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ORIGINAL ARTICLE

Validation of a statistical shape model-based 2D/3D reconstruction method for determination of cup orientation after THA

G. Zheng · J. von Recum · L.-P. Nolte · P. A. Grützner · S. D. Steppacher · J. Franke

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Abstract
Purpose The aim of this study was to validate the accuracy and reproducibility of a statistical shape model-based 2D/3D reconstruction method for determining cup orientation after total hip arthroplasty. With a statistical shape model, this method allows reconstructing a patient-specific 3D-model of the pelvis from a standard AP X-ray radiograph. Cup orientation (inclination and anteversion) is then calculated with respect to the anterior pelvic plane that is derived from the reconstructed model.
Materials and methods The validation study was conducted retrospectively on datasets of 29 patients (31 hips). Among them, there were 15 men (15 hips) and 14 women (16 hips). The average age of the patients was 69.4 ± 8.5 $(49-82)$ years. Each dataset has one postoperative X-ray radiograph and one postoperative CT scan. The postoperative CT scan for each patient was used to establish the ground truth for the cup orientation. The cup anteversion and inclination that were calculated from the 2D/3D reconstruction method were compared to the associated ground truth. To validate reproducibility and reliability, two observers performed measurements for each dataset twice in order to measure the reproducibility and the reliability of the 2D/3D reconstruction method.
Results Our validation study demonstrated a mean accuracy of $0.4 \pm 1.8°$ $(-2.6°$ to $3.3°)$ for inclination and a mean accuracy of $0.6 \pm 1.5°$ $(-2.0°$ to $3.9°)$ for anteversion. Through the Bland-Altman analysis, no systematic errors in accuracy were detected. The method showed very good consistency for both parameters.
Conclusions Our validation results demonstrate that the statistical shape model-based 2D/3D reconstruction-based method is an accurate, consistent, and reproducible technique to measure cup orientation from postoperative X-ray radiographs. The best results were achieved with radiographs including the bilateral anterior superior iliac spines and the cranial part of non-fractured pelvises.

Keywords 2D/3D reconstruction · Statistical shape model · Total hip arthroplasty · Cup orientation · X-ray radiograph

Introduction

Previous studies demonstrate that both short- and long-term results of total hip arthroplasty (THA) have been well associated with correct component positioning [1–7], and surgical experience indicates that the mal-orientation of the acetabular component in terms of anteversion and inclination is correlated with prosthetic impingement, dislocation, wear, osteolysis, and prosthetic loosening [1–3,5–7]. Accurate assessment of the cup orientation is essential for evaluation of outcome after THA and is typically done based on two-dimensional (2D) postoperative anteroposterior (AP) X-ray radiographs [8–14]. While 2D plain pelvic radiographs can be easily obtained, their accurate interpretation is subject to substantial error if the individual pelvis orientation with respect to the X-ray plate is not taken into consideration [8,9,14]. It is thus of special interest to develop improved

G. Zheng (✉) · L.-P. Nolte
Institute for Surgical Technology and Biomechanics,
University of Bern, Stauffacherstrasse 78, 3014 Bern, Switzerland
e-mail: guoyan.zheng@ieee.org; guoyan.zheng@istb.unibe.ch

J. von Recum · P. A. Grützner · J. Franke
BG Trauma Centre Ludwigshafen at Heidelberg University Hospital,
Ludwigshafen, Germany

S. D. Steppacher
Department of Orthopaedic Surgery, Inselspital, University of Bern,
Bern, Switzerland

methods to measure the postoperative cup orientation for a reasonable follow-up after THA, e.g., to detect cup loosening or cup migration.

When a three-dimensional (3D) CT scan has been obtained at some point during treatment, CT-based 2D/3D rigid image registration methods [15–21], including the method proposed by our own group [19–21], have been developed to measure the postoperative cup orientation. This is usually done with respect to an anatomical reference extracted from the CT scan, which is a plane called the anterior pelvic plane (APP) defined by the anterior superior iliac spines (ASIS) and the pubic tubercles [22–24]. In such methods, a rigid transformation between the CT scan coordinate system and the X-ray image coordinate system is estimated by first performing an intensity-based rigid 2D/3D registration, which then allows computing the orientation of the acetabular cup with respect to the APP extracted from the CT scan. Though accurate [16–21], the extensive usage of the CT-based 2D/3D image registration methods in clinical routine is still limited. This may be explained by the need for a CT scan of the patient at some point during treatment, the availability of which for a vast majority of THA procedures performed nowadays [19], not to mention earlier cup design, is questionable.

