QUANTIFYING MEASUREMENT UNCERTAINTY FOR LOCATING HIP IMPLANT

By

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I dedicate this to Dr. Banks and all the other people in this study.

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LIST OF ABBREVIATIONS

3D/2D	Three dimensions and two dimensions
ACETABULAR AXIS	The axis perpendicular to the rim of the cup and passing through the center of the cup
CT	Computed tomography
THA	Total Hip Arthroplasty

Abstract of Thesis Presented to the Graduate School
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Accurate placement of the acetabular cup during total hip arthroplasty is critical to long-term clinical success. Measurements of cup position and orientation from postoperative CT scans are accepted as the gold standard reference measurement, yet there have been no reports of the uncertainties associated with this method. We studied pre- and post-operative CT scans for ten patients who received THA and measured the radiographic inclination and radiographic anteversion in an anatomic coordinate system. To quantify measurement uncertainties, we repeated the measurements several times and separately varied factors that might contribute to measurement error. Our results suggest the best measurements are achieved using full pelvis bone models with the acetabular area removed, and by matching the pre- and post-operative pelvis models using 3D global registration. This standardized measurement has an accuracy, precision and bias of 0.3°, 0.7° and 0° for radiographic inclination, and 0. 2°, 0.6° and 0.1° for radiographic anteversion. We found similar results when using shorter pelvis bone segments for registration. Including the periacetabular bone and/or using manual landmark identification resulted in less accurate measurements. Post-operative CT measurements of cup position is a useful and accurate measurement reference

standard. Our results quantify the measurement uncertainty for this procedure and put previous reports of intraoperative measurement results into context.

CHAPTER 1
INTRODUCTION

Accurate placement of the acetabular cup is a critically important part of total hip arthroplasty (THA) since inaccurate cup position may cause serious complications such as dislocation [1-4], accelerated wear of the liner [4] and cup loosening [5]. Consequently, there have been many studies [6-9] measuring cup orientation and evaluating the accuracy, precision and bias of various surgical technologies by comparing intraoperative placement measurements with postoperative measurements from computed tomography (CT) scans. Several different post-op CT measurements techniques have been used, and they can be separated into three categories: 2D, 2D/3D and 3D. Typical 2D methods [10] use projections of post-op CT images on the coronal plane and sagittal plane to measure the cup inclination and anteversion on 2D images. 2D/3D methods [11] generate a 3D cup model to reach the best possible match in all 2D views, then define the cup plane and cup axis to measure the inclination and anteversion. Widely used 3D methods [6, 7] create 3D models of both the pelvis and the implanted cup, establish an anatomic coordinate system based upon bony landmarks, and virtually translate and rotate the cup using 3D registration. Finally, the radiographic inclination and anteversion angles are calculated based on the definitions of Murray et al. [12].

Collectively, these post-op CT measurements are accepted as ‘gold standard’ reference measurements, yet none of these studies has reported the accuracy, precision or bias of the measurement. We, too, have interest measuring the accuracy of cup placement and have developed techniques to perform the measurement using 3D global registration with pre- and post-operative CT scans. The purpose of this study is to assess the accuracy, precision and bias of acetabular cup orientation measurements and to consider the contributions of various factors to measurement uncertainties. Our goal is to provide an assessment of the quality of these measurements and to put the results of previous related studies into a quantitative context.

CHAPTER 2
MATERIALS AND METHODS

Subjects

Ten anonymous patients were involved in this study to determine the cup position and quantify the measurement uncertainty. All patients had THA surgeries assisted by the RIO robot system (MAKO Surgical, Davie, FL) which is a haptically-guided robotic-arm system. Each patient was pre-operative and post-operative scanned with CT to create pre-operative pelvis model, post-operative pelvis model and post-operative cup model.

Measurement of Acetabular Cup Orientation

The measurement procedure for quantifying acetabular cup orientation uses CT-derived pre- and post-operative pelvic bone models, with the periacetabular region removed, and global registration to spatially align the pelvises and cups in a well-defined anatomic coordinate reference frame. There are six steps to measure the orientation of the acetabular cup of each patient:

1. The pre- and post-operative pelvic bone models, and post-operative cup model were constructed from pre- and post-operative CT scans by segmentation with open-source software (ITK-SNAP, Penn Image Computing and Science Laboratory, [13]). Stereolithography (STL) format models of acetabular cups in all sizes were provided by the manufacturer (MAKO Surgical, Davie, FL).

2. A common reference frame was established for the measurement (Fig. 2-1). This anatomic coordinate system was based on the pre-operative alignment of the pelvis anatomy and adjusted according to several anatomical landmarks. The origin of the coordinates was placed at the acetabular cup center. Then the medial/lateral axis was aligned parallel to a line passing through the right and left anterior-superior iliac spines (ASIS). Finally, the anterior/posterior axis was unchanged from the pre-op CT table orientation to the anatomic coordinate system, which means that each patient has a specific pelvis tilt.

