



Original research

Mechanical and Anatomical Alignment Guide Techniques Are Superior to Freehand in Achieving Target Orientation of an Acetabular Component

Robert Bruce-Brand, FRCS^{*}, Paul Magill, FRCS, Christopher O'Neill, FRCS, Paul Karayiannis, MRCSEd, Janet Hill, MEng, PhD, David Beverland, FRCS

Primary Joint Unit, Musgrave Park Hospital, Belfast, UK

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ABSTRACT

Background: Achieving accurate and consistent acetabular component orientation remains a major challenge in total hip arthroplasty.

Methods: We used a pelvic model to compare freehand techniques vs mechanical and anatomical alignment guides in achieving a target operative inclination (OI) and operative anteversion (OA). Thirty subjects comprising consultant orthopedic surgeons, orthopedic trainees, and nonsurgical staff positioned an acetabular component in a pelvic model using 3 different methods for guiding inclination and another 3 for guiding version.

Results: Using either a standard mechanical alignment guide (MAG) or a spirit level MAG technique eliminated outliers from target OI, while the freehand method resulted in 46.7% of measurements outside the OI target range. The spirit level MAG technique significantly outperformed the standard MAG technique in median unsigned deviation from target OI (0.8° vs 2.1°, $P < .001$). Either method of referencing the transverse acetabular ligament for version yielded lower deviations from target OA than the freehand method and fewer outliers from the $\pm 5^\circ$ target range. Surgical experience was not a significant factor for accurately achieving target OI and OA.

Conclusions: Even in an idealized in vitro model, a wide range of OI and OA is seen with the freehand technique of cup placement by subjects of all levels of surgical experience. Using either a standard MAG or a spirit level MAG reduces deviations in target OI, with the spirit level MAG method yielding the best accuracy. Using the transverse acetabular ligament to guide cup anteversion yields more accurate OA.

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Introduction

Correct orientation of the acetabular component (cup) in total hip arthroplasty (THA) is important to avoid instability, impingement, and excessive wear [1–3]. Surgeons usually judge the success of placing the cup in the desired position from postoperative

radiographs, assessing radiographic inclination and radiographic anteversion. Traditionally orthopedic surgeons have targeted the safe zone proposed by Lewinnek et al. of $40^\circ \pm 10^\circ$ of radiographic inclination and $15^\circ \pm 10^\circ$ of radiographic anteversion [4].

Achieving consistent cup inclination and anteversion remains a major challenge in THA, irrespective of patient position or surgical approach [5]. Multiple guidance modalities and surgical techniques have been developed to improve the accuracy and consistency of cup placement [5–14]. Nonetheless, even experienced surgeons have outliers resulting in ranges of $\pm 20^\circ$ for radiographic anteversion and inclination [15–17].

Cup inclination and anteversion are influenced by the landmarks referenced by the surgeon during the surgery, the intended orientation relative to these landmarks, the tools used to aid achieving the target position, surgical experience, and pelvic position.

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^{*} Corresponding author. 33 Ballygudden Road, Eglinton BT47 3AG, UK. Tel.: +44 287 134 5171.

E-mail address: robbrucebrand@gmail.com

Intraoperatively, the cup is usually inserted with an introducer handle that is colinear to the component axis and perpendicular to the face of the component. Operative inclination (OI) can then be defined as the intraoperative angle between the cup introducer handle and the sagittal plane of the pelvis [18]. During surgery in lateral decubitus, assuming the pelvis is neutrally positioned, the theater floor becomes a surrogate for the pelvic sagittal plane (Fig. 1). However, because the pelvic sagittal plane may not be parallel to the floor, O'Neill et al. introduced the term apparent OI for this angle [19].

When operating in lateral decubitus, most surgeons use a freehand technique or mechanical alignment guide (MAG) to determine OI [20]. Traditionally MAGs have been designed for a target OI of 45°. Based on previous work where we found radiographic inclination to be a mean of 6° higher than OI, our unit uses as standard a 35° MAG (DePuy Synthes, Leeds, UK) (Fig. 2a) [16]. The design of MAGs is usually based on the desired target angle for OI being achieved when the vertical limb is perpendicular to the floor and the horizontal limb is parallel to the floor. If the vertical limb is not perpendicular to the floor, the inclination will be less than target. In a randomized control trial by O'Neill et al., the MAG was not as accurate as an inclinometer in part because of this design limitation [19]. To address this factor, we introduced a “spirit level MAG” in this study where the horizontal limb was removed and the surgeon asked to ensure that the vertical rod was orthogonal to the floor in both planes using a spirit level (Fig. 2b).

Operative anteversion (OA) is illustrated in Figure 3. During surgery in lateral decubitus, the theater table can substitute for the long axis of the patient again typically by using a MAG set to 30° of anteversion. However, most surgeons use the appearance of the cup in the acetabulum or the transverse acetabular ligament (TAL) as a guide to version with the latter being the most commonly used one in the UK [20]. The concept of the TAL technique is simply placing the face of the cup parallel to the TAL to control version [14]. A surgeon's ability to discriminate orientation accurately can be negatively affected by observer body tilt due to the phenomenon of the oblique effect [21]. In order to assess the impact of this factor, in the preferred technique of this study, we directed subjects to orientate themselves such that the cup face and TAL were horizontal with respect to their field of vision.