In order to address above limitation that is common to all CT-based 2D/3D rigid image registration methods, we developed a 2D/3D reconstruction-based method for determining cup orientation after THA [25,26]. This method allows reconstructing a patient-specific 3D-model of the pelvis from a standard AP X-ray radiograph using a statistical shape model-based deformable registration technique. Cup orientation (inclination and anteversion) is then calculated with respect to the anterior pelvic plane that is derived from the reconstructed 3D-model. Previously [26], we presented a preliminary evaluation study involving datasets from a limited number of pelvises (10 cadaveric pelvises and 5 patients). The goal of this study is to conduct a more thorough validation study on a relatively larger patient population. We hypothesize that our 2D/3D reconstruction-based method is an accurate, consistent, and reproducible technique for measuring postoperative cup orientation from postoperative X-ray radiographs.

Materials and methods

The 2D/3D reconstruction-based method

The mathematical background of the 2D/3D reconstruction-based method, details of the implemented algorithm, and the preliminary evaluation were previously reported [25,26]. Briefly, the method uses a statistical shape model-based 2D/3D deformable registration technique that can reconstruct a patient-specific 3D-model from a single standard AP pelvic X-ray radiograph (Fig. 1). Statistical shape modeling is an efficient way to represent the shape variations in collected data, which is typically parameterized by an average shape model and a set of principal shape modes. Based on a statistical shape model of the pelvis that is constructed from CT scans of 14 pelvises, our 2D/3D reconstruction-based method uses a sophisticated, three-stage sequential optimization procedure to estimate not only the affine transformation between the statistical shape model and the input image but also the weights for the principal shape modes by matching the silhouettes detected from the statistical shape model to contours extracted from the input radiograph [25,26]. Required input includes a digital radiograph, the pixel size, and the film-to-source distance. No specific calibration of the X-ray, a CAD (computer-assisted design) model of the implant, or a CT scan of the patient is required. Cup orientation (inclination and anteversion) is then calculated with respect to the anterior pelvic plane that is derived from the reconstructed 3D-model (see Fig. 2 for a schematic illustration of the 2D/3D reconstruction-based estimation of postoperative cup orientation). This is done by first calculating the radiographic

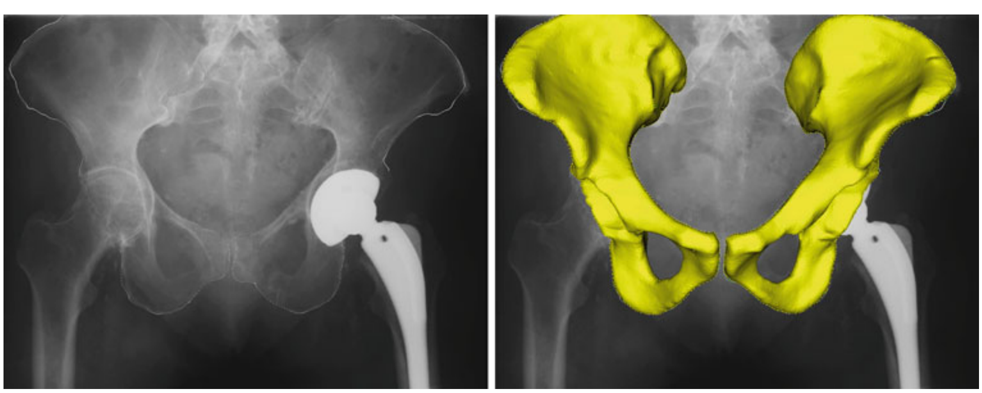

Fig. 1 To estimate the cup orientation, the 2D/3D reconstruction-based method first reconstructs a patient-specific 3D-model from the X-ray radiograph by matching a model that is instantiated from the statistical shape model to the X-ray radiograph. For visual verification, the method shows the pelvic contours (*left*) that are semi-automatically extracted from the input radiograph and the reconstructed 3D-model (*right*)

