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Computer navigation of the acetabular component in total hip arthroplasty: a narrative review

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- Total hip arthroplasty (THA) is a common procedure for primary osteoarthritis, but increasing numbers are also being performed for other pathologies such as secondary arthritis, inflammatory arthropathies and trauma. Estimates suggest that around 8.5 million people in the UK are affected by joint pain secondary to arthritis and a rising ageing population has resulted in an increase in THA operations of around 4% per year over the last six years.
- Multiple studies have shown that THA provides improved quality of life scores, but there remains the burden of complications which account for 15% of £1bn NHS liability payouts. DaPalma et al analysed the financial impact of complications following THA and found the additional cost of a dislocation within six weeks of surgery is 342% of the primary cost.
- Following primary THA, complications may occur as a result of incorrect component positioning of the femoral stem, the acetabular cup or both. It is known that acetabular malposition may lead to increased rates of dislocation, impingement, edge-loading, polyethylene wear, pelvic osteolysis and prosthesis failure.
- Acetabular component positioning has been described as the single most important factor in dictating risk of dislocation following THA. Furthermore, instability and dislocation after primary THA is the most common single reason for revision surgery accounting for 22.5% of all revisions and 33% of acetabular revisions.
- We outline the currently available methods of acetabular navigation comparing freehand techniques with computer and robotic-assisted navigation of the acetabular component.

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Introduction

Total hip arthroplasty (THA) is a common procedure for primary osteoarthritis but increasing numbers are also being performed for other pathologies such as secondary arthritis, inflammatory arthropathies and trauma. Estimates suggest that around 8.5 million people in the UK are affected by joint pain secondary to arthritis, and a rise in the ageing population has resulted in an increase in THA operations of around 4% per year over the last six years.[1]

Multiple studies have shown that THA provides improved 'quality of life' scores, but there remains the burden of complications which account for 15% of £1bn NHS liability payouts.[2] DaPalma et al analysed the financial impact of complications following hip arthroplasty and found the additional cost of a dislocation within six weeks of surgery is 342% of the primary cost.[3]

Following primary THA, complications may occur as a result of incorrect component positioning of the femoral stem, the acetabular cup or both. It is known that acetabular malposition may lead to increased rates of dislocation,[4] impingement,[5] edge-loading,[6] polyethylene wear,[7] pelvic osteolysis[4] and prosthesis failure.[8]

Acetabular component positioning has been described as the single most important factor in determining the risk of dislocation following THA.[9] Furthermore, instability and dislocation after primary THA is the most common single reason for revision surgery, accounting for 22.5% of all revisions and 33% of acetabular revisions.[10]

We outline the currently available methods of acetabular navigation, comparing freehand techniques with computer- and robotic-assisted navigation of the acetabular component.

Acetabular cup placement prior to computer navigation in THA

There is a lack of consensus as to the appropriate position of acetabular cup placement. Traditionally acetabular cup placement has been defined according to the anterior pelvic plane (APP) as a surrogate marker for pelvic position. APP is identified by joining three bony landmarks in the pelvis: both anterior superior iliac spines (ASIS) and the symphysis pubis, as described by Robinson et al in 1922.[11]

Lewinneck used a three-legged jig device to find APP which contained a spirit level to ensure horizontal positioning.[12] By comparing post-operative radiographs of THAs that had dislocated with stable hips, they recommended 40° (+/- 10°) abduction and 15° (+/- 10°) anteversion. Cups placed outside this zone exhibited an increased dislocation risk of four times, when compared with controls. Alternative safe zones have been described by Barrack et al[13] and McCollum et al[14] and all are supported by a retrospective analysis of 127 dislocations, which shows that failure to place the cup within a conceptual safe zone increases the risk of dislocation.[15]

In current practice there are various ways by which surgeons aim to achieve acetabular cup placement within a pre-determined 'safe zone'. The most common type of navigation utilises a simple mechanical alignment rod. The surgeon uses experience to judge the position of cup anteversion compared with the patient's superior shoulder, and the position of inclination when compared with the floor, with the additional visual assistance of an alignment rod which can be attached to the cup impactor. However there are multiple studies which show that surgeons using this manual referencing system often place the acetabular components outside the safe zone and there is significant variability in final cup placement.[16-18] An analysis of 1952 total hip arthroplasties by Callanan et al[19] indicated that only 62% of cases were placed within their desired inclination of between 30° and 45°, suggesting that surgeons cannot rely on the assumption that the patient's pelvic position is orientated in line with the floor or the long axis of the body.

