



Brief Report

Anterior Pelvic Roll During Primary Total Hip Arthroplasty in the Lateral Decubitus Position: A Systematic Review

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Abstract

Background: Conventional lateral decubitus positioning for Total Hip Arthroplasties (THAs) is highly imprecise and further loss-of-position occurs during the procedure itself. This unintended movement is poorly recognised and can introduce substantial error in definitive acetabular component orientation. Failure to achieve desired target cup position is strongly-associated with a number of adverse outcome measures, including bearing wear, increased revision rate and dislocation.

Methods: A structured, systematic literature review was performed following PRISMA search principles to provide a contemporary summary-of-understanding in this area and to highlight clinical and knowledge deficiencies.

Conclusions: Lateral positioning is generally imprecise and error prone. Unintended intra-operative pelvic movement routinely exceeds recommended 'clinically-relevant' limits. These changes increase the potential for final cup placement outside of accepted/functional 'safe zones' or away from intended insertional targets, potentially leading to future adverse outcomes. Further research into more consistent and reliable positioning aids is indicated. Current evidence supports technology-assisted techniques/navigation to accurately quantify intra-operative pelvic movement in real-time and allow for error correction to optimise target cup insertion.

Keywords: Hip navigation; Pelvic roll; Pelvic tilt; Technology-assisted surgery; Total hip arthroplasty

Introduction

Optimal insertional orientation of the acetabular component during Total Hip Arthroplasty (THA) is a critical determinant of many tangible outcomes, including construct stability. At its extreme, malpositioning may lead to prosthetic dislocation. With the majority of THAs currently still being introduced from a lateral decubitus patient position, factors which introduce inconsistency or error in achieving the desired final cup position have been extensively explored. Sound previous research has confirmed the following: 1.

there is great inconsistency and often poor reproducibility in the accuracy with which a true decubitus position is achieved during the 'set up' phase of a THA operation; 2. conventional positioning devices perform poorly in maintaining the initial set up position during the performance of a THA; 3. there is considerable patient loss-of-position during the operation itself (i.e. the position of the pelvis changes during surgery); 4. an erroneous pelvic position (from the start of the operation) and/or a loss of position during the procedure introduces a substantial potential for error in the ultimate insertional orientation of the cup; 5. suboptimal cup position has been strongly associated with a number of poor outcome measures, including wear, increased revision rate and

dislocation. A number of previous investigations have attempted to quantify the ‘average’ amount of unintended pelvic movement which occurs during the performance of a routine primary THA. Interpretation of such information has - in many instances - been clouded by inconsistent data collection methods or by unreliable measurement approaches. The purpose of this study, following PRISMA search principles, was to comprehensively review and summarise the available literature regarding the assessment and consequence of unintended intra-operative pelvic movement and its impact of the orientation of definitive acetabular component placement during THA.

Search Strategy and Selection Criteria

To ensure a relevant, accurate and representative synopsis of the current state-of-understanding of intra-operative pelvic movement and the impact of such changes on ultimate cup position during primary THA, a structured and systematic search and retrieval of publications was performed according to the accepted Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The search results are depicted in Figure 1. Three databases: (i) Cochrane; (ii) EMBASE; and (iii) Medline were searched from inception until 27 September 2021. Search results were limited in the first instance to articles available in the English language with available abstracts. The following MESH terms were used: [(THA OR THR) OR (total hip arthroplasty OR total hip replacement)] AND [(anterior roll OR rotation OR roll) OR (pelvic tilt)] AND [(lateral OR decubitus) AND position*] AND [movement]. Titles and abstracts of identified records were screened to exclude obviously irrelevant studies. Articles that described changes in pelvic position during surgery, and/or specifically during hip arthroplasty in the lateral position were reviewed. No limitations were placed on age, gender, date, type of study, or length of follow-up. Articles were excluded if they did not specifically discuss or report quantified change in pelvic position during hip surgery, or if no full-text in English language was available. The bibliographies of relevant papers were manually reviewed to identify further studies, with additional data sourced from international joint registries. Initially, 113 articles were identified during preliminary database searching. After exclusion of duplicates, articles which did not match the search intent (i.e. papers not specifically exploring content related to intra-operative pelvic movement) and articles not available in full text form, 91 full text papers were manually reviewed. At the end of the review process, 65 articles were deemed appropriate for inclusion. As a relatively new topic in the field, it was identified that there existed a lack of quantitative research within the domain thus preventing formal ‘meta-analysis’, per se. With the preserved intent of providing a contemporary synopsis of the topic, a structured review of the identified literature was performed in keeping with meta-synthesis principles.