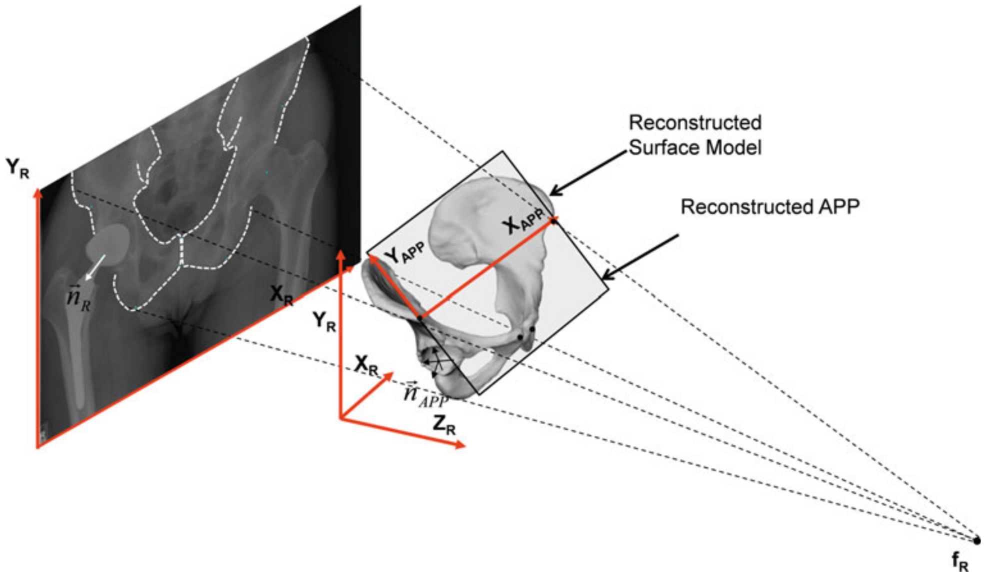

Fig. 2 Schematic representation of how to use the 2D/3D reconstruction-based method to estimate the post-operative cup orientation. To get a more accurate measurement of the cup orientation $\vec{n}_{App}$, the cup orientation $\vec{n}_R$ measured from the radiograph using the Widmer's method [12] is transformed from the radiographic coordinate system to a coordinate system that is established from the anterior pelvic plane derived from a 3D-model that is reconstructed from the input radiograph using a statistical shape model-based 2D/3D reconstruction method [25,26]

inclination and radiographic version according to the Widmer's method [12], and then transforming the computed cup orientation from the radiographic coordinate system to a coordinate system that is established on the derived APP to estimate the patient-specific cup orientation. If there is any doubt about cup retroversion, the method introduced by Seradge et al. [27], which requires the acquisition of more radiographs, can be used to determine whether the cup is anteverted or retroverted.

Validation

The validation study was conducted retrospectively on datasets of 29 patients (31 hips, please note that none of the patient datasets used in our previous work [21,25,26] has been used here). Among them, there were 15 men (15 hips) and 14 women (16 hips). The average age of the patients was 69.4 ± 8.5 $(49 - 82)$ years. Each dataset has one postoperative X-ray radiograph and one postoperative CT scan. The postoperative CT scans had a variable pixel spacing ranging from 0.64 to 0.98 mm/pixel with a variable interslice distance ranging from 2.0 to 3.0 mm (more specifically, 22 postoperative CTs had a constant interslice distance of 2 mm and the other 7 postoperative CTs had variable interslice distances). The postoperative CT scan for each patient was used to establish the ground truth for the cup orientation. The average cup anteversion and inclination measured from the postoperative CTs were, respectively, $22.6 \pm 10.6°$ (3.2°–51.4°) and $45.5 \pm 7.8°$ (26.6°–62.9°). The mean pelvic tilt of the APP on the postoperative CTs was $1.3 \pm 5.8°$ (−15.2° to 10.7°) and the mean pelvic rotation was $2.3 \pm 3.4°$ (−2.6° to 11.1°). As a retrospective study, not all radiographs that we obtained were acquired in a perfect condition and were often acquired in a deep centering condition [21]. We define deep centering as those radiographs in which the anterior superior iliac spines and the cranial part of the pelvis were not imaged (See Fig. 3 for an example). Previously, in an attempt to validate a CT-based 2D/3D rigid registration method for measuring postoperative cup orientation, we have found inferior results for deep centered X-rays [21]. This motivated us in this study to separate the datasets into two groups in order to estimate a potential influence on the 2D/3D reconstruction accuracy. More specifically, the first group contain all radiographs with deep centering (7 radiographs) or of pelvises with fractures (2 radiographs), or with both (1 radiograph), or of a non-hemispherically shaped cup (1 radiograph) and the second group consist of the remaining radiographs (18 radiographs).

