The use of ultrasound in acquisition of the anterior pelvic plane in computer-assisted total hip replacement

A CADAVER STUDY

S. Parratte, MD, Arthroplasty Fellow
P. Kilian, MD, PhD, Professor and Chairman of Orthopaedic Surgery
V. Pauly, MS, Statistician
P. Champsaur, MD, PhD, Professor of Radiology and
J.-N. A. Argenson, MD, PhD, Professor of Radiology and Anatomy
From Aix-Marseille University, Marseille, France

We have evaluated in vitro the accuracy of percutaneous and ultrasound registration as measured in terms of errors in rotation and version relative to the bony anterior pelvic plane in computer-assisted total hip replacement, and analysed the intra- and inter-observer reliability of manual or ultrasound registration.

Four clinicians were asked to perform registration of the landmarks of the anterior pelvic plane on two cadavers. Registration was performed under four different conditions of acquisition. Errors in rotation were not significant. Version errors were significant with percutaneous methods (16.2°; \( p < 0.001 \) and 19.2° with surgical draping; \( p < 0.001 \)), but not with the ultrasound acquisition (6.2°; \( p = 0.13 \)). Intra-observer repeatability was achieved for all the methods. Inter-observer analysis showed acceptable agreement in the sagittal but not in the frontal plane.

Ultrasound acquisition of the anterior pelvic plane was more reliable in vitro than the cutaneous digitisation currently used.

Malpositioning of the acetabular component during total hip replacement (THR) increases the risk of dislocation,\(^1,2\) reduces the range of movement\(^3\) and can lead to early wear or loosening.\(^4\) Lewinnek et al\(^1\) recommended a safe zone for placement of the acetabular component as an angle of abduction of 40° (SD 10°) and anteversion of 15° (SD 10°). This zone has recently been further defined in a computer model and the concept of combined component position introduced.\(^5\) Mechanical guides for intra-operative alignment are not accurate enough to achieve the desired orientation of the implant.\(^6\) In order to avoid malpositioning, computer-assisted navigation systems have been developed.\(^7\) Some are independent of pre-operative imaging and are described as imageless navigation systems.\(^8,10\)

The reliability and the radiological efficacy of imageless systems have been assessed in prospective randomised studies.\(^9,10\) Almost all of these systems require accurate recognition of the anterior plane of the pelvis.\(^9\) The bony anterior plane, known as the Lewinnek plane,\(^1\) is the basis for all measurements of angles during the procedure using the navigation software and after operation when using the evaluation software for a three-dimensional (3D) reconstruction.\(^11\) Three bony landmarks, the two anterosuperior iliac spines and the pubic symphysis, are necessary for the imageless system.\(^8\) During the procedure percutaneous registration of these landmarks is performed.\(^8,10\) In a previous study,\(^10\) we described discrepancies between the intra-operative and the post-operative measurement of alignment of the acetabular component in a patient with a body mass index (BMI) > 27 kg/m². Registration of the anterior pelvic plane had been modified by subcutaneous fat; we described this as the ‘cutaneous Lewinnek plane’\(^10\) (Fig. 1). A cadaver study,\(^8\) described significant inaccuracy with the percutaneous manual method for registering pelvic landmarks. In a model study, Wolf et al\(^12,13\) demonstrated that a minor failure to correctly identify the anatomical landmarks can lead to improper alignment of the acetabular component. An error in the frontal plane will directly modify the angle of abduction, and an error in the sagittal plane will affect the angle of anteversion.\(^12,13\) Clinical, cadaver and model studies have shown the clear need to develop new tools, such as 2.5D ultrasound computer-assisted systems for the acquisition of the anterior plane of the pelvis during computer-assisted THR.\(^9,10,12-14\) The principle is based on a 3D reconstruction of the bony anatomy from data collected intra-operatively by the surgeon using an ultrasound probe connected to a 3D optical localiser. The computer then...
performs an automatic extraction of the points acquired by the surgeon to reconstruct the bony anterior plane.15

We considered that the use of an integrated ultrasound system might improve registration of the anterior pelvic plane in computer-assisted THR. We aimed to evaluate in vitro the accuracy of percutaneous and ultrasound registration, as measured by errors of rotation and version relative to a reference bony anterior pelvic plane, using dedicated navigation software, and to analyse in vitro the intra- and inter-observer reliability of manual or ultrasound registration of the anterior pelvic plane.

