Intra- and extra-articular planes of reference for use in total hip arthroplasty: a preliminary study

Jerome Hausselle • Pierre Etienne Moreau •
Loic Wessely • Emmanuel de Thomasson • Ayman Assi •
Sebastien Parratte • Jerome Essig • Wafa Skalli

Received: 6 January 2012 / Accepted: 13 February 2012 / Published online: 21 March 2012
© Springer-Verlag 2012

Abstract

Purpose Acetabular component malalignment in total hip arthroplasty can lead to potential complications such as dislocation, component impingement and excessive wear. Computer-assisted orthopaedic surgery systems generally use the anterior pelvic plane (APP). Our aim was to

investigate the reliability of anatomical landmarks accessible during surgery and to define new potential planes of reference. **Methods** Three types of palpations were performed: virtual, on dry bones and on two cadaveric specimens. Four landmarks were selected, the reproducibility of their positioning ranging from 0.9 to 2.3 mm. We then defined five planes and tested them during palpations on two cadaveric specimens. **Results** Two planes produced a mean orientation error of 5.0° [standard deviation (SD 3.3°)] and 5.6° (SD 2.7°). **Conclusions** Even if further studies are needed to test the reliability of such planes on a larger scale in vivo during surgery, these results demonstrated the feasibility of defining a new plane of reference as an alternative to the APP.

J. Hausselle (✉) • A. Assi • W. Skalli
LBM, Arts et Metiers ParisTech,
151 bd de l'Hôpital,
75013 Paris, France
e-mail: jerome.hausselle@gmail.com

A. Assi
e-mail: ayman.assi@gmail.com

W. Skalli
e-mail: wafa.skalli@ensam.eu

P. E. Moreau
Polyclinique Saint Roch,
43 rue du Faubourg Saint Jaumes,
34000 Montpellier, France

L. Wessely
Polyclinique Keraudren, rue Ernestine de Tremaudan,
29200 Brest, France

E. de Thomasson
Institut Mutualiste Montsouris,
42 bd Jourdan,
75014 Paris, France

S. Parratte
Institut du Mouvement et de l'Appareil Locomoteur,
270 bd Sainte marguerite,
13009 Marseille, France

J. Essig
Clinique Médipôle Garonne,
45 rue de Gironis,
31100 Toulouse, France

Introduction

Total hip arthroplasty (THA) is one of the most successful joint replacements. Nevertheless, problems may still occur, such as instability, dislocation, impingement, excessive wear or aseptic loosening. Acetabular component malalignment is a key factor explaining such complications [1–9]. Concerning dislocations, for example, which range between 2% and 11% [8, 10–12], Lewinneck et al. [1] proposed a safe zone for cup orientation to prevent risk of dislocation, which was $40^\circ \pm 10^\circ$ in abduction and $15^\circ \pm 10^\circ$ in anteversion. Although these values vary from one study to another [13], a global safe zone is well defined [10]. Moreover, cup malalignment is also responsible for the ceramic-on-ceramic squeaking sound [14]. Indeed, cups outside the safe range are 29 times more likely to squeak, either during walking if anteversion is too high or during flexion if anteversion is too low.

Researchers and surgeons have developed several techniques to ensure the correct cup alignment. Mechanical alignment

guides allow positioning the cup with respect to precisely defined subcutaneous or bony anatomical landmarks [2, 6, 7]. A major drawback is that the device may not exactly be in contact with the targeted landmarks and may not be secured in the final position [2]. Moreover, a basic assumption is that the patient's trunk and pelvis are aligned in a known orientation during surgery and remain postoperatively in that particular position [7, 11, 13]. A recent study of 15 alignment guides showed that angles ensuring a safe cup positioning may differ from the ones advised by manufacturers [6]. Another difficulty comes from the minimally invasive techniques, which offer less space and no direct visualisation to ensure correct placement of the guides [7]. Therefore, several companies have developed computer-assisted orthopaedic surgery (CAOS) systems to ensure a safer placement of prostheses components. Three types of systems exist [10], which rely either on preoperative computed tomography (CT)-scan images, intraoperative fluoroscopic images or intraoperative registration of bony landmarks (imageless systems). Regardless of type, these systems ensure a more accurate cup alignment than freehand surgery and use of alignment guides [3–5, 7, 10, 15–17]. The same results were found for positioning femoral-head components during resurfacing hip arthroplasties [18, 19]. Imageless systems are less expensive and easier to use than CT-based ones [5, 7] but, because they rely solely on subcutaneous anatomical landmarks, soft tissues may introduce positioning errors [5, 10].