Ground truth measurements of cup orientation with respect to the APP extracted from the postoperative CTs were done using a program developed in-house (Fig. 4). For each patient, one observer (G.Z.) defined the four anatomical landmarks (both the anterior superior iliac and pubic tubercles) of the APP from a 3D-model that was segmented from the associated postoperative CT scan using the commercially available software Amira® (TGS Europe, Paris, France). Then, three points on the cup opening rim were interactively picked to define the cup opening plane. The ground truth cup orientation was then calculated using the plane normal to the cup opening and the extracted APP.

The cup anteversion and inclination that were calculated from the 2D/3D reconstruction-based method were compared to the associated ground truth. To validate reproducibility and reliability, two observers (G.Z. and J.F.) performed measurements for each dataset twice using the 2D/3D reconstruction-based method. Each time, the measurement was done from scratch to detect the possible influence of the user interaction on measurement accuracy.

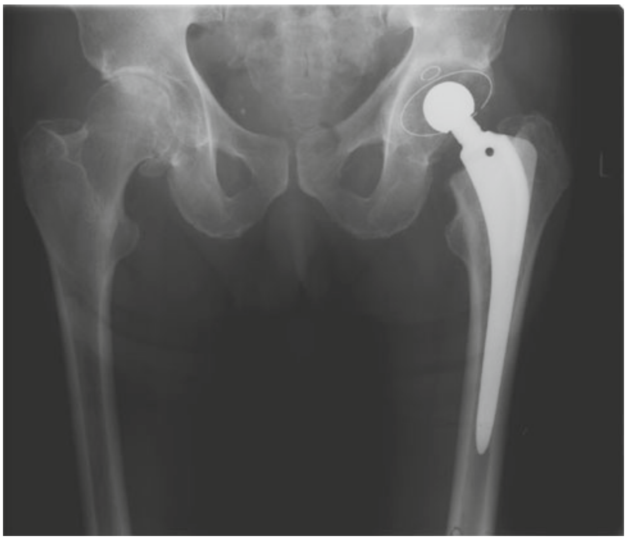

Fig. 3 This image shows an X-ray radiograph that was acquired in a deep centering condiction

Statistical analysis

Without additional explanation, all data were statistically analyzed with MicrosoftExcel® 2007. Comparison of accuracy of anteversion and inclination between cases in the first group and those in the second group was assessed using the Mann-Whitney U-test that was calculated using a web-based solution [29]. The graphical Bland-Altman analysis [30] was used for both parameters to detect potential systematic errors in the method by plotting the difference between the two measurement techniques (2D/3D reconstruction-based measurement vs. postoperative CT scan-based measurement) against their averages. The intraclass correlation coefficient (ICC) [28] was used to grade the reproducibility and the reliability of the repeated measurements as follows [31]: ICC $< 0.20 =$ poor; 0.21–0.40 $=$ fair; 0.41–0.60 $=$ moderate; 0.61–0.80 $=$ good; and $> 0.80 =$ very good. For all the statistical tests, we set the level of significance at 0.05.