3. After the anatomic coordinate system was defined, the post-operative pelvis and cup were imported into software with the pre-operative pelvis model. Global registration was used to align the pre-op and post-op pelvises based on an iterative closet point

registration algorithm (Geomagic Studio, Geomagic Corp., Morrisville, NC). To retain the relative position between post-operative pelvis and cup, the post-operative cup was moved using the same coordinate transformation (4x4) used to align the post-operative pelvis (Fig. 2-2).

4. The implant cup model was imported into software, the origin of the cup was moved to the origin of the anatomic coordinate system, and the cup acetabular axis was aligned with the proximal/distal axis of the pelvis (z-axis of anatomic coordinate system). The acetabular axis was defined as the axis perpendicular to the rim of the cup and passing through the center of the cup.

5. Global registration was used to align the implant cup model to match the post-op cup model. The coordinates of the acetabular axis were obtained in this step.

6. According to Murray's [12] definition, the RI (radiographic inclination) and RA (radiographic anteversion) were calculated.

Sources of Uncertainty

There are two categories for sources of uncertainty, systematic uncertainties and controllable uncertainties (Fig. 2-3). Systematic uncertainties arise from steps 3 and 5 in the measurement process and cannot be avoided. When matching the post-operative pelvis to the pre-operative pelvis, and implant cup model to the CT-derived post-operative cup model, either global registration or manual alignment can be used to align the pelvises and cups based on views. Controllable uncertainties include the quality of pelvis bone models and post-operative cups, whether the acetabulum of the pelvis was used, and the amount of pelvis used for registration. Each of these factors was explored to determine their effects on registration accuracy. The quality of pelvis bone models and post-operative cups will not be discussed in this paper since the resolution of CT images was fixed for all patients.

A series of evaluations were conducted to assess measurement uncertainties for cup orientation measurements. First, the repeatability of the standard method, as outlined above, was determined by performing a repeated measurements experiment.

This experiment was conducted using both automated global registration, and alignment based upon manual identification of anatomic landmarks. Second, the impact of geometric changes in the periacetabular region on cup measurements was assessed by performing measurements with pre-operative intact and removed periacetabular bone in the pelvis models. (The theory is that this area will change as a result of surgery, and so should not be used for alignment.) Finally, an experiment was conducted to determine how much pelvis is required to provide accurate registration results. If less pelvis can be used, then the patient can receive a less extensive CT scan, and much less time is consumed creating the pre- and post-operative bone models by segmenting CT scans.

Global Registration vs. Manual Alignment

The accuracy, precision and bias of the standard measurement was assessed by performing the measurements twice for each of ten patient data sets using global registration for bone alignment. These measurements were repeated twice more using manual procedures to align the pelvises and cups for all ten patients. The experiments provided a total of four RI (Radiographic Inclination) and RA (Radiographic Anteversion) measurements from the same data, two from the standard measurement, and two from the measurement using manual alignment. Paired two-sample t-tests were performed between two trials of each measurement, and the t-test was also applied between two the measurement methods. Accuracy, precision and bias were calculated by treating the results of the standard measurement as the reference.

Impact of the Acetabulum

During THA surgery the acetabulum is reshaped by reamers and removal of osteophytes, so the pre-operative acetabular region is different from the post-operative acetabular region. Since 3D registration is based upon alignment of similar surfaces, it is important to know if the altered acetabular region will have an effect on registration accuracy. Therefore, the measurements were repeated on the ten patients by using full pelvis models with and without the acetabular bone included. A paired two-sample t-test was performed to compare the measurements with acetabular bone to the standard measurement, and accuracy, precision and bias were calculated.

Impact of the Amount of Pelvis

This experiment was designed to test the effect of post-operative pelvis bone extent (in the superior-inferior direction) on measurement accuracy. Both the pre- and post-operative pelvises were progressively reduced along z-axis (longitude axis) from the full pelvis model. Bone model reductions were symmetric about the acetabular center (the origin of the anatomic coordinate system). The bone model sizes evaluated were +/- 60mm, +/- 50mm, +/- 40mm and +/- 30mm from the acetabular center (Figure 2-4). Measurements were performed on all patients with these differing amounts of post-op pelvis and a one-factor ANOVA test was performed to detect if any measurements were significantly different from others. In addition, the accuracy, precision and bias of these measurements compared to the standard measurement using the full pelvis were calculated.

