PELVIC POSITION AND MOVEMENT DURING HIP ARTHROPLASTY

ABSTRACT

Acetabular component orientation is influenced not only by the orientation at which the surgeon implants the component but also the orientation of the pelvis at the time of impaction. Hence, the orientation of the pelvis at set-up and its movement during the operation are critically important. Using a validated photogrammetric technique, during 67 hip arthroplasties, we measured how 3 surgeons orientated the patients' pelvis, how much the pelvises moved and what effect these had on final cup orientation. Pelvic orientation at set-up varied widely (Mean/SD; tilt: 8°/16°, obliquity: -4°/6°, rotation: -8°/7°). Significant differences in pelvic positioning were detected between surgeons ($p<0.001$). The mean angular movement of the pelvis between set-up and cup implantation was 9° (SD:6°). Factors influencing pelvic movement included surgeon, approach (posterior>lateral), procedure (resurfacing>THR) and type of support ($p<0.001$). Although on average surgeons achieved their desired cup orientation, there was considerable variability (2SD=16°) in cup orientations. We conclude that error in positioning the patient at set-up and movement of the pelvis during the operation account for much of the variability in cup orientation. In order to improve reliability of achieving optimal cup orientation improved methods of positioning and holding the pelvis are required.

INTRODUCTION

Wide scatter of cup orientation is invariably reported, with the range and variability [defined as 2 Standard Deviations (SDs)] being up to 60° and 20° respectively, for both inclination and anteversion even in high volume centres[1-3]. The resultant cup orientation is influenced by both the orientation of the cup and the orientation of the pelvis at the time of impaction. The different types of cup orientations (operative, anatomical and radiographic) relative to the axis system of the pelvis have been refined by Murray[4] (Figure 1).

Based on these definitions, recommendations have been made about how a cup should be implanted during surgery (operative orientation) in order to achieve a recommended target (radiographic orientation) on post-operative radiographs. However, these recommendations are based on the assumption that the pelvis is in a 'neutral' orientation both at the time of cup impaction and at the time of radiographic assessment. A 'neutral' orientation equates to zero rotation about all three axes. Pelvic rotation about any of the axes will have an effect, which will be different pending on axis of rotation, on the subsequent radiographic cup orientation. Pelvic tilt and rotation primarily influence anteversion, whilst pelvic obliquity mainly influences inclination[5]. Individual pelvic orientation can widely vary; in the physiological supine position the pre-operative pelvic tilt has been reported to have a range of 34° (-24 to 10°) amongst arthritic patients[6].

During non-navigated procedures, the precise orientation of the pelvis is not known. At the pre-operative set-up, the surgeon aims to position the pelvis in a neutral orientation relative to the operating table, with the reference planes of pelvis parallel to the reference planes of the table; and aims to provide adequate support so that the neutral orientation is maintained during the operation. **When setting up the patient, the surgeon usually identifies specific pelvic anatomical landmarks and based on these adjusts the position of the pelvis to achieve the target neutral pelvic alignment.** At the time of cup impaction the surgeon usually assumes that the pelvis **has remained** in this neutral position and implants the cup in what he/she believes to be the correct orientation. However, the pelvis may not be neutrally positioned at set-up and/or may move due to retraction during the operation.

We hypothesise that a major factor contributing to the reported variability in cup orientation is that the intra-operative orientation of the pelvis is not known. There is little information available about pelvic orientation during hip arthroplasty. The aims of this study were therefore to determine firstly the **variability in pelvic orientation** at set-up, and secondly the amount of pelvic movement that takes place intra-operatively between set-up and cup impaction.

PATIENTS AND METHODS

When positioning the pelvis at set-up, the surgeon aligns pelvic planes with the table. In order to define the pelvic planes, anatomical landmarks must be identified. For this study, it was therefore necessary to develop a stereophotogrammetric measurement technique that could be used during surgery in order to measure the position the surgeon had identified the landmarks to be at. Stereo-photogrammetry (SPG) allows the spatial measurement of three-dimensional (3-D) objects from a stereo-pair set of images[7]. Common points are identified on each image and if the location of each camera relative to the image plane is known, the 3-D coordinates and hence location can be determined. A custom application, Fotop™, written in Matlab (R2011, The MathWorks, Natick, MA, USA) was developed to perform the measurements. The object of interest was the pelvis. The 3-D locations of specific pelvic landmarks and of a guide wire drilled into the pelvis were captured. These measurements allowed determination of pelvic orientation at set-up and the movement of the wire, during surgery, was used to assess pelvic movement. A detailed explanation of planes defined, calculations made, validation of technique and a mathematical analysis quantifying possible inaccuracies due to wand misplacement are provided in Appendix 1.

