2D-3D reconstruction-based implant migration measurement

B. Thelen, S. Balestra, S. Schumann, L. Nolte, G. Zheng

Institute for Surgical Technology & Biomechanics, University of Berne, Switzerland

Contact: benedikt.thelen@istb.unibe.ch

***Abstract**:*

This paper presents a phantom-based study for validating a newly developed 2D-3D reconstruction-based method for measuring implant migration after total hip arthroplasty (THA). Based on a mock-up setup, three different methods were used to determine the cup orientation with respect to the anterior pelvic plane (APP) of a plastic pelvis: (a) the optical tracking method; (b) the fiducial-based method; and (c) the 2D-3D reconstruction-based method. It was found that the incremental anteversion and inclination angles measured by the newly developed 2D-3D reconstruction-based method are comparable with those measured by the other two methods.

Keywords: implant migration, 2D-3D reconstruction, optical tracking

1 Background

The initial and the secondary implant positions after the cementless total hip arthroplasty (THA) documents the stability of the implanted components. Postoperative migration of implants is therefore one important parameter for initial and follow-up quality documentation. Due to the concerns on cost and radiation, postoperative migration is typically measured on two-dimensional (2D) postoperative anteroposterior (AP) pelvic X-ray radiographs. The existing methods either determine only a 2D migration in the AP pelvic X-ray radiograph plane [2] or require invasive implantation of metal fiducials to determine precise three-dimensional (3D) migration [1]. Recently, a precise X-ray image calibration method as well as a 2D-3D reconstruction method has been reported for a robust and accurate reconstruction of a 3D patient-specific model of acetabular surface from 2D X-ray radiographs [3]. However, there is little known work reported to use 2D-3D reconstruction for implant migration measurement. The aim of this work is to determine the incremental orientation variation of a cup implant using 2D-3D reconstruction techniques and to validate the methodology using optical tracking and implanted metal fiducials.

2 Materials and Methods

Mockup setup: First a mockup was built that allowed simulating cup migration with respect to a fixed pelvis. The mockup was composed of a cadaver pelvis that was not part of the statistical shape model (SSM) population but represented by it (male, caucasian), a plastic cup and a fixation frame made from X-ray translucent Plexiglas. The construction allowed the cup to move on a spherical joint by hand and to hold the position during acquisition, while the pelvis was fixed permanently to the frame (see figure 1).
Four metal markers where placed coplanar with the cup opening plane. The placement was designed to provide reliable landmarks in the X-ray images. Furthermore ten metal nails with indents that allowed pointer tool picking were placed on the pelvis to mark the anterior pelvic Plane (APP) and six other prominent landmarks. During acquisition the orientation of the cup with respect to the APP was determined using an infrared passive optical tracking camera from Northern Digital Inc. Ontario, Canada (see fig. 1).

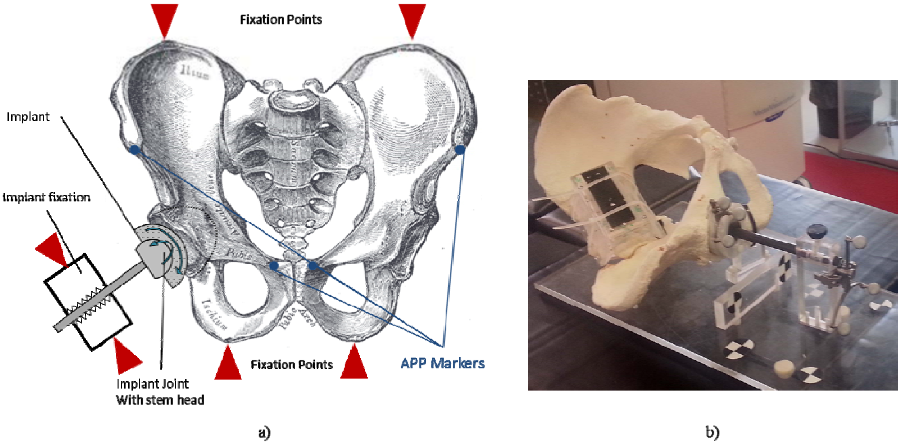


Figure 1: (a) Drawing of the mockup, (b) experimental setup showing the cadaver bone, the phantom (fixed to the sacrum), the base construction with the joint allowing the cup to rotate and the optical markers.