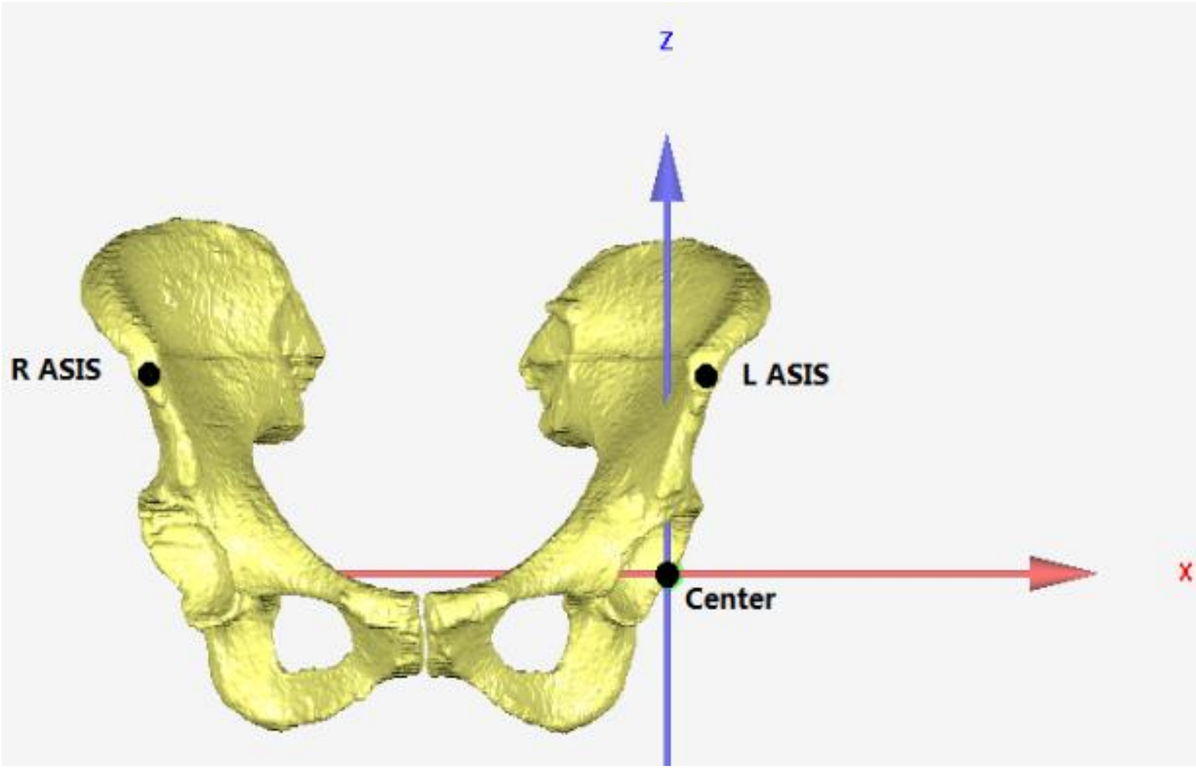

Figure 2-1. Anatomic coordinates were derived from the pre-op CT orientation and aligned to the medial/lateral axis formed by ASIS points. The x-axis (red) is the medial/lateral direction and the z-axis (blue) is the proximal/distal direction. The y-axis (green, covered by the center) is the anterior/posterior direction, and is perpendicular to the image shown.

