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Determining Cup Position, Leg Length, and Offset using Intraoperative 2D/3D Registration in Direct Anterior Approach Total Hip Arthroplasty: A Cadaveric Laboratory Study

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Introduction: Intraoperative 2D fluoroscopy has well-documented variability in accuracy when measuring acetabular position, leg length, and offset in total hip arthroplasty (THA).

Objective: To evaluate the accuracy of a new 2D/3D registration software for intraoperative measurement of THA parameters.

Methods: Eight direct anterior approach (DAA) THAs were performed on four bilateral pelvis-to-toe cadavers by eight surgeons. 3D planning of the acetabular and femoral components was performed on preoperative computed tomography (CT) scans. Intraoperative 2D fluoroscopic images captured the trial and final positioned implants. Preoperative 3D models of the pelvis, cup, femur, and femoral head were registered to the 2D fluoroscopic images intraoperatively using a novel 2D/3D registration software

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that reported cup position, leg length, and offset. The mean absolute error (MAE) of the final registered measurements was compared to the ground-truth values measured on postoperative CT.

Results: Cup anteversion and inclination MAE were 1.7° and 1.5°, with maximum errors of 3.4° and 3.1°, respectively. Cup mediolateral and superoinferior MAE were <1 mm, with maximum errors ≤1.6 mm. Leg length and offset MAE were 2.5 and 1.9 mm, with maximum errors of 4.8 and 3.4 mm, respectively.

Conclusion: This cadaver study demonstrated high accuracy and efficiency of 2D/3D registration for determining cup position, leg length, and offset in DAA THA, potentially overcoming some of the limitations associated with using 2D intraoperative imaging.

Level of Evidence: V (Laboratory Cadaveric Study)

***Keywords*:** 2D/3D registration; Accuracy; Direct anterior approach; Intraoperative fluoroscopy; Total hip arthroplasty

INTRODUCTION

Total hip arthroplasty (THA) is a highly successful surgery in terms of pain relief, function, and prosthetic survivorship.[1–4] However, complications continue to occur in 3–27% of patients, with the most common complications being mechanical loosening, infection, instability, and periprosthetic fractures.[5–8] Additionally, it has been reported that 51.3% of revisions due to these complications may be preventable.[9] While some complications with hip surgery are inevitable, optimizing intraoperative parameters may decrease the risk. The most notable area where optimized component position may decrease the risk of complications is in patients with adverse or limited spino-pelvic motion.[10–12] However, even in patients without a true complication, suboptimal prosthetic position may result in edge loading, increased wear, prosthetic cup impingement, hip flexor irritation, or other soft tissue pain.[13,14]

Intraoperative 2D fluoroscopy has well-documented variability in accuracy when measuring acetabular position, leg length, and offset in THA.[15,16] This has been reported for both anterior- and posterior-approach THA.[17] Surgeons have reported poor intraoperative radiographic estimation of cup position and the ability to match the desired radiographic pelvic position.[18–20] While 2D intraoperative radiographic visualization of the pelvis is commonplace in anterior approach hip surgery and appears to improve outcomes, limitations exist.[21]

With advances in computer algorithms, it is possible to map a 2D image to a 3D image, which can be applied to fluoroscopic images. Compared with existing systems, this represents the only 2D-to-3D technology that enables assessment of pelvic orientation using only intraoperative fluoroscopy. The purpose of this study is to evaluate the accuracy of a new 2D/3D registration software for intraoperative measurement of acetabular position, leg length, and offset in THA. A laboratory cadaveric study was conducted to evaluate this system. It is common that new technology undergoes cadaveric validation with a goal of translating into clinical improvements.

METHODS

System and software

We evaluated an image-based, pinless delivery system (ApolloHipX, Corin Ltd, United Kingdom [UK]) for intraoperative measurement of cup position, leg length, and offset in THA. The system registers 3D models of the pelvis and femur determined from preoperative computed tomography (CT) scans and 3D models of implants to 2D intraoperative fluoroscopic images using an intensity-based matching algorithm (**Figure 1**). This allows for the calculation of component position, leg length, and offset within the 3D model workspace after registration, improving accuracy. The intraoperative registration steps entail selecting six predefined pelvis and femur landmark points on the 2D fluoroscopic images for initial registration (**Figure 2A and C**). The software then automatically registers the 3D models to the 2D fluoroscopic images using an intensity-based matching algorithm (**Figure 2B and D**), after which users can adjust the registration for improved fit by rotating or translating the 3D model in all six degrees of freedom while controlling the contour overlay on the fluoroscopic image. The system then provides measurements of cup inclination, anteversion, superior–inferior and medial–lateral translation for the acetabular component relative to the pelvis (**Figure 2B**), and leg length and offset of the femur relative to the pelvis (**Figure 2D**).