X-ray image acquisition: The acquisition started with the fixation of a calibration phantom to the pelvis. A pointer digitization based registration of the optical tracking space and the fiducails as well as the cup opening plane was performed. Next, 15 datasets were acquired. Each dataset was composed of three images (AP, outlet, 30° oblique). For each dataset the cup was oriented by hand with the help of the optical tracking software. All images were acquired with a standard clinical Philips X-ray machine. During acquisition, the orientation of the cup was tracked by the camera giving absolute readings for the anteversion and inclination angles at a rate of approx. 20 Hz. All positions recorded by the camera where stored to allow detailed analysis during evaluation. The images were stored in DICOM format for further processing.

Evaluation: The experimental setup provided three sources of measurements for the anteversion and inclination angles. (a) The optical tracking system provided a real time estimation of the angles using the optical tracking markers placed on the cup and the base frame. These values were stored onto hard disk. Measurements obtained by this method are labeled as ‘optical’. (b) Through a semi-automatic algorithm using Hough transform the X-rays where calibrated and a custom software was used to pick the markers on the X-ray’s and determine the 3D position of the markers. Next, these 3D points where used to determine the APP orientation. Since the plastic cup also contained a metal ring parallel to the

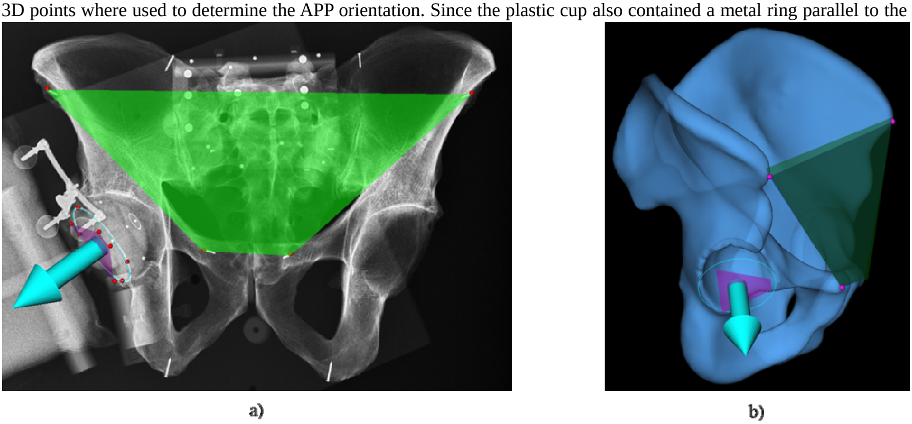


Figure 2: (a) Fiducial based APP with AP radiograph, (b) reconstructed pelvis model with APP (blue) and fiducial based APP overlayed (green) for comparison

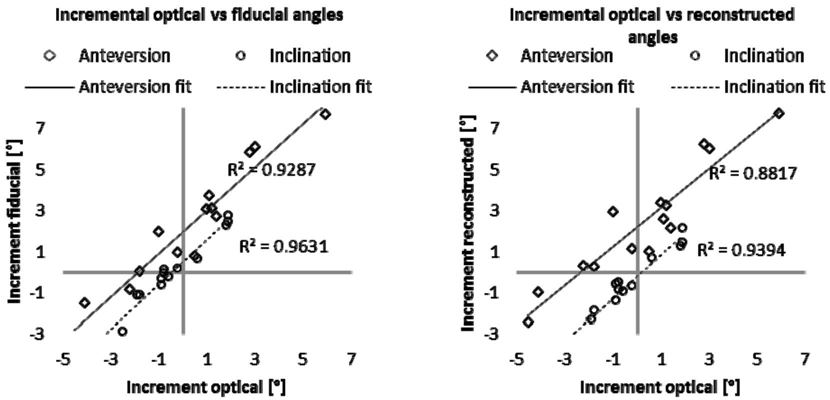
cup plane it was used to determine the 3D orientation of the cup. (c) With the help of a SSM-based 2D-3D reconstruction algorithm [3] the pelvis was reconstructed for each dataset from the three calibrated X-ray images. The APP was then extracted based on four vertices determined on the mean model (see fig.2b). In the SSM-based 2D-3D reconstruction method four 3D points where determined from the reconstructed shape model using fixed vertices. The cup orientation was determined as in method (b). During the study 15 reconstructions where performed and the reconstructed surfaces where compared to a reference surface from a computer tomography (CT) scan of the used bone, the mean Hausdorff distance of the surfaces was 1.44 ± 0.15 mm. The anteversion and inclination angles between these planes are labeled 'reconstructed'.

