The relationship between operative and radiographic cup orientation –

Which factors influence resultant cup orientation?

ABSTRACT

There is great variability in cup orientation following hip arthroplasty. The aims of the study were to compare the cup orientation at impaction with the orientation measured on post-operative radiographs and identify factors that influence the difference between the two orientations. Sixty-seven hip arthroplasties were prospectively studied. Intra-operatively, the orientation (IOO) of the acetabular component after impaction relative to the operating table was measured using a validated stereo-photogrammetry protocol. Post-operatively, the radiographic orientation (RO) was measured; the mean inclination/anteversion was 43 (SD:6)/19 (SD:7). A simulated radiographic orientation (SRO) was calculated based on how the orientation would have appeared had an on-table radiograph been taken intra-operatively. The difference between RO and IOO was 5°(SD:5°)/-8°(SD:8°). The difference between SRO and IOO, which quantifies the effect of the different way acetabular orientation is measured, was 3°/-6°(SD:2°). The difference between RO and SRO, which is a manifestation of the change in pelvic position between component impaction and radiograph, was 1°/-2°(SD:7°).

This study demonstrated that in order to achieve a specific radiographic orientation target, surgeons should implant the cup 5° less inclined and 8° more anteverted than their target. Great variability (2SD: about ± 15°) in the post-operative radiographic cup orientation was seen. The two, equally contributing causes for this are variability in the orientation at which the cup is impacted, and the change in pelvic position between impaction and post-operative radiograph.

INTRODUCTION

Acetabular component (cup) orientation is an important factor contributing to complications, function and survival of hip arthroplasty[1,2]. Thus, optimal orientations within defined zones have been characterised in order to minimise risk of dislocation[3], impingement[4,5] and increased wear[1] following Total Hip Arthroplasty(THA) and Metal-on-Metal Hip Resurfacing Arthroplasty (MoMHRA)[2]. These zones tend to be different and there is no consensus as to what is optimal.

Acetabular orientation (inclination/anteversion) is measured in different ways in different situations. Murray defined the three different situations, namely operative, anatomical and radiographic[6]. Although these orientation angles are different, they are interrelated in a non-linear manner. Recommendations for optimal orientation are usually based on measurements made on post-operative, supine, pelvic radiographs. The inclination and anteversion measured in this manner is different from that measured at operation. There are two reasons for this: Firstly, the angles of inclination and anteversion measured relative to the pelvis are differently defined and secondly, the positions of the pelvis relative to the measurement reference frame are different.

In clinical situations the axis system of the pelvis is not usually the same as the axis system for measurements. Radiographic assessment measurements are made relative to the X-ray film and the longitudinal axis of the pelvis is usually not parallel to this, with the pelvis commonly being extended. At the beginning of the operation the surgeon attempts to position the pelvis in a neutral position relative to the operating table, with the reference planes of pelvis parallel to the reference planes of table, and provides adequate support so that the neutral orientation is maintained during surgery. At the time of cup impaction the surgeon usually assumes that the pelvis is in a neutral position relative to the table and implants the cup in what he believes to be the correct orientation relative to the table. However, the pelvis may not be neutrally positioned at set-up and may move considerably during the operation. Thus, the pelvis may not be in neutral position at the time of cup-impaction.

Most recommendations made to date[2,3,7] have described the target radiographic orientation but do not provide recommendations as to how to achieve this intra-operatively. Hill *et al,* photographed the cup introducer following impaction and compared cup inclination measured from photographs with the radiographic inclination[8]. The authors noted a mean difference of 13° and recommended considerably less operative inclination to achieve the radiographic target.

Amongst studies of radiographic cup orientation[1-3,7,9], a wide scatter of orientation is reported even in the hands of experienced hip surgeons[1,9], suggesting failure to achieve a specific orientation target in a high proportion of cases. However, it remains unknown if radiographic cup mal-orientation is a consequence of intra-operative cup mal-orientation in a well-aligned pelvis or that of surgeons implanting the cup in an acceptable orientation with the pelvis in a different position to what they expect, or if it is a combination of both.