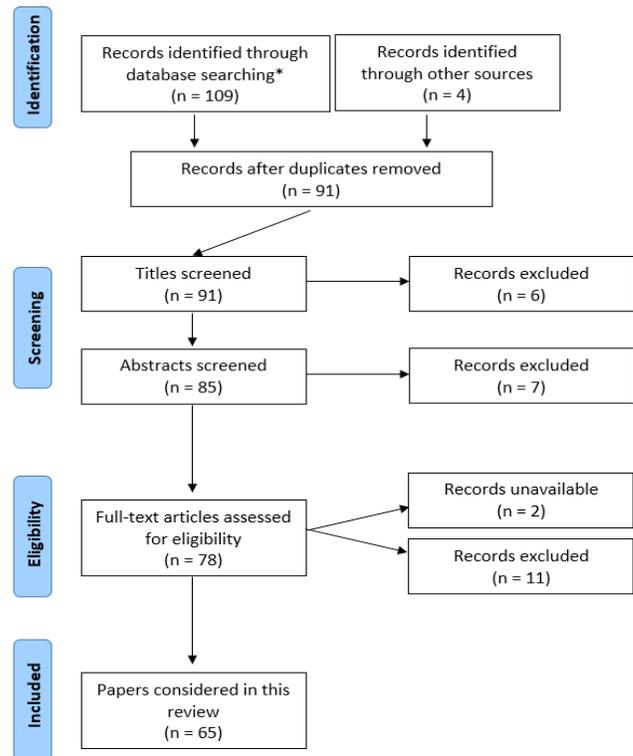


Figure 1: PRISMA search summary. * Mon Sept 27 10:57:10 2021 Search: [(THA OR THR) OR (total hip arthroplasty OR total hip replacement)] AND [(anterior roll OR rotation OR roll) OR (pelvic tilt)] AND [(lateral OR decubitus) AND position*] AND (movement) AND (English\Language).

Understanding pelvic movement

While most surgeons agree that accurate implantation of the acetabular component of a THA is important for patient outcomes, the ‘ideal’ position is not universally agreed [1,2]. While the historic reference of Lewinek’s safe zone has formed the basis of most ‘target’ cup positions [3,4], many contemporary authors suggest that there may be merit in a ‘patient-specific’ orientation goal and that ‘one size’ does not fit all. Indeed, many proponents advocate for individualised patient assessment - often in the form of pre-operative functional imaging [5-7] - to inform intra-operative decision making. The key determinant ‘pelvic tilt’ (or ‘roll’) reflects the divergent angle between the Anterior Pelvic Plane (APP) and a vertical line in the anatomical (standing) position [8] (Figure 2). The large study of 1517 THAs by Pierrepoint and colleagues (2017) suggested that in nearly 20% of patients the extent of functional sagittal pelvic rotation (reflecting pelvic tilt) could lead to construct instability using historical ‘safe zone’ targets [7]. Certainly an awareness of spinopelvic movement parameters allows informed consideration of customised/patient specific cup implantation targets [7,9]. Many centres now

incorporate pre-operative spinopelvic movement assessment into routine work up pathways [10]. While it is clear that fundamental clinical assessment alone is insufficient to fully appreciate the linked movement characteristics of the human spine and pelvis on a patient-by-patient basis [10], how best to interpret often complex pre-operative imaging data and how to optimally apply this information to target cup planning [8] remains unclear and represents an opportunity for future investigation.