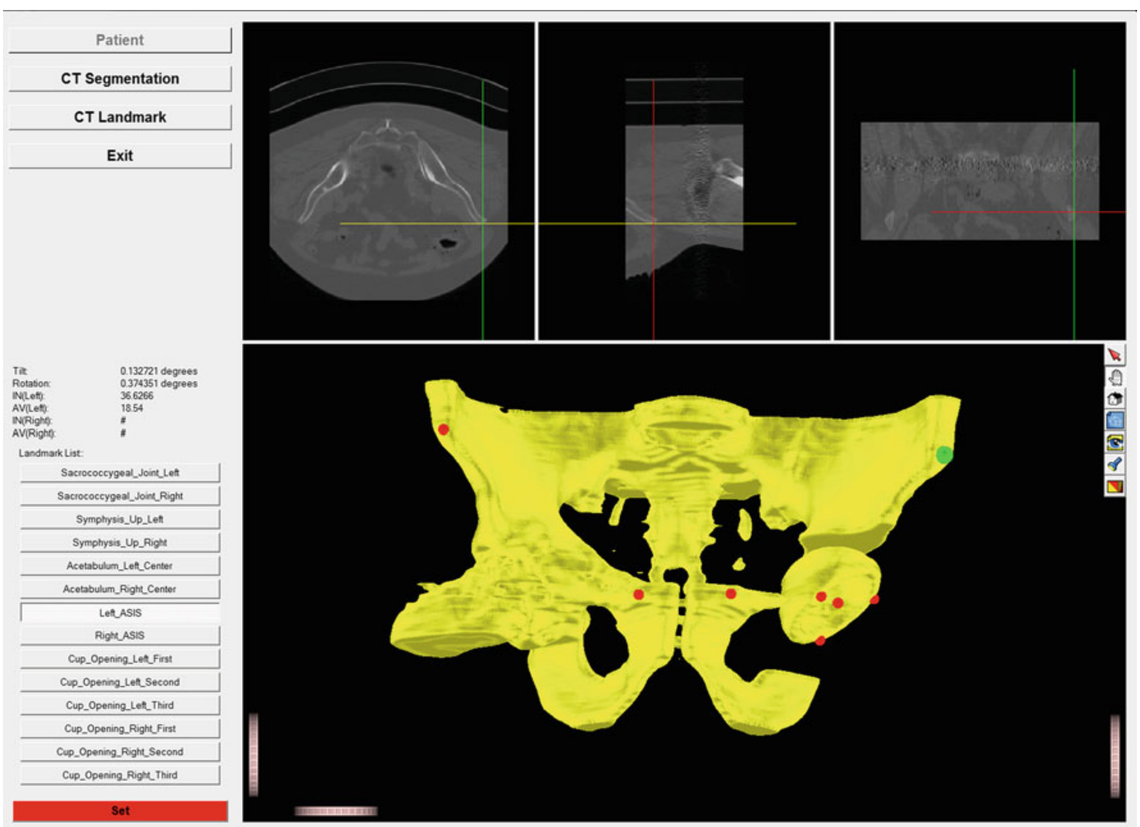

Fig. 4 The software interface developed in-house for measuring the ground truth cup orientation and the pelvic orientation (tilt and rotation) from the postoperative CT. The surface model was interactively segmented using the commercially available software Amira® (TGS Europe, Paris, France)

Results

The mean accuracy for the second group was 0.4 ± 1.8° (−2.6° to 3.3°) for inclination and 0.6 ± 1.5° (−2.0° to 3.9°) for anteversion, and the mean accuracy for the first group was 2.4 ± 2.3° (−2.1° to 6.3°) for inclination and 0.1 ± 2.8° (−4.6° to 5.1°) for anteversion. Comparing the measurements from the first group to those from the second group using the Mann-Whitney U-test, we found a significant difference in measuring cup inclination ($P = 0.01$) but not in measuring cup anteversion ($P = 0.3$). Bland-Altman analysis of those measurements from the first group indicated that no systematic error was detected for the 2D/3D reconstruction-based method (Fig. 5), as the means of the measurement pairs were spread evenly and randomly for both inclination and anteversion.

A very good reproducibility and reliability was found for both parameters (see Table 1 for details).

Table 1 Results of reproducibility and reliability

Parameters	ICC intraobserver #1*	ICC intraobserver #2*	ICC interobserver*
Anteversion	0.96 (0.91–0.98)	1.0 (0.99–1.0)	0.97 (0.93–0.98)
Inclination	0.98 (0.97–0.99)	1.0 (1.0–1.0)	0.99 (0.99–1.0)

* Mean (95% confidence interval)

Discussions and conclusions

Accurate assessment of the acetabular cup orientation is important for evaluation of outcome after THA, but the inability to measure acetabular cup orientation accurately limits one's ability to determine optimal cup orientations, to assess new treatment methods of improving acetabular cup orientation in surgery, and to correlate the acetabular cup orientation to osteolysis, wear, and instability. The goal of this study was to validate this new 2D/3D reconstruction-based method for determining cup orientation after THA with a retrospective evaluation study involving datasets of 29 patients. We confirmed prior studies of the 2D/3D reconstruction-based method [25,26], and further demonstrated that CAD models of specific implants and patient CT scans are not necessary for accurate measurement of cup orientation as long as the cup has a circular opening surface. We showed our 2D/3D reconstruction-based method to be an accurate, consistent, and reproducible technique to measure cup orientation from postoperative X-ray radiographs.

