Accuracy of Robotic Arm Assisted Total Hip Replacement Planning Tool

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Abstract

Background: Preoperative templating is an integral part of planning a successful total hip arthroplasty (THA), and helps minimise complications that can arise both intraoperatively and postoperatively. The aim of our study is to determine the reliability of the robotic arm assisted (MAKO fully enhanced) total hip replacement surgical system as a surgical planning tool (not to validate the robot in its execution as it has previously been done) in comparison to conventional acetate and digital templating.

Method: The planning stages of fifty consecutive uncemented THA performed by a single robotic orthopedic surgeon was analyzed against what was achieved during the surgery. The variables analyzed were cup inclination, cup anteversion, combined anteversion, hip length, hip combined offset, femur size, femur component neck angle and cup size.

Results: There was a significant correlation between planned and actual results. The component sizes were planned to accuracy within one size in 100% of femurs, 100% of femur neck-shaft angles and 98% of cups. Cup inclination, anteversion and combined anteversion were planned to accuracy within three degrees in 84%, 96% and 94% of cases respectively. Hip length and combined offset were planned to accuracy within three millimeters in 88% and 78% of cases respectively.

Conclusion: The robotic arm assisted total hip replacement surgical system is a predictable and accurate planning tool and is superior to conventional acetate and digital templating.

Level of evidence: Level III

Keywords: Robotic arm assisted; MAKO; Robotic hip; Templating; Hip arthroplasty

Introduction

Preoperative templating is an integral part of planning a successful total hip arthroplasty (THA) and helps minimize complications that can arise both intraoperatively and postoperatively. These include instability, leg length discrepancy, intraoperative fractures, loss of bone stock, failure to achieve bone in growth and increased length of surgical procedure [1]. Between two to three per cent of THA patients suffer a hip dislocation postoperatively leading to significant cost and morbidity implications [2]. In some cases these complications necessitate surgical revision [3]. Planning also allows the team to prepare the instrumentation required for each operation and have the proper inventory of implants available [4]. Templating is traditionally done with template view X-rays of the pelvis and hip. These X-rays are magnified between 110 and 120% and printed to be used with overlay acetate templates. Alternatively, the X-rays are taken with a reference mark (i.e. template ball) and uploaded into templating software if digital templating is to be used.

When surgery is planned, optimal fit of the implant is crucial as this influences the reconstructing leg length, offset and the center of

rotation [5]. Other considerations include cup inclination and cup anteversion. The surgeon has to think three-dimensionally to achieve the most reliable preoperative plan. During surgery, the acetabulum is serially reamed until the subchondral bone is exposed and a well-fitting acetabular cup is inserted (press fit or cemented). The optimal fitting femoral stem (uncemented or cemented) is inserted after the medullary canal is broached using sequentially larger broaches. Templating is a guide to this process and loose implants affect the survival of the prostheses [6].

Several studies have looked at the efficacy and accuracy of the different methods of templating (Table 1). Both digital and acetate templating of the cup and femur overall have less than 50% accuracy in exact match and less than 85% accuracy for being within one size.

Paper	Templating Method	Accuracy Acetabular Cup		Accuracy Femoral Stem		Femoral Offset	
		Exact	+/- 1 Size	Exact	+/- 1 Size	Exact	+/- 1 Size
Rajamani et al. [6]	Acetate	78%	98%	56%	83%		

Petretta et al. [1]	Acetate	28%	77%	33%	75%		
	Digital	28%	70%	25%	60%		
Si et al. [28]	Digital	43.30 %	78.90 %	40%	84.40 %		
Riddick et al. [37]	Acetate	53%	87%	49%	92%		
	Digital			37%	53%		
Kniesel et al. [38]	Digital	27%	67%				
	Digital			37%	53%		
Shaarani et al. [12]	Digital	38%	80%	36%	75%	91%	
Kearney et al. [2]	Acetate	27%	75%	37%	91%	91%	100%
Bertz et al. [16]	Digital	60%	94%	64%	95%		
Whiddon et al. [27]	Acetate	31%	67%	33%	82%		
	Digital	39%	78%	61%	90%		
Gamble et al. [29]	Acetate	20%	60%	40%	85%		
	Digital	38%	80%	35%	85%		
Kumar et al. [32]	Digital	56%	91%	62%	78%	93%	
Steinberg et al. [33]	Digital	50%	88%	47%	87%	97%	
Iorio et al. [34]	Digital		60%		74%		
	Acetate		78%		77%		
Crooijmans et al. [36]	Acetate	51.50 %	89.70 %	76.50 %	97.10 %		
	Digital	14.70 %	36.80 %	7.40 %	55.90 %		
	Acetate	42.20 %	82.80 %	32.80 %	84.40 %		
	Digital	25%	62.50 %	10.90 %	50%		
Unnanuntana et al. [30]	Acetate	42.20 %		68.80 %	98.20 %	91%	
Gonzalez Della Valle et al. [10]	Digital	25%	81%	58%	94%	75%	
	Acetate	51%	97%	69%	98%	86%	
The et al. [31]	Acetate	67%		56%			
	Digital	84%		58%			
Davila et al. [35]	Digital	39%	86%	19%	72%		
The et al. [5]	Digital	36%	72%	35%	79%		
	Acetate	23%	73%	37%	89%		
	Digital	16%	72%	34%	79%		
	Acetate	34%	73%	30%	89%		