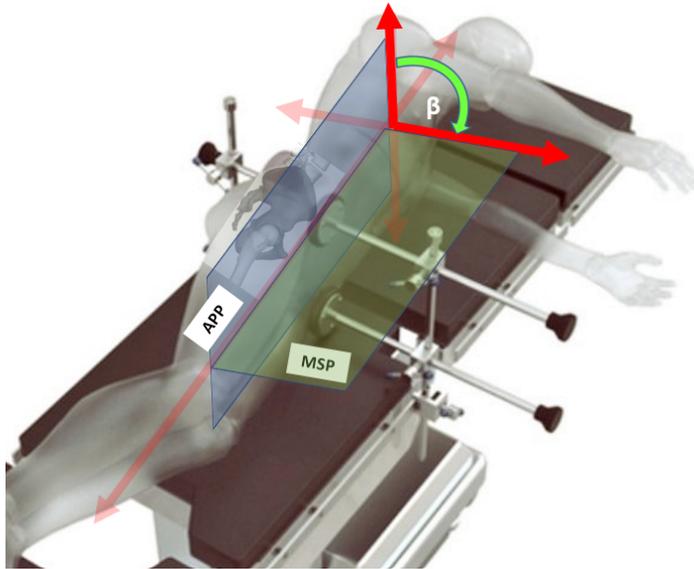


Figure 2: Pelvic tilt. Measurement of the anterior tilt angle in a lateral decubitus position. Forward tilt is determined as the angle subtended by the difference in degrees from the true APP (i.e. the vertical starting position) to the measured APP as it approaches the MSP (i.e. as the pelvis rolls anteriorly) Kurmis AP, et al. (2022). APP = anterior pelvic plane; MSP = mid-sagittal plane; β = anterior tilt angle

Langston et al. (2018) [11] suggested that a change in pelvic tilt of 13° or more on pre-op assessment may be deemed unfavourable as this will result in a change in the functional anteversion of the acetabulum of 10° . This has the potential to place even a well-orientated component outside of the target safe zone [11]. In the same work, the authors suggested that unfavourable pelvic mobility was independently associated with limited lumbar flexion, a more posterior standing pelvic tilt and increasing age [11,12]. Unsurprisingly, they strongly advocated for pre-operative functional x-ray imaging [11]. It is noteworthy that none of the three associated factors are immediately amendable to peri-operative correction prior to elective THA and may also thus be considered immutable. Even with such informed pre-surgical patient data, what best to ‘do’ with this information is less clear. Simply centring the implanted cup to the middle of the functional movement range has inherent risk and may not necessarily result

in optimal construct orientation to accommodate the rigors of daily activity.

The process of high precision data capture with pre-operative functional imaging is also not without its challenges. True lateral pelvic x-rays (required for accurate angular measurement) can be technically challenging to obtain and - under present conditions - at best reflect a series of pre-determined static captures of the bony relationship between the lower lumbosacral spine, pelvis and proximal femur. These are not dynamic measures and do not directly take into account the critical impact of the surrounding soft tissue envelopes. Using the more commonly employed proprietary functional x-ray series, the relationship of the key bony elements in the extremes of motion are not represented - likely the positions most vulnerable to permit prosthetic dislocation. Recent work has suggested potential enhanced value with pre-operative simultaneous biplanar imaging [13], as compared to conventional plain film x-rays. The proprietary EOS imaging system (Euronext: EOSI; Paris, France) is touted to reduce the radiation dose by two thirds as compared to equivalent plain x-ray imaging [13,14]. The technology permits simultaneous capture of precisely orthogonal x-ray images in an upright, physiological load-bearing position and is claimed to be more accurate and less dependent on patient positioning [13]. Given that some have suggested limited practical utility of plain film x-rays in judging sagittal pelvic tilt [15] consideration of EOS (or other high precision imaging modalities) may hold merit. However, while the current science may suggest a role for EOS in replacing pre-operative radiographic assessment [13], the technology is not universally available and carries associated expense.