**Material and Methods**

We used two female cadavers with pre-mortem BMIs of 23 kg/m² and 30 kg/m², respectively. Four clinicians (SP, JNA, XF, PVO) of varying experience were recruited for the study. All were familiar with standard hip replacement, but only two with the use of computer-assisted surgery. None had experience in the use of the ultrasound method of registration. Each had five practice attempts before beginning the proper trials. Each was asked to register the landmarks of the anterior pelvic plane under four different conditions: cutaneous acquisition, draped cutaneous acquisition, ultrasound acquisition, and direct bone acquisition. Each operator undertook registration of the anterior pelvic plane ten times in a randomly changed order for each of the four conditions, with a one-minute break between each attempt. The accuracy of their registrations was not disclosed to the operators during the trials.

**Data acquisition.** A dedicated navigation software application was developed using an integrated 2.5D ultrasound device13 which allowed digitisation of the anterior pelvic plane, either by manual acquisition using a pointer or with an ultrasound probe (Praxim Medivision, Grenoble, France). The principle of ultrasound acquisition is based on a 3D reconstruction of the bony anatomy from data collected intra-operatively using an ultrasound probe connected to a 3D optical localiser. Each clinician was instructed to place the probe over the two anterosuperior iliac spines and the pubic symphysis and then press the foot pedal to record the corresponding image. Each ultrasound image was processed with a near real-time snake-based segmentation method, resulting in a list of eligible points of bone interface.15 With this method, the point on the centre scan line which has the highest probability of belonging to the bone surface is automatically selected, but the clinician is able to override this selection according to his or her own opinion.15 This concept is known as echo-point technology (Praxim Medivision).

The two specimens were prepared and placed supine on an operating table. The dedicated navigation system required the placement of an iliac reference tracker using two pins placed in the right iliac crest for each specimen, as for conventional hip navigation.3-10 The different acquisitions were performed according to the study design for the four operators on the two cadavers. The first acquisition was the cutaneous acquisition: the anterior pelvic plane was acquired with a manual pointer by direct percutaneous palpation on the skin with the specimen in the supine position. Then, during the draped cutaneous acquisition it was defined with surgical drapes covering the skin as in a conventional THR using navigation through a Watson-Jones approach.10 During the ultrasound acquisition, it was defined using the echo-point technology without surgical draping. After all the surgeons had performed their acquisitions, the two anterior superior iliac spines and the pubic symphyses were dissected and the soft-tissue removed to expose the underlying bone. This allowed the surgeons to perform acquisition directly on the bony landmarks.

**Data analysis.** For each operator, each acquired computed anterior pelvic plane was constructed from the 3D coordinates of the two anterior superior iliac spines and the pubic symphyses. A collection of ten points, corresponding to the ten trials in a randomly changed order, from the pubic symphysis and the two anterior iliac spines for each condition of acquisition were obtained for each operator. A global mean anterior pelvic plane was computed using the direct bone acquisition data from the four operators for each cadaver. This was considered as the reference plane in all the analyses.16 According to Wolf et al,12,13 an error in assessment of the frontal plane will lead to an incorrect degree of abduction of the cup and could be defined as a rotation error ($\theta_1$) (Fig. 2a). They also noted that an error in evaluation of the sagittal plane will result in this placement in anteversion and could be defined as a version error ($\theta_2$) (Fig. 2b). An isolated error in the sagittal plane of 4.5° (version error, $\theta_2$ angle) will result in final placement of the acetabular component in 47° of abduction and 25° of anteversion, rather than the expected angles of 45° and 20°, respectively.12,13 For each operator with each method of acquisition on each cadaver the rotation error ($\theta_1$ angle) and the version error ($\theta_2$ angle) were measured for each
calculation of the anterior pelvic plane relative to the global reference plane as previously defined.\textsuperscript{16}