Table 1: Review of the literature from January 2005 to June 2017 on accuracy of acetate and digital templating.

Also, conventional templating methods do not allow for reliable planning of optimal cup inclination, cup anteversion and hence combined anteversion. However, with new advances in robotic surgery, we have the ability to plan and execute total hip arthroplasty with increasing precision. The robotic arm assisted (RAA) system allows surgeons to preoperatively plan cup inclination and cup anteversion to an accuracy of one degree. The combined anteversion is set and the optimal range is planned after measuring the broach anteversion. The broach anteversion is set by the femur canal and the broach is free to find its own best fitting path. The cup anteversion can then be changed to achieve optimal combined anteversion. Hip length and offset change compared to ipsilateral preoperative and contralateral hip position can be adjusted to an accuracy of one millimeter. The component sizes (cup size, femur size and femur component neck angle) can also be templated as with conventional methods. Figure 1 demonstrates the flow of preoperative planning and final results with the RAA total hip replacement system.

Previous studies have validated this RAA total hip replacement system with postoperative CT scanning and X-rays [7-9]. The aim of our study was not to validate the system but to determine the reliability of the RAA total hip replacement surgical system as a surgical planning tool in comparison to conventional acetate and digital templating. Preoperative planning with templates has become an indispensable part of modern total hip arthroplasty [10].

Figure 1: Key steps in MAKO fully enhanced THA planning and execution. A: Acetabular component preoperative planning. B: The hip length is the distance (mm) from the ASIS axis to the lesser trochanter landmarks with the femurs in mechanical axis alignment. Combined offset is the distance (mm) from the midline axis to the femoral canal axes with the femoral canal axes aligned vertically. C: Femoral component preoperative planning with planned implant details. D: After broaching, broach anteversion measured and acetabular component anteversion can be adjusted if required to achieve desired combined anteversion. E: Final readings after components implanted and hip enlocated.

Method

Data on fifty consecutive RAA (MAKO fully enhanced) THA were retrospectively analysed. All surgeries were performed by the same experienced robotic arthroplasty fellowship trained surgeon at a single

site. All cases analysed were primary THA for osteoarthritis with uncemented components. Components used were Stryker Accolade II stem and Stryker Tritanium cup. Preoperative variables analysed were cup inclination, cup anteversion, combined anteversion (after measuring broach anteversion), hip length versus pre-operative hip, hip combined offset vs pre-operative hip, femur size, femur component neck angle and cup size. The preoperative plan for these variables were analyzed against the final measurements recorded after the components were implanted and hip enlocated (Figure 1). The RAA THA system uses patient specific information gathered from a preoperative CT scan to plan the surgery. During surgery, the femur and acetabulum are correlated with the CT using three landmark points and 32 registration points for each. The accepted registration error is less than or equal to 0.5 mm. The registration is then verified by placing the probe on the surface of the bone. Verification is accepted only if the distance to bone is less than one millimeter. If more than one registration point is greater than one millimeter, the registration should be repeated.

To determine how far from the planned result each variable was, a difference score was calculated (actual minus planned). Positive differences show that the actual result was larger than the planned and negative differences show that actual result was smaller than the planned. All data were assessed for outliers (more than three standard deviations above or below the mean). The first analysis for each variable describes the strength of the association between the planned and actual values using a correlation. The second analysis investigates bias in the difference between planned and actual results, that is whether the actual result is either consistently under or over planned results. This is done using a one-sample t-test and comparing the difference scores to a hypothesized difference of zero.