The images were obtained in posterior–anterior (PA) view following standard imaging techniques for fluoroscopy-guided total hip replacement in direct anterior approach (DAA), with the patient in supine position, the X-ray source located under the table, and the detector placed close to the operative hip joint and roughly parallel to the table. As a minimum requirement, images used for cup registration must show the operative hip joint and pubic symphysis, while images used for femur registration must show the hip joint,

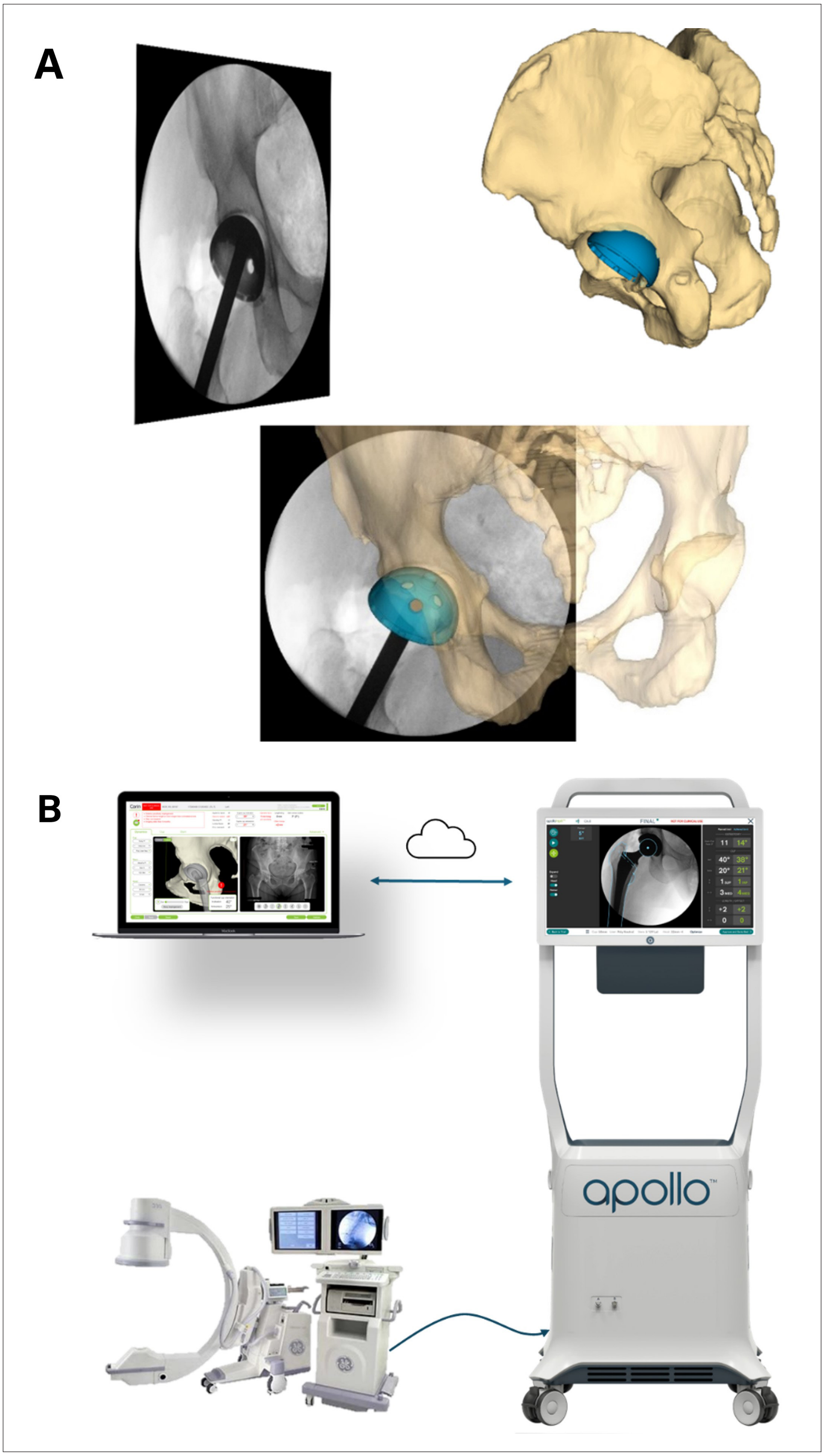

Figure 1. Overview of 2D/3D registration system. (A) 2D/3D registration of preoperative 3D computed tomography and cup model to intraoperative 2D fluoroscopic image based on image intensity matching. (B) The algorithm was integrated into an intraoperative delivery system for real-time 2D/3D registration (ApolloHipX, Corin Ltd, United Kingdom).