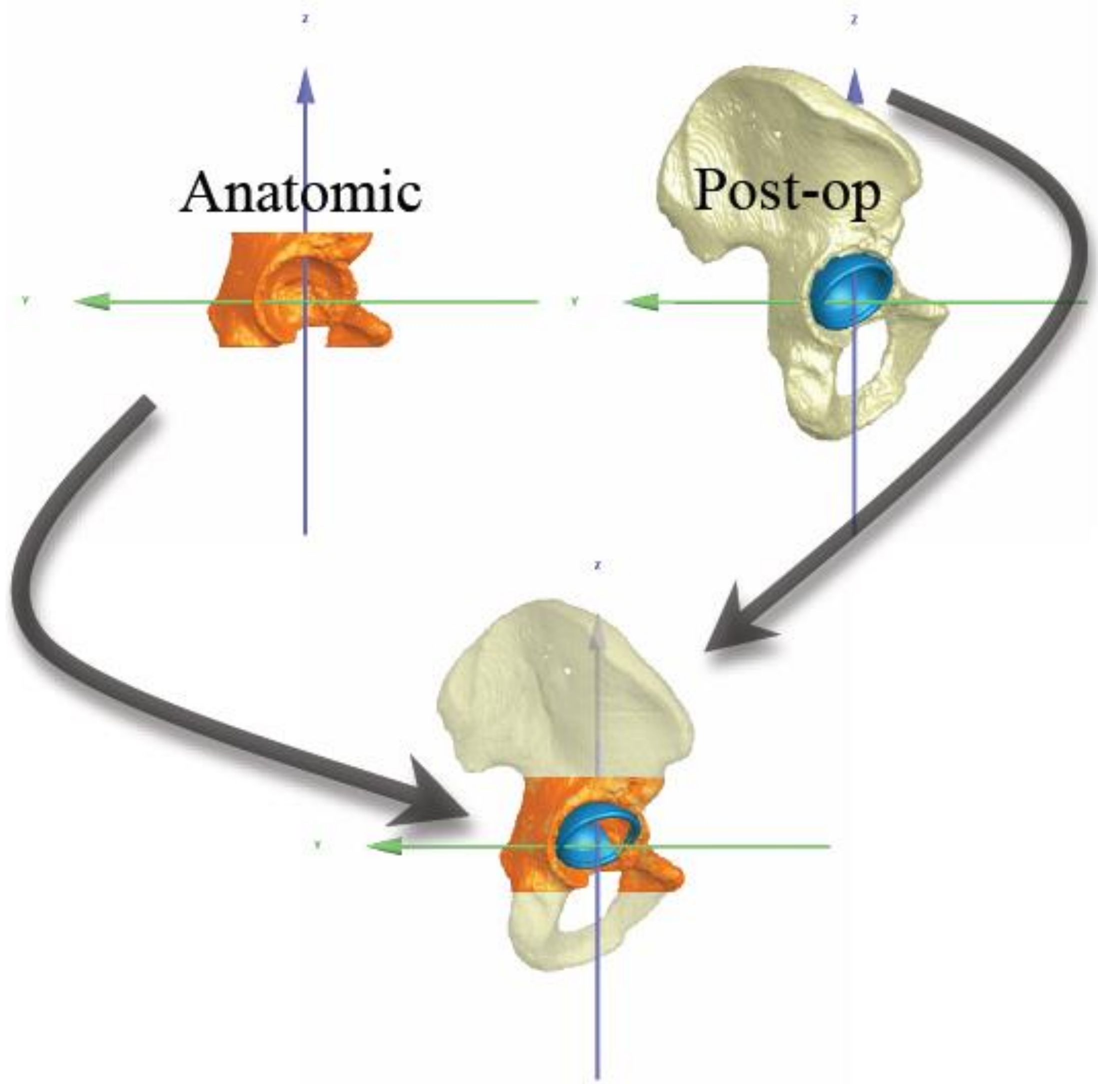

Figure 2-2. The post-operative pelvis model (white) is registered to the pre-op pelvic model (orange), preserving the pre-op coronal plane. All measurement are recorded relative to the anatomic coordinates. In the standard measurement, full pre-op and post-op pelvises without acetabulum were used to measure the cup position.

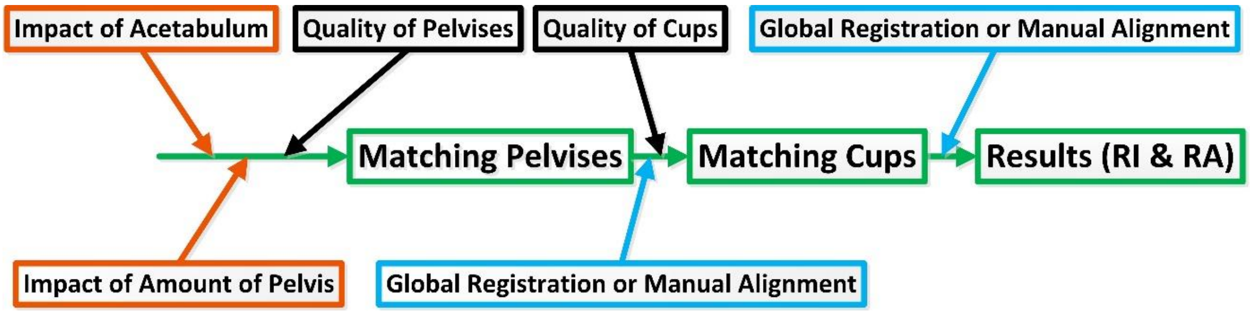

Figure 2-3. Flow chart of measuring the orientation of acetabular cup and list of uncertainty sources. The words in green frames show the process to measure the cup position. The words in blue frames show the systematic uncertainties. The words in orange frames show the controllable uncertainties. The words in black frames show the uncertainty sources not discussed.

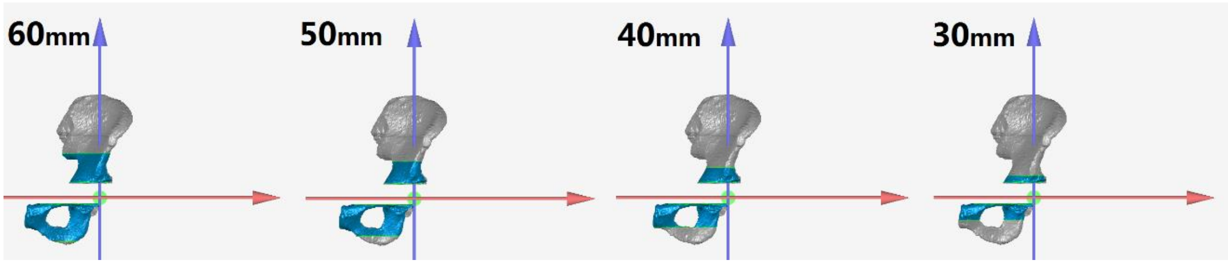

Figure 2-4. Flow chart of measuring the orientation of acetabular cup and list of uncertainty sources. The words in green frames show the process to measure the cup position. The words in blue frames show the systematic uncertainties. The words in orange frames show the controllable uncertainties. The words in black frames show the uncertainty sources not discussed.