Results

Descriptive statistics are presented in Table 2 and accuracy of templated measurements in Table 3.

Cup inclination (deg)			
	Planned	Actual	Diff
Range	40 to 45	36 to 47	-4 to 7
Mean	40.2	39.5	-0.74
SD	0.99	2.54	2.28
Cup anteversion (deg)			
	Planned	Actual	Diff
Range	17 to 30	15 to 30	-4 to 4
Mean	21.6	21.4	-0.16
SD	2.9	3.33	1.77
Combined anteversion (deg)			
	Planned	Actual	Diff
Range	14 to 45	14 to 43	-4 to 4
Mean	30.9	30.8	-0.18
SD	5.78	5.85	1.86

Hip length vs pre-op hip (mm)			
	Planned	Actual	Diff
Range	-3 to 10	-3 to 12	-3 to 4
Mean	3.26	3.84	0.58
SD	3.01	3.18	2.1
Hip combined offset v pre-op hip (mm)			
	Planned	Actual	Diff
Range	-11 to 5	-10 to 11	-5 to 8
Mean	-2.8	-2	0.8
SD	3.92	4.38	2.88
Femur size			
	Planned	Actual	Diff
Range	2 to 10	1 to 10	-1 to 1
Mean	5	5.1	0.1
SD	1.85	1.83	0.46
Femur neck angle			
	Planned	Actual	Diff
Range	127 to 132	127 to 132	0 to 0
Mean	128	128	0
SD	2.02	2.02	0
Cup size			
	Planned	Actual	Diff
Range	48 to 60	50 to 60	-4 to 2
Mean	54.1	54	-0.12
SD	3.18	3.17	0.75

Table 2: Descriptive statistics including range (min to max), mean, and standard deviation (SD).

Cup inclination (deg)	
±1 deg	60%
±3 deg	84%
Cup anteversion (deg)	
±1 deg	60%
±3 deg	96%
Combined anteversion (deg)	
±1 deg	58%
±3 deg	94%
Hip length vs pre-op hip (mm)	

±1 mm	46%
±3 mm	88%
Hip combined offset v pre-op hip (mm)	
±1 mm	34%
±3 mm	78%
Femur size	
exact match	78%
±1 size	100%
Femur neck angle	
exact match	100%
±1 size	100%
Cup size	
exact match	92%
±1 size	98%

Table 3: Accuracy of templated measurements.

Cup inclination (degrees)

Cup inclination was planned accurately in 60% of cases +/- 1° and 84% +/- 3°. There were two outliers present (patient 18 and 50 had differences of +7) in the data. There was a significant moderate correlation between planned and actual, $r(50)=0.45$, $p=0.001$. There was a significant bias in the direction of the difference, $t(49)=2.30$, $p=0.026$, where the actual cup inclination was consistently smaller than planned.

Cup anteversion (degrees)

Cup anteversion was planned accurately in 60% of cases +/- 1° and 96% +/- 3°. There were no outliers present in the data. There was a significant strong correlation between planned and actual, $r(50)=0.85$, $p<0.001$. There was also no significant bias in the direction of the difference, $t<1$, $p=0.53$.

Combined anteversion (degrees)

Combined anteversion was planned accurately in 58% of cases +/- 1° and 94% +/- 3°. There were no outliers present in the data. There was a significant strong correlation between planned and actual, $r(50)=0.95$, $p<0.001$. There was also no significant bias in the direction of the difference, $t<1$, $p=0.50$.

Hip length vs pre-operative hip (mm)

Hip length was planned accurately in 46% of cases +/- 1mm and 88% +/- 3mm. There were no outliers present in the data. There was a significant strong correlation between planned and actual, $r(50)=0.77$, $p<0.001$. There was a trend towards a significant bias in the direction of the difference, $t(49)=1.95$, $p=0.057$, with hip length in comparison to pre-operative hip being longer than planned.

Hip combined offset vs pre-operative hip (mm)

Combined offset was planned accurately in 34% of cases +/- 1mm and 78% +/- 3mm. There were no outliers present in the data. There was a significant strong correlation between planned and actual, $r(50)=0.77$, $p<0.001$. There was a trend towards a significant bias in the direction of the difference, $t(49)=1.97$, $p=0.055$, where the trend was towards hip combination offset vs. pre-op hip being longer than planned.

Femur size

Femur size was planned accurately in 78% of cases with exact match and 100% +/- one size. There were no outliers present in the data. There was a significant very strong correlation between planned and actual femur size, $r(50)=0.97$, $p<0.001$. There was no significant bias in the direction of the difference, $t(49)=1.53$, $p=0.13$.