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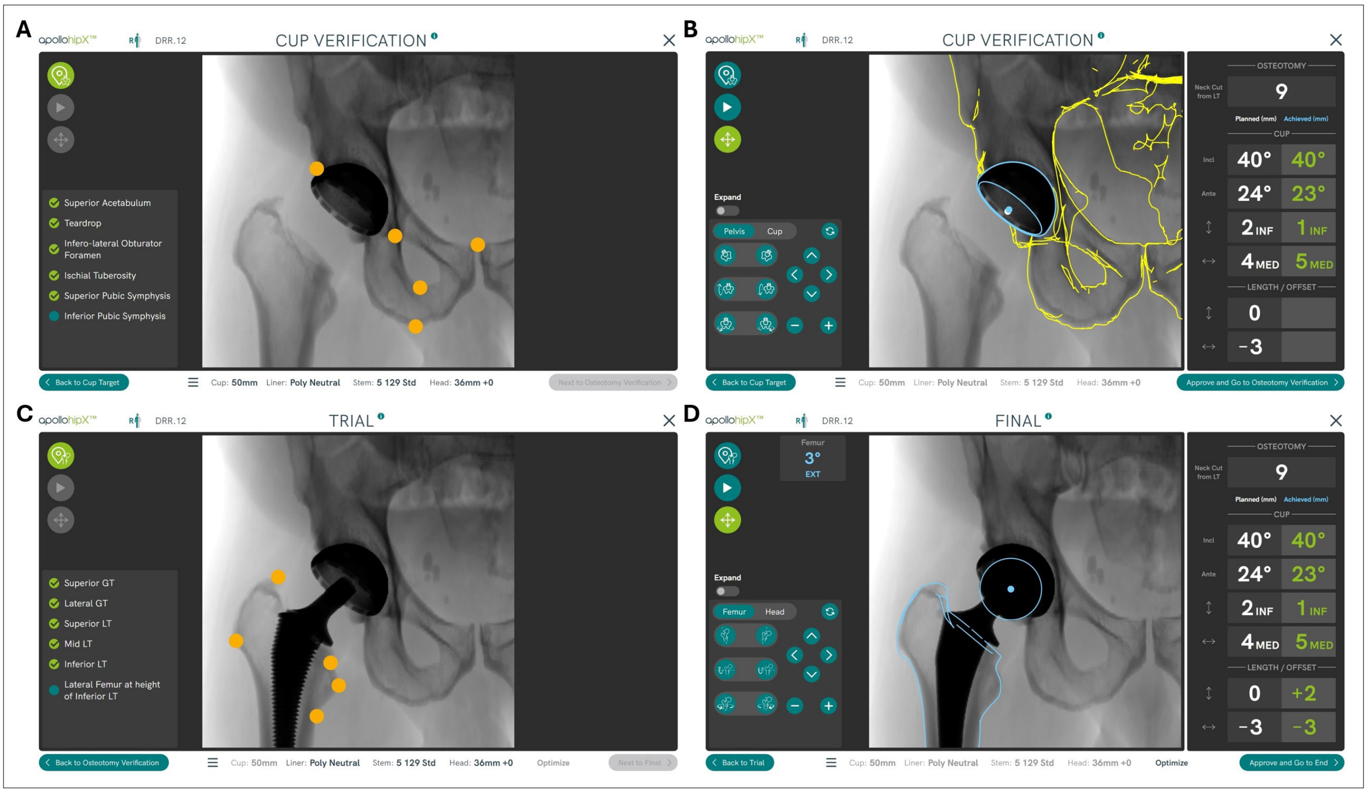

Figure 2. Example screenshots illustrating the surgical workflow. (A) Registration is initiated by selecting six predetermined points on the pelvis (orange dots). (B) The software then automatically matches the 3D model of the pelvis and cup to the 2D images and reports the cup position in the 3D model workspace (right side). Similarly, femoral registration is initiated with six points on the femur (C), and the software automatically registers the femoral model (D). In each case, the user can make refinements to the registration if needed in all directions using the arrows/buttons (B and D, bottom left).

greater trochanter, and lesser trochanter. No other constraints were imposed during image acquisition.