Intra-operatively, three considerations become important with respect to the accuracy of definitive cup placement. Firstly, is the original position of the patient (as a surrogate for the true pelvis position). In the lateral set up, the surgeon/surgical team endeavour to ensure the patient’s pelvic sagittal plane is horizontally orientated. In most practical senses, this refers to this key alignment plane being parallel to the theatre floor [16,17]. Classically, surgeons have relied on palpation of key bony landmarks (i.e. ASIS and pubic symphysis) [18-20] to determine if the APP [21] is indeed perpendicular to the flat level surface of the operating table. Direct and accurate localisation of the contralateral ASIS for APP determination can be challenging in the lateral position [21]. Unsurprisingly, there is considerable inaccuracy in this subjective process [22] which assumes both landmark symmetry and an ability of the surgeon to accurately appreciate the location of such landmarks. An array of commonly-used positioning aids are employed for achieving and maintaining the true lateral orientation for THA. These usually involve some combination of posterior sacral block [23] and an anterior symphyseal bolster or ASIS post [23] - the latter of which may involve single or paired extensions. More proprietary universal

lateral positioners [24] or peg boards [25] are also used with reasonable effect. In a 2019 UK nationwide investigation however, Rutherford and colleagues explored surgeons' sentiment towards current positioning tools [26]. More than 35% of respondents were 'unhappy' with their current supports [26], while less than a third (31%) felt their current positioning supports were rigid and stable. The need for better positioning tools is almost unanimously championed [23,25].

Previous authors have proposed customised pelvic orientation devices for use during initial set up claiming simplicity of use and improved accuracy and reproducibility in achieving a pelvis horizontal in the sagittal plane¹⁶. To date, despite the potential value of such positioning aids, they have failed to attract mainstream uptake and use. Iwakiri and colleagues (2017) [27] reported a custom variation of an existing positioning device with the addition of an extra compression pad [27]. Described as 'simple, minimally invasive and cost effective'[27] the authors were able to show significant reductions in intra-operative sagittal pelvic tilt. Other studies have shown highly significant differences ($p < 0.001$) in the maintenance of intra-operative pelvic position when comparing the type of mechanical support used [25]. Beyond blaming the tools, multiple studies have shown significant variation in the ability of surgeons/surgical teams to accurately position the pelvis for THA surgery [25]. The 2011 work of Nishikubo and colleagues used in-theatre fluoroscopy to check for pelvic positioning errors prior to commencement of surgery [28]. With a pelvis orientated with 0° of tilt versus the horizontal sagittal plane as the target standard, they reported a mean positioning error of nearly 6° - this before the operation had even begun [28]. The later study of Lambers et al. (2016) reported a more modest error of closer to 3° but a wider range of recorded starting errors as high as 13 degrees [29]. In a subanalysis the same authors suggest that malpositioning is indeed a common occurrence in everyday practice and is more likely with increasing patient Body Mass Index (BMI) [29].

The second critical element is the ability of the set up to maintain consistently the position of the patient during the operation itself. This too is a multi-factorial consideration. Pelvic movement affects perceived cup inclination and version and may lead to an unintended cup implantation error [30]. While the recommendations are not uniformly agreed, Otero and co-authors (2018) suggested that 'proper' (acceptable) positioning could perhaps be defined whereby there was $< 10^\circ$ of subsequent pelvic positional change during the THA procedure itself [31]. The initial patient position is maintained by positioning devices presumed to be rigid and stable - in many instances however this is not the case. Especially with increasing BMI [32] and general patient size, the effectiveness with which these one-size-fits-all devices secure and

maintain the position of the pelvis is poor. Further undermining this consideration, Milone and colleagues (2017) suggested that rigid positioning alone was an unreliable way of ensuring accurate final cup placement [24]. While almost all commonly employed such equipment is designed to provide stable support against unyielding bony landmarks (ASIS etc.), simply tightening them further to increase the rigidity of support is also not without risk. In their recent 2020 publication, Ueno and colleagues demonstrated a 2.64% rate of medically-important soft tissue ulceration secondary to pelvic positioner use for routine primary THAs [33].