CHAPTER 3
RESULTS

Global Registration vs. Manual Alignment

Repeated measures of cup orientation angles using global registration showed good accuracy (0.24°), precision (0.65°) and negligible bias (Table 3-1). Manual alignment had poorer results by all metrics. There were no significant differences detected for repeated measures or between method comparisons. The global registration-based measurement is the standard for subsequent comparisons.

Impact of the Acetabulum

Inclusion of the periacetabular bone resulted in slight increases in accuracy, precision and bias results compared to the standard measurement (Table 3-2). Statistical comparison of radiographic inclination angles resulted in a p-value of 0.07, which would be significant for a 90% confidence level. These results show inclusion of the periacetabular bone tends to degrade the measurement of cup orientation from pre- and post-operative CT scans.

Impact of the Amount of Pelvis

One-factor ANOVA revealed no significant differences in cup orientation results using different amounts of pelvis bone (Table 3-3). There appears to be a slight improvement in the accuracy and precision results for measurements using 40mm or greater models, but this is not a statistically supported observation.

Comparison of Factors

Comparing the results of the three separate evaluations shows that pelvis model extent had the smallest effect on cup orientation measurements, while manual alignment had the greatest effect (Table 3-4). (Assuming all measurements were independent, one would expect the measured accuracy, precision and bias figures for all measurements to be greater than twice the figures for the standard measurement, since they are measured by subtracting the standard measure.).

Table 3-1. Cup orientation measurement results of RI using global registration and manual alignment methods.

Radiographic Inclination						
Paired Two Sample T Test						
	Global Registration		Manual Alignment		GR vs. MA	
	Trial One	Trial Two	Trial One	Trial Two	GR	MA
Mean	38.73°	38.36°	38.14°	39.25°	38.73°	38.70°
Variance	35.33°	35.88°	28.33°	32.18°	35.33°	28.99°
P Value	0.9397		0.2546		0.5369	
	Global Registration			Manual Alignment		
	Accuracy	Precision	Bias	Accuracy	Precision	Bias
	0.2847°	0.7462°	-0.0094°	1.7972°	4.7280°	1.1059°

GR = global registration; MA = manual alignment; Variance = the square of the standard deviation.

Table 3-2. Cup orientation measurement results of RA using global registration and manual alignment methods.

Radiographic Anteversion						
Paired Two Sample T Test						
	Global Registration		Manual Alignment		GR vs. MA	
	Trial One	Trial Two	Trial One	Trial Two	GR	MA
Mean	19.00°	19.51°	18.91°	19.41°	19.00°	19.16°
Variance	27.04°	30.61°	47.98°	36.62°	27.04°	40.14°
P Value	0.3091		0.3580		0.6115	
	Global Registration			Manual Alignment		
	Accuracy	Precision	Bias	Accuracy	Precision	Bias
	0.2361°	0.5780°	-0.1005°	1.8193°	4.9955°	0.2943°

Table 3-3. The impact of using the periacetabular bone on the RI and RA.

Radiographic Inclination			Radiographic Anteversion		
Paired Two Sample T Test			Paired Two Sample T Test		
	Acetabulum	Standard		Acetabulum	Standard
Mean	38.35°	38.73°	Mean	19.17°	19.00°
Variance	39.92°	35.33°	Variance	26.67°	27.04°
P Value	0.0734		P Value	0.2608	
Acetabulum			Acetabulum		
Accuracy	Precision	Bias	Accuracy	Precision	Bias
0.5723°	1.1608°	0.3794°	0.3469°	0.8442°	-0.1634°

Acetabulum = the measurement used full pelvis with acetabulum.

Table 3-4. The impact of the amount of pelvis on the RI.

Radiographic Inclination						
Single Factor ANOVA Test						
	30	40	50	60	Standard	
Mean	38.26°	38.57°	38.83°	38.90°	38.73°	
Variance	32.64°	33.61°	40.92°	33.08°	35.33°	
P Value	0.9993					
	30			40		
	Accuracy	Precision	Bias	Accuracy	Precision	Bias
	0.5630°	1.2413°	-0.4688°	0.4515°	1.3221°	-0.1566°
	50			60		
	Accuracy	Precision	Bias	Accuracy	Precision	Bias
	0.4425°	1.4760°	0.0962°	0.4821°	1.1839°	0.1694°

The numbers (30, 40, 50 and 60) are the distances from acetabular center which indicates the amount of post-op pelvis used in the measurement.

Table 3-5. The impact of the amount of pelvis on the RA.

Radiographic Anteversion						
Single Factor ANOVA Test						
	30	40	50	60	Standard	
Mean	19.32°	18.91°	19.23°	18.91°	19.00°	
Variance	27.48°	25.57°	26.63°	24.22°	27.04°	
P Value	0.9996					
	30			40		
	Accuracy	Precision	Bias	Accuracy	Precision	Bias
	0.6264°	1.6260°	0.3147°	0.3861°	1.1152°	-0.0989°
	50			60		
	Accuracy	Precision	Bias	Accuracy	Precision	Bias
	0.5248°	1.3299°	0.2305°	0.5872°	1.7338°	-0.0909°

The numbers (30, 40, 50 and 60) are the distances from acetabular center which indicates the amount of post-op pelvis used in the measurement.