Further studies have suggested that the transverse acetabular ligament (TAL) is a good reference point for acetabular component positioning and a potential adjunct to the alignment rod method. Kelley and Swank[20] found 82% and 71% of their cups were placed within the Lewinneck-defined safe zones for inclination and anteversion respectively when using TAL referencing, which is an improvement compared with the results reported from use of the mechanical alignment rod. In an additional study of 121 patients undergoing THA,[21] which include primary osteoarthritis and dysplastic hip patients, the TAL was identified and its position assessed by aligning it with the trial acetabular component by computer navigation. They found that only 5% of the natural TAL position fell outside of the recommended safe zones of component positioning.

Archbold et al[22] claimed to have identified the TAL in 99.7% of 1000 consecutive THAs, and when using TAL as the reference for acetabular cup placement, the clinical outcome was satisfactory with only a 0.6% dislocation rate. However this study lacks supporting data on post-operative assessment of cup position. Conflicting reports suggest the TAL is identifiable in less than half of THA operations.[23]

Conflicting data exists which questions the reliability of the TAL as a method of navigation. MRI studies have shown that the natural anteversion of the TAL in healthy subjects ranges from 5.3° to 36.1° which would render this landmark useless in judging cup placement.[24] Furthermore, natural acetabular position in the native hip is inconsistent and known to change with osteoarthritis, dysplasia and osteonecrosis. A study of the natural orientation of the acetabulum in arthritic hips showed a smaller angle of inclination and anteversion for both sexes.[9] In osteoarthritis secondary to dysplasia there is no correlation between TAL position and the patient's acetabular anatomy. A study of 80 hips undergoing THA for dysplasia by pre-operative CT scans showed a range of between 14°-18° of acetabular anteversion. When compared with a control cohort of patients with osteonecrosis there was a significant difference in range and mean anteversion between groups.[25] This research group subsequently used TAL as a navigation aid for cup placement with a target of 15° +/- 19° anteversion resulting in 39% of cups implanted outside of the target range.

Computer navigation in THA

Computer navigation in THA began in 1992 and has also been used in hip resurfacing,[26] knee arthroplasty[27] and PAO surgery.[28] However, the uptake has been hampered by concerns about cost, increased operation time and blood loss.

Aside from the traditional mechanical alignment rod with or without use of the TAL, there are two types of computer navigation systems used for acetabular cup placement. These can be subdivided into image-based and imageless navigation.[29] The aim of all computer-assisted arthroplasty, regardless of type, is to provide real-time feedback to surgeons and allow execution of pre-operative planning[30] often in the form of a heads-up display or computer readout (Fig. 1).

Image-based navigation relies on pre-operative CT imaging or intra-operative fluoroscopy. Both of these techniques have been criticised in the literature for imposing increased planning time and cost to the operating team and radiation to the patient. As an alternative, imageless navigation relies upon localisation of bony landmarks of the pelvis in order to feedback the patient's pelvic position to sensors mounted on the reamer which indicate its position compared with the anterior pelvic plane (Figs 2a & 2b). A four-stage process, regardless of commercial system used, has been described and includes set-up, registration, planning and execution stages.[30]

The set-up and registration stages are performed in the operating theatre with the patient anaesthetised. Our