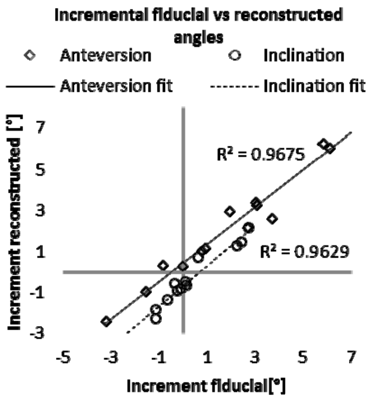
3 Results

An extensive comparison of the incremental angles (difference of angle in a dataset to the angles of the first dataset) was conducted. The following plots show the correlation of the datases measured with the three different methods.

	Fiducial-Optical		Reconstruction-Optical		Reconstruction-Fiducial	
	Anteversion [°]	Inclination [°]	Anteversion [°]	Inclination [°]	Anteversion [°]	Inclination [°]
Mean	1.95	0.45	2.18	-0.24	-0.23	0.69
STD	0.81	0.35	0.96	0.42	0.56	0.33
Max	3.12	0.92	3.95	1.35	1.13	1.18
Min	0.29	0.05	0.48	0.05	0.07	0.03

Table 1: The differences of incremental measurements done with the different methods





Correlation of anteversion (Absolute)			
	Optical	Fiducial	Reconstructed
Optical	1	0.51	0.48
Fiducial	-	1	0.93
Reconstructed	-	-	1
Correlation of inclination (Absolute)			
	Optical	Fiducial	Reconstructed
Optical	1	0.96	0.95
Fiducial	-	1	0.92
Reconstructed	-	-	1
Correlation of anteversion (Incremental)			
	Optical	Fiducial	Reconstructed
Optical	1	0.93	0.88
Fiducial	-	1	0.97
Reconstructed	-	-	1
Correlation of inclination (incremental)			
	Optical	Fiducial	Reconstructed
Optical	1	0.96	0.94
Fiducial	-	1	0.96
Reconstructed	-	-	1

Figure 3: The linear correlation between the incremental measurements done with the tree methods shown graphically and a table containing the correlation values for the incremental and the absolute angles of the three methods.

4 Discussion

As the main interest in this work is the migration of the cup, the absolute angles obtained by the three methods play a secondary role. The biggest focus is given to the incremental angles of each method. When comparing the absolute and the incremental angles of all three measurement types we noticed that the difference of the obtained results is smaller for the inclination than for the anteversion. Table 1 shows the differences between the incremental measurements. The difference between the reconstruction based method and the fiducial based method is smaller than the difference of the optical method to any of the two methods. When comparing the correlations of the incremental and absolute angles as shown in figure 3, we notice that reconstructed and fiducial based angles correlate very well, while the optical method do not always correlate. The reason for this is the calibration which is the basis of both the reconstructed and the fiducial measurement method. On one hand the size of the used calibration phantom limits the quality of the X-ray calibration. On the other hand the close correlation indicates that the error produced by the 2D-3D reconstruction is relatively small.

5 Conclusion and future work

In this paper, we propose a method to determine the cup orientation from calibrated X-ray images and SSM based 2D-3D reconstruction. From the results we conclude that the non-invasive SSM-based 2D-3D reconstruction method provides a valid method to determine the cup orientation as compared to fiducial based methods.

The main error contribution of our method at this point is the calibration of the X-ray images. Since the used phantom was originally designed for smaller scaled applications like C-arms, it needs to be redesigned in the future. For the determination of the cup orientation we used a metal ring inside the plastic cup instead of the initially implanted markers. While this method produced more repeatable results than using only the four markers it is also applicable in real surgical cases where the orientation of the cup in a planar x'ray may only be determined form the silhouette, but it also makes in plane rotation difficult to track.

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7 References

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