The accuracy achieved by the 2D/3D reconstruction-based method in this study is comparable to other studies that were based on 2D/3D matching of a 3D CT scan of the patient with the X-ray radiograph. Based on a manual adjustment procedure, Blendea et al. [16] reported a mean accuracy of 0.8±1.3° (−2.2° to 4.7°) for abduction and a mean accuracy of 0.0±2.0° (−4.5° to 5.0°) for version. The same group later introduced an automated matching procedure and reported a mean accuracy of 0.4 ± 0.8° (maximum error of 2.2°) for abduction and a mean accuracy of 0.6 ± 0.8° (maximum error of 2.0°) [17]. When measurements based on a single X-ray radiograph were used, Penney et al.[18] reported a mean accuracy of 2.3° for anteversion and a mean accuracy of 0.9° for inclination for their 2D/3D matching method. These values changed to 1.3° and 0.9°, respectively, if the average value of the results measured from different X-ray radiographs of the same patient was taken. Common to all of the 2D/3D matching methods mentioned above is that these methods require not only a CT scan of the patient but also CAD models of the specific implants. Recently, we introduced an automated 2D/3D matching method for estimating cup orientation postoperatively [19,20]. Measurements on blinded and randomized radiographs of 80 cadaver and 327 patient hips showed a mean accuracy of 0.7±1.7° (−3.7° to 4.0°) for inclination and 1.2±2.4° (−5.3° to 5.6°) for anteversion in the cadaver trials, and 1.7 ± 1.7° (−4.6° to 5.5°) for inclination and 0.9±2.8° (−5.2° to 5.7°) for anteversion

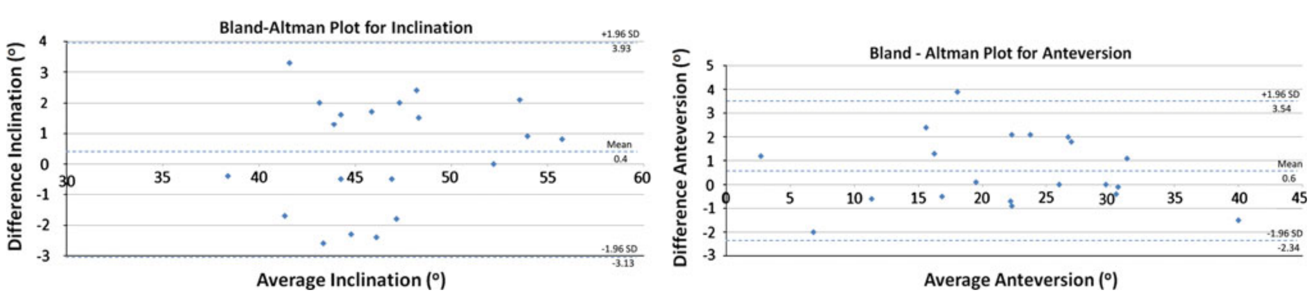

Fig. 5 Bland-Altman analysis [30] for inclination (*left*) and anteversion (*right*). The Bland-Altman analysis was done by plotting the difference between the two measurement techniques (2D/3D reconstruction-based measurement versus postoperative CT-based measurement) against their averages. An even, random spread for both parameters demonstrated that no systematic error was detected for the 2D/3D reconstruction-based method

in the clinical data [21]. Although this method does not need CAD models of specific implants any more, it still requires obtaining a CT scan of the patient at some time during treatment.