We developed an in vitro pelvic model in which the primary outcome was to determine whether the use of a spirit level MAG for OI, and the use of TAL viewed horizontally for OA, would reduce the number of observations outside a target range ($\pm 5^\circ$ for both inclination and version) when compared to a standard MAG for OI and undirected viewing of the TAL for OA. The secondary outcome was to determine whether prior surgical experience had any impact on the numbers that fell outside target for each technique. Our hypothesis was that the spirit level MAG would reduce outliers in inclination, a focus on horizontal viewing of the TAL would reduce

outliers in version, and surgical experience would reduce outliers in both inclination and version.

Material and methods

Pelvic model

A Sawbones pelvis (Sawbones Europe AB, Sweden) was held on a customized mount and rigidly secured onto a horizontal board such that the pelvic sagittal plane was parallel to the floor (Fig. 2). A physical representation of the TAL was manufactured specifically for the model and screwed onto the pelvis. The acetabulum had an original diameter of 58 mm and was reamed to 60 mm with the face of the reamer parallel to the TAL so that the placement of a 60-mm cup gave appropriate tactile feedback. A soft-tissue envelope was not simulated.

Measurement of acetabular component orientation

A digital inclinometer (DWL-80E; DigiPas USA, Avon, CT) placed on the long axis of the cup handle was used to measure cup inclination (Fig. 4). This provides a digital reading accurate to 0.2° [22]. The inclinometer was calibrated after each series of experiments.

A digital camera (Crosstour CT7000 1080p; ShenZhen Long Tou Optics, Shenzhen, China) was rigidly mounted to a supporting rod of the pelvic model to provide a clear view of the acetabulum (Fig. 2). A Wi-Fi connection between the camera and a smart phone allowed photographs to be taken with remote activation. Photographs of the cup in the acetabulum were analyzed using an open-source digital image processing software program (GNU Image Manipulation Program version 2.10, The GIMP Development Team, <https://www.gimp.org>) to measure the anteversion angle of the cup (Fig. 5). The anteversion angle was measured between the long axis of the cup handle and a precalibrated zero anteversion line obtained by carefully positioning the cup face parallel to TAL with the aid of a focusable laser line module attached to the cup handle (MXD1230) and taking reference photographs.

Nonlinearities in photographic anteversion measurements (due to the wide-angle lens and the camera being mounted not perfectly orthogonal to the zero anteversion line) were minimized by referencing study photographs against a comprehensive series of calibrated photographs. The calibration was performed via a custom electronic meter we developed comprising a microprocessor (ATmega328; Microchip, San Jose, CA), a 9-axis absolute orientation sensor (an inertial measurement unit combining a 3-axis accelerometer, a 3-axis gyroscope, and a 3-axis geomagnetic sensor, the BNO055; Bosch Sensortec, Stuttgart, Germany), and a liquid-crystal display (Fig. 6). This provided an electronic reading of anteversion independent of inclination. The sensor was calibrated before each

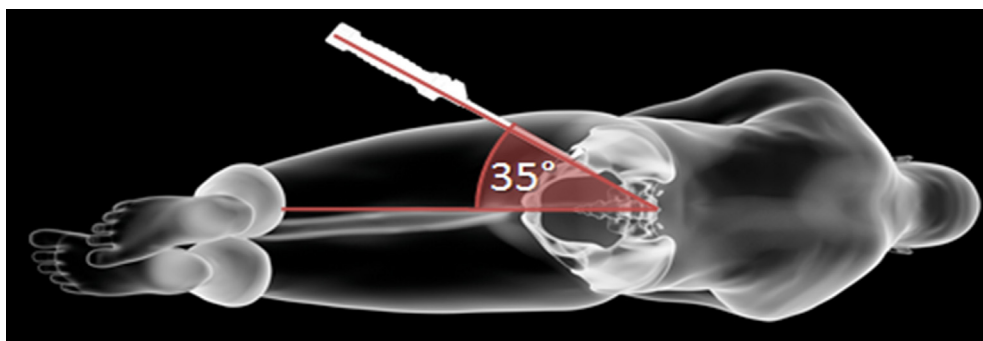


Figure 1. Schematic showing operative inclination—defined as the angle between the acetabular axis and the sagittal plane of the pelvis.