The primary aim of this prospective, *in vivo*, study was to measure cup orientation at the time of impaction (intra-operative orientation) and determine how it differed from the cup orientation measured on the post-operative X-ray (radiographic orientation). The secondary aim was to determine how factors such as pelvic movement, orientation definitions and the orientation the surgeon implants the component influence this difference.

MATERIALS AND METHODS

Cohort

This IRB approved prospective, consecutive case series of 67 arthroplasty patients was a collaboration between two centres (Nuffield Orthopaedic Centre, Oxford, UK and ANCA Medical Centre, Ghent, Belgium). Inclusion criteria were primary arthroplasty surgery for primary osteoarthritis, without evidence of severe rotational or fixed flexion deformity, and American Society of Anaesthesiologist(ASA) grades I – II[10].

Patient demographics and anthropometric parameters (weight, height and BMI) were recorded prospectively (Table 1). Fifty-two (78%) of the patients underwent THA, whilst the remaining 15 (22%) underwent MoMHRA. 35 (69%) of the THA were done through a posterior approach; the remaining 17 (31%) were performed by the antero-lateral (Hardinge) approach. All HRAs were operated using the posterior approach. All patients were operated in the lateral decubitus position. The procedures were performed by three 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 orientation is 40°/20°. Surgeon B is a specialist hip surgeon, who has performed over 7,000 hip arthroplasties, including over 3,500 MoMHRAs; his routine hip arthroplasty practise 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°. All three surgeons take the native acetabular anatomy into account but none aim to consistently replicate transverse acetabular ligament (TAL) anteversion. All cups implanted were uncemented. All THA cups were press-fit, hemispherical. These included Trilogy (Zimmer, Warsaw, IN) (n=40), DeltaMotion (DePuy, Leeds, UK) (n=5) and FIXA cup (Adler. Milano, IT) (n=7). Forty had a polyethylene liner and twelve had a ceramic liner.

Intra-operative measurements

Intra-operative measurements were made using the principles of stereo-photogrammetry (SPG), using a validated protocol (Appendix 1). Stereophotogrammetry allows the spatial measurement of three-dimensional(3-D) objects from a stereo-pair set of images[11]. 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^{TM}, written in Matlab (R2011, The MathWorks, Natick, MA, USA) was developed to perform the measurements. The object of interest was the cup introducer. The 3-D location of the cup introducer after impaction was captured. These measurements allowed determination of intra-operative cup orientation.

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. The surgeon positioned the patient on the operating table as per routine practice. A calibration object, consisting of 12 spherical markers, was placed over the patient aligned with the operating theatre table. A stereo-pair of images were captured using the cameras, then the calibration object was removed; this initial stereo-pair of images was used in order to calibrate the measurement volume and then the calibration object removed (Figure 1). All subsequent measurements were thereafter made in a coordinate frame aligned to the operating theatre table. Surgery was carried out as routine and a stereo-pair of images was captured following cup implantation with the introducer still attached and retractors in place in order to measure the 3-D location of the cup introducer and therefore orientation of the cup (Figure 2).

Knowledge of the 3-D location of the cup introducer relative to theatre table allowed for calculation of the intra-operative cup inclination (IOI)/ intra-operative cup anteversion (IOA) and simulated radiographic cup inclination (SRI)/ simulated radiographic cup anteversion (SRA). The IOI and IOA is the orientation that the cup is implanted relative to the table and this is the orientation that the surgeon believes he/she is implanting the cup, as he assumes the pelvis is in a neutral position. The SRI/SRA angles are the angles that would have been measured from a radiograph had it been taken during the operation, with the film placed perpendicular to the reference plane of the theatre table (Figure 1). These angles were calculated based on Murray's definitions of operative inclination/anteversion and radiographic inclination/anteversion respectively relative to the theatre table.

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[12], a validated method of estimating radiographic orientation with an accuracy of 2°, was used to calculate radiographic cup inclination (RI) and anteversion (RA) according to the definitions of Murray[6,13,14]. Measurements were performed independently by two observers (GG, HP) blinded to other parameters with excellent intra- and inter-observer correlation (interclass correlation coefficients> 0.95, p< 0.001).

Analyses

Orientation Scatter

The scatter in both the intra-operative and radiographic component orientations were determined for the whole cohort.