Cadaver testing

Eight DAA THAs were performed on four bilateral fresh-frozen pelvis-to-toe cadavers by eight surgeons with varying prior experience with the technology (five surgeons were involved in the development of the system, while three surgeons had no exposure to the system prior to the cadaver test). All data and specimens used in this study were anonymized and obtained from a locally accredited tissue provider. This study was performed in compliance with local regulations and institutional policies. The specimen demographics (mean ± standard deviation [range]) were: age (years): 65.0 ± 2.9 [62–67], height (m): 1.69 ± 0.04 [1.65-1.73], weight (kg): 75.7 ± 27.3 [56.7 - 107.0], body mass index (kg/m^2): 26.2 ± 8.4 [20.8–35.9], and sex: 2 females and 2 males.

The 3D planning of the acetabular and femoral components was performed on preoperative CT scans by biomedical engineers using the OPSInsight™ planning system (Corin Ltd, UK).[22,23] Each surgeon was given a brief demonstration of the operation of the system prior to the surgery and then proceeded through the application workflow, first implanting and measuring the cup (**Figure 2A and B**) and then implanting the femoral stem and measuring leg length/offset (**Figure 2C and D**). 2D fluoroscopic images were taken to capture the trial and final positioned implants. The preoperative 3D models of the pelvis, cup, femur, and femoral head were registered to the 2D fluoroscopic images intraoperatively using the 2D/3D registration software to report their position to the surgeon users during the trialing and final implantation phases. The standard deviation is representative of the inter-operator variability, as each surgeon completed one hip.

Measurements

The ground-truth measurements for the accuracy assessment were obtained using postoperative CT scans. The specimens were CT scanned postoperatively with the final acetabular and femoral implants in place. The 3D model of the pelvis generated from the preoperative CT scan was matched to the pelvis in the postoperative CT scan to define a common coordinate system and the six degrees of freedom transformation matrix between the pre- and postoperative CT scans (**Figure 3A**). A 3D virtual cup of the identical implanted size was fit to the acetabular component in the postoperative CT scan (**Figure 3B**), and the cup reference was then transformed into the preoperative reference frame using the pre-to-postoperative transformation matrix of the pelvis calculated from the 3D/3D match of the pelvis model. The image pixel volume was used to assist the matching process, as shown in **Figure 3B**.

The reliability of measuring cup position in postoperative CT images was evaluated across seven cases with four independent observers measuring each case (28 measurements total). The resulting intraclass correlation coefficients for supine cup anteversion and inclination were 0.992 and 0.950, respectively, indicating excellent agreement and reliability.[24]

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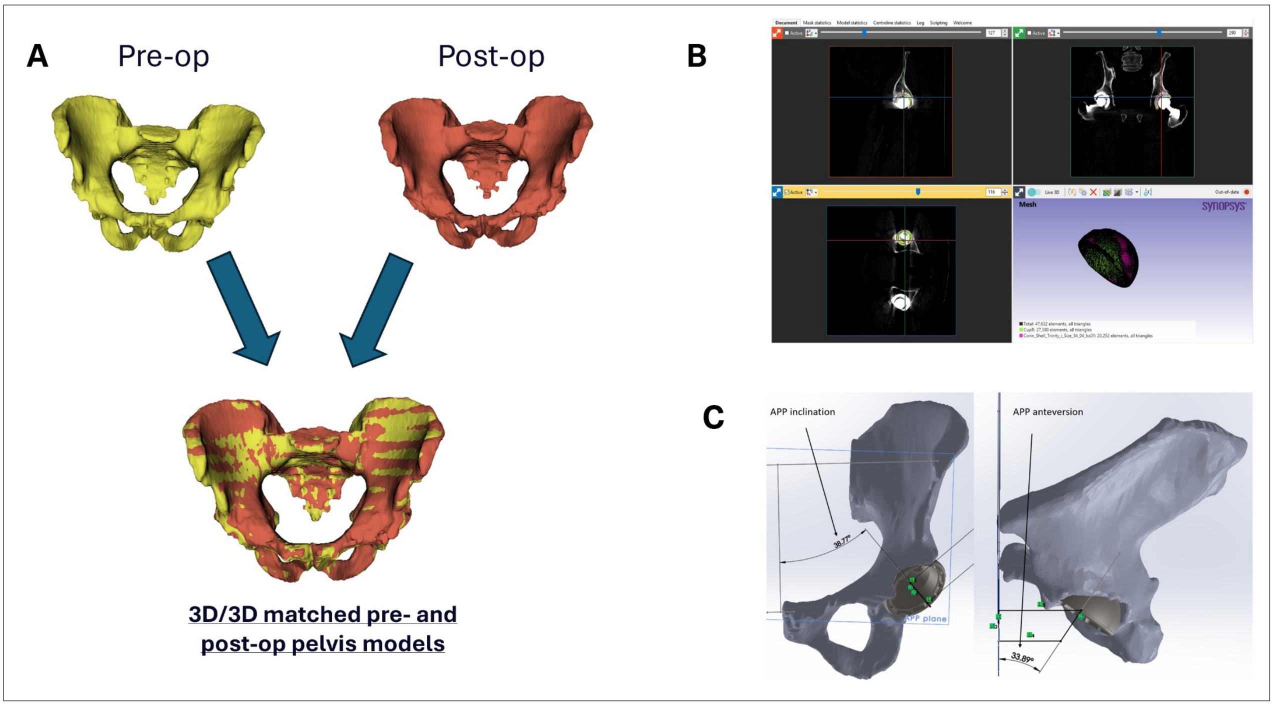