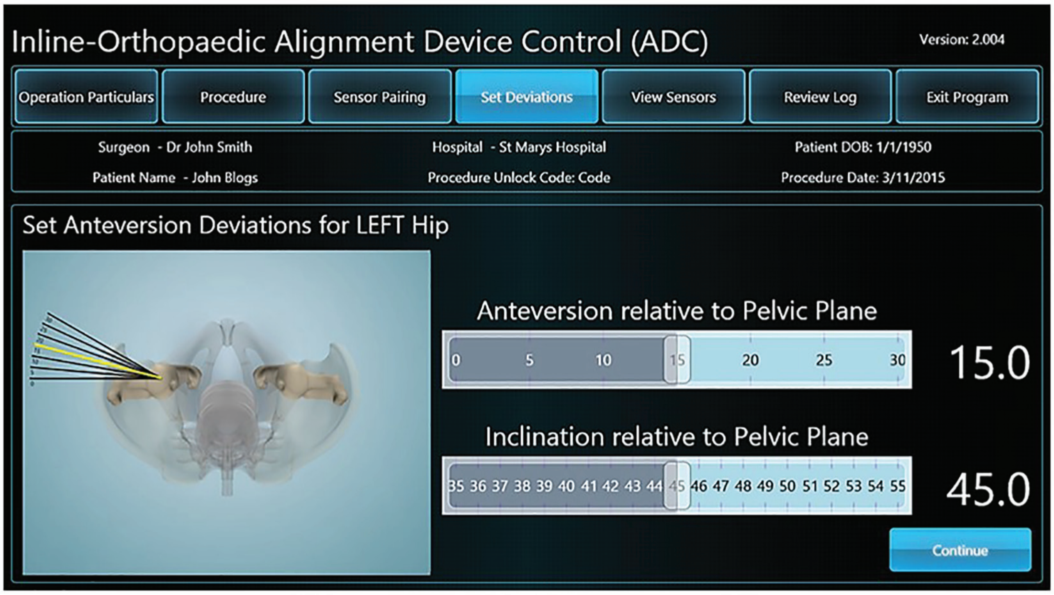

Fig. 1 Screenshot from the InLine Orthopaedics navigation system indicating anteversion and inclination (Image courtesy of InLine Orthopaedics).

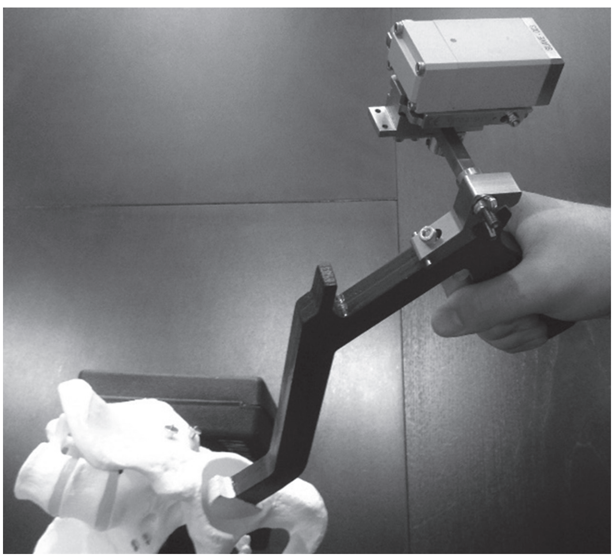

Fig. 2a Dry-bone model showing an example sensor attached to a mock reamer (Image courtesy of InLine Orthopaedics).

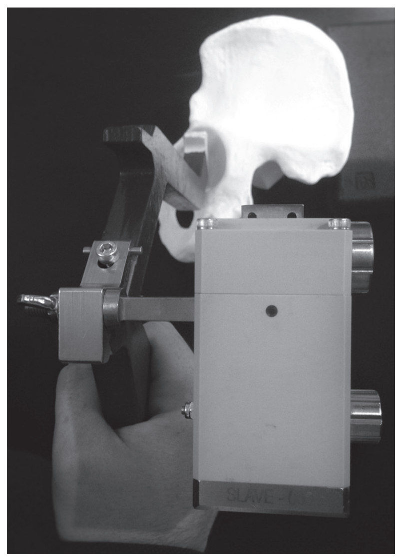

Fig. 2b Dry-bone model showing an example of a sensor attached to a mock reamer (Image courtesy of InLine Orthopaedics).

group recommend and utilise a lateral position, which facilities our approach to the hip. The bony landmarks we use are the bilateral ASIS and pubic symphysis (Fig. 3).

Evidence for computer navigation

In a prospective randomised controlled trial of 130 patients undergoing THA, equally divided between free-hand technique and navigated technique of acetabular component placement, post-operative CT was used to determine the achieved cup position at three months. There was a significant improvement in the mean anteversion angles achieved using navigation, but the study failed to show an improvement in inclination.[31]

There is further evidence of the benefit of imageless navigation with regards to inclination. Suksathien et al[7] conducted a retrospective comparison of acetabular component position on post-op CT scans in 31 THAs compared with 30 controls. Significant differences in both mean anteversion and inclination were observed.

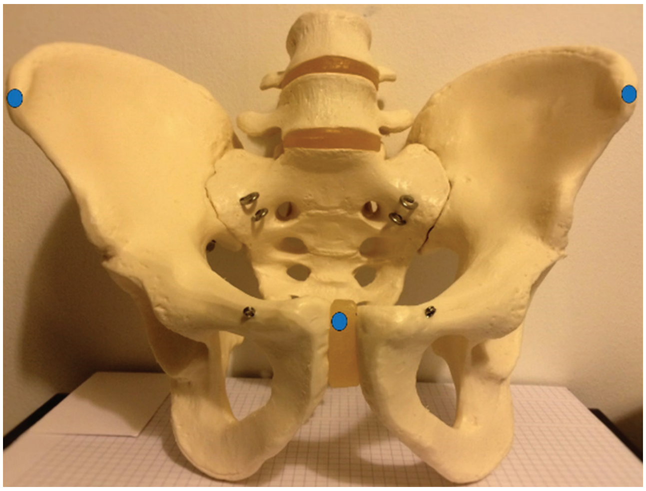

Fig. 3 Bony landmarks used as a reference guide for the anterior pelvis plane (APP) (Image courtesy of InLine Orthopaedics).