Differences in Orientations

The differences between the post-operative radiographic cup inclination/anteversion (RI/RA) and intra-operative cup inclination/anteversion (IOI/IOA) were defined as Δ*inclination* and Δ*anteversion* and were calculated as:

Δ*inclination* = RI – IOI,

Δ*anteversion* = RA – IOA

In order to determine if the difference between the intra-operative orientation and the post-operative radiographic orientation was a manifestation of the different definitions or of pelvic movement, the simulated radiographic orientation was utilized.

<u>*Difference due to definition (ΔD)*</u>

The differences between the intra-operative and the simulated radiographic orientation is a manifestation of the different **definitions** used and were calculated as:

ΔD*inclination* = SRI – IOI

ΔD*anteversion* = SRA – IOA

Difference due to pelvic position (ΔP)

The differences between the simulated radiographic orientation and the post-operative radiographic orientation is a manifestation of the different **position** of the pelvis at the time of implantation and during the X-ray and were calculated as:

$\Delta P_{inclination} = RI - SRI$,

$\Delta P_{anteversion} = RA - SRA$

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. 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

There was a wide scatter of cup orientations as evident from Table 2 (Figures 3-4). The mean IOI was 37.6° (SD:5.4°, range: 28.1° to 49.5°) and mean IOA was 26.8° (SD:8.0°, range: 7.8° to 44.4°). The mean RI was 42.6° (SD:6.1°, range: 27.6° to 54.7°) and the mean RA was 18.7° (SD:7.2°, range: 3.9° to 35.1°). The mean SRI was 41.2° (SD:5.5°, range: 30.9 to 52.6) and the mean SRA was 20.7° (SD:6.5°, range: 6.4 to 35.4) (Table 2).

Factors influencing orientation scatter

Amongst the different patient-related factors tested as possibly having an effect on orientations (Table 3), only age had moderate negative correlation with IOI and positive correlation with RA. No other factor tested had an effect.

Surgical factors influencing the scatter were identified, namely surgeon and procedure performed. As evident in Table 2, surgeons implanted the components with different IOI/IOA (means: 33/34°, 42/27°, 35/19°) and hence had a resultant different RI/RA (means: 40/22°, 46/12°, 39/14°) (Figures 5-6). The intra-surgeon variability (12°) was slightly less than that of the whole cohort (16°) and it was evident that the three surgeons had different intra-operative practise. As a result the different surgeons achieved different portions of cups with the various target radiographic orientations.

Differences in orientation

There were significant difference in intra-operative orientation and subsequent radiographic orientation. Δ*inclination* was 5.0° (SD:5.4° range: -9.8° to +15.2°) and Δ*anteversion* was -7.8° (SD:7.5° range: -22.8° to +17.5°) (p<0.001). ΔD*inclination* was 3.5° (SD:1.9°, range: 0.3° to 9.4°) and ΔD*anteversion* was -6.0° (SD:2.3°, range: -1.4° to -11.4°). ΔP*inclination* was 1.3° (SD:5.1°, range: -13.1° to +10.5°) ΔP*anteversion* was -2.0° (SD:6.8°, range: -16.2° to +22.6°).

No patient factors were found to have a significant effect on the differences between the orientations (Table 3). However, surgical factors (surgeon, procedure and approach) were found to influence Δ*inclination* and Δ*anteversion*. The three surgeons had significantly different Δ*anteversion* but not Δ*inclination* (Table 2). This difference was due to both definition (ΔD*anteversion:* p<0.001) and position (ΔP*anteversion:* p=0.02) (Figure 7).

In order to compare MoMHRA and THA we used only Surgeon B's cases as this surgeon performed 15 of the 16 MoMHRAs. Type of procedure did not have an effect on Δinclination (p=0.3) but did on Δanteversion (p=0.04) (Table 4) (Figure 8). MoMHRAs had a Δ*anteversion* of -11° (SD: 7°), compared to -5° (SD:8°) for the THAs. There was a significant difference in ΔP*anteversion* between the two procedures [THAs (2.6°, SD:7.7°); HRAs (-3.3°, SD:5.5°)] (p=0.04), but no difference in ΔD*anteversion* (p=0.08).