Patient cohort

Sixty-seven arthroplasty patients were prospectively recruited in this IRB approved study between two specialist arthroplasty centres (Nuffield Orthopaedic Centre, Oxford, UK and ANCA Medical Centre, Ghent, Belgium) between October 2010 and November 2011.

Inclusion criteria were primary hip arthroplasty surgery for osteoarthritis, absence of fixed deformities of the hip and American Society of Anaesthesiologist (ASA) grades (I – II)[8].

Patient demographics and anthropometric parameters (weight, height and BMI) are detailed in Table 1. The majority of patients (n=52, 78%) underwent Total Hip Replacement (THR), whilst the remaining 15 (22%) underwent Hip Resurfacing Arthroplasty (HRA). All patients were operated in the lateral decubitus position. The procedures were performed by 3 surgeons (A, B and C). Surgeon A is a senior clinical fellow who has performed 300 hip arthroplasties; he performs his arthroplasties via the posterior approach and his target cup orientation (inclination/anteversion) is 40°/20°. Surgeon B is specialist hip surgeon, who has performed over 7,000 hip arthroplasties, including over 3,500 HRAs; his routine hip arthroplasty practice is via the posterior approach and his target cup inclination/anteversion is 45°/20°. Surgeon C is a specialist hip surgeon, having performed over 13,000 hip arthroplasties; he operates routinely via the lateral approach and his target cup inclination/anteversion is 40°/15°. The choice of pelvic support was made as per surgeon's preference reflecting their practice. Surgeons used the same support posteriorly over the sacrum (Figure 2) but different supports anteriorly. Surgeon B routinely used a single support over the pubic symphysis (pubis only), Surgeons A and C used a single support over the operated anterior superior iliac spine (ASIS) (ASISx1). Surgeons A and C were invited to place an additional support over the contra-lateral ASIS in the last 12 cases (6 each) enrolled in the study (ASISx2). Details of surgical practice, including prostheses used and cup size are included in Table 1.

Intra-operative measurements

Two cameras (Logitech Webcam Pro 9000 HD, Logitech, Romanel-sur-Morges, Switzerland) were mounted on the theatre's laminar air flow hoods orientated at approximately 90° to each other and arranged so that the operating field was fully captured. **All three surgeons positioned patients on the operating table in the manner routine to their practice aiming to orientate the pelvis neutrally relative to the table using the frontal plane defined by the two ASISs and the pubis.** The table was set in the middle of the theatre space as defined by the laminar flow hood. A calibration object, consisting of 12 spherical markers, was placed over the patient and aligned with the operating theatre table. A stereo-pair of images were captured using the cameras; this initial stereo-pair of images was used to calibrate the measurement volume. All subsequent measurements were made in a coordinate frame aligned to the operating theatre.

Surgeons were then asked to locate, using a wand, **the specific anatomical landmarks that they had used to align the pelvis and stereo-pair of images were captured**. The landmarks captured were: the two Anterior-Superior-Iliac-Spines (ASISs), the pubic symphysis (PS) and the Lumbo-Sacral junction (LSJ). (Figure 3). The wand was manufactured with such specifications (pointed end and length) in order to allow its placement between patient's supports/bony landmarks and capture even when pointing at the non-operated side.

Patients were prepped and draped. Prior to skin incision, a wire was inserted in the iliac wing of the operated hemi-pelvis and a stereo-pair of images was captured from which the location of the wire at the beginning of the operation (t_0) could be determined. Surgery was carried out and a stereo-pair of images was captured following cup implantation with the introducer still attached and the retractors in place in order to measure the location of the wire at the time of impaction (t_1).