Femur neck angle

There was perfect correlation between planned and actual.

Cup size

Cup size was planned accurately in 92% of cases with exact match and 98% +/- one size. There was close to perfect correlation between planned and actual, with only four patients having any difference at all.

Discussion

Preoperative templating for THA has been accepted as an essential step to facilitate the surgical process [11]. With increasing numbers of younger and more active patients the goals have evolved from pain relief to include restoration of high function [12]. The RAA THA system planning is able to achieve greater accuracy than conventional acetate and digital templating as can be seen by our results compared to the literature in Table 1.

Component size was planned with close to 100 % accuracy within +/- one size. With increasing use of uncemented prostheses, more emphasis has been placed on choosing the correct implant size to avoid subsidence with too small a component or fracture with too large a component [12].

About one in every three patients reports a sensation of leg length discrepancy (LLD) after THA [13-15]. Edeen et al. [13] reported that even a small discrepancy could induce dissatisfaction. LLD is a common cause for postoperative dissatisfaction [16] and it is reported as the second most cited cause of medical malpractice litigation among American association of hip and knee surgeons [17]. Our results show that we were able to achieve our planned leg length to within 3mm in 88% of cases.

Femoral offset is the distance from the center of rotation of the femoral head to a line bisecting the long axis of the femur. Previous studies have shown that increasing femoral offset will improve hip abductor strength, enhance range of motion, reduce limping, decrease dislocation risks; cup strain and polyethylene wear [15,18,19]. Another study showed that a 15% or greater decrease in offset compared to the non-operated side was associated with an increased frequency of gait disorders [20]. We were able to achieve our planned offset to within 3mm in 78% of cases. The femoral neck-shaft angle determines the size of the anatomical femoral offset [21]. We were able to plan the correct neck-shaft angle of the final prosthesis in 100% of cases. Dislocation is

one of the more serious complications; one possible cause is decreased femoral offset. It is stated that femoral offset is restored in only 40% of THA patients however preoperative templating can lead to offset restoration in up to 90% of patients [2]. This may also be consequent to increased accuracy of femoral stem anteversion and acetabular cup anteversion. This is important to ensure the optimal relationship of the femoral head in the cup without impingement of the two throughout all body positions [22]. The sum of the cup and stem anteversion is known as the combined anteversion and this has been investigated by both mathematical models and clinical studies [23-26] to determine the optimal range for men and women. This concept is particularly important in uncemented components as the femoral anteversion is guided by the femoral bone geometry which is highly variable [22]. Hence the RAA system first measures the broach anteversion and the cup anteversion can be adjusted accordingly. We were able to achieve our planned combined anteversion in 94% of case +/- 3 degrees.

There were several limitations to our study. First, our study only included uncemented components. Cemented components could potentially lead to deviation away from the plan as the components have the flexibility to change orientation during the cementing process. Also, all the planning and surgery was performed by an experienced robotic orthopedic surgeon and the level of accuracy achieved could be different in less experienced hands. This study was a retrospective analysis and at the time of surgery the authors did not have an intention to write this paper hence the risk of bias on size matching was controlled. Finally, the component position was determined using the RAA system and not with postoperative CT analysis. However, two studies have previously performed cadaveric THA to validate this RAA system with postoperative CT scanning. The first study found the root mean square (RMS) error for the robotic-assisted surgery was within three degrees for cup placement and within one millimetre for leg length equalization and offset [7]. The second study found the Inclination to be $2.7 \pm 2.2^\circ$, cup anteversion $2.2 \pm 1.4^\circ$, hip length 1.6 ± 1.2 mm and combined offset 1.3 ± 0.8 mm [8]. Domb et al. analysed the cup position in 50 RAA THAs radiographically and found the cup positioning were placed 100% of the time within the Lewinnek "Safe Zone" for anteversion and inclination [9]. With this level of precision, we were satisfied to use the RAA system for our component position measurements.

Conclusion

The RAA total hip replacement surgical system is a predictable planning tool with superior accuracy compared to conventional acetate and digital templating. Although longevity of THA continue to improve, incidence of dislocation and impingement related failures continue to rise [7,15]. Compounded with increasing patient expectations, we are at an era where accurate planning and precise execution is crucial to prevent complications and meet the demands of our patients.

Source of Funding & Conflicts of Interest

None.

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