Figure 3. Overview of measurement process. (A) Preoperative (Pre-op) and postoperative (Post-op) 3D models of the pelvis and femur (not shown) were matched using 3D/3D registration to define a common coordinate system for the accuracy evaluation. (B) 3D implant models were registered to the postoperative computed tomography (CT) images to determine acetabular implant positioning, leg length, and offset values, using the pixel image volume to assist the fitting process. (C) Cup inclination and anteversion are first calculated relative to the anterior pelvic plane (APP), and then adjusted for pelvic tilt in supine. The APP is defined as the plane containing the left and right anterior superior iliac spines and the midpoint between the pubic symphyses. The APP inclination is defined as the angle between a line on the APP that is perpendicular to the line between the anterior superior iliac spine points and runs through the midpoint between the pubic symphyses and the cup axis projected onto the APP (left). The APP anteversion is defined as the line between the cup axis and the APP. The final (functional) cup position is then determined by adjusting the APP orientations for the degree of pelvic tilt in the supine position as measured in the preoperative CT scan.

Cup orientation

Intraoperative and postoperative cup anteversion and inclination were reported in the supine reference frame using the preoperative CT scan. Cup orientations were first calculated in the anterior pelvic plane (APP) of the pelvis from the preoperative CT scan, as shown in **Figure 3C**. The final (functional) cup position was then determined by adjusting the APP orientations for the degree of pelvic tilt in the supine position, as measured in the preoperative CT scan, according to the equations published by Lembeck *et al*.[25]

Cup position

The cup position was calculated using the postoperative liner center of rotation (COR) by virtually assembling the liner into the cup model that is fitted to the postoperative CT. The mediolateral (ML) position is the distance along the medial–lateral (right–left) axis measured on the patient's preoperative pelvic coronal plane (PCP) between the liner COR and the preoperative operative side hip center (defined by fitting a 3D sphere to the femoral head). The PCP was defined as the plane that includes the left and right anterior superior iliac spines and is parallel to the global superior–inferior axis (*Z*-axis) of the CT scan volume with the patient lying supine.

The superoinferior (SI) height is the distance along the patient's superior–inferior axis on the preoperative PCP between the liner COR and the preoperative operative side hip center. Height is positive if the liner center is more superior than the preoperative hip center.

Leg length and offset

Leg length and offset were calculated by registering the femur, pelvis, and the cup with liner (for the COR) in the postoperative CT and transforming them into the preoperative CT reference frame. The change in leg length is the difference between the liner CORs registered to the pelvis and to the femur, measured along the *Z* (longitudinal) direction of the preoperative CT. Similarly, the change in offset was defined as the distance between the two liner CORs, but measured in the preoperative femoral plane, which contains the proximal anatomic axis and the native femoral head center. Offset was measured in the ML direction, which is perpendicular to the femoral proximal anatomic axis.

The postoperative calculated values were compared to the intraoperative values calculated from the Apollo-HipX system to assess the accuracy of the system. The intraoperative values were calculated using the same method and along the same directions as the postoperative values.