CAOS systems generally use the anterior pelvic plane (APP) as a reference, defined by the anterosuperior iliac spines and pubic tubercles. This plane is located by palpation of anatomical landmarks during surgery, but the presence of soft tissues overlying these points may introduce inaccuracies [5, 10, 20]. Moreover, differences between values given by CAOS systems and direct CT-scan measurements lie between 0.0° [standard deviation (SD) 2.8] and 3.5° (SD 4.4°) in abduction, and 3.4° (SD 3.6°) and 6.5° (SD 7.3°) in anteversion [10, 13]. In addition, the APP is supposed to be aligned with the vertical axis in the standing position, which is not always the case [21]. Therefore, the APP may not be as reliable as initially thought. The goal of this study was to define reliable anatomical landmarks that could be palpated intraoperatively, and to propose new alternative planes of reference.

Materials and methods

To test several anatomical landmarks, we considered three pelvic regions (Fig. 1a): acetabulum, acetabular fossa and acetabular notch. We also considered the subcutaneous and bony points needed for APP plane definition, for

Fig. 1 **a** Anatomical regions and anterior pelvic plane (APP) palpated points: example of a virtual palpation. **b** Experimental setup for palpation on cadaveric specimen using the Stryker system

comparison purposes. These points were the anterosuperior iliac spines (ASIS) and pubic tubercles. Three parts made up this work: a reproducibility study was conducted regarding palpations on dry bones, then points were virtually palpated on digital pelvic models and on cadaveric specimens. We used a home-made software developed at the LBM, Arts et Metiers ParisTech, to perform the virtual palpations. This software allowed manipulating 3D models and acquiring surface point co-ordinates. Palpations on dry and cadaveric bones were performed using a commercial navigation system (Stryker, Pusignan, France). For such an imageless system, a reference pin was needed and was screwed on the iliac wing (Fig. 1b).

Reproducibility study

Four orthopaedic surgeons palpated each anatomical region of interest six times on three dry half pelvises, leading to a total of 72 data sets. Using the navigation system, the

number of palpated points was set for each anatomical region: 100 points for the acetabulum and acetabular fossa, and 30 points for the acetabular notch. For each anatomical point defined, its intra- and interoperator reproducibility was assessed as the 95% confidence interval (CI), defined as twice the root mean square (RMS value). This RMS value was calculated as follow:

- Intraoperator RMS: for each pelvis (j), the operators palpated six points. The standard deviation (SD_j) of the distances between each of these points and their barycentre was computed and the RMS value was calculated as [22]:

$$RMS = \sqrt{\frac{\sum_{j=1}^3 SD_j^2}{3}}$$

- Interoperator RMS: for each pelvis j, we randomly selected one palpation for each operator, giving a total of four points. The RMS value was calculated as previously mentioned.

Virtual palpations

We used five 3D pelvic models reconstructed from millimetric CT-scan images using AMIRA® (Mercury Computer Systems, USA). Three operators (including one orthopaedic surgeon) palpated twice each anatomical region of interest and bony APP points, leading to a total of 60 data sets. The number of palpated points for each region was left to the operator's judgment. This one stopped the palpation when considering the region of interest covered. The optimal number of points was estimated by calculating distances between landmarks built using all palpated points, and landmarks built using only a subset of these points. For each landmark, we randomly selected 10^4 subsets and computed mean and SD of the calculated distances.

Palpations on cadaveric specimens

We used two cadaveric specimens: one male and one female. One surgeon fixed the screws to the pelvis to precisely locate the bony APP points, i.e. ASIS and pubic tubercles. Three operators palpated once each anatomical region of interest and each bony APP point, leading to a total of six data sets. Moreover, in order to compare bony and subcutaneous APP planes, two operators also palpated ten times the external APP points. Because of the navigation system, we had to set in advance the number of palpated points for each

anatomical region. We chose 30 points for the acetabulum and acetabular fossa and ten points for the acetabular notch.