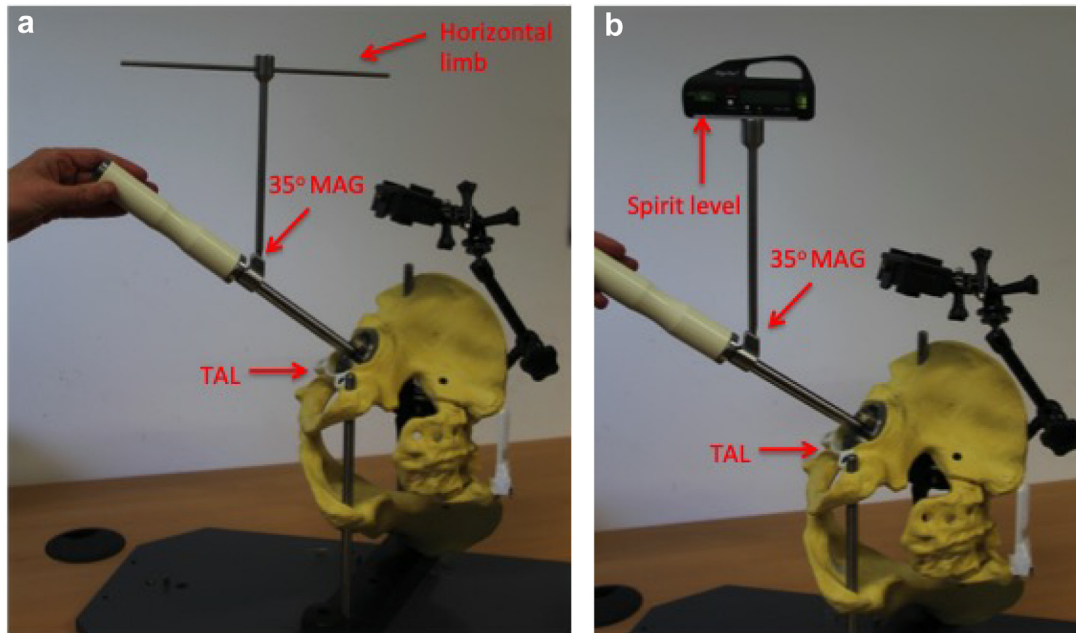


Figure 2. Experimental setup. Photographs show the pelvic model mounted with the sagittal plane parallel to the floor, the transverse acetabular ligament (TAL) in situ, and a cup held in the acetabulum with a mechanical alignment guide (MAG) attached to the cup handle. (a) The standard mechanical MAG with its horizontal limb which was to be placed parallel to the floor. (b) The modified MAG with a spirit level which was to be leveled in 2 orthogonal planes.

series of photographs to compensate for local magnetic fields and ferromagnetic materials.

Subjects

Ten subjects were recruited from each of the following 3 groups:

- 1) Consultant orthopedic surgeons specialized in hip arthroplasty
- 2) Orthopedic trainees (levels ST4-8 of the UK Higher Specialist Training scheme)
- 3) Nonsurgical group (research and nursing staff)

Potential subjects in each group were e-mailed simultaneously with information on the study and invited to participate, and the first ten in each group who replied in the affirmative were recruited. Written consent was obtained from all subjects.

Participants were provided with the same set of instructions, allowed to familiarise themselves with the pelvic model, and given the opportunity to ask questions. It was ensured that each participant was comfortable with the concept of OI and OA and knew the

target values. The participant then stood behind the pelvis as for a THA from the posterior approach and was provided with a 60-mm acetabular component (Pinnacle Hip solutions; DePuy Synthes, Leeds, UK) attached to an introducer handle.

Each subject was given 3 tasks:

- 1) Using a freehand technique to determine both OI and OA. The TAL was detached from the pelvic model before this task. For OI, the subject was asked to place the cup in the acetabulum with an inclination of 35° to the floor without a MAG. For OA, the subject was asked to choose what they felt was the appropriate version using only bony landmarks, with no TAL visible.
- 2) Using the standard MAG and TAL to determine OI and OA. The MAG comprising both vertical and horizontal rods was attached to the cup handle, and the TAL was attached to the pelvic model (Fig. 2a). For OI, the subject was asked to place the cup in the acetabulum with an inclination of 35° to the floor by ensuring that the horizontal limb of the MAG was parallel to the floor. For OA, the subject was asked to place the face of the cup parallel to the TAL with no specific instruction as how to view the TAL.

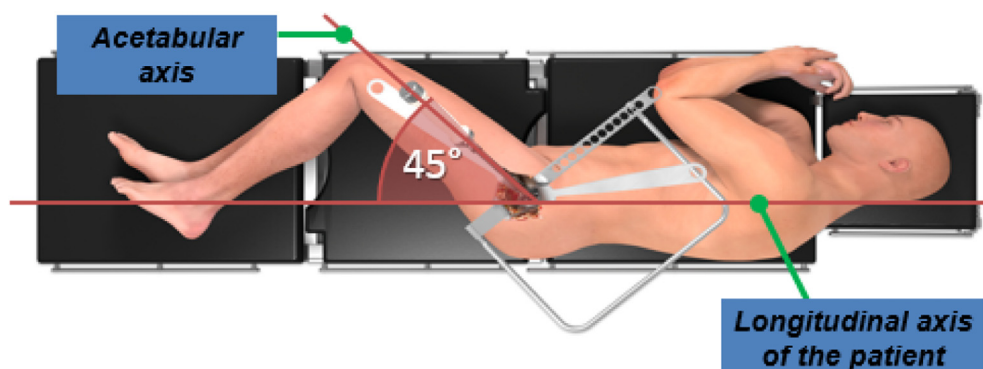


Figure 3. Schematic showing operative anteversion—defined as the angle between the long axis of the patient and the acetabular axis as projected onto the sagittal plane.