Data analysis

Accuracy was determined as the mean absolute error (MAE) between the intraoperative registration of the final implant position, leg length, and offset, relative to the ground-truth values, as measured on postoperative CT described above. Data normality was confirmed using Shapiro–Wilk's normality test. Paired Student's *t*-tests were used to assess differences between postoperative and intraoperative measurements. All analysis was performed in R version 4.4.2 (R Foundation for Statistical Computing, Austria). A p-value < 0.05 was considered statistically significant.

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Table 1. Intraoperative and postoperative measurements and their difference (Δ) for cup anteversion (Ant) and inclination (Incl)

	Ant (°)			Incl (°)		
Specimen no.	**Intraoperative**	**Postoperative**	**Δ**	**Intraoperative**	**Postoperative**	**Δ**
S1	20.5	21.3	–0.8	32.5	29.5	3.0
S2	10.9	13.2	–2.3	40.0	39.7	0.2
S3	25.1	24.8	0.4	42.7	45.8	–3.1
S4	17.2	19.6	–2.4	41.1	44.2	–3.0
S5	22.3	24.3	–2.1	35.3	34.4	0.9
S6	13.5	13.5	0.0	35.3	35.0	0.3
S7	14.1	17.5	–3.4	36.9	37.0	–0.2
S8	38.2	40.2	–2.0	45.5	46.5	–0.9
Mean	20.2	21.8	–1.6	38.7	39.0	–0.3
SD	8.7	8.6	1.3	4.4	6.1	2.0
Minimum	10.9	13.2	–3.4	32.5	29.5	–3.1
Maximum	38.2	40.2	0.4	45.5	46.5	3.0
p-value			0.011*			0.644

Note: *$p<0.05$.

RESULTS

Cup positioning accuracy

Intraoperative and postoperative cup anteversion values were (mean ± standard deviation) 20.2 ± 8.7° and 21.8 ± 8.6° (mean difference: −1.6 ± 1.3°, $p=0.011$), respectively, and cup inclinations were 38.7 ± 4.4° and 39.0 ± 6.1° (mean difference −0.3 ± 2.0°, $p=0.644$), respectively (**Table 1**). Cup anteversion and inclination MAEs were 1.7° and 1.5°, respectively (maximum error: 3.4° and 3.1°, respectively; **Figure 4**). MAEs for ML and SI cup positions were <1 mm, with maximum errors ≤1.6 mm (**Figure 4**). There were no significant differences in the signed mean error (0.4 mm, $p = 0.250$, and −0.2 mm, $p=0.542$, respectively; **Table 2**).

Leg length and offset accuracy

Leg length and offset MAEs were 2.5 and 1.9 mm, respectively (maximum error: 4.8 and 3.4 mm, respectively; **Figure 4**). Intraoperative leg length was greater than postoperative leg length by 2.5 ±1.6 mm on average (7.5 vs. 4.9 mm, $p=0.003$; **Table 3**). Intraoperative and postoperative offsets were not significantly different (Δ1.2 mm, $p=0.127$)

2D/3D registration algorithm computation time

The mean combined convergence time of the 2D/3D registration algorithm was 13.6 s for the pelvis and cup (15 s maximum) and 12 s for the femur and femoral head (14 s maximum). The software was run on a standard clinical computer used in the commercially available Apollo station.

DISCUSSION

This cadaver study demonstrated high accuracy and low variance in achieving the desired and optimal prosthetic position under laboratory conditions, with short processing times. Further studies are needed to determine the clinical benefits of this algorithm, as the present investigation was limited to assessments of accuracy, efficiency, and anticipated clinical usability.

Accuracy and processing time are consistent with those reported in prior studies of 3D hip planning and implementation. A randomized controlled trial conducted by Fontalis *et al*.[26] found that 3D templating had higher accuracy in restoring native joint mechanics during THA compared to 2D planning. Their results, consisting of 60 primary THA, demonstrated significantly less medialization of the horizontal COR and more accurate vertical COR reconstruction. Likewise, Foissey *et al*.[27] published a retrospective study comparing primary conventional THA to primary robotic THA, all performed via DAA. Their results showed superior cup orientation and COR restoration with the use of 3D planning and robotics compared to conventional approaches. These studies are supported by a meta-analysis conducted by Llombart-Blanco *et al*.,[28] consisting of 12 studies with THAs completed with MAKO assistance. The use of MAKO robotics demonstrated improved prosthesis placement and radiological outcomes. While effective, these technologies come with high cost, a need for a robotic arm, and a requirement for pelvic pin placement. A meta-analysis by Ramadanov *et al*.[29] further provides a clinical bridge to our study, demonstrating the importance of optimizing acetabular cup position in improving patient outcomes.