Furthermore, there was an associated decrease in the range of component positions. Interestingly, when assessing anteversion and inclination in combination, this group found that 100% of the computer-navigated cups were within the defined safe zone, compared with only 48.4% of non-navigated cups. There was no significant difference in operative time.

There have been a number of meta-analyses to assess the effectiveness of navigation in correctly placing the acetabular component. A recent meta-analysis[32] included 13 randomised controlled trials comparing navigated and non-navigated THA. The sample size included 1071 hips, and when navigation was used there were significantly more acetabular components placed in the safe zones for both anteversion and inclination. However, this study noted that there was no difference in rate of post-operative dislocation between groups. This conclusion is backed up by a similar study by Moskal et al,[8] but by contrast this group found a reduction in the rate of dislocation in the navigated group compared to the non-navigated group. In summary, multiple meta-analyses have shown that computer navigation results in improved cup placement, an improvement in cup placement variability and a reduced risk of outliers from the safe zone, but no strong correlation with improved clinical outcome at short-term follow-up.[29,33,34,35]

The limitations of computer navigation

Reliance on imageless computer navigation systems on the APP has been criticised as a potentially inaccurate method for determining pelvic position due to registration errors and its lack of accounting for pelvic tilt.[36,37] An ultrasound study has assessed thickness of skin and fat over the three reference points and found that there will be inaccuracy specifically with anteversion analysis.[38] This is particularly problematic in obese patients.[37]

Wolf et al[39] have demonstrated this theoretical effect, showing that inaccurate registration of the APP results in incorrectly placed acetabular components.

Deep and Picard[30] have analysed the overall impact of incorrectly registering the bony landmarks and provided tables to indicate the theoretical inaccuracy in cup placement. However, the error ranges described were large (between 1 cm and 4 cm), and we would suggest such inaccuracy should be unlikely, especially when performed by experienced orthopaedic surgeons.

Concern over registration has led some groups to use invasive methods. Dorr et al[40] used skin puncture over the bony landmarks to improve registration; however, there is concern about donor site morbidity with theoretical, but not reported, increased risk of infection, bleeding, fracture and mechanical pull-out.

Aside from registration issues, the reliability of APP has been questioned by some. Barbier et al[41] reported a prospective, single-centre study of 44 patients imaged using a three-dimensional pelvic imaging system three months following computer-navigated THA. They found significant differences between operative navigation records and post-operative imaging. More specifically, operative anteversion appeared to show the weakest correlation, with mean anteversion at operation of 20.9^{o}, but 29.5^{o} in post-operative imaging. The reason for this poor correlation is thought to be due to both the difficulty in registering APP pre-operatively and the inter-observer variation intra-operatively.

An additional study by Lin et al[42] described the limitations of computer navigation in their experience. A 50-patient cohort study equally divided between computer-navigated and non-navigated THA had post-operative CT scans to assess position of the cup relative to Lewinneck's safe zones. Whilst their data supports navigation, which resulted in 100% cup placement within the target zone compared to 92% in the non-navigated group, there was a significant discrepancy between the intra-operative navigation recordings and post-operative CT scans. They found that the absolute difference between operative inclination and inclination on CT was 0^{o} +/- 2.8^{o}; however, isolated anteversion difference was significant at 3.4^{o} +/- 3.6^{o}. The explanation for this is difficulty in registering the bony landmarks for APP pre-operatively but also the concept that extremes of pelvic tilt can affect the relationship between acetabular anatomy and the APP. While we can determine APP, pelvic tilt is dynamic. The Dorr group[40] shows the influence of pelvic tilt on the final anteversion measured post-operatively – 1^{o} of ventral-to-dorsal tilt corresponded to a 0.8^{o} change in acetabular anteversion.[40,43] Failure to account for the variation in pelvic tilt could lead to the previously described complications, including dislocation.[15]

Future developments in navigation – the role of robotics

Robotic-assisted joint arthroplasty surgery has been heralded as the next step in accurate acetabular cup placement.[44] It is estimated that robotic technology is now used in 80 000 procedures per year. There are various classifications of surgical robot available for arthroplasty, but that most commonly applied to acetabular navigation is the 'semi-automated robot'. Stryker's Mako robotic arm-assisted system (Stryker, Kalamazoo, MI, USA) (Fig. 4) requires pre-operative CT scanning of the patient's pelvis in order to pre-determine the appropriate reaming and cup implantation.