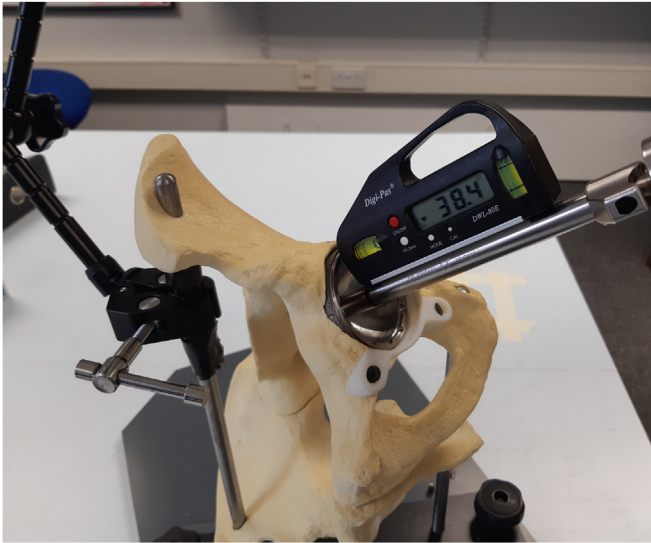


Figure 4. Measuring cup inclination. A digital inclinometer was placed on the long axis of the cup handle to measure cup inclination.

3) Using the spirit level MAG and TAL viewed horizontally to determine OI and OA (Fig. 2b). For OI, the subject was asked to orientate the cup in the acetabulum so that the spirit level on the MAG was level in 2 orthogonal planes. For OA, the subject was again asked to place the face of the cup parallel to the TAL but only after orientating themselves such that the cup face and TAL were horizontal with respect to their field of vision. This task represented the preferred technique.

For each task, when the subject was satisfied with the cup position in the acetabulum, they were asked to hold the cup handle steady (without impaction) while the following was performed:

1) A photograph was taken with remote activation using a smart phone

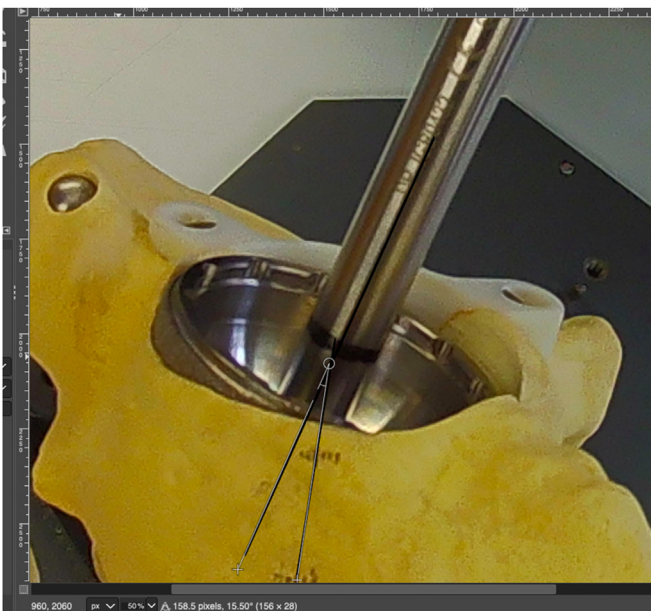


Figure 5. Digital image processing—determining the anteversion angle using a digital image processing software.

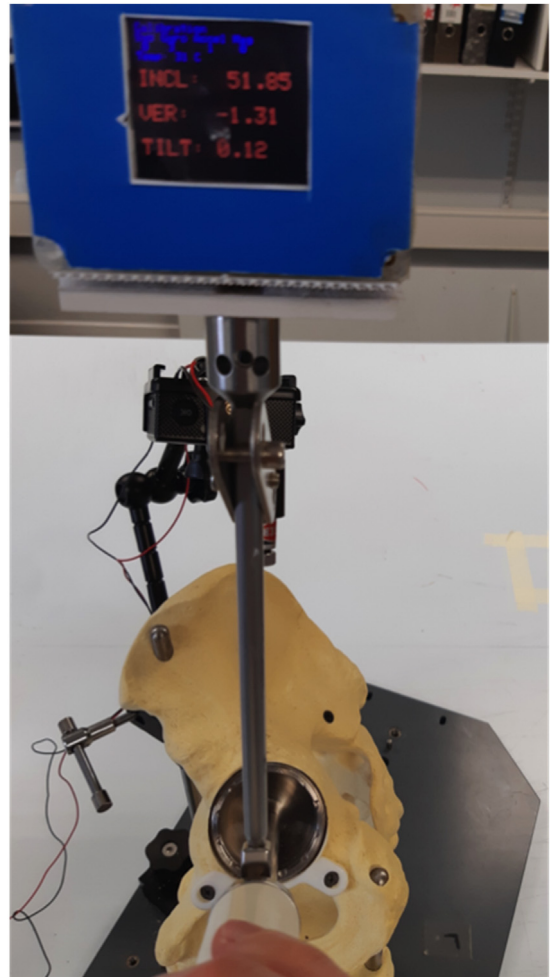


Figure 6. Calibration of the photographic system. A custom device was attached to the mechanical alignment guide to calibrate the photographic system for version measurements.

2) The digital inclinometer was placed longitudinally on the cup handle and the inclination value recorded by an independent observer.