Surgeons' reproducibility of anatomical loci identification

A key step in establishing anatomical planes is the identification of relevant anatomical landmarks, which depends upon the process used by the surgeon to identify a given anatomical feature. This part of the study set out to examine how reproducible surgeons were in re-identifying landmarks on the same patient and what the difference between surgeons in identifying landmarks on the same patient was. Since we were ultimately interested in pelvic orientation, the variability in identifying landmarks was expressed in terms of the variability in the pelvic orientation angles. Surgeons were asked to identify the pelvic loci pre-operatively twice, with an interval of five minutes between measurements, in three cases. The inter-observer reproducibility was determined by having the assistant surgeon identify the pelvic loci in 12 cases.

Radiographic orientation measurements

Radiographic cup orientation measurements were made from standardised post-operative, supine antero-posterior (AP) pelvic and lateral hip radiographs. The Ein-Bild-Roentgen-Analysis (EBRA) software[9], a validated method of estimating radiographic orientation, was used to calculate radiographic cup inclination (RI) and anteversion (RA) from AP radiographs[4,10,11]. Lateral hip radiographs allowed determination of anteversion or retroversion of the acetabular component. Measurements were performed independently by two observers (GG, HP) blinded to other parameters with excellent intra- and inter-observer correlation of 1.5° and 2° respectively (interclass correlation coefficients > 0.95, p< 0.001).

Analysis of a second set of radiographs obtained at follow-up for 20 patients revealed an intra-subject difference of 1° (SD:1)/2° (SD:2) for cup inclination/anteversion respectively.

Data Analysis

Pelvic Orientation Scatter

Transposition of the anatomical pelvic landmarks identified by the surgeon into the axis system defined by the calibration object enabled the calculation of the 3-D orientation of the pelvis relative to the operating table at set-up. We hence determined the scatter in pelvic orientation at set-up in all three planes (tilt/obliquity/rotation).

Pelvic Movement

We calculated the angular pelvic movement that takes place during the operation between set-up and impaction (ΔW_{Imp}) by capturing the wire's orientation at set-up (t_0, prior to skin incision), and at cup impaction (t_1) (Figure 4). In addition, we investigated the effect of: type of support (pubis only Vs. ASISx1 Vs. ASISx2), procedure type (HRA Vs. THR), approach (posterior Vs. lateral) and surgeon on the amount of pelvic movement.

Cup orientations

In order to determine how accurately surgeons achieved their desired target, we calculated Δinclination and Δanteversion for each patient as defined below:

Δinclination = Surgeon-specific Inclination target – RI achieved

Δanteversion = Surgeon-specific Anteversion target – RA achieved.

In addition, we determined whether surgeons had achieved cup orientation within their target zone (personal orientation target ± 10°).

Statistics

Variability was defined as two standard deviations (SDs). Non-parametric statistical tests (Mann-Whitney *U*, Kruskal Wallis, Spearman's rho) were used. Chi-square test was used for cross-tabulated data. Correlation was characterised as poor (0.00-0.20), fair (0.21-0.40), moderate (0.41-0.60), good (0.61-0.80), or excellent (0.81-1.00). Statistical significance was defined as $p \leq 0.05$. Statistical analyses were performed with IBM SPSS Statistics version 19, (SPSS, an IBM Company, Chicago, IL, USA).

RESULTS

A high degree of intra-observer repeatability was seen for tilt/ obliquity and rotation (mean difference: 1°/1°/1°, variability of 6°/4°/5°). Repeatability testing between surgeons demonstrated greater variability for tilt/obliquity/rotation (mean difference: 3°/1°/1°, variability: 10°/12°/12°).

A wide scatter of pelvis orientation at set-up was detected for the whole cohort, as detailed in Table 2 and Figure 5. The scatter was much greater for pelvic tilt (mean: -8°, SD:16°, range: -50° to 29°) in comparison to pelvic rotation (mean: -8°, SD:7°, range: -27° to 3.5°) and obliquity (mean: -4°, SD:6°, range: -19° to 8°). There were significant difference in pelvic set-up between the surgeons ($p<0.001$) for both pelvic tilt and rotation, whilst the difference in pelvic obliquity was close to significance ($p= 0.09$).