In order to compare the two approaches, posterior and antero-lateral, we only used THAs. Surgical approach (Table 5) influenced Δ*anteversion* but not Δ*inclination*. Greater differences in Δ*anteversion* were detected with the posterior (-9°) compared to the lateral (-5°) approach. This difference was mostly due to the different definitions used [ΔD*inclination*/ ΔD*anteversion* (p<0.001)] rather than position (p=0.32).

DISCUSSION

In this study the mean acetabular inclination and anteversion measured on the post-operative radiographs were respectively 42° and 19°. These angles are ideal. However, as in all other studies, there was considerable scatter. The inclination ranged from 28° to 57°, and the anteversion ranged from 4° to 35°. An alternative way to quantify the variability is with ±2SD which includes about 95% of cases. Using this definition the variability in inclination and anteversion was 12° and 15° respectively. The surgeons involved in this study were all experienced and as they were aware of the nature of the study took great care to achieve optimal orientation. Therefore, in general a much wider range of orientation, with occasional gross outliers would be expected. Despite there being no evidence-base there is a consensus that an acceptable range is about ±10°; however, for hard-on-hard bearings it is likely that the acceptable range is narrower. There is, therefore, a need to improve the methods for achieving optimal orientation. Computer-navigated surgery does improve a surgeon's ability to achieve a pre-defined target orientation[15,16], however, certain limitations such as cost and time constraints have prevented its wide-scale use[17]. It is hence, timely and important to define the pragmatic relationship between intra-operative and radiographic cup orientation and identify factors that influence it. This study investigated in detail the various factors that contribute to acetabular orientation, allowing us to make recommendations as to how the variability can be decreased.

There were highly significant ($p<0.001$) differences in the mean post-operative orientation achieved by the different surgeons. As a result the surgeons achieved different percentages of hips within with different potential target zones. The main reason for these differences was that the surgeons aimed to implant the components in different positions. The variability in orientation at implantation was similar for the three surgeons; about 7° for inclination and 12° for anteversion. Although the surgeons used guides to assist with cup implantation, the variability in IOI/IOA suggests that the surgeons tended not to align the guides with the operating table. This was presumably because they felt the guides did not achieve the correct orientation. There is therefore a need to modify the guides.

To identify factors that influence the component orientation other than the position the surgeon implants the component, we subtracted the intra-operative orientation from the post-operative radiographic orientation. The two main factors contributing to this difference were the definitions of measuring orientation and the difference in position of the pelvis at operation and X-ray. The individual effect of these can be studied by considering the simulated radiographic orientation. The different definitions resulted in little variability (about ±2°) but a change in the mean inclination of about 4° and a change in mean anteversion of about -6°. In contrast, pelvic movement resulted in large variability in the final orientation, but did not significantly affect the mean inclination (1°) or anteversion (-2°). The variability in inclination resulting from pelvic movement was ±10° and the variability in anteversion was ±15°. This variability occurs because the relationship between the pelvis and the measuring reference plane is different during the operation and when the postoperative radiograph was taken. Factors that contribute to this include pelvic orientation at set-up, pelvic movement during surgery and pelvic orientation at X-ray. Previous studies have shown that surgeons have difficulty in reliably identifying pelvic landmarks[18] and reproducibly orientating the patients in a neutral position on the table[19,20]. Significant pelvic movement during THA has also been demonstrated[21,22]. **The variation due to the different definitions is systematic (always in one direction), whereas the variation in pelvic position can be in either direction.**

Patient-factors, including BMI, had no significant effect on the orientation. This is likely because none of the surgeons performed minimally-invasive surgery, nor compromised operating field visibility and accessibility so as to minimise for the length of scar. In contrast, surgical factors, especially procedure type had a significant effect on orientation. Reviewing Surgeon B's practise, hence controlling for the variables of patient positioning, type of support and approach, it was evident that MoMHRA was associated with greater difference in orientations than THA. This was mostly due to the difference in pelvic orientation between impaction and X-ray and reflects the different amount of pelvic movement that occurs during the two procedures. This is perhaps not surprising as more retraction is needed to expose the acetabulum with an intact femoral neck. This increased traction causes pelvic movement which gives rise to different pelvic orientation at the time of impaction with the two procedures. The current study's findings show that in order to achieve a RA of 20°, surgeons should impact a MoMHRA cup with an IOA of 30°, whilst a THA would only require a IOA of 25°.

