a technique described by Woo and Morrey.[28] For leg-length discrepancy measurements, the authors used the interobturator line (line tangent to the inferior aspect of both obturator foramina) as a reference on the pelvis, and the most superomedial point on both lesser trochanters as the references on the femurs. For global offset measurements, they used the technique described by Dastane et al.[16]

Two observers (Y.F.E. and T.J.J.), blinded from each other's results, collected the radiographic data to determine interobserver reliability. Each observer performed the measurements twice, 2 months apart, to determine intraobserver reliability. Cup inclination and anteversion angles were measured on the postoperative AP pelvis radiographs. To measure radiographic leg-length change, leg-length discrepancy was measured on the pre- and postoperative radiographs. Subtracting the preoperative from the postoperative leg-length discrepancy provided the radiographic leg-length change in the operated on extremity. The same principle was applied to measure radiographic global offset change.

Sixty-one cases of robotic-assisted THA were included. All cases had available cup inclination and anteversion data measured by the robotic system intraoperatively. Because the robotic system software was still under development when the authors adopted its use at their institution, 12 of the first cases did not have intraoperative measurements of leg-length change and global offset change. Measuring cup inclination and anteversion intraoperatively was possible from the beginning with the first version of the software. Measuring leg-length change and global offset change became possible with later versions, allowing the authors to gather 49 cases with all 4 measurements.

SPSS version 20 statistical software (SPSS, Inc, Chicago, Illinois) was used to perform all statistical analyses in this study. The means of all the radiographic parameters measured by both observers were calculated. Pearson's correlation coefficient was used for intra- and interobserver reliability analyses. Demographic data of the authors' patient cohort were reported as well. Calculation of the mean and range was done for all the robotic and radiographic measurements of all parameters studied.

Comparison between the robotic and postoperative radiographic measurements was performed. Student's *t* test was used to compare the means of cup inclination, cup anteversion, leg-length change, and global offset change. The percentages of robotic-measured cup inclination and anteversion angles that fell within 5°, 10°, and greater than 10° of radiograph-measured angles were calculated. The percentages of robotic-measured leg-length change and global offset change measurements that fell within 5, 10, and greater than 10 mm of radiograph-measured values were calculated. Student's *t* test was used for comparison between pre- and postoperative radiographic leg-length discrepancy and global offset. The percentages of cases that had radiograph-measured leg-length discrepancy within 5, 10, and greater than 10 mm were reported. A *P* value less than .05 was considered statistically significant.

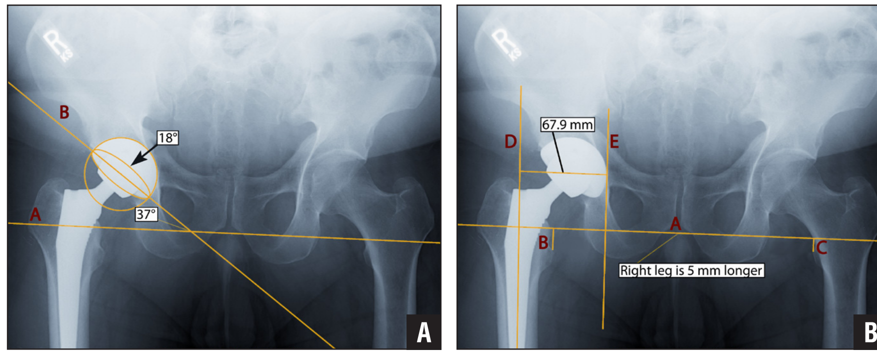

Figure 1: Supine anteroposterior pelvis radiograph showing measurements for cup anteversion and inclination angles. Line B is the tangent line to the opening of the acetabular cup and intersects with the interobturator reference line A on the pelvis, giving the inclination angle (37°). The ellipse that measures the anteversion angle (18°) is delineated by the contour of the acetabular cup opening and is concentric with the circle surrounding the acetabular cup (A). Supine anteroposterior pelvis radiograph showing measurements for leg-length discrepancy and global offset. Line A is the reference on the pelvis. Leg-length discrepancy of 5 mm is the difference between lines B and C. Line D delineates the anatomic axis of the femur, and line E is parallel to the anatomic axis, tangent to the teardrop (or to the most medial aspect of the acetabular cup when the cup is more medial than the teardrop). The perpendicular distance between lines D and E passing through the center of the femoral head gives the global offset value of 67.9 mm (B).

Results

The study cohort comprised 27 males and 34 females. There were 31 right THAs and 30 left THAs. Mean patient age was 60.5 years (range, 39.5 to 90.5 years).