Statistical analyses

The primary outcome measures were unsigned deviations from target OI $\pm 5^\circ$ and target OA $\pm 5^\circ$. Comparisons of median unsigned deviations from target OI and target OA were made according to participant group and tasks. Statistical analysis was carried out using SPSS version (version 22; IBM, Armonk, NY), and all data were assessed for normality using Shapiro-Wilk test. Chi-squared test was used to compare categorical variables. For nonparametric continuous variables, Kruskal-Wallis test was used. Statistical significance level was set at $P < .05$. Data were presented as the number falling outside target as well as the median, interquartile range (IQR), and range.

Results

Operative inclination

The target range for OI was $35^\circ \pm 5^\circ$. The median OI of all readings was 35.0° , IQR $32.7^\circ - 37.0^\circ$, and range $20.3^\circ - 44.0^\circ$.

Table 1
Comparison of different methods of guiding operative inclination.

Outcome measure	Task 1, N = 30	Task 2, N = 30	Task 3, N = 30	P values
Number (%) outside target range	14 (46.7%)	0 (0%)	0 (0%)	<.001 ^a
Median inclination (IQR)	30.9 ^c (29.1–35.1)	37.0 ^d (35.5–37.7)	35.0 (34.2–35.8)	<.001 ^b
Median unsigned deviation from target OI of 35.0° (IQR)	4.3 ^e (3.5–6.9)	2.1 ^f (1.0–2.8)	0.8 (0.3–1.1)	<.001 ^b

^a Chi-square analysis.

^b Kruskal-Wallis test followed by Mann-Whitney post-hoc analysis.

^c Inclination measured by task 1 was significantly lower than that by task 2, $P < .001$, and task 3, $P = .001$.

^d Inclination measured by task 2 was significantly greater than that by task 3, $P < .001$.

^e Task 1 deviation from target was significantly greater than task 2 and task 3 deviations, $P < .001$.

^f Task 2 deviation from target was significantly greater than task 3 deviation, $P < .001$.

Fourteen (15.6%) of the 90 inclinations were outside the target range of $35^\circ \pm 5^\circ$. All these outliers were with the freehand technique (task 1).

The median inclination (IQR) for all participants was 30.9° (29.1° – 35.1°) for the freehand technique (task 1), 37.0° (35.3° – 37.7°) using the standard MAG (task 2), and 35.0° (34.2° – 35.8°) using the spirit level MAG technique (task 3). While both MAG techniques were significantly better in achieving target OI compared to the freehand technique and eliminated $>5^\circ$ outliers, the spirit level MAG technique also significantly outperformed the standard MAG technique in median unsigned deviation (0.8° vs 2.1° , $P < .001$) (Table 1).

Operative anteversion

The target OA was parallel to TAL $\pm 5^\circ$. Eight of the 90 OAs (8.9%) fell outside this target range, and 6 of these were with the freehand technique (task 1). The median unsigned deviation from target OA for all readings was 2.0° , IQR $1.0 - 4.0^\circ$, and range 0.0 to 10.0° .

The freehand technique (task 1) had significantly more version readings outside the $\pm 5^\circ$ target range than the other 2 version methods (Table 2).

Task 2 (using TAL) and task 3 (using TAL viewed horizontally) produced significantly lower median unsigned deviations from target OA than the freehand method (1.0° , 2.0° , and 3.0° , respectively). Tasks 2 and 3 did not differ significantly in this regard (Table 2) with only one outside target range for each task.

Effect of surgical experience on OI

There was no significant difference between participant groups in number of outliers or median unsigned deviation from target OI for each of the 3 tasks and when combining data from all 3 tasks (Table 3).

Effect of surgical experience on OA

There was no significant difference between participant groups in the number of outliers, mean unsigned deviation from target OA for combined task data, or for individual tasks (Table 4).

Table 2
Comparison of different methods of guiding operative anteversion.

Outcome measure	Task 1, N = 30	Task 2, N = 30	Task 3, N = 30	P values
Number (%) outside target range	6 (20%)	1 (3.3%)	1 (3.3%)	.032 ^a
Median unsigned deviation from target operative anteversion in degrees (IQR)	3.0 ^c (2.0–5.0)	1.0 (1.0–3.0)	2.0 (1.0–3.0)	.001 ^b

^a Chi-square analysis.

^b Kruskal-Wallis test followed by Mann-Whitney post-hoc analysis.

^c Anteversion measured by task 1 was significantly greater than that measured by task 2, $P < .001$, and task 3, $P = .006$.

Discussion

Cup orientation is described in terms of inclination and anteversion, both of which may be defined from 3 different perspectives: radiographic, operative, and anatomical [18]. It is important to be aware of the different definitions. In order to achieve a given target radiographic inclination, the surgeon needs to be aware that a lower angle of OI is required. OI is measured relative to the sagittal plane while radiographic inclination is measured around an oblique axis. The 2 are related by the trigonometrical equation $\sin(\text{OI}) = \sin(\text{radiographic inclination}) \times \cos(\text{radiographic anteversion})$. As anteversion increases, so does radiographic inclination as compared to OI [6,18]. Hill et al. found radiographic inclination to be a mean of 6° higher than OI [16].