The surgical technique requires the surgeon to perform exposure and soft tissue clearance before the robot performs acetabular reaming according to pre-operatively planned parameters. The surgeon remains in control of the robotic arm during acetabular preparation in order to make fine adjustments to cup placement (Fig. 5); however, the Mako robotic arm will restrict the movement of the surgeon to the pre-defined cup position, and will not allow significant deviation from the surgical planning.

Indeed there is already evidence that robotic-assisted acetabular cup placement outperforms conventional methods of cup placement.[45] In a matched-pair control study of 100 patients undergoing THA equally divided between robotic-assisted and conventional surgery, post-operative radiographic analysis showed that robotic-assisted surgery resulted in 100% of cups within the Lewinneck's safe zone and 92% within Callanan's safe zone. This was significantly better than conventional methods, which resulted in 80% and 62% respectively.

A recent multi-surgeon retrospective analysis of acetabular component placement in 1980 patients compared six modes of guidance including mechanical alignment rod, TAL referencing, fluoroscopy-guided, computer-navigated and robotic-guided systems.[46] The TraumaCad software system was used to analyse post-operative radiographs to determine acetabular inclination and anteversion. There was a consistent target for cup positioning of 40^0 inclination and 20^0 anteversion throughout the groups. Computer-navigated and robotic-assisted acetabular placement resulted in a significantly greater number of cups within the Lewinneck's safe zone when compared with other systems, but when adjusted for Callanan's safe zones robotic-assisted acetabular navigation improved accuracy of cup placement significantly when compared to all modalities. The average achieved anteversion and inclination across the study was 42^0 and 20^0 respectively. However, there was a significantly smaller standard deviation in the computer navigated and robotic-assisted groups when compared with all other methods.

A drawback of the robotics study[46] is that the author experienced one (2%) case of robotic-assisted failure requiring conversion to the conventional method of cup placement. This indicates the importance of acetabular cup placement being supervised or performed by a senior experienced surgeon in order to use good judgement when required. Further theoretical limitations on employing such equipment include set-up and running costs, restriction of implant choice for robotic system compatibility, exposure to radiation via CT, and operative time.

Fig. 4 The Stryker Mako robotic arm-assisted system (Image courtesy of Stryker Orthopaedics).

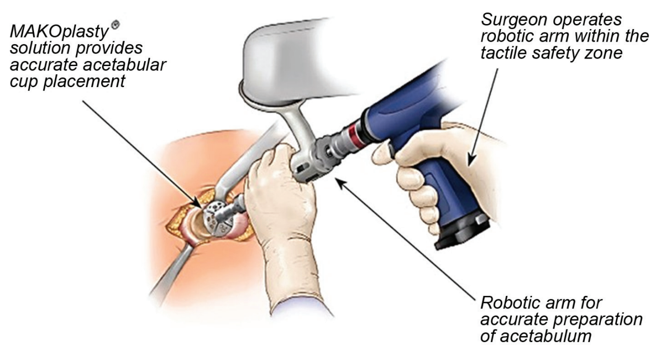

Fig. 5 Diagram showing Mako robotic arm in use (Image courtesy of Stryker Orthopaedics).

Discussion

Acetabular navigation is evolving, and the driving force is the desire to improve clinical outcomes following THA and reduce complications associated with inaccurate cup placement. There is strong literature evidence to indicate an advantage of using computer-assisted navigation but there is a lack of long-term follow-up data to prove the clinical merits. It has been suggested that due to the current excellent outcomes following THA, it may be difficult to determine a clinical benefit of accurate cup placement over the short-term, and longer outcome studies will be required.[30]

We have shown that there remains a lack of consensus as to the best 'safe-zone', leaving surgeons divided in their opinion. An example of this has been shown in the most recent meta-analysis to date.[29] Seven studies including 485 THAs showed that whilst there was no significant difference in mean cup position between non-navigated and navigated groups, there was a significant reduction in the variability of cup position when navigation was used when compared with specific surgeon-determined safe zones.

Multiple meta-analyses indicate that computer navigation has advantages in cup placement over non-navigated methods and the future of hip arthroplasty is likely to involve computer-navigated or even robotic-assisted methods, but future research needs to prove a cost-effective long-term clinical benefit to patients.

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CONFLICT OF INTEREST

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