Postoperative cross-table lateral radiographs were analyzed, and all patients were found to have anteverted cups. Therefore, all version measurements given by the Trauma-Cad software were true anteversion measurements. The inter- and intraobserver Pearson correlation coefficients (*r*) for all radiographic measurements were all greater than 0.8 ($P<.001$ for all).

Cup Inclination and Anteversion

Mean inclination and anteversion angles for the robotic and radiographic measurements are reported in **Table 1**, as well as the comparison between the robotic- and radiographic-measured angles. The percentages of robotic-measured angles within 5°, 10°, and greater than 10° of radiographic-measured angles are shown in **Figure 2A**.

Leg-Length Discrepancy, Change in Leg Length, Global Offset, and Change in Global Offset

Mean postoperative radiographic leg-length discrepancy is reported in **Table 2**. The percentages of cases that had radiographic postoperative leg-length discrepancy within 5, 10, and greater than 10 mm are shown in **Figure 2B**.

Mean leg-length change and global offset change for the robotic and radiographic measurements are reported in **Table 2**. The percentages of cases that had radiographic leg-length change or global offset change within 5, 10, and greater than 10 mm are shown in **Figure 2C**. Comparison between the robotic- and radiographic-measured leg-length change and global offset change is reported in **Table 2**. The percentages of robotic-measured leg-length change and global offset change within 5, 10, and greater than 10 mm of radiographic measurements are shown in **Figure 2D**.

Table 1

Anteversion and Inclination Measurements (N=61)

Measurement	Mean±SD	95% CI	*P*
Inclination			
Robotic-measured	38.9°±3.2°	38.1-39.7	
Radiographic-measured	40.3°±3.3°	39.5-41.1	
Robotic- vs radiographic-measured	3.2°±2.7°	2.5-3.9	.006
Anteversion			
Robotic-measured	20.3°±2.8°	19.6-21.0	
Radiographic-measured	16.9°±3.0°	16.1-17.7	
Robotic- vs radiographic-measured	3.8°±2.6°	3.1-4.5	<.001

Abbreviation: CI, confidence interval.

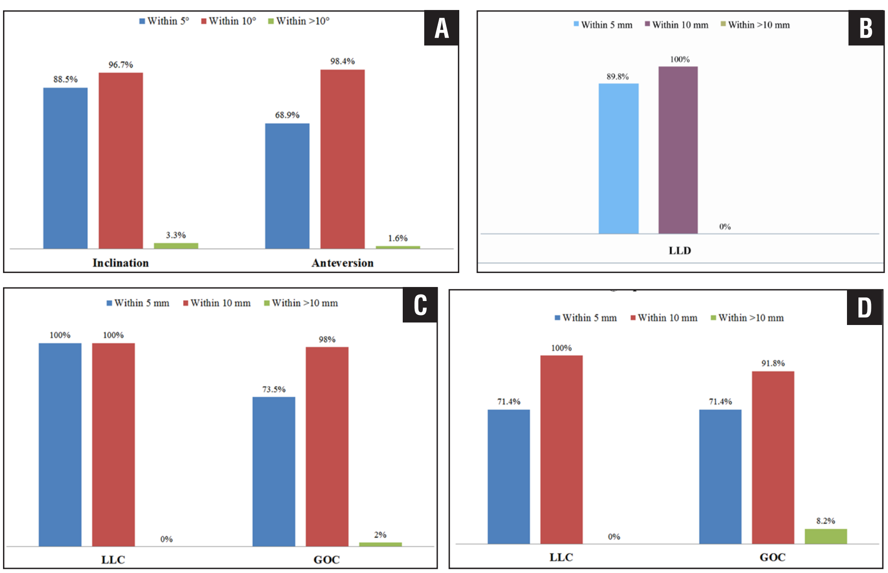

Figure 2: Comparison of robotic-measured inclination and anteversion angles with radiographic-measured angles (A). Leg-length discrepancy (LLD) on postoperative radiographs (B). Radiographic-measured leg-length change (LLC) and global offset change (GOC) (C). Comparison of robotic-measured leg-length change (LLC) and global offset change (GOC) with radiographic-measured distances (D).