Table 3-6. Cup orientation measurement results of RI for all evaluations.

Radiographic Inclination							
	Standard	30	40	50	60	Acetabulum	MA
Accuracy	0.2847°	0.5630°	0.4515°	0.4425°	0.4821°	0.5723°	1.7972°
Precision	0.7462°	1.2413°	1.3221°	1.4760°	1.1839°	1.1608°	4.7280°
Bias	-0.0094°	-0.4688°	-0.1566°	0.0962°	0.1694°	0.3794°	1.1059°

Table 3-7. Cup orientation measurement results of RA for all evaluations

Radiographic Anteversion							
	Standard	30	40	50	60	Acetabulum	MA
Accuracy	0.2361°	0.6264°	0.3861°	0.5248°	0.5872°	0.3469°	1.8193°
Precision	0.5780°	1.6260°	1.1152°	1.3299°	1.7338°	0.8442°	4.9955°
Bias	-0.1005°	0.3147°	-0.0989°	0.2305°	-0.0909°	-0.1634°	0.2943°

CHAPTER 4
DISCUSSION

Post-operative CT-based measurement of acetabular cup position is accepted as a gold standard measurement method, yet its accuracy, precision and bias has not been reported. Therefore, we studied the impact of various sources of measurement uncertainty on acetabular cup angle measurements. Our results suggest global registration of 3D pelvis bone models and cups provides the best results. Similar results can be obtained by using partial pelvis bone models with lesser extent in the proximal/distal direction. Our results suggest removing periacetabular bone from the pelvis model improves measurement accuracy, Manual alignment of pelvis models based upon the identification of bony landmarks resulted in less accurate measurements.

This study has several limitations. The sample size is too small to provide powerful statistical comparisons. Anonymous patient data were drawn from a single surgeon and clinic, so there may be some bias in patient anatomy or stereotypic differences in cup implantation. Finally, the impact of CT scan quality on cup measurements was not included, because scans at different resolutions were not available for study. We expect that higher resolution CT images will provide better measurement results.

Because the post-op CT measurement has been accepted as a gold standard measurement, the bias and precision of the measurement had not been considered in reporting the precision and bias of other intraoperative cup measurement techniques. The bias and precision figures reported for previous studies, e.g. [6, 7], represent the combination of errors from the intraoperative and CT-based measurements. Based upon the bias and precision of our standard measurement (post-op CT measurement), we can recalculate the bias and precision of previous reports [Table 4-1]. The refined bias is smaller and the refined precision remains the same. Since the bias is the mean of differences, we may conclude that the results of of previous intraoperative measurements are closer to the true values than reported.

The importance of this study is quantifying the standard measurement and impact of various sources of uncertainty in the post-operative CT-based measurement of acetabular cup position. The post-op CT-based measurement that is accepted as a gold standard has an accuracy of less than 0.3°, a precision less than 0.7° and an absolute bias less than 0.1°. These data (including the accuracy, precision, bias of uncertainty resources) increase confidence in the use of results from post-operative CT-based measurements, help surgeons better to understand the accuracy of various implant placement technologies, and provide a rigorous method to demonstrate improvements in the techniques for implanting total hip replacements.

Table 4-1. Original and refined results from other intro-op measurement.

	Radiographic Inclination			Radiographic Anteversion		
Original	Standard	Dorr et al.	Ryan et al.	Standard	Dorr et al.	Ryan et al.
Bias	-0.0094°	0.03°	0.52°	-0.1005°	0.73°	0.35°
Precision	0.7462°	4.4°	3.4°	0.578°	4.1°	5.5°
Refined		Dorr et al.	Ryan et al.		Dorr et al.	Ryan et al.
Bias		0.0261°	0.5074°		0.6253°	0.2482°
Precision		4.4326°	3.5179°		4.101°	5.4959°

Refined means that these results were calculated as considering the bias and precision of the post-op CT standard measurement.