The significance of the current study over our previous study [26] should be discussed. Previously [26], we presented a preliminary evaluation study involving datasets from 10 cadaveric pelvises and 5 patients. Though accurate results were observed, one limitation was identified: we only validated our approach on a limited number of cases. Furthermore, the influences of several important factors on the accuracy of the method, such as the X-ray image acquisition condition as well as pelvic fractures, cannot be experimentally determined in our previous study due to the limited number of cases used in that study. The reliability and the repeatability of our 2D/3D reconstruction-based method were also not investigated. In the current study, not only did we further validate the 2D/3D reconstruction-based method with a relatively larger patient population but also we investigated the reliability and the repeatability of this method as well as the influences of the X-ray image acquisition condition and the pelvic fractures on the accuracy of the method. More specifically, we found that the best results were achieved with the radiographs that included the anterior superior iliac spines and the cranial part of non-fractured pelvises. Thus, it is recommended that these landmarks should be included in the radiograph whenever the 2D/3D reconstruction-based method will be used in clinical routine.

The advantages of this 2D/3D reconstruction-based method over other methods for postoperative calculation of acetabular cup orientation are apparent. Several studies [8,9,14,18–21] have shown that the radiographic measurement methods, though easy to use, cannot produce accurate results, especially for the anteversion measurements due to the wide variability in individual pelvic orientation relative to the X-ray plate during image acquisition. Previous studies [18,19] reported that errors in measuring the cup anteversions with the radiographic measurement method could be high, exceeding 20°. However, postoperative CT scan-based methods, which are regarded as the most reliable methods for measuring postoperative cup orientation [8,9,14,32,33], are not widely used in clinical routine because they incur not only additional expense but also a high additional radiation dose to the patient. The recently introduced CT-based 2D/3D rigid image registration methods [15–20] have shown reasonably accurate results in calculation of postoperative cup orientation. But again, their extensive usage in clinical routine is still limited, largely due to the requirement of having a CT scan of the patient at some point during treatment, which brings in the radiation issue. Furthermore, it is questionable whether the CT scan would be available for the vast majority of THA procedures currently performed [18]. In contrast, the present 2D/3D reconstruction-based method only requires a single standard postoperative AP X-ray radiograph to reconstruct the patient-specific surface model of the pelvis and to calculate the postoperative cup orientation. No further CT scan of the patient is needed, which eliminates the radiation issue. This has both a clear medical and an economic advantage in the clinical setting.

While accurate, our method has several limitations. Although the 2D/3D reconstruction-based method is applicable to all types of bearing, the precondition of the implant that can be measured by this approach should have a circular opening surface of the acetabular cup, and the best results were achieved with hemispherically shaped cups. The second limitation is due to the fact that Widmer's method [12] is used to calculate the cup radiographic version from the plain radiograph. The assumption behind Widmer's method [12] is that the X-ray radiograph should be acquired in a standardized way. The third limitation discussed here is related to the 2D/3D reconstruction method itself. As a statistical shape mode-based method, the efficacy of the 2D/3D reconstruction method largely depends upon how well the unknown, patient-specific shape variation can be covered by the statistical shape model that is constructed from a fixed number of training models. Our experimental results confirmed that less accurate results were observed on those pelvises with fractures, whose shape variations might not be completely covered by our statistical shape model. One of the future directions that are worth exploring is to investigate whether a patient-oriented statistical shape model (e.g., a patient's gender-oriented statistical shape model) will further improve the accuracy of our approach.

The potential sources of errors existing in the study have to be discussed. First, any difference between the definition of the APP on the reconstructed surface model and on the postoperative CT scan would result in differences in the calculations. Second, not all cups in the present study have a smooth cup opening rim, which could affect the ground truth measurements. Last but not least, its accuracy is dependent on the manual implementation of Widmer's method [12] with interactively defined landmarks. Nonetheless, the last two sources of errors can be completely eliminated by performing a rigid 2D/3D matching between the X-ray radiograph and a CAD model of the implant, if it is available.

In summary, we validated a new 2D/3D reconstruction-based method for estimating cup orientation postoperatively from a standard X-ray radiograph. For the first time, a patient-specific 3D-model can be reconstructed from a single conventional AP pelvic X-ray radiograph using a statistical shape model-based method. The postoperative cup orientation can then be measured with respect to the APP that is extracted from the reconstructed 3D-model. No specific calibration of either the X-ray radiograph, a CAD model of the implant, or a CT scan of the patient is required. The accuracy achieved by the method demonstrated in this study is comparable to those reported in previous studies that depend on 2D/3D matching of a CT scan of the patient with an X-ray radiograph. This method may have significant potential for assessment of implant design, evaluation of surgical technologies, and future refinement of the "safe zone" [5].

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Conflict of interest None.

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