Few technical difficulties were encountered using the robotic system. One case necessitated repeat femoral registration due to failure of the first registration. The robotic system had automated double-checks that detected if the patient-specific 3-D hip model matched the intraoperative digitalized check points. The final outcome was not affected in this case, and the cup was found to be within the safe zone.[2,3] In another case, the cup using robotic guidance was judged to be placed outside the safe zone. This judgment was based on the traditional intraoperative landmarks, including bony landmarks, the transverse acetabular ligament, and the alignment guide. The cup was repositioned in the conventional way and found to be within the safe zone.[2,3]

Discussion

The current authors evaluated the ability of the robotic system to estimate the postoperative radiographic parameters of cup inclination and anteversion, as well as the change in leg length and global offset. Ninety-six point seven percent of robotic-measured values were within 10° of radiographic-measured values for inclination angle, 98.4% were within 10° for anteversion angle, 100% were within 10 mm for leg-length change, and 91.8% were within 10 mm for global offset change. One hundred percent of cases had radiographic leg-length discrepancy less than 10 mm, 100% had radiographic leg-length change less than 5 mm, and 73.5% had radiographic global offset change less than 5 mm.

Precise placement of components and reconstruction of biomechanics[11,16] is an important goal of THA. Placing the acetabular cup in the safe zone[2,3] and minimizing changes in leg length[11] and global offset[16] have been proven to decrease short- and long-term complications and improve long-term survivorship of the implant. Computer-assisted surgery has been introduced to decrease technical error and improve consistency and accuracy in performing THA.[22,29]

Acetabular cups placed outside a safe zone of inclination (40°±10°)[3] and anteversion (15°±10°)[2,3] are associated with higher complication rates. Radiographic measurements of inclination and anteversion are still considered the standard of practice in THA. Estimating the cup angles intraoperatively remains a challenging task, despite surgeon experience and the availability of intraoperative visual cues and aiding guides.[29,30] With advances in computer-assisted surgery, a great opportunity arises to minimize human errors and improve accuracy in performing delicate surgery.

In the current study, 88.5% of robotic-measured inclination and 68.9% of robotic-measured anteversion were within 5° of radiographic measurements, whereas 96.7% and 98.4% were within 10°, respectively (**Figure 2A**). Bosker et al[31] compared manually estimated intraoperative measurements of cup inclination and anteversion to postoperative radiographic measurements in 200 cases. Their data showed that 64.5% of radiographic-measured inclination and 61% of radiographic-measured anteversion were within 5° of the angles estimated intraoperatively. The results of the current study demonstrate superior accuracy of the robotic system in estimating cup inclination despite comparable accuracy in estimating cup anteversion, providing the surgeon with a useful tool to improve cup placement.

Mean difference between the robotic-measured and the radiograph-measured angles was 3.2° (range, 0° to 17.5°) for inclination (P=.006), and 3.8° (range, 0° to 11.3°) for anteversion (P<.001) (**Table 1**). Kumar et al[29] compared intraoperative navigation and freehand estimated measurements for inclination and anteversion to postoperative measurements done on CT scans in 56 patients. Their results showed the mean navigation values deviated from the postoperative CT values by 5.3° (range, 1° to 13°) for inclination and 5.6° (range, 1° to 17°) for anteversion, and the mean freehand values deviated for the same by 11.4° (range, 1° to 30°) and 10.8° (range, 2° to 26°), respectively. These values showed the superior accuracy of navigation in estimating the postoperative CT angles over the conventional technique. The current study's results using the robotic system were superior to those reported by Kumar et al[29] using navigation. However, the current authors used postoperative radiographs in their comparison to robotic measurements, whereas Kumar et al[29] used postoperative CT scans, with added cost and radiation.

Leg-length discrepancy is currently one of the most common causes of medical litigation against orthopedic surgeons.[8] Lengthening the operative extremity is sometimes necessary to get a stable hip joint, which is extremely important to prevent postoperative dislocations.[32] Leg-length discrepancy of more than 1 cm has been well documented to be associated with adverse short- and long-term outcomes, including nerve palsies,[8,9] abnormal gait,[10] and low back pain.[11] Nerve palsies can be detected in the immediate postoperative period, whereas abnormal gait and low back pain are detected much later in the follow-up period.

Table 2

Leg-Length Discrepancy, Leg-Length Change, and Global Offset Change Measurements (N=49)

Measurement	Mean±SD, mm	95% CI	*P*
Leg-length discrepancy			
Postop radiograph	2.5±1.9	2.0-3.0	
Leg-length change			
Robotic-measured	3.9±3.0	3.1-4.7	
Radiographic-measured (preop vs postop)	1.6±1.3	1.2-2.0	<.001
Robotic- vs radiographic-measured	3.5±2.6	2.8-4.2	<.001
Global offset change			
Robotic-measured	4.3±3.8	3.2-5.4	
Radiographic-measured (preop vs postop)	3.4±3.0	2.6-4.2	0.2
Robotic- vs radiographic-measured	4.5±3.7	3.5-5.5	0.1

Abbreviations: CI, confidence interval; postop, postoperative; preop, preoperative.