APPENDIX
MATLAB CODE USED TO CALCULATE CUP ORIENTATION

```
function [anatomic radiographic] = THA_Accuracy_Analysis(P)

%-----------------------------------------------------------------------%
%
% Computes the Anatomic and Radiographic Inclination and Anteversion of
% Planned, Adjusted and Post-op acetabular corientation according to
% Murray 1993.
%
% Definitions:
%
% Anatomic Inclination (AI) = angle between acetabular axis and
% longitudinal axis.
%
% Anatomic Anteversion (AA) = angle between the transverse axis and the
% projected acetabular axis onto the tranverse plane.
%
% Radiographic Inclination (RI) = angle between the longitudinal axis and
% the projected acetabular axis onto the coronal plane.
%
% Radiographic Anteversion (RA) = angle between the acetabular axis and the
% coronal plane.
%
%-----------------------------------------------------------------------%
%
% INPUTS
%
% P           --- Vector of patient numbers to be processed ( eg. [1 3 5 29] )
%
% OUTPUTS
%
% n = number of input patient numbers
%
% anatomic    --- (nx6) Matrix:
%
%                 [Planned_AI, Planned_AA, Adjusted_AI, Adjusted_AA, Measured_AI,
Measured_AA]
%
% radiographic --- (nx6) Matrix
%
%                 [Planned_RI, Planned_RA, Adjusted_RI, Adjusted_RA, Measured_RI,
Measured_RA]
%
%-----------------------------------------------------------------------%

% Load Session File Data
[FileName PathName isok] = uigetfile('*.mat','Load session file data...');
if isok
    data = load(fullfile(PathName,FileName));
end

%-----------------------------------------------------------------------%

%Initialize Variables
data.T_Anatomy_Plan = cell(29,1);
anatomic = zeros(length(P),6);
radiographic = zeros(length(P),6);
Mout = zeros(2,1);
Pout = zeros(2,1);
CPout = zeros(2,1);
```

```
%----------------------------------------------------------------------%

% Compute Planned Cup Position Using Adjusted Cup Coordinates
for i = 1:length(P)
    data.T_Anatomy_Plan{P(i)}  =
inv(data.T_Anatomy_Bone{P(i)})*data.T_Bone_Plan{P(i)}*inv(data.T_Cup1_Cup2{P(i)});
    data.T_Anatomy_Plan2{P(i)}  =
inv(data.T_Cup1_Cup2{P(i)})*data.T_Bone_Plan{P(i)}*inv(data.T_Anatomy_Bone{P(i)});
end

% Compute Adjusted Cup Plane
for i = 1:length(P)
    data.Cup_Plane{P(i)}  =
inv((inv(data.T_Anatomy_Bone{P(i)})*data.T_Pelvis_Bone{P(i)})')*data.Cup_Plane{P(i)};
    data.Cup_Plane{P(i)}= data.Cup_Plane{P(i)}/norm(data.Cup_Plane{P(i)}(1:3));
end

%----------------------------------------------------------------------%

% For every patient number selected
for i = 1:length(P)

    % Measured cup ----------------------------------------------------%

        % Anatomic

            % Compute angle between acetabular axis and longitudinal axis
            Mout(1)= acosd(dot(data.T_Anatomy_Cup2{P(i)}(1:3,3),[0 0 1]));

            % Project acetabular axis onto transverse plane Bx(AxB) and
            proj = cross([0 0 1],cross(data.T_Anatomy_Cup2{P(i)}(1:3,3),[0 0 1]));

            % Compute angle between projected axis and medial (transverse) axis
            Mout(2)= acosd(dot(proj/norm(proj),[1  0 0]));
            if proj(1) < 0
                Mout(2)= acosd(dot(proj/norm(proj),[-1  0 0]));
            end

        % Radiographic

            % Project acetabular axis onto coronal plane
            rproj = cross([0 -1 0],cross(data.T_Anatomy_Cup2{P(i)}(1:3,3),[0 -1 0]));

            % Compute angle between projected axis and proximal (longitudinal) axis
            Mrout(1) = acosd(dot(rproj/norm(rproj),[0  0 1]));

            % Compute angle between the acetabular axis and the coronal plane
            Mrout(2) = 90-acosd(dot(-1*data.T_Anatomy_Cup2{P(i)}(1:3,3),[0 -1 0]));

    % Planned cup -----------------------------------------------------%

        % Anatomic

            % Compute angle between acetabular axis and longitudinal axis
            Pout(1)= acosd(dot(data.T_Anatomy_Plan{P(i)}(1:3,3),[0 0 1]));

            % Project acetabular axis onto transverse plane Bx(AxB) and
            proj = cross([0 0 1],cross(data.T_Anatomy_Plan{P(i)}(1:3,3),[0 0 1]));

            % Compute angle between projected axis and medial (transverse) axis
            Pout(2)= acosd(dot(proj/norm(proj),[1  0 0]));
            if proj(1) < 0
                Pout(2)= acosd(dot(proj/norm(proj),[-1  0 0]));
            end
```

```
        % Radiographic

            % Project acetabular axis onto coronal plane
            rproj = cross([0 -1 0],cross(data.T_Anatomy_Plan{P(i)}(1:3,3),[0 -1 0]));

            % Compute angle between projected axis and proximal (longitudinal) axis
            Prout(1) = acosd(dot(rproj/norm(rproj),[0  0 1]));

            % Compute angle between the acetabular axis and the coronal plane
            Prout(2) = 90-acosd(dot(-1*data.T_Anatomy_Plan{P(i)}(1:3,3),[0 -1 0]));

    % Cup Plane (Hessian normal form assumed) ----------------------------%

        % Anatomic

            % Compute angle between acetabular axis and longitudinal axis
            CPout(1)= acosd(dot(data.Cup_Plane{P(i)}(1:3),[0  0 1]));
            if data.Cup_Plane{P(i)}(3)  < 0
                CPout(1)= acosd(dot(data.Cup_Plane{P(i)}(1:3),[0 0 -1]));
            end

            % Project acetabular axis onto transverse plane Bx(AxB) and
            proj = cross([0  0 1],cross(data.Cup_Plane{P(i)}(1:3),[0  0 1]));

            % Compute angle between projected axis and medial (transverse) axis
            CPout(2)= acosd(dot(proj/norm(proj),[1  0 0]));
            if proj(1)  < 0
                CPout(2)= acosd(dot(proj/norm(proj),[-1  0 0]));
            end

        % Radiographic

            % Project acetabular axis onto coronal plane
            rproj = cross([0 -1 0],cross(data.Cup_Plane{P(i)}(1:3),[0  -1 0]));

            % Compute angle between projected axis and proximal (longitudinal) axis
            CProut(1) = acosd(dot(rproj/norm(rproj),[0  0 1]));
            if CProut(1) > 90
                CProut(1) = 180-CProut(1);
            end

            % Compute angle between the acetabular axis and the coronal plane
            CProut(2) = 90-acosd(dot(data.Cup_Plane{P(i)}(1:3),[0 -1 0]));

            % Correct sign error due to right and left side geometry
            %
            % Note this assumes all cases were implanted with positive
            % anteversion!
            CProut(2) = abs(CProut(2));

%------------------------------------------------------------------------%

    % Update output matrices
    anatomic(i,1:6) = [Pout(1) Pout(2) CPout(1) CPout(2) Mout(1) Mout(2)];
    radiographic(i,1:6) = [Prout(1) Prout(2) CProut(1) CProut(2) Mrout(1) Mrout(2)];

end

% Print to
screen
radiographic
anatomic
```