**Statistical analysis.** Statistical analysis was performed using SPSS software (version 12, SPSS Inc., Chicago, Illinois). Errors in version and rotation, as defined by Wolf et al,\textsuperscript{12,13} registered during the different acquisitions of the anterior pelvic plane were described using means and standard deviations, or medians and ranges for continuous variables. First, the accuracy of each method of acquisition, defined in terms of errors in rotation and version for all the operators on the two cadavers, were assessed with analysis of variance (ANOVA), using the Bonferroni test for post hoc comparisons.\textsuperscript{17} For the first step, the null hypothesis was that there was no difference between the different methods of registration for errors in either rotation or version, relative to the previously defined global reference plane.\textsuperscript{15} Then an intra- and inter-observer analysis of the reliability and the repeatability of each method of acquisition was performed, with ANOVA using the Bonferroni test for post hoc comparisons,\textsuperscript{17} for the four operators for each cadaver. For this second step the null hypothesis was that there was no difference in errors of either rotation or version between the four observers and between the different trials of each observer for the different conditions of registrations. All calculations assumed two-tailed tests and a significance level of \( p = 0.05 \).

**Results**

The results for each method of acquisition, for each operator on each cadaver for errors in rotation are presented in Table I and for errors in version in Table II. The mean (SD) of the global rotation error around the reference plane for the two cadavers and the four operators was 2\(^\circ\) (SD 0.21; 1.5\(^\circ\) to 2.4\(^\circ\)) for the cutaneous acquisition method, 3.8\(^\circ\) (SD 0.21; 3.4\(^\circ\) to 4.2\(^\circ\)) for the draped cutaneous acquisition method, and 2.8\(^\circ\) (SD 0.21; 2.4\(^\circ\) to 3.3\(^\circ\)) for the ultrasound acquisition method. For rotation, we were able to accept the null hypothesis that there was no significant difference observed for the different methods, used relative to the global reference plane (\( p = 0.22 \)) for the cutaneous acquisition, 0.12 for the draped cutaneous acquisition, and 0.19 for the ultrasound acquisition methods). The mean (SD) of the global version error around the reference plane for the two cadavers and the four operators was 16.2\(^\circ\) (SD 4.1; 15.4\(^\circ\) to 17\(^\circ\)) for the cutaneous acquisition method, 19.25\(^\circ\) (SD 4.1; 18.4\(^\circ\) to 21.2\(^\circ\)) for the draped cutaneous acquisition method, and 6.2\(^\circ\) (SD 4.1; 5.4\(^\circ\) to 7\(^\circ\)) for the ultrasound acquisition method. The null hypothesis for version was rejected as the differences from the global plane\textsuperscript{15} were statistically significant for the cutaneous and draped cutaneous acquisition methods for the two cadavers (\( p < 0.0001 \)) and statistically greater for the cadaver with the greater BMI (\( p < 0.001 \)) (Table II). We were able to accept the null hypothesis for the ultrasound acquisition method, as no statistical difference was observed from the global plane (\( p = 0.13 \)).\textsuperscript{16}

For rotation there was no statistical difference between the intra-observer comparisons for all the conditions of acquisition on each cadaver (\( p = 0.878 \)). The agreement between the different observers was within 3\(^\circ\), and a statistical difference was found for the inter-observer analysis (\( p < 0.01 \)) for all the methods and for the two cadavers (\( p = 0.009 \)) (Fig. 3a). For version, there was no statistical difference between the intra-observer analyses (\( p = 0.936 \)) for all the methods, and using ultrasound acquisition the degree of agreement was within 2\(^\circ\). The results of the inter-
observer analysis for errors in version demonstrated no statistical difference for all the conditions of acquisition and for the two cadavers (p = 0.130) (Fig. 3b). The degree of agreement between the different observers was within 4˚ for the ultrasound acquisition method. No statistical difference was found between the skilled operators and the others for any of the acquisitions.