There are several limitations to our study. Surgeons have different philosophies about implanting cups. Some aim to replicate native anatomy, knowing that they are likely to achieve recommended targets in a significant number of primary osteoarthritis cases. Others aim to achieve a given orientation in all cases, but most use a combination of these approaches. The findings of this study are most applicable to surgeons aiming to achieve a specific orientation, but is also useful for surgeons aiming to restore anatomy particularly if this is very abnormal. We measured the radiographic orientations from supine AP pelvic radiographs, rather than CT scans. Although such radiographic measurements do not account for pelvic tilt, they were used for several reasons; they are routine practice for assessment following arthroplasty, they have been the method used to define target orientation and are not associated with increased radiation and cost. In this study, there were no cases of extreme cup mal-orientation as reported in other series. Such cases would have enabled us to investigate which factors contribute to the mal-orientation. There was no record of length of incision or depth of subcutaneous fat at the incision. Although there were no minimally invasive surgeries performed and BMI was recorded, these two factors could have led to impingement of the introducer on the skin and altered the measured orientations.

In summary, this study demonstrates that the variability in cup orientations seen on post-operative radiographs results from two main factors that are equally important. These are the variability of the intra-operative cup orientation at impaction and the variability in pelvic orientation at impaction compared to that at the time of X-ray evaluation. In order to reduce cup orientation scatter both factors have to be addressed. The different definitions (operative and radiographic) have minimal effect on variability, however they cause significant offsets. To improve accuracy of implantation jigs should be modified so as to implant the socket about 5° less inclined (intra-operative inclination) and 8° more anteverted (intra-operative anteversion) than their **defined** target radiographic orientation. **Jig modification would account for the difference due to definitions but not that due to pelvic position. In order to reduce variability due to pelvic movement, improved methods of pelvic support and retraction are required.**

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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)	0.004
Weight/ Kg		72.4 (47.1 – 123.6)	72.5 (47.1 – 123.6)	72.0 (50.0 – 80.0)	0.47
BMI/ Kg/m^2		25.5 (17.5 – 38.6)	26.1 (17.5 – 38.6)	23.2 (17.9 – 28.0)	0.10
Cup size/ mm		53.5 (46 – 60)	52.8 (46 – 60)	56.3 (52 – 60)	<0.001
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
IOI/ °	37.6°/ 5.5° 28.1° to 49.5°	32.9° / 2.6° 28.1° to 38.6°	42.0°/ 4.2° (35.0° to 49.5°)	35.0°/ 3.0° 30.8° to 40.6°	<0.001
IOA/ °	26.8°/ 8.0° 7.8° to 44.4°	34.0°/ 5.4° 25.1° to 44.4°	26.6°/ 5.7° (10.8° to 36.3°)	19.0°/ 6.4° 7.8° to 30.4°	<0.001
SRI/ °	41.2°/5.5° 30.9° to 52.6°	38.1°/ 3.8° 30.9° to 46.0°	45.6°/ 3.9° 39.1° to 52.6°	36.7°/ 3.3° 33.1° to 44.4°	<0.001
SRA/ °	20.7°/ 6.5° 6.4° to 35.4°	27.7°/ 4.2° 21.2° to 35.4°	19.4°/ 4.6° 7.6° to 26.9°	15.4°/ 5.2° 6.4° to 25.6°	<0.001
RI/ °	42.6°/ 6.1° 27.6° to 54.7°	39.9°/ 6.0° 28.4° to 48.4°	46.1°/ 4.3° 35.5° to 54.7°	39.3°/ 5.7° 29.1° to 46.8°	<0.001
RA/ °	18.7°/ 7.2° 3.9° to 35.1°	22.4°/ 6.9° 11.5° to 34.9°	18.9°/ 5.8° 8.1° to 35.1°	14.3°/ 7.9° 3.9° to 29.5°	0.009
Δ*inclination*/°	5.0°/ 5.5° -9.8° to 15.2°	7.0°/ 5.2° -4.7° to 14.6°	4.1°/ 6.0° -9.8° to 15.2°	4.3°/ 4.3° -4.1° to 10.4°	0.21
Δ*anteversion*/°	-7.8°/ 7.5° -22.8° to 17.5°	-11.6°/ 5.5° -22.8° to 4.6°	-7.6°/ 8.3° -21.2° to 17.5°	-4.7°/ 6.7° -19.0° to 5.8°	0.005
ΔD*inclination*/°	3.4°/ 1.9° 0.3° to 9.4°	5.2°/ 1.9° 2.6° to 9.4°	3.3°/ 1.4° 0.3° to 6.1°	1.7°/ 1.1° 0.3° to 4.0°	<0.001
ΔD*anteversion*/°	-6.0°/ 2.3° -11.4° to -1.4°	-6.2°/ 1.8° -9.9° to -3.4°	-7.2°/ 2.0° -11.4° to -2.8°	-3.6°/ 1.5° -7.5° to -1.4°	<0.001
ΔP*inclination*/°	1.3°/ 5.2° -13.1° to 10.5°	1.5°/ 4.8° -10.5° to 9.3°	0.4°/ 5.4° -13.1° to 10.5°	2.6°/ 4.9° -7.4° to 9.6°	0.37
ΔP*anteversion*/°	-2.0°/ 6.8° -16.2° to 22.6°	-5.5°/ 5.4° -16.2° to 8.0°	-0.3/ 7.2 -11.7 to 22.6	-1.1°/ 6.4° -15.3° to 8.9°	0.02
% with RI: 35 – 55°	88	79	100	77	0.04
% with RA: 10 – 30°	84	84	94	65	0.04
% within RI/RA: 35 – 55°/ 10 – 30°	76	74	94	47	0.001
% with RI: 30 – 50°	79	58	87	88	0.03
% with RA: 5 – 25°	86	95	81	82	0.5
% within RI/RA: 30 – 50°/ 5 – 25°	69	53	71	81	0.1