The mean amount of wire movement that took place between set-up and impaction (ΔW_{Imp}) was 9° (SD:6°, range: 0° – 28°). ΔW_{Imp} was not influenced by anthropometric factors. The following surgical factors were identified to have a significant effect on ΔW_{Imp}; surgeon ($p<0.001$, Figure 6), pelvic supports used ($p=0.004$, Figure 7), approach ($p<0.001$, Figure 8) and procedure type (Figure 9, $p=0.02$). Amount of ΔW_{Imp} had a moderate (rho=0.45, $p<0.001$) correlation with pelvic tilt at set-up.

The mean radiographic cup inclination was 43° (SD:6°, range: 28° – 55°) and the mean radiographic cup anteversion was 19° (SD:7°, range: 4° – 35°). The mean Δinclination was 1° (SD:6°, range: -10° to 17°), whilst the mean Δanteversion was 0° (SD:7°, range: -15° to 12°). None of the anthropometric or surgical factors influenced Δinclination. No anthropometric factor influenced Δanteversion. On the contrary, two surgical factors influenced Δanteversion; type of pelvic support ($p=0.03$) and procedure ($p=0.006$) (Tables 2 – 4).

To-date at an average follow-up of 58 months (range: 37 – 71), none of the patients have had any complications; none have returned nor are due to return to theatre for any reason.

DISCUSSION

This study demonstrates that a wide variability exists in both pelvic positioning at set-up (2SD=**12 to** 32°) and pelvic movement (2SD=12°) during hip arthroplasties. This would lead to great variability in pelvic orientation at impaction and hence influence the final cup orientation. Although the desired target zone orientation was **achieved in a significant proportion (80%) of cases**, there was considerable variability in both inclination (2SD=12°) and anteversion (2SD=14°). **In order to reduce the variability in pelvic orientation** improved methods of positioning and holding the pelvis are required.

The wide variability in pelvic orientation detected is due to both patient and surgical factors. There is a well documented variability in individual pelvic tilt. With the patient anaesthetised, although surgeons perceived their landmarks to be aligned in neutral orientation, they in fact were not. Furthermore, consistent inter-surgeon differences (e.g. Surgeon C positioned pelvis with greater external rotation of operated side) and similar intra-surgeon variability in pelvic orientation were observed. Testing the repeatability of pelvic landmark identification revealed an intra-observer variability of 6°, which doubled when considering repeatability between surgeons (12°). The intra-observer repeatability is a surrogate measure of how repeatedly a surgeon could set-up a given patient, whilst the inter-observer repeatability is a surrogate measure of the differences between surgeons in perceiving the neutral orientation for a given patient's pelvis. There is an innate difficulty in accurately identifying pelvic landmarks due to body habitus and patient positioning for surgery. Such difficulties have been highlighted in navigation studies[12]. These findings highlight an innate limitation in the

ability of surgeons to reliably and repeatedly achieve a neutral pelvic orientation at set-up.

The greatest variability in pelvic orientation was in tilt. Surgeon B positioned the pelvis, closest to neutral with the least amount of pelvic tilt and had the smallest variability. This is unsurprising since the support he uses is over the pubis symphysis and as such routinely checks for the position of the pubic symphysis relative to the ASISs, all points that define anterior pelvic plane/tilt, during patient set-up. We, therefore, recommend that during set-up surgeons should routinely assess for pelvic tilt as high degree of deviation from neutral is common. The measured pelvic tilt angles were higher than previously reported in the literature[6,13,14]. Pelvic tilt angles have typically been measured whilst in a physiological position (supine/standing/sitting)[6,13,14] or in the lateral position with instant feedback[15]. This is the first study to determine pelvic tilt angles in a non-physiological position and with no instantaneous results-feedback. Placement of the posterior-support in the rostro-caudal direction along the lumbo-sacral spine varies amongst surgeons and can significantly influence pelvic tilt by providing a torque about the sacroiliac joints. By adjusting its position surgeons should be able to optimise pelvic tilt. The operated hemi-pelvises tended to be externally rotated at set-up. This was most pronounced with the single ASIS support (-11°, SD:6°), in comparison to the double ASIS (-7°, SD:7°) and pubis only (-5°, SD:5°) supports ($p=0.02$). A support over the operated ASIS coupled with a posterior support, which is typically narrower than the width of the patient, would in combination provide an externally rotated force to the operated hemi-pelvis. It is therefore preferable to use a double support anteriorly, rather than a single ASIS support.