Reliability of landmark positions and plane orientations

To build anatomical planes of interest, we defined several anatomical landmarks based on the palpated regions or points (Fig. 2a): ASIS, pubic symphysis (PS, barycentre of the pubic tubercles), hip-joint centre point (JC, centre of the sphere that best fitted the points palpated on the acetabulum), acetabular notch point (AN, barycentre of the points representing this region). In addition, two different landmarks of the acetabular fossa region were tested. We obtained the first landmark (AF1) by finding the least-square plane fitting the acetabular fossa region and by orthogonally projecting JC on this plane (Fig. 2b). We obtained the second landmark (AF2) by finding the least square plane fitting the acetabular fossa and notch regions and by orthogonally projecting JC on this plane (Fig. 2c). Three types of planes were built (Fig. 3):

Fig. 2 Anatomical points: **a** Anterior pelvic plane (APP) points [anterior superior iliac spines (ASIS) and pubic symphysis (PS)], acetabular notch (AN) and joint centre (JC), defined as the centre of the sphere fitting the acetabulum. **b** Least-square plane fitting the acetabular fossa points and projection of the joint centre on this plane [first landmark (AF1)]. **c** Least-square plane fitting the acetabular fossa and notch points and projection of the joint centre (JC) on this plane [second landmark (AF2)]

Fig. 3 Anatomical planes: **a** Anterior pelvic plane (APP) based on the two anterosuperior iliac spines (ASIS) and pubic symphysis (PS). **b** Intra-articular plane based on joint centre (JC), acetabular notch (AN) and one of the landmarks (AF1 or 2). **c** First type of extra-articular plane, based on JC, one of the AFs and the homolateral anterosuperior iliac spines (ASIS). **d** Second type of extra-articular plane, based on JC, AN and homolateral ASIS

- Two APP planes: left ASIS – right ASIS – PS, with either bony (Fig. 4a) or subcutaneous points.
- Two intra-articular planes: JC – AF1 or AF2 – AN (Fig. 4b).
- Three extra-articular planes: JC – AF1 or AF2 – ASIS (Fig. 3c) and JC – AN – ASIS (Fig. 3d).

To assess the most reliable landmarks, the following procedure was executed for each of them. For each pelvis,

distances between palpated points and their barycentre were computed. We then calculated the SD of the distances for all pelvises and considered it as the positioning error. We followed the same kind of procedure to assess the most stable plane, the distances being replaced by the angles between the normals of all the planes and their barycentre. We again considered the SD of all angles as the orientation error.

Sensitivity of plane orientations

We used the mean distances between anatomical points to build a tetrahedral model of the hip (Fig. 5a), which consisted of four points: JC, AN, AF2 and ASIS. Then, 10^4 calculations were performed for each of the six following positioning reproducibility values (0.5, 1.0, 1.5, 2.0, 2.5 and 3 mm). The procedure included modification of each point position by adding a gaussian noise related to the reproducibility value considered, thus obtaining a modified tetrahedron. The normal of each plane was then calculated and its stability assessed as described above.

Results

Reproducibility study

Intraoperator values ranged from 0.4 to 2.1 mm for JC and AN, respectively, whereas interoperator values ranged from 0.9 to 2.3 mm (Table 1).

Fig. 4 **a** For each anatomical landmark, mean position error between palpated points and their barycentre. Whiskers represent 1 standard deviation

a)

b)

Fig. 5 Monte Carlo simulations: **a** Tetrahedron model of the hip region, with the four associated points: anterosuperior iliac spines (ASIS), joint centre (JC), acetabular notch (AN) and landmark 2 (AF2). The dots around each point show an example of the 10^4 noisy points used during the simulation, for a reproducibility of 3 mm. **b** Mean orientation error for each plane versus point position reproducibility. Whiskers represent 1 standard deviation. The extra-articular planes JC – AF2 – ASIS and JC – AN – ASIS were more stable than the intra-articular one JC – AF2 – AN, because of the higher distances between JC, AF2 and ASIS and JC, AN and ASIS, respectively