Table 2: Intra-operative, simulated radiographic, radiographic component orientations, Δ*inclination*/Δ*anteversion*, ΔD*inclination*/ΔD*anteversion*, ΔP*inclination*/ΔP*anteversion*,

percentage of cases within specific radiographic orientation targets for the whole cohort and as per surgeon.

Factor	**Age/** Years	**Height/** m	**Weight/** Kg	**BMI/** Kg/m^2	**Cup Size/**mm
Δ*inclination*/°	rho=0.01 p=0.97	rho=0.03 p=0.80	rho=0.14 p=0.34	rho=0.09 p=0.35	rho=-0.14 p=0.6
Δ*anteversion*/°	rho=0.34 p=0.01	rho= 0.04 p=0.79	rho=0.09 p=0.53	rho=0.23 p=0.43	rho=-0.04 p=0.8
ΔD*inclination*/°	rho=0.12 p=0.45	rho=0.1 p=0.49	rho=-0.11 p=0.48	rho=-0.11 p=0.48	rho=0.13 p=0.4
ΔD*anteversion*/°	rho=-0.16 p=028	rho=0.1 p=0.49	rho=0.06 p=0.68	rho=0.06 p=0.71	rho=0.22 p=0.1
ΔP*inclination*/°	rho=-0.16 p=0.9	rho=-0.03 p=0.84	rho=-0.11 p=0.45	rho=-0.1 p=0.60	rho=0.03 p=0.85
ΔP*anteversion*/°	rho=-0.4 p=0.05	rho=-0.1 p=0.59	rho=0.1 p=0.51	rho=0.13 p=0.38	rho=0.06 p=0.66

Table 3: Patient factors and their correlation (Spearman's rho) with Δinclination, Δanteversion, ΔDinclination, ΔDanteversion, ΔPinclination and ΔPanteversion.