Suboptimal patient positioning and pelvic movement during surgery can introduce errors in component orientation. Hill et al. showed a mean difference between apparent OI and radiographic inclination of 13° [16]. Of this 13° difference, 7° was explained by the impact of OA, but the other 6° was due to errors in patient positioning (pelvic sagittal plane not parallel to the floor). Consequently, in our institution, we focus on ensuring that the pelvic sagittal plane is parallel to the floor and then aim for 35° of OI to counteract the impact of OA and achieve a radiographic inclination of approximately 40° . We believe that the traditional 45° MAG is no longer appropriate in lateral decubitus.

Our idealized in vitro experiment was designed to assess the role that freehand and conventional MAG-assisted cup placement and the oblique effect play in creating outliers from target OI and OA. Limitations of traditional MAGs include their dependence on the pelvic sagittal plane being parallel to the floor, their target angles being set at desired radiographic inclination angles rather than at the lower OI required, and inaccuracies if the vertical limb is not held perpendicular to the floor. We addressed the latter factor in this study by assessing a spirit level MAG to ensure the MAG was level in 2 orthogonal planes. A 35° MAG has been standard in our unit for several years, addressing the second factor.

Ongoing research into improved external supports aims to address the first factor but was not within the scope of this study.

Despite the idealized in vitro setup used in this study, a wide range of OI ($20.3^\circ - 44.0^\circ$) and OA (0.0° to 10.0°) were seen with the freehand technique of cup placement. For OI, 46.7% of freehand readings were outside the target range of $\pm 5^\circ$ compared to none for either of the MAG techniques. Furthermore, the spirit level MAG

Table 3
Comparison of operative inclination data between study participant groups.

Outcome measure	Consultants, N = 10	Trainees, N = 10	Nonsurgical, N = 10	P values
No (%) outside target range—task 1	4 (40%)	4 (40%)	6 (60%)	.585 ^a
No (%) outside target range—task 2	0 (0%)	0 (0%)	0 (0%)	NS ^a
No (%) outside target range—task 3	0 (0%)	0 (0%)	0 (0%)	NS ^a
No (%) outside target range—all tasks	4 (13%)	4 (13%)	6 (20%)	.713 ^a
Median inclination (IQR)—task 1	31.3 (28.7–34.6)	30.9 (27.1–33.7)	31.5 (29.7–39.7)	.567 ^b
Median inclination (IQR)—task 2	37.1 (36.6–37.7)	36.8 (35.7–38.1)	36.0 (34.3–38.2)	.816 ^b
Median inclination (IQR)—task 3	34.8 (34.5–35.4)	34.7 (34.0–36.1)	35.4 (34.0–36.3)	.717 ^b
Median inclination (IQR)—all tasks	35.0 (33.1–36.9)	34.7 (30.9–36.7)	35.3 (32.5–37.7)	.664 ^b
Median unsigned deviation from target OI (IQR) for all tasks	1.8 (0.8–2.9)	1.8 (1.0–4.1)	2.5 (0.9–4.5)	.638 ^b

NS, nonsignificant.

^a Chi-square analysis.

^b Kruskal-Wallis test.

technique outperformed the standard MAG technique in mean unsigned deviation from target OI (0.8° vs 2.1°, $P < .001$).

For OA, the differences were less dramatic, but again 20% of freehand readings were outside the target range compared to 3.3% for each of the TAL techniques (tasks 2 and 3). Unexpectedly there was no difference between tasks 2 and 3. In task 3, the preferred technique of our hypothesis, subjects orientated themselves such that the cup face and TAL were horizontal with respect to their field of vision. We had hypothesized that this would reduce OA by reducing the oblique effect. From studies of human vision, the oblique effect is a well-established phenomenon in which our ability to discriminate orientation is significantly better around the cardinal (horizontal or vertical) axes than at an oblique axis [23–25]. Meng and Qian showed that the oblique effect depends on perceived orientation (relative to the retina) rather than physical orientation (relative to gravitational force) [21]. Observer body tilt, hence, affects how accurately we discriminate orientation [21]. The fact that we could show no advantage when viewing the TAL horizontally may have been because the subject was distracted by trying to ensure the spirit level was level in 2 orthogonal planes to control OI.

The relationship between native acetabular version and the anterior pelvic plane varies between patients by up to 30° [26,27]. Furthermore, the degree of pelvic tilt cannot be accurately determined intraoperatively. In our institution, we reference the TAL for OA. The TAL is a consistent internal landmark for OA, and although it is variable between patients, we argue it is correct for that patient [15]. Ensuring each acetabular reamer and the implanted cup is cradled inferiorly by the TAL and keeping the face of the reamer/cup parallel to this well-defined landmark provide an effective version guide. Surgeons should ensure that the face of the cup and the TAL are horizontal with respect to their field of gaze. Historically, we found that using the TAL to guide version reduced our primary dislocation rate from 3.7% to 1% [14].

The findings in our study are supported by other literature. Saxler et al. found via postoperative CT scans that only 26% of

acetabular components positioned using a freehand technique in a multicentre study were within Lewinnek's safe zone [28]. DiGioia et al. found that 78% of components implanted freehand were malpositioned based on intraoperative computer-assisted measurements [7]. Hassan et al. found that even with the use of a MAG, 42% of components were outside the safe zone [29].