Reliability of landmark positions and plane orientations

The number of points picked during virtual palpations ranged from 10 to 183, depending on the region and the operator. The mean number for the acetabulum was 97 (SD 35), for the acetabular fossa 61 (SD 23) and for the acetabular notch 21 (SD 6). For each region, the mean was between the number of points defined for palpations on dry bones (respectively 100, 100 and 30) and on cadaveric specimens (respectively 30, 30 and 10). Mean positioning errors between landmarks and their barycentre ranged from 0.8 to 17.8 mm (Table 2). Concerning virtual palpations, values did not exceed 3.1 mm, obtained for

Table 1 Anatomical landmarks: intra- and interoperator reproducibility (mm) from palpations on dry bones

	Intraoperator (mm)				Interoperator (mm)
	Op. 1	Op. 2	Op. 3	Op. 4	
JC	0.4	0.9	0.9	1.3	0.9
AF1	1.1	1.7	1.5	1.3	2.1
AF2	1.7	1.1	1.7	1.8	1.6
AN	1.4	0.8	1.0	2.1	2.3

JC joint centre, AF1 first landmark, AF2 second landmark, AN acetabular notch

AF1, whereas a minimum value of 0.9 mm was obtained for JC. Concerning palpations on cadaveric specimens, values for subcutaneous APP landmarks were up to 17.8 mm for PS, whereas values for bony points ranged from 0.9 mm for PS to 5.6 mm for AF1.

Mean orientation errors ranged from 0.1° to 9.7° (Table 3). The bony APP plane was the most stable as operators palpated the screws, whereas the extra-articular plane JC – AF1 – ASIS was the least stable.

Sensitivity of plane orientations

Orientation errors of anatomical planes varied linearly with the reproducibility of the associated landmarks. As expected, intra-articular plane JC – AF2 – AN was less stable than extra-articular ones JC – AF2 – ASIS and JC – AN – ASIS. The mean orientation error of this intra-articular plane increased $>5^\circ$ when landmark reproducibility >2 mm.

Table 2 Positions of anatomical landmarks: mean and standard deviation (SD) of positioning error (mm) between landmarks and their barycentre, for virtual and cadaveric palpations

	Virtual mean (SD) (mm)	Cadaveric mean (SD) (mm)
ASIS (subcutaneous)		12.6 (8.2)
PS (subcutaneous)		17.8 (8.1)
ASIS	2.9 (2.3)	0.8 (0.4)
PS	2.3 (1.3)	0.9 (0.4)
JC	0.9 (1.0)	1.8 (1.0)
AF1	3.1 (2.0)	5.6 (2.5)
AF2	1.5 (0.9)	2.4 (1.0)
AN	2.1 (1.2)	1.4 (0.3)

ASIS anterosuperior iliac spines, PS pubic symphysis, JC joint centre, AF1 first landmark, AF2 second landmark, AN acetabular notch

Table 3 Orientations of anatomical planes: mean and standard deviation (SD) of orientation error (°) between planes and their mean for virtual and cadaveric palpations

	Virtual mean (SD) (°)	Cadaveric mean (SD) (°)
APP (subcutaneous)		3.0 (1.7)
APP	1.4 (1.5)	0.1 (0.1)
JC – AF1 – AN	6.2 (5.2)	9.5 (4.9)
JC – AF2 – AN	5.2 (3.0)	5.0 (3.3)
JC – AF1 – ASIS	5.4 (5.0)	11.8 (5.8)
JC – AF2 – ASIS	2.7 (1.9)	5.6 (2.7)
JC – AN – ASIS	5.1 (4.0)	4.7 (5.0)

APP anterior pelvic plane, JC joint centre, AF1 first landmark, AF2 second landmark, AN acetabular notch, ASIS anterosuperior iliac spines

Discussion

The purpose of this study was to propose reliable anatomical bony landmarks accessible in the surgical approach. These landmarks were then used to build potential planes of reference as an alternative to the APP. Results of the reproducibility study (Table 1) showed that all defined landmarks were reproducible enough to be used to build intra- or extra-articular pelvic planes. In order to obtain reliable landmarks, i.e. presenting an error (mean + 1SD) <1 mm (Fig. 5), the minimum number of points to be palpated should be about 40 for JC, 70 for AF1 and AF2 and 20 for AN. These numbers are low enough to allow palpation during surgery, as CAOS systems usually permit continuous acquisition during displacement of the palpation probe device.