Discussion

Computer-assisted navigation systems have shown their value in reducing the spread of the standard deviation of positioning of the acetabular component of THR.\(^8,10\) However, the accuracy of the system is directly dependent on the information fed into the computer,\(^8,10,12,13\) which, if incorrect, particularly during the percutaneous acquisition of the anterior pelvic plane, will lead to inaccuracy in the final alignment of the acetabular component.\(^8,10,12,13\) We carried out a prospective randomised study\(^10\) which showed significant discrepancies between peri- and post-operative values in orientation of the acetabular component in patients with a BMI > 27 kg/m\(^2\). These differences were not related to the method of measurement, which was based on post-operative 3D CT reconstructions.\(^10,11\) We considered that the discrepancies might have been related to the effect of the thickness of the fat around the two anterior iliac spines and the pubic symphyses during acquisition of the anterior pelvic plane.\(^9\) Errors introduced during registration of anatomical landmarks may affect the final orientation of the acetabular component.\(^12,13\) Wolf et al\(^12,13\) considered that an error of 4.5˚ in flexion resulted in a malalignment of 5˚ of version and 2˚ of abduction. A model to compensate for these errors has been proposed, but it cannot be used in the operating theatre.\(^12,13\) We have used ultrasound acquisition of the bony anterior pelvic plane to limit the effect of the

| Table I. Results of the rotation error (θ₃ angle) for cadaver 1 and 2. For each operator and each acquisition condition the mean and (SD) of rotation error around the reference plane are presented |
|---|---|---|---|---|---|
| Operator | 1 | 2 | 3 | 4 | All operators |
| Cadaver 1 | | | | | |
| DCA* | 2.2 (1.4) | 2.2 (1.1) | 1.4 (0.9) | 4.9 (2.1) | 2.6 (1.8) |
| UA† | 2.3 (1.8) | 2.3 (1.8) | 3.9 (2.4) | 1.9 (1.2) | 2.6 (1.8) |
| CA‡ | 2.3 (0.6) | 2.1 (1.3) | 3.1 (0.8) | 1.8 (1.0) | 2.3 (1.2) |
| All methods | 2.2 (1.2) | 2.2 (1.2) | 2.8 (1.4) | 2.9 (1.4) | 2.5 (1.3) |
| Cadaver 2 | | | | | |
| DCA | 2.6 (1.5) | 4.8 (1.4) | 2.7 (0.8) | 9.7 (2.9) | 4.95 (1.65) |
| UA | 2.6 (1.2) | 2.3 (2.0) | 5.0 (2.7) | 2.4 (1.7) | 3.1 (1.9) |
| CA | 1.6 (0.7) | 1.7 (0.8) | 1.3 (0.5) | 2.1 (1.1) | 1.7 (0.7) |
| All methods | 2.2 (1.13) | 2.9 (1.4) | 3.0 (1.33) | 4.7 (1.9) | 3.2 (1.4) |

* DCA, draped cutaneous acquisition
† UA, ultrasound acquisition
‡ CA, cutaneous acquisition

| Table II. Results of the version error for cadaver 1 and 2 (θ₂ angle). For each operator and each acquisition condition the mean and (SD) of version error around the reference plane are presented |
|---|---|---|---|---|---|
| Operator | 1 | 2 | 3 | 4 | All operators |
| Cadaver 1 | | | | | |
| DCA* | 15.9 (2.9) | 17.5 (1.8) | 12.3 (0.9) | 14.2 (3.0) | 15.0 (2.15) |
| UA† | 7.6 (3.7) | 5.1 (3.0) | 3.9 (3.3) | 6.5 (3.1) | 5.7 (3.3) |
| CA‡ | 9.2 (2.2) | 10.2 (1.0) | 9.7 (2.3) | 11.3 (1.6) | 10.1 (1.8) |
| All methods | 10.9 (2.9) | 11.0 (1.9) | 8.7 (2.2) | 10.7 (2.5) | 10.3 (2.4) |
| Cadaver 2 | | | | | |
| DCA | 24.1 (1.2) | 20.8 (1.4) | 22.9 (1.5) | 26.4 (2.0) | 23.55 (1.5) |
| UA | 8.1 (2.8) | 7.4 (2.5) | 5.0 (4.3) | 6.1 (3.6) | 6.6 (3.3) |
| CA | 21.7 (1.5) | 21.2 (2.6) | 24.0 (2.6) | 22.2 (2.2) | 22.3 (2.2) |
| All methods | 18.0 (1.8) | 16.5 (2.1) | 17.3 (2.8) | 18.2 (2.6) | 17.5 (2.3) |