Further studies have shown that surgical navigation and robotics reduces the rate of malpositioned acetabular components [9,10]. However, these technologies have not been widely adopted in THA because of cost, additional operative time, and, in the case of image-based systems, increased radiation exposure.

We have shown that freehand cup placement is an important cause of outliers. Our hypothesis that a spirit level MAG would reduce outliers in inclination compared to a conventional MAG was borne out. We were unable to show that the oblique effect was an important contributor. In this idealized in vitro setup, surgical experience did not prove to be of any benefit.

There are several limitations to this study. Participant numbers were relatively low with ten subjects in each group. An in vitro model was used which does not account for many of the challenges posed by real-world surgery. These include limitations of external supports used to stabilize the pelvis, difficulties in visualization and identification of landmarks caused by the soft-tissue envelope and degenerative changes, and movement of the pelvis during surgery. We have no doubt surgical experience is invaluable in overcoming these challenges.

We believe that failure to ensure that the sagittal plane is parallel to the floor at the time of cup insertion remains the dominant cause of outliers for cup inclination, and this is a focus of ongoing research [15]. We are strong proponents of the use of TAL to guide version even in the dysplastic hip. This key anatomical landmark can be difficult to identify when covered in osteophyte. However, we have shown with the right surgical techniques that it can be identified in over 99% of cases [13].

Our study did not assess radiographic inclination and version. Our photographic system calibrated by a custom accelerometer

Table 4
Comparison of operative anteversion data between study participant groups.

Outcome measure	Consultants, N = 10	Trainees, N = 10	Nonsurgical, N = 10	P values
No (%) outside target range—task 1	2 (20%)	2 (20%)	2 (20%)	1.000 ^a
No (%) outside target range—task 2	0 (0%)	0 (0%)	1 (10%)	.355 ^a
No (%) outside target range—task 3	0 (0%)	0 (0%)	1 (10%)	.355 ^a
No (%) outside target range—all tasks	2 (6.7%)	2 (6.7%)	4 (13.3%)	.578 ^a
Median unsigned deviation from target OA (IQR)—task 1	3.5 (3.0–4.8)	3.5 (2.3–4.0)	2.5 (2.0–4.8)	.754 ^b
Median unsigned deviation from target OA (IQR)—task 2	1.5 (1.0–2.0)	2.0 (1.0–3.8)	1.0 (0.0–1.0)	.101 ^b
Median unsigned deviation from target OA (IQR)—task 3	1.0 (1.0–3.0)	2.5 (1.0–3.8)	2.0 (1.0–3.0)	.560 ^b
Median unsigned deviation from target OA (IQR)—all tasks	2.0 (1.0–3.0)	3.0 (1.0–4.0)	2.0 (1.0–3.0)	.365 ^b

NS, nonsignificant.

^a Chi-square analysis.

^b Kruskal-Wallis test.

device is not validated, although accelerometer-based navigation systems have been validated in THA [30–32].

A further limitation of the study is the potential confounding factor of learning opportunities from previous tasks.

Conclusions

Freehand acetabular component placement results in a high percentage of outliers from target OI and OA, and although this is often overshadowed by errors in patient positioning in lateral decubitus clinically, it still constitutes an important factor. Using a MAG significantly reduces outliers from target OI. The spirit level MAG with a simple vertical rod and spirit level performed best. Using TAL yielded a more consistent OA. In this idealized in vitro setup, surgical experience did not prove to be of any benefit.

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Conflicts of interest

D. Beverland received royalties from DePuy Synthes and INNOMED; is in the speakers' bureau of or gives paid presentation for DePuy Synthes; is a paid employee and consultant for DePuy Synthes; and receives research support and financial and material support from DePuy Synthes.