As expected, lowest dispersions were found during cadaveric palpations for the bony APP points ASIS and PS (Table 1). These dispersions were higher for palpations on the virtual models, showing that these APP points are not easy to precisely locate. Moreover, dispersions were much higher for subcutaneous points, which is the main cause of inaccuracies between intraoperative angles given by CAOS systems and postoperative CT-based controls [5, 10, 20]. This result is due to soft tissues overlying anatomical landmarks. Indeed, Ybinger et al. [13] correlated soft tissue thickness with differences in both anteversion and abduction values between CAOS and CT-based measures. The influence of soft tissues also explains why a high body mass index can affect the accuracy of cup placement [15]. This demonstrates why reliable bony landmarks, such as JC, AF2 and AN, in the operative approach (Table 1) could be useful to replace these subcutaneous points. AF2 is more reliable than AF1 because the former is projected on the plane fitting both the acetabular fossa and notch regions, and that plane is more stable than the one used to define AF1.

Although the subcutaneous APP is quite stable because of the rather large distances between its associated points (Table 2), the orientation errors between its normal and the true normal of the bony APP were 3.1° and 6.3° for the two cadaveric pelvises. This shows that, despite its relative stability, the subcutaneous APP presents a difference with the bony APP, which may itself not be aligned with the vertical axis or stayed in the same position during surgery [3, 5, 7, 10, 11, 23].

Two planes may be of interest as an alternative to the APP: one extra-articular plane, JC – AF2 – ASIS; and one intra-articular plane, JC – AF2 – AN (Table 2). The intra-articular plane is obviously more interesting, as all the anatomical landmarks involved could be palpated intraoperatively, without any use of subcutaneous points or additional incision to palpate the bony ASIS. This approach is consistent with the development of minimally invasive techniques [7]. The Monte Carlo simulation highlighted the fact that landmark reproducibility has to be less than two millimetres in order to obtain reliable intra-articular planes (Fig. 5b). A simulation using the interoperator reproducibility calculated for JC, AF2 and AN (Table 1) led to a mean orientation error of 4.8° (SD 3.1°). The results of this study are encouraging and show that two of the five planes proposed may be used as an alternative to the APP. Nevertheless, even if the feasibility of palpating the necessary anatomical landmarks has been demonstrated on cadaveric specimens, a more extensive study should be conducted in vivo during surgery. Indeed, we must ensure that the reproducibility of such landmarks is low enough to attain a reliable orientation of the resulting plane.

Conclusion

Although computer-assisted orthopaedic systems have been proven to be more reliable than freehand techniques in terms of cup orientation, they all rely on the APP, which may not be as stable and reproducible as thought. In order to propose alternative planes of reference, we defined several anatomical landmarks accessible during surgery in the operative approach and assessed their reproducibility during palpations on 3D virtual models, on dry bones and on two cadaveric specimens. Using these landmarks, we found two potential replacement planes for the APP: one extra-articular plane, involving the homolateral ASIS, and one intra-articular plane, involving only landmarks inside the region accessible during surgery. These planes do not present the drawbacks linked to the subcutaneous APP. Nevertheless, further studies are needed to assess the reliability of these two planes in vivo during surgery.

Acknowledgments The authors thank Stryker France for funding this work and Laurent Geais for his help.

Conflict of interest statement All authors agree that there are no conflict of interest issues in this research.