Mean radiographic postoperative leg-length discrepancy in the current study was 2.5 mm (range, -5.8 to 6.8 mm) (**Table 2**), with 89.8% of measurements at 5 mm or less, and 100% at 10 mm or less (**Figure 2B**). All patients in the study cohort were within the conventional safe zone of 1 cm for leg-length discrepancy. Mean change in leg length measured on radiographs was 1.6 mm (range, -4.5 to 4.3 mm) (**Table 2**), with 100% of measurements at 5 mm or less (**Figure 2C**). No case was lengthened or shortened more than 5 mm. Edwards et al[9] reported on thresholds for nerve damage following lower extremity lengthening, offering thresholds of 27 mm for peroneal nerve damage and 44 mm for femoral nerve damage. In all cases in the current study, leg-length change was lower than these previously mentioned thresholds.

Use of the robotic system helped estimate the amount of radiographic leg-length change to within 5 mm in 71.4% of the cases and within 10 mm in 100% of cases (**Figure 2D**). Judging leg-length change intraoperatively using anatomic landmarks and alignment guides is challenging due to the variability in the position of the operated on extremity intraoperatively.[32-34] Keeping leg-length change to a minimum without jeopardizing implant stability is necessary to ensure favorable outcomes in THA.

Maintaining an adequate global offset is important for optimal mechanical function of the hip joint.[16] Deviating from an acceptable range of global offset can result in a painful hip and worse outcomes.[16] Decreasing the global offset leads to a decrease in the lever arm working across the hip joint. This decrease leads to a decrease in abductor muscle power, resulting in limping and a Trendelenburg gait.[12,13] Another result of decrease in global offset is an increase in the forces across the articulating surfaces, leading to increased wear.[12,14] However, an increase in global offset results in an increase in the lever arm across the hip joint, which may lead to pain,[15] increased wear,[14] and leg-length discrepancy.[16]

Mean global offset change measured on radiographs was 3.4 mm (range, -9.6 to

11.9 mm) (**Table 2**), with 73.5% of cases having 5 mm or less of change and 98% having 10 mm or less of change (**Figure 2C**). Measurement of global offset change was done radiographically on the involved extremity, comparing the postoperative view with the preoperative one. This comparison depends on proper radiographs, which might occasionally be rotated. Sometimes advanced arthritis in the hip with loss of joint space superiorly and medially leads to underestimation of the true native hip offset. Dastane et al[16] reported their global offset change on postoperative radiographs, comparing the operated on with the non-operated on extremity. Mean global offset change in their study was 1.4 mm (range, -12.7 to 15.3 mm). Keeping offset change within 5 mm is required to maintain proper biomechanics around the hip joint and limit complications.[14,16] In the current study, the robotic system was able to estimate global offset change to within 5 mm of radiographic-measured global offset change in 71.4% of cases and to within 10 mm in 91.8% of cases (**Figure 2D**).

Strengths of this study are that the robotic-measured data were collected prospectively and all cases were performed by a single surgeon using a single approach. The use of 1 type of acetabular implant adds to the strengths of this study. The surgical technique remained the same throughout the series, and planned cup position was the same for all cases (40° for inclination and 20° for anteversion). Both TraumaCad software and the robotic-assisted THA system follow the coronal plane of the pelvis for measurements, making comparison accurate. Furthermore, data measurement on radiographs was done by 2 observers, which allowed for inter- and intraobserver reliability measurements.

This study had several limitations. The cases in this cohort are among the first robotic-assisted THA cases performed by the senior surgeon; therefore, these results may reflect the early part of the learning curve for use of this technology. However, due to the current paucity of literature on results of robotic-assisted THA, the authors felt that this early data would be of value to the field. Future studies may concentrate on cases performed after surpassing this learning curve. Femoral anteversion was not studied because the earlier software versions of the robotic system did not allow for femoral anteversion measurements. Measuring femoral anteversion is best done on CT scan, with added expense and radiation exposure. Another limitation was the use of 2 different types of femoral stem implants. The reason is that the smaller sizes of one of the implants was not available, necessitating the use of another stem type to fit into narrow femoral canals. The patient sample size was small, and the current study focuses on radiographic outcomes. Ongoing studies aim to report clinical outcome data follow-up.

Conclusion

Use of robotic-assisted THA allowed for accurate and reproducible estimation of the postoperative radiographic measurements of cup inclination, cup anteversion, leg-length change, and global offset change. Further studies are needed to relate the radiographic outcomes to the long-term clinical outcomes and cost-effectiveness of the robotic-assisted THA system.

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