Procedure	**THA** **Mean/SD** **Range**	**HRA** **Mean/SD** **Range**	**p-value**
IOI/ °	40.7°/3.7° 35.0° – 48.6°	43.4°/ 4.3° 35.6° – 49.5°	0.06
IOA/ °	26.4°/ 5.4° 16.3° – 36.3°	26.7°/ 6.3° 10.8° – 33.8°	0.6
RI/ °	45.8°/ 4.9° 35.5° – 54.7	46.8°/ 3.9° 40.0° – 52.4°	0.92
RA/ °	21.8°/ 6.0° 11.9° – 35.1°	15.9°/ 3.9° 8.1 – 20.7°	0.002
SRI/ °	44.3°/ 3.6° 39.1° – 51.8°	46.8°/ 3.9° 40.7° – 52.6°	0.12
SRA/ °	19.6°/ 4.3° 11.3° – 25.1°	19.2°/ 5.0° 7.6° – 26.9°	0.94
Δinclination/ °	5.2°/ 7.2° -9.8° to 15.2°	3.0°/ 4.4° -4.5° to 8.6°	0.32
Δanteversion/ °	-4.7°/ 8.5° -15.0° to 17.5	-10.8°/ 7.1° -21.2° to 3.5°	0.04
ΔDinclination/ °	3.3°/ 1.4° 1.2° to 6.1°	3.3°/1.5° 0.3° to 5.2°	0.78
ΔDanteversion/ °	-6.9°/ 1.8° -11.4° to -5.0°	-7.6°/ 2.1° -9.9° to -2.8°	0.08
ΔPinclination/ °	1.2°/ 6.4° -13.1° to 10.5°	-0.4°/ 4.1° -7.9° to 6.7°	0.29
ΔPanteversion/ °	2.6°/ 7.7° -5.5° to 22.6°	-3.3°/ 5.5° -11.7° to 6.3°	0.04

Table 4: Orientation measurements for THAs and HRAs performed by Surgeon B.

Approach	Lateral (n=17) Mean/SD Range	Posterior (n=35) Mean/SD Range	p-value
IOI/ °	35.0°/ 3.1° 30.8° – 40.6°	36.4°/ 5.0° 28.1° – 48.6°	0.28
IOA/ °	19.0°/ 6.4° 7.8° – 30.4°	30.6°/ 6.5° 16.3° – 44.4°	<0.001
RI/ °	39.3°/ 5.7° 27.6° – 46.8°	42.6°/ 6.2° 28.4° – 54.7°	0.08
RA/ °	14.3°/ 7.9° 3.9° – 29.5°	22.1°/ 6.4° 11.5° – 35.1°	0.002
SRI/ °	36.7°/ 3.3° 33.1° – 44.4°	41.0°/ 4.8° 30.9° – 51.8°	0.001
SRA/ °	15.4°/ 5.2° 6.4° – 25.6°	24.0°/ 5.8° 11.3° – 35.4°	<0.001
Δinclination/ °	4.3°/ 4.3° -4.1° to 10.3°	6.2°/ 6.1° -9.8° to 15.2°	0.20
Δanteversion/ °	-4.7°/ 6.7° -19° to 5.8°	-8.5°/ 7.7° -22.8° to 17.5°	0.02
ΔDinclination/ °	1.7°/ 1.1° 0.3° to 4.0°	4.3°/1.9° 1.2° to -9.4°	<0.001
ΔDanteversion/ °	-3.6°/ 1.5° -7.5° to -1.4°	-6.5°/ 1.8° -11.4° to -3.4°	<0.001
ΔPinclination/ °	2.6°/ 4.9° -7.4° to 9.6	1.3°/ 5.5° -13.1° to 10.5°	0.46
ΔPanteversion/ °	-1.1°/6.4° -15.3° to 8.9°	-1.8°/ 7.6° -16.2° to 22.6°	0.36

Table 5: Orientation measurements for different approaches in THAs only.

Appendix 1

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. A gauge object consisting of two retro-reflective spherical markers (diameter 10 mm) mounted on an aluminium rod was measured five times simultaneously by the Fotop™ and Vicon Nexus systems, determining both the position in space (translation) and the angle it is at (rotation) relative to the co-ordinates. These tests demonstrated that the SPG (Fotop™) method was accurate within 0.1 mm (95% CI: -2 to + 2 mm) in terms of translation and 0.03° (95%CI: -1.6° to +1.6°). These provided validity that the SPG method accurately measured the 3-D co-ordinates of the object of interest in this study.