The accuracy of intraoperative fluoroscopy is clinically acceptable but still varied.[15–21] Although this study did not directly compare the 2D/3D technology with intraoperative 2D fluoroscopy, this technology holds promise for improv-

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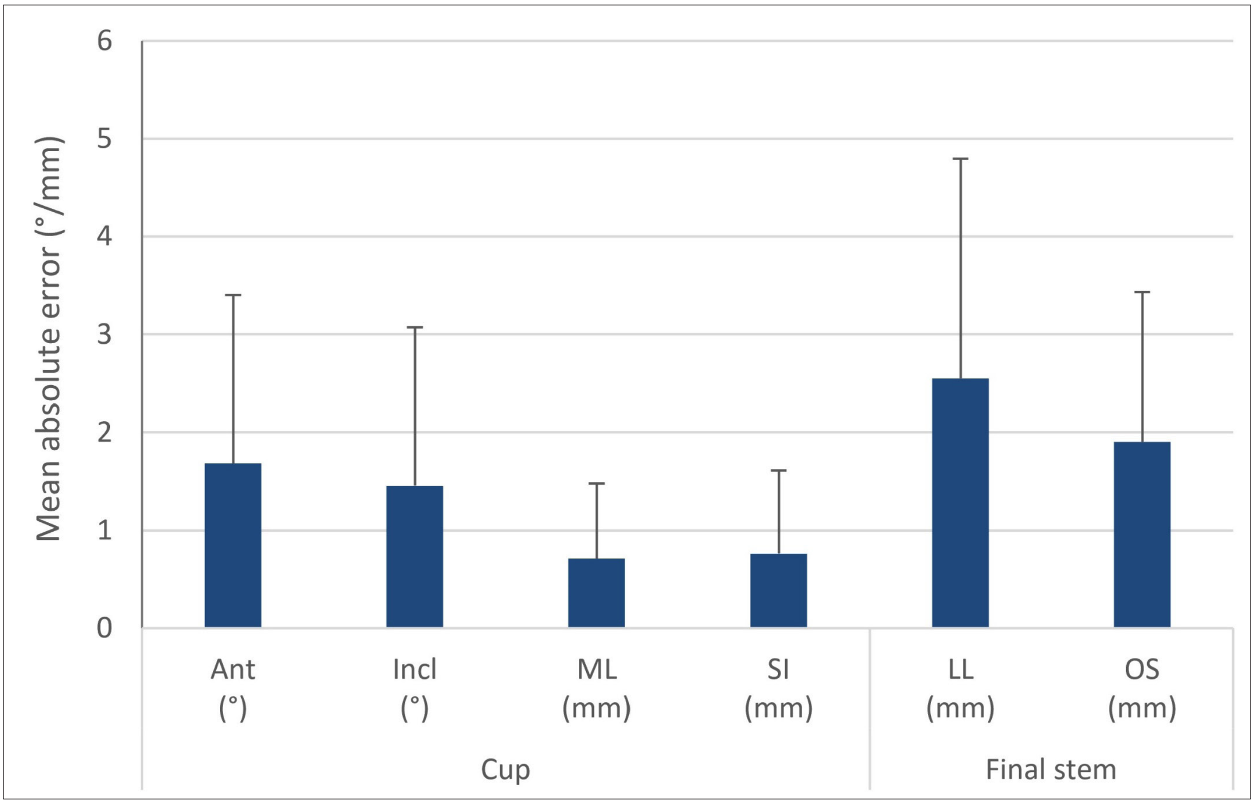

Figure 4. Mean absolute error in cup position, leg length (LL), and offset (OS). Error bars indicate maximum absolute error. Abbreviations: Ant, anteversion; Incl, inclination; ML, mediolateral; SI, superior–inferior.

Table 2. Intraoperative and postoperative measurements and their difference (Δ) for cup mediolateral (ML) and superoinferior (SI) position