LIST OF REFERENCES

[1] Berry DJ. Unstable total hip arthroplasty: detailed overview. Instr Course Lect. 2001:50:265–274.

[2] Fackler CD, Poss R. Dislocation in total hip arthroplasties. Clin Orthop Relat Res. 1980:151:169–178.

[3] Jolles BM, Zangger P, Leyvraz PF. Factors predisposing to dislocation after primary total hip arthroplasty: a multivariate analysis. J Arthroplasty. 2002;17:282–208.

[4] Kennedy JG, Rogers WB, Soffe KE, Sullivan RJ, Griffen DG, Sheehan LJ. Effect of acetabular component orientation on recurrent dislocation, pelvic osteolysis, polyethylene wear, and component migration. J Arthroplasty. 1998;13:530–534.

[5] Hedlundh U, Ahnfelt L, Hybbinette CH, Weckstrom J, Fredin H. Surgical experience related to dislocations after total hip arthroplasty. J Bone Joint Surg Br. 1996;78:206–209.

[6] Ryan JA, Jamali AA, Bargar WL. Accuracy of computer navigation for acetabular component placement in THA. Clin Orthop Relat Res 2010;468:169.

[7] Dorr LD,Malik A,Wan Z, LongWT,HarrisM. Precision and bias of imageless computer navigation and surgeon estimates for acetabular component position. Clin Orthop Relat Res. 2007;465:92–99.

[8] Jenny JY, Boeri C, Dosch JC, Uscatu M, Ciobanu E. Navigated non-image-based positioning of the acetabulum during total hip replacement. Int Orthop. 2009;33:83–87.

[9] Ybinger T, Kumpan W, Hoffart HE, Muschalik B, Bullmann W, Zweymuller K. Accuracy of navigation-assisted acetabular component positioning studied by computed tomography measurements: methods and results. J Arthroplasty. 2007;22:812–817.

[10] McArthur B, Cross M, Geatrakas C, Mayman D, Ghelman B. Measuring acetabular component version after THA CT or plain radiograph. Springer. 2012:10:2810-2818.

[11] Jaramaz, B., Eckman, K., 2006. 2D/3D registration for measurement of implant alignment after total hip replacement. In: Larsen, R., Nielsen, M., Sporring, J. (Eds.), Ninth International Conference on Medical Image Computing and Computer-Assisted Intervention (MICCAI 2006), Part 2, Lecture Notes In Computer Science, vol. 4191. Springer, Copenhagen, Denmark, pp. 653–661.

[12] Murray DW. The definition and measurement of acetabular orientation.J Bone Joint Surg Br. 1993;75:228–232.

[13] Paul A. Yushkevich, Joseph Piven, Heather Cody Hazlett, Rachel Gimpel Smith, Sean Ho, James C. Gee, and Guido Gerig. User-guided 3D active contour segmentation of anatomical structures: Significantly improved efficiency and reliability. Neuroimage 2006 Jul 1;31(3):1116-28.

BIOGRAPHICAL SKETCH

Zenan Zhang was born in Zoucheng, Shandong Province, China. He got his Bachelor of Science in mechanical engineering from Beijing Jiaotong University, Beijing, China by studying bio-inspired robots from 2007 to 2011. From 2011 to 2013, Zenan was enrolled in University of Florida, US to pursue his Master of Science in mechanical engineering. His interest is the postoperative CT measurement of measuring positions of acetabular cups and stems guided by Dr. Scott A. Banks.