A considerable amount of pelvic movement was detected, similar to previous work by Asayama *et al* who reported that internal rotation is the primary movement that takes place during THR[16]. In agreement with Asayama *et al*, we found that anthropometric factors did not influence amount of intra-operative pelvic movement. This is possibly because none of the surgery performed was minimally invasive and none of the surgeons would compromise intra-operative visibility for length of scar.

Although patient factors did not influence pelvic movement, surgical factors did, in particular: pelvic support, approach and procedure type. Although these factors are inter-related and surgeon-dependent, significant differences were identified even when these factors were uncoupled. The support with the least constraint anteriorly, the pubis only support, demonstrated the greatest amount of pelvic movement amongst THRs. In contrast, the use of supports over both ASIS anteriorly (ASISx2) significantly reduced amount of movement that takes place. We, therefore, recommend that surgeons should consider having at least two supports anteriorly, hence achieving three-point stabilisation and increasing pelvic constraint. Similarly to Ezoe *et al*, we identified significantly more intra-operative movement with the posterior approach (9°) compared to the lateral approach (4°) in THR[17]. During the posterior approach, the intact strong anterior capsule and ileo-femoral ligament coupled with the strong retraction and the leg-twisting manoeuvre probably apply an increased torque to the pelvis.

Lastly, type of procedure influenced amount of intra-operative pelvic movement. Analysing the procedures of Surgeon B only, hence eliminating certain factors (surgeon, approach and supports), we found significantly greater amount of intra-operative pelvic movement for HRAs compared to THRs (16 Vs. 10°) (p=0.02). This is unsurprising, as for HRAs the intact femoral head and neck obscure the acetabulum and hence greater retraction is needed for adequate view.

The variability in cup orientation (12 – 14°) was similar to the variability in pelvic rotation and obliquity at set-up (12 – 13°), but not tilt (32°). This measured reduction in variability relative to tilt is an encouraging finding demonstrating that surgeons' are able to in-part account for pelvic tilt during the operation. This probably occurs by the amount of intra-operative pelvic movement as shown in this paper (correlation of pelvic tilt with ΔW_{Imp}) and by adjusting the intra-operative cup orientation accordingly to account for the native acetabular orientation.

This study has certain strengths and limitations. Its strengths include its prospective nature and novel concept and findings. Certain limitations however exist. Firstly, the pelvic orientation was determined by surgeons identifying landmarks. However, as we aimed to determine how surgeons set-up a patient we feel that the method described accurately reflects how a surgeon perceives pelvic orientation at set-up. Secondly, although the software (Fotop™) was able to calculate movement of pelvis, it was not able to detect the 3D direction of movement based on calculations from a single wire. **In order to examine the effect of pelvic orientation at impaction further study is necessary correlating the cup orientation at impaction with the resultant radiographic orientation post-operatively.**

In conclusion, this study demonstrated wide variability in pelvic orientation, particularly tilt, at set-up for a given surgeon and between surgeons and pelvic movement during hip arthroplasty. These findings, in part, explain the variability seen in post-operative cup orientations. To minimise this variability we recommend that surgeons carefully position the pelvis at set-up, taking particular note of tilt assessed by the relative position of the symphysis and ASISs. We also recommend the use of improved supports and increased care with retraction and leg twisting during the posterior approach and hip resurfacing in order to minimise amount of pelvic movement during surgery.