	ML (mm)			SI (mm)		
Specimen no.	Intraoperative	Postoperative	Δ	Intraoperative	Postoperative	Δ
S1	2.8	1.4	1.4	–1.9	–1.0	–0.9
S2	–0.3	–1.4	1.1	–2.1	–0.5	–1.6
S3	0.2	–0.5	0.7	–1.5	–0.4	–1.1
S4	–0.5	0.6	–1.0	–1.3	–1.0	–0.3
S5	0.6	–0.9	1.5	0.5	–1.1	1.6
S6	–3.9	–4.1	0.2	–0.5	–0.9	0.3
S7	–0.9	–0.7	–0.2	–2.2	–2.3	0.1
S8	–0.8	–0.4	–0.4	–3.0	–3.1	0.1
Mean	–0.3	–0.7	0.4	–1.5	–1.3	–0.2
SD	1.9	1.6	0.9	1.1	0.9	1.0
Minimum	–3.9	–4.1	–1.0	–3.0	–3.1	–1.6
Maximum	2.8	1.4	1.5	0.5	–0.4	1.6
p-value			0.250			0.542

ing accuracy and reducing variability in prosthetic positioning. Furthermore, given that 3D images can be understood from the 2D fluoroscopy, there is no need to reposition the C-arm to match a desired pelvic tilt. This has the theoretical advantage of decreased fluoroscopy time and increased intraoperative efficiency. This is especially pertinent as the potential adverse effects of radiation exposure to orthopedic surgeons are being better understood.[30–32] Moreover, this technology allows for preoperative 3D planning to be implemented utilizing only intraoperative fluoroscopy. When compared to existing systems, this proposed technique saves time on registration and avoids the need for optical

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Table 3. Intraoperative and postoperative measurements and their difference (Δ) for leg length (LL) and offset (OS)

	LL (mm)			OS (mm)		
Specimen no.	**Intraoperative**	**Postoperative**	**Δ**	**Intraoperative**	**Postoperative**	**Δ**
S1	9.1	8.1	1.0	4.0	1.3	2.7
S2	6.3	1.5	4.8	–3.6	–4.6	0.9
S3	2.9	2.9	0.1	2.6	0.7	2.0
S4	9.4	5.5	3.8	7.4	5.7	1.6
S5	11.2	8.9	2.3	4.4	0.9	3.4
S6	9.7	6.8	2.9	0.4	–1.1	1.4
S7	2.1	–1.8	3.9	–0.7	2.2	–2.9
S8	9.1	7.5	1.6	10.7	10.5	0.2
mean	7.5	4.9	2.5	3.1	2.0	1.2
SD	3.4	3.7	1.6	4.6	4.5	1.9
min	2.1	–1.8	0.1	–3.6	–4.6	–2.9
max	11.2	8.9	4.8	10.7	10.5	3.4
p-value			0.003*			0.127

Note: *p<0.05.

trackers and additional pin sites. Additionally, there was no loss in accuracy. Therefore, this system potentially confers cost and patient advantages without losing precision.

The main limitation of this study is the lack of true clinical validation. While the technique was demonstrated to be accurate in a small number of cadavers, it has not been implemented in the real world. Furthermore, these cadaver procedures were performed primarily by the designers of this system, who are all high-volume hip surgeons. Moreover, even if improvements in prosthetic positioning accuracy and decreased variance are clinically validated, it is yet to be shown that these translate into fewer complications, such as lower dislocation rates, or improved clinical outcomes, including reduced wear and soft-tissue pain. In addition, factors encountered during surgery, including soft-tissue tension, intraoperative fluoroscopy variation, and patient positioning, may affect accuracy. Lastly, radiation exposure and additional intraoperative time were not evaluated in this study. It is anticipated, however, that the use of this technology would lead to a smaller number of fluoroscopic shots.

CONCLUSION

The main purpose of this study was to validate the algorithm and demonstrate the capability of the software to automatically register points on a 2D fluoroscopic image and map them onto a 3D model. This process was achieved with low processing time, high accuracy, and minimal variability. The results suggest that this method holds promise as an efficient method for integrating 3D imaging and surgical planning without altering the surgical workflow or requiring robotic assistance.

AUTHORS' DISCLOSURE

We thank Jenfun Shi for performing the accuracy measurements, and Drs. Michael Bradley, Jacob Haynes, Stephen Kayiaros, Travis Small, and Michael Solomon for assisting with the cadaver testing. This study used only de-identified information from cadaveric specimens obtained from an accredited commercial provider Association for Advancing Tissue and Biologics. All specimens were donated with informed consent for research purposes, and the study complied with applicable institutional and national regulations. Therefore, institutional review board approval was not required.

CONFLICT OF INTEREST

Corin provided funding for travel expenses and/or compensation for time spent during the cadaver lab testing associated with this study for Dr. Camdon Fary, Dr. Eric M. Slotkin, A/Prof. James A. Sullivan, and Dr. Arjun Saxena. Jevan Arulampalam, Moritz F. Ehlke, Christopher Plaskos, and Jim Pierrepont are employees of Corin.

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