* DCA, draped cutaneous acquisition
† UA, ultrasound acquisition
‡ CA, cutaneous acquisition
surrounding soft tissue. We found that the accuracy of percutaneous assessment of the anterior pelvic plane was limited. Using the standard and draped cutaneous methods, the range of error for version was > 15˚ for the thin cadaver and > 20˚ for the cadaver with the greater BMI. Such errors in the acquisition of the anterior pelvic plane may have dramatic consequences on the final alignment of the cup, particularly in version.12,13 With the ultrasound acquisition method the mean error was 6.2˚ (SD 4.1) and statistically comparable to the global regional plane even in the cadaver with the greater BMI. These results confirmed our view that ultrasound registration of the anterior pelvic plane may improve the accuracy. Intra-observer reliability was good for all the methods of acquisition. However, inter-observer agreement was statistically reliable for acquisition in the sagittal plane, particularly when using the ultrasound acquisition method, but not the acquisition in the frontal plane even when using this method.

A limitation of our study is that we only evaluated errors in rotation and version during the registration of the anterior pelvic plane and not the final position of the acetabular component itself. However, based on the model of Wolf et al.,12,13 we could estimate the consequence on positioning of the acetabular component. When designing our study we aimed to estimate the errors in the frontal and sagittal planes, rather than having a global ideal of the error through analysis of the final positioning of the acetabular component. To our knowledge, this is the first study to evaluate and compare the reliability of a computer-assisted system integrating ultrasound with a standard tracking system for the acquisition of the anterior pelvic plane in cadavers. The use of ultrasound in navigation systems has been described in minimally-invasive surgery and following trauma. It has been used and validated in pelvic surgery but not for the acquisition of the anterior pelvic plane in THR.18,19 Spencer et al.,8 in a previous cadaver study, indicated the inter- and intra-observer reliability of the manual registration of the anterior pelvic plane in THR. On a thin cadaver they found significant inter-observer variability of the inclination and anteverision of the acetabular component.8 Our results are consistent with this in terms of range of errors and of limited inter-observer repeatability.8 In another study, Richolt, Effenberger and Rittmeister20 described the use of ultrasound to evaluate how the distribution of soft tissue affects the accuracy of anteverision when using palpation in image-free navigation of the acetabular cup. The thickness of the subcutaneous soft tissue was measured in 72 patients scheduled for THR, as well as the distance between the different bony landmarks. The results suggested that the median of misinterpretation of anteverision was 2.8˚,20 which is much smaller than we observed. However, their methods may be open to question in terms of reliability and repeatability, as the ultrasound was used as an assessment tool and not integrated into a navigation system.20

The results of our study only partially confirmed our hypotheses and were not as good as we had expected concerning the accuracy of the ultrasound method. A mean of...
3° of error for rotation and of 6° for version were observed. Two technical points may explain these results. First, insufficient hydration of the cadavers may have resulted in a poor quality of ultrasound image. Secondly, the absence of visual feedback of the navigated ultrasound plane in a model of the hip on the computer screen gave the operators some problems concerning the mental representation of the ultrasound images of the real landmarks, and may explain the poor inter-observer reliability observed in the frontal plane.\(^{2,1}\)

To our knowledge, ultrasound technology has not so far been used for the registration of the anterior pelvic plane in computer-assisted THR. Our study confirms the inaccuracy induced by percutaneous manual palpation in THR, particularly concerning tilt. This may lead to malpositioning of the acetabular component, especially in version. The use of ultrasound acquisition of the anterior pelvic plane is more accurate, reliable and reproducible in vitro than simple cutaneous palpation.

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References