References

- Lewinneck GE, Lewis JL, Tarr R, Compere CL, Zimmermann JR (1978) Dislocations after total hip-replacement arthroplasties. *J Bone Joint Surg Am* 60:217–220
- DeChenne CL, Jayarama U, Lovellb T, Dongc N, Cusick M (2005) A novel acetabular alignment guide for THR using selective anatomic landmarks on the pelvis. *J Biomech* 38:1902–1908
- Haaker RGA, Tiedjen K, Ottersbach A, Rubenthaler F, Stockheim M, Stiehl JB (2007) Comparison of conventional versus computer-navigated acetabular component insertion. *J Arthroplasty* 22:151–158
- Jolles BM, Genoud P, Hoffmeyer P (2001) Accuracy of computer-assisted cup placement in total hip arthroplasty. *Int Congress Series* 1230:314–318
- Kalteis T, Handel M, Herold T, Perlick L, Baethis H, Grifka J (2005) Greater accuracy in positioning of the acetabular cup by using an image-free navigation system. *Int Orthopaedics* 29:272–276
- Minoda Y, Ohzono K, Aihara M, Umeda N, Tomita M, Hayakawa K (2010) Are acetabular component alignment guides for total hip arthroplasty accurate? *J Arthroplasty* 25:986–989
- Najarian BC, Kilgore JE, Markel DC (2009) Evaluation of component positioning in primary total hip arthroplasty using an imageless navigation device compared with traditional methods. *J Arthroplasty* 24:15–21
- Saxler G, Marx A, Vandevelde D, Langlotz U, Tannast M, Wiese M, Michaelis U, Kemper G, Grützner PA, Steffen R, von Knoch M, Holland-Letz T, Bernsmann K (2004) The accuracy of free-hand cup positioning - a CT based measurement of cup placement in 105 total hip arthroplasties. *Int Orthopaedics* 28:198–201
- Wolf A, DiGioia AM III, Mor AB, Jaramaz B (2005) A kinematic model for calculating cup alignment error during total hip arthroplasty. *J Biomech* 38:2257–2265
- Lin F, Lim D, Wixson RL, Milos S, Hendrix RW, Makhosous M (2011) Limitations of imageless computer-assisted navigation for total hip arthroplasty. *J Arthroplasty* 26:596–605
- Sotereanos NG, Miller MC, Smith B, Hube R, Sewecke JJ, Wohlrab D (2006) Using intraoperative pelvic landmarks for acetabular component placement in total hip arthroplasty. *J Arthroplasty* 21:832–840
- Yoon YS, Hodgson AJ, Tonetti J, Masri BA, Duncan CP (2008) Resolving inconsistencies in defining the target orientation for the acetabular cup angles in total hip arthroplasty. *Clin Biomech* 23:253–259
- Ybinger T, Kumpan W, Hoffart HE, Muschalik B, Bullmann W, Zweymüller K (2007) Accuracy of navigation-assisted acetabular component positioning studied by computed tomography measurements. *J Arthroplasty* 22:812–817
- Walter WL, O'Toole GC, Walter WK, Ellis A, Zicat BA (2007) Squeaking in ceramic-on-ceramic hips. The importance of acetabular component orientation. *J Arthroplasty* 22:496–503
- Parratte S, Argenson JN (2007) Validation and usefulness of a computer-assisted cup-positioning system in total hip arthroplasty. A prospective, randomized, controlled study. *J Bone Joint Surg Am* 89:494–499
- Kruger S, Zambelli PY, Leyvraz PF, Jolles BM (2009) Computer-assisted placement technique in hip resurfacing arthroplasty: improvement in accuracy? *Int Orthop* 33:27–33
- Kumar MA, Shetty MS, Kiran KG, Kini AR (2012) Validation of navigation assisted cup placement in total hip arthroplasty. *Int Orthop* 36:17–22
- Pitto RP, Malak S, Anderson IA (2009) Accuracy of a computer-assisted navigation system in resurfacing hip arthroplasty. *Int Orthop* 33:391–395
- Schnurr C, Michael JWP, Eysel P, König DP (2009) Imageless navigation of hip resurfacing arthroplasty increases the implant accuracy. *Int Orthop* 33:365–372
- Lin F, Lim D, Wixson RL, Milos S, Hendrix RW, Makhosous M (2008) Validation of a computer navigation system and a CT method for determination of the orientation of implanted acetabular cup in total hip arthroplasty: a cadaver study. *Clin Biomech* 23:1004–1011
- Pinoit Y, May O, Girard J, Laffargue P, Ala Eddine T, Migaud H (2007) Low accuracy of the anterior pelvic plane to guide the position of the cup with imageless computer assistance: variation of position in 106 patients. *Rev Chir Orthop Reparatrice Appar Mot* 93:455–460
- Gluer CC, Blake G, Lu Y, Blunt BA, Jergas M, Genant HK (1995) Accurate assessment of precision errors: how to measure the reproducibility of bone densitometry techniques. *Osteoporos Int* 5:262–270
- Rousseau MA, Lazennec JY, Boyer P, Mora N, Gorin M, Catonné Y (2009) Optimization of total hip arthroplasty implantation. *J Arthroplasty* 24:22–26