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		Cohort (n=67)	Arthroplasty		
			THA (n=52)	HRA (n=15)	p-value
Gender	Male	24	15	9	0.03
	Female	43	37	6	
Age/ years		67.1 (41.4 – 86.8)	70.2 (46.2 – 86.8)	56.5 (41.4 – 69.1)	<0.001
Height/ m		1.7 (1.5 – 1.9)	1.7 (1.5 – 1.9)	1.8 (1.7 – 1.9)	0.01
Weight/ Kg		72.4 (47.1 – 123.6)	72.5 (47.1 – 123.6)	72.0 (50.0 – 88.0)	0.76
BMI/ Kg/m^2		25.5 (17.5 – 38.6)	26.0 (17.5 – 38.6)	23.2 (17.9 – 28.0)	0.07
Cup size/ mm		53.5 (46 – 60)	52.8 (46 – 60)	56.3 (52 – 60)	0.001
Supports	Pubis	31	16	15	<0.001
	ASIS x 1	24	24	-	
	ASIS x 2	12	12	-	
Approach	Lateral	17	17	-	0.01
	Posterior	50	35	15	

Table 1: Cohort demographics and surgical details.

	Cohort (n=67) mean/SD range	**Surgeons**			
		Surgeon A (n=19) mean/SD Range	Surgeon B (n=31) mean/SD range	Surgeon C (n=17) mean/SD range	p-value
Pelvic Tilt/°	-8/ 16 -50.0 to 29	-16/ 10 -35 to -3	5/ 9 -18 to 29	-21/ 15 -50 to -2	<0.001
Pelvic Obliquity/°	-4/ 6 -19 to 8	-4/ 6 -13 to 5	-2/ 4 -11 to 8	-6/ 7 -19 to 7	0.09
Pelvic Rotation/°	-8/ 7 -27 to 4	-7/ 6 -17 to 0	-5/ 5 -18 to 4	-13/ 6 -27 to -3	<0.001
ΔWimp/°	9/ 6 0 to 28	8/ 5 2 to 22	13/ 6 5 to 28	4/ 3 0 to 11	<0.001
RI/ °	43/ 6 28 to 55	40/ 6.0 28 to 49	46/ 4 36 to 55	39/ 6 28 to 47	<0.001
RA/ °	19/ 7 34 to 35	22/ 7 12 to 35	19/ 6 8 to 35	14/ 8 4 to 30	0.009
Δ*inclination*/°	-0/ 5 -10 to 17	0/ 6 -8 to 12	-1/ 4 -10 to 10	1/ 6 -7 to 17	0.67
Δ*anteversion*/°	0.0/ 7 -15 to 12	-2/ 7 -15 to 9	1/ 6 -15 to 12	1/ 8 -15 to 11	0.24
Within individual target zone n (%)	57 (80%)	14 (74)	29 (94)	14 (82)	0.15

Table 2: Pelvic orientation at set-up, amount of pelvic movement during surgery, radiographic cup orientations and Δ*inclination/anteversion* for the whole cohort and as per surgeon.

		ΔWimp/° Mean/SD Range	p-value	ΔRI/ ° Mean/SD Range	p-value	ΔRA/ ° Mean/SD Range	p-value
Approach	Lateral (n=17)	4/ 3 0 to 11	<0.001	1/ 6 -7 to 17	0.54	1/ 8 -14 to 11	0.59
	Posterior (n=50)	11/ 6 2 to 28		-1/ 5.0 -10 to 12		0/ 6 -15 to 12	
Supports	Pubis (n=31)	7/ 5 0 to 22	<0.001	1/ 6 -8 to 17	0.42	-3/ 7 -15 to 10	0.03
	ASIS x 1 (n=24)	13/ 6 5 to 28		-1/ 4 -10 to 10		1/ 6 -15 to 12	
	ASIS x 2 (n=12)	5/3.0 0 to 12		-1/ 5 -8 to 6		3/ 6 -10/ 11	

Table 3: The effect of gender and of different surgical factors on pelvic movement intra-operatively and Δ*inclination/anteversion (*ΔI and ΔA*)* .

Procedure	**THA (n=16) Mean/SD Range**	**HRA (n=15) Mean/SD Range**	**p-value**
ΔWimp/°	10/ 1 5 to 17	16/ 7 7 to 28	0.02
RI/ °	46/ 5 36° – 55	46/ 4 40 – 52	0.91
RA/ °	22/ 6.0 12 – 35	16/ 4 8 – 21	0.002
Δ*inclination*/°	-1/ 5 -10 to 10	-1/ 4 -7 to 5	0.9
Δ*anteversion*/°	-2/ 6 -15 to 8	4/ 4 -1 to 12	0.003
Within individual target zone n (%)	15 (94)	14 (93)	0.9

Table 4: Pelvic and cup orientation measurements for THAs and HRAs performed by Surgeon B.