References

- [1] Biedermann R, Tonin A, Krismer M, Rachbauer F, Eibl G, Stöckl B. Reducing the risk of dislocation after total hip arthroplasty: the effect of orientation of the acetabular component. *J Bone Joint Surg Br* 2005;87(6):762.
- [2] Patil S, Bergula A, Chen PC, Colwell CW, D'Lima DD. Polyethylene wear and acetabular component orientation. *J Bone Jt Surg Ser A* 2003;85-A(4):56.
- [3] Little NJ, Busch CA, Gallagher JA, Rorabeck CH, Bourne RB. Acetabular polyethylene wear and acetabular inclination and femoral offset. *Clin Orthop Relat Res* 2009;467(11):2895.
- [4] Lewinnek GE, Lewis JL, Tarr R, C.L.C, Zimmerman J. Dislocations after total hip replacement arthroplasties. *J Bone Jt Surg Am* 1978;60(2):217.
- [5] Domb BG, Redmond JM, Louis SS, et al. Accuracy of component positioning in 1980 total hip arthroplasties: a Comparative analysis by surgical technique and Mode of guidance. *J Arthroplasty* 2015;30:2208.
- [6] Darrith B, Bell AJ, Valle CJD, Culvern C. Can the use of an inclinometer improve the positioning of the acetabular component in total hip arthroplasty? *Bone Jt J* 2018;100B:862.
- [7] DiGioia AM, Jaramaz B, Plakseychuk AY, et al. Comparison of a mechanical acetabular alignment guide with computer placement of the socket. *J Arthroplasty* 2002;17(3):359.
- [8] Jolles BM, Genoud P, Hoffmeyer P. Computer-assisted cup placement techniques in total hip arthroplasty improve accuracy of placement. *Clin Orthop Relat Res* 2004;426:174.
- [9] Leenders T, Vandeveld D, Mahieu G, Nuyts R. Reduction in variability of acetabular cup abduction using computer assisted surgery: a prospective and randomized study. *Comput Aided Surg* 2002;7(2):99.
- [10] Kalteis T. Imageless navigation for insertion of the acetabular component in total hip arthroplasty: Is it as accurate as CT-based navigation? *J Bone Jt Surg - Br* 2006;88(2):163.
- [11] Steppacher SD, Kowal JH, Murphy SB. Improving cup positioning using a mechanical navigation instrument. *Clin Orthop Relat Res* 2011;469(2):423.
- [12] Schulz AP, Seide K, Queitsch C, et al. Results of total hip replacement using the Robodoc surgical assistant system: Clinical outcome and evaluation of complications for 97 procedures. *Int J Med Robot Comput Assist Surg* 2007;3(4):301.
- [13] Archbold HAP, Mockford B, Molloy D, McConway J, Ogonda L, Beverland D. The transverse acetabular ligament: an aid to orientation of the acetabular component during primary total hip replacement. A Prelim STUDY 1000 CASES Investig Postoper Stab 2006;88(7):883.
- [14] Beverland D. The transverse acetabular ligament: Optimizing version. *Orthopedics* 2010;33(9):631.
- [15] Beverland DE, O'Neill CKJ, Rutherford M, Molloy D, Hill JC. Placement of the acetabular component. *Bone Jt J* 2016;98-B(1 Supp A):37.
- [16] Hill JC, Gibson DP, Pagoti R, Beverland DE. Photographic measurement of the inclination of the acetabular component in total hip replacement using the posterior approach. *J Bone Jt Surg Br* 2010;92(9):1209.
- [17] Barrack RL, Krempec JA, Clohisy JC, et al. Accuracy of acetabular component position in hip arthroplasty. *J Bone Jt Surg Ser A* 2013;95(19):1760.
- [18] Murray DW. The definition and measurement of acetabular orientation. *J Bone Joint Surg Br* 1993;72(2):228.
- [19] O'Neill CK, Hill JC, Patterson CC, Molloy DO, Gill HS, Beverland DE. Reducing variability in apparent operative inclination during total hip arthroplasty: findings of a randomised controlled trial. *HIP Int* 2018;28(3):234.
- [20] Rutherford M, O'Connor JD, Hill JC, Beverland DE, Lennon AB, Dunne NJ. Patient positioning and cup orientation during total hip arthroplasty: assessment of current UK practice. *HIP Int* 2019;29(1):89.
- [21] Meng X, Qian N. The oblique effect depends on perceived, rather than physical, orientation and direction. *Vis Res* 2005;45(27):3402.
- [22] Digi-Pas UK Calibration Certificates n.d. <http://www.digipas.co.uk/support/calibration.php>. [Accessed 29 September 2021].
- [23] Appelle S. Perception and discrimination as a function of stimulus orientation: the "oblique effect" in man and animals. *Psychol Bull* 1972;4:266.
- [24] Howard IPI. Human visual orientation. *Hum Vis Orientat* 1982.
- [25] Westheimer G. The distribution of preferred orientations in the peripheral visual field. *Vis Res* 2003;43(1):53.
- [26] Archbold HAP, Słomczykowski M, Crone M, Eckman K, Jaramaz B, Beverland DE. The relationship of the orientation of the transverse acetabular ligament and acetabular labrum to the suggested safe zones of cup positioning in total hip arthroplasty. *HIP Int* 2008;18(1):1.
- [27] Babisch JW, Layher F, Amiot LP. The rationale for tilt-adjusted acetabular cup navigation. *J Bone Jt Surg - Ser A* 2008;90(2):357.
- [28] Saxler G, Marx A, Vandeveld D, et al. The accuracy of free-hand cup positioning - a CT based measurement of cup placement in 105 total hip arthroplasties. *Int Orthop* 2004;28(4):198.
- [29] Hassan DM, Johnston GHF, Dust WNC, Watson G, Dolovich AT. Accuracy of intraoperative assessment of acetabular prosthesis placement. *J Arthroplasty* 1998;13(1):80.
- [30] Shiratani Y, Hamano H, Wada Y. Is a portable accelerometer-based navigation system useful in total hip arthroplasty?: a systematic review and meta-analysis. *Orthop Traumatol Surg Res* 2021;107(1):102742.
- [31] Hayashi S, Hashimoto S, Takayama K, et al. Evaluation of the accuracy of acetabular cup orientation using the accelerometer-based portable navigation system. *J Orthop Sci* 2020;25(4):612.
- [32] Tetsunaga T, Yamada K, Tetsunaga T, et al. An accelerometer-based navigation system provides acetabular cup orientation accuracy comparable to that of computed tomography-based navigation during total hip arthroplasty in the supine position. *J Orthop Surg Res* 2020;15:147.