Appendix 1.

Planes defined & calculations made

Calculation of the pelvis body fixed coordinate system was done by constructing a mediolateral axis through the two ASISs' locations (Figure 1). The pubis location together with the mediolateral axis was used to define the frontal plane. A vertical axis was constructed in this plane arising from the mid-point between the ASISs' locations and perpendicular to the mediolateral axis. The final axis was formed by the cross product of the mediolateral and vertical axes.

Validation of stereo-photogrammetric method

The validity of the SPG technique described above was tested at the Oxford Gait Laboratory. The laboratory is equipped with a 12-camera Vicon Nexus Motion Analysis System (Vicon Motion Systems, Oxford, UK), which captures data at a rate of 100 Hz. Following static and dynamic laboratory calibration, the calibration residual (standard indicator of system accuracy) of the motion analysis system on the day of validity testing was 0.66 mm. The material and finish of the spherical markers of the Fotop™ calibration object were selected to enable direct measurement of the calibration object using the Vicon Nexus system, which locates the 3D coordinates of spherical markers visible to infra-red light. The wand (described above) was measured five times simultaneously by the Fotop™ and Vicon Nexus systems. Comparing the measurements made by the two systems (Vicon take as gold standard) demonstrated that the SPG technique had a mean accuracy of 0.1 mm (range: ±2 mm) in terms of translation and 0.03° (range: ±1.6°) in terms of rotation.

Mathematical analysis quantifying possible inaccuracies

Error analysis was performed by generating a 1000 random error values from a normal distribution with a mean value of zero and a standard deviation of 5 mm (Figure A1 shows the distribution of error values). The position of the pelvis with no error had a pelvic tilt of -20°, obliquity of 3° and rotation of -12°. These values were used to apply simulated errors to the pubis location for a given subject and then the influence of these errors on the calculated angles of tilt, obliquity and rotation of the pelvis was determined. The greatest effect was on tilt (Figure A2), the interquartile range of the calculated change in tilt was 2.5°. There was negligible change in the values of the pelvis obliquity and rotation angles.

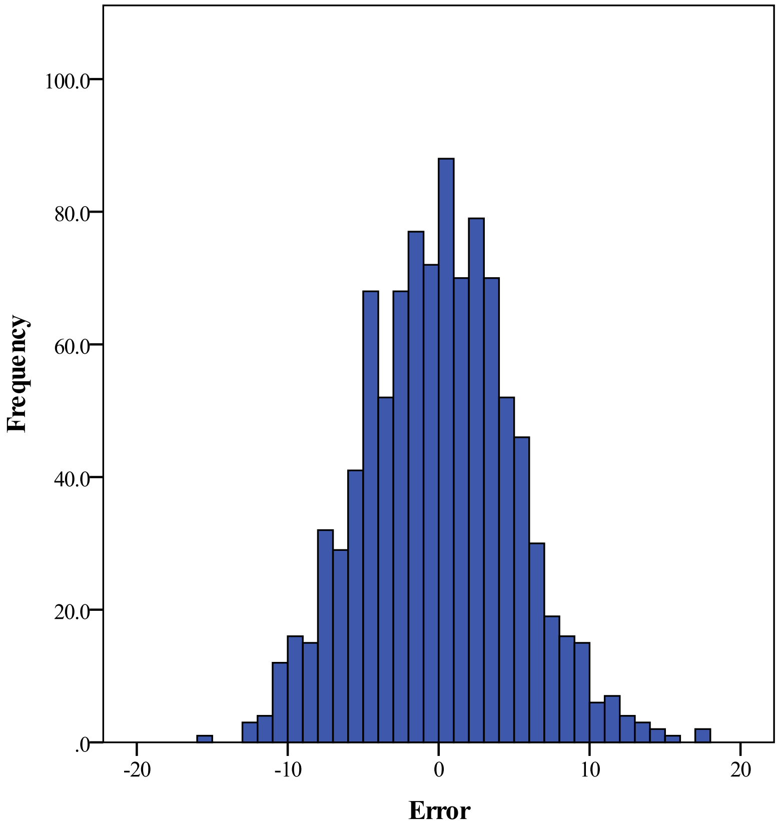

Figure A1. Distribution of 1000 simulated measurement errors (mean: 0 mm, SD: 5 mm, range: -15 to 18 mm).

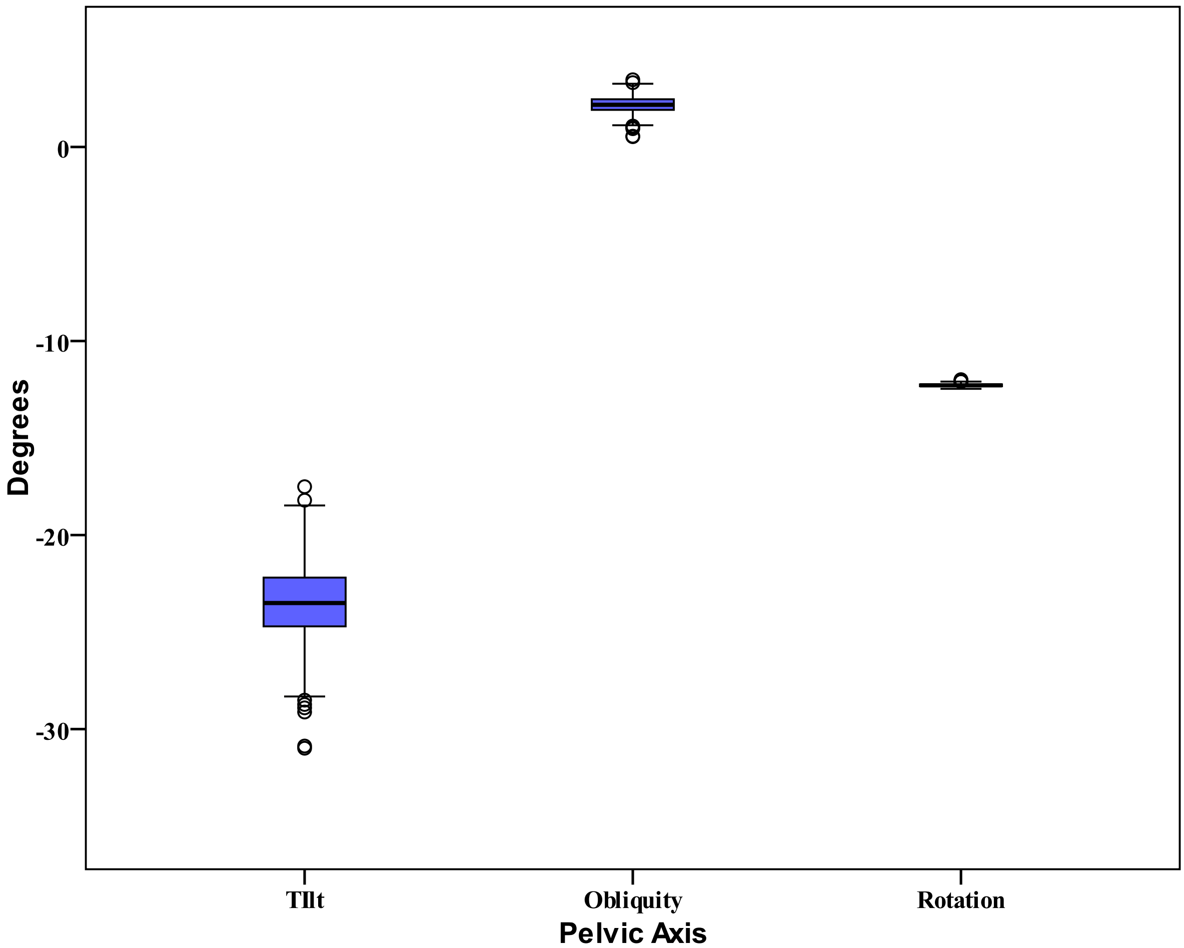

Figure A2. Effects of 1000 simulated pubis measurement errors on calculated pelvic orientation angles of tilt, obliquity and rotation. The thick bar shows the interquartile range in the variation of the calculated angles.