The pelvis is exposed to many discrete deforming forces during a conventional THA which may result in iatrogenic pelvic tilt [32]. The process of mechanical cup reaming and implant impaction are obvious examples [32], but 'strong' traction from exposure-permitting retractors are also a recognised culprit [32,34]. While traction for safe exposure may be an unavoidable evil during primary THA, authors who have considered this important force mechanism recommend releasing or 'backing off' retractor tension during the critical stage of definitive cup impaction [33], which may permit some measure of tilt correction [32]. The 2019 work of Della Valle et al. however suggests that retractor removal is unlikely to facilitate complete correction of anterior roll which had been induced earlier during the case [30].

Thirdly, the surgeon must be able to accurately, consistently and reproducibly introduce the acetabular component with the correct 3D orientation and then impact it whilst precisely maintaining this. As a fundamental tenant of the assumption that surgeons can reliably perform this task Somerville et al. (2021) [34] explored the accuracy with which a cohort of experienced trauma and arthroplasty surgeons visually assessed cup anteversion and inclination angles [34]. There was great variability amongst the group with results ranging from 'very poor' to 'very good' with only moderate inter-observer reproducibility [34]. There have been many proposed methods for improving the precision and/or reproducibility of cup insertion. Such measures have included: following anatomical landmarks [31], the use of intra-operative imaging [28], manual instrumentation jigs and alignment guides [16] or the use of intra-operative navigation [35]. The most commonly cited anatomic landmark for cup insertion remains the Transverse Acetabular Ligament (TAL) [1]. The value of this local feature has been questioned however, the earlier work of Epstein et al. (2011) suggesting the TAL was only appreciably present in 47% of osteoarthritic hips [36] and that, even when it was identified, its presence did not improve the attainment of target cup position [36]. They concluded that cup orientation using the TAL was no more accurate than an unassisted freehand insertion technique [36], with the subsequent work of Beverland et al. (2016) actively recommending against using the TAL to determine final cup inclination [1].

Intra-operative imaging has been touted as a potentially useful step to improve the accuracy of final cup position although this too is not without its inherent challenges. Difficulty in the physical process of introducing imaging equipment into sterile fields and capturing meaningful images (i.e. accurately perpendicular to the long axis of the pelvis), concerns regarding radiation exposure and fundamental problems with the interpretation of an image captured in a decubitus position (as compared to the 'routine' AP supine state) are all noteworthy considerations. While some authors advocate the use of imaging routinely [37,38] (most often fluoroscopy [29]) as an intra-operative aide - especially in the setting of a high BMI patient [29] - others have suggested limited utility through such means citing mismatch between apparent intra-operative and radiographic cup orientation [17]. Hayakawa et al. (2009) suggested mean errors of $>5^\circ$ in both cup inclination and anteversion perception using intra-operative radiographs versus the post-operative gold standard [39] concluding that in-theatre determinations may not reflect post-operative targets. Using conventional instrumented cup implantation techniques there are many proprietary differences between implant systems which cloud comparability. In essence, the AP inclination angle (i.e. 'lateral opening' or 'abduction' angle) is visually-appreciated as the angle between the cup insertion handle and the sagittal plane [16]. Critically, if at the time of cup insertion the pelvic sagittal plane is not (or is no longer) parallel to the floor, an error of component placement will occur [16]. Body axis alignment (or appreciation thereof) directly influences cup version, as can changes in pelvic flexion and extension.

Whilst a relatively recent addition to the arthroplasty surgeon's armamentarium in many parts of the world, the use of intra-operative computer-assisted hip navigation provides another means for aiding cup insertion [24,40]. In its two most basic forms, such systems use either pre-operative 'imaging informed' or 'imageless' [19,41] approaches. As with accepted Total Knee Arthroplasty (TKA) applications, both portable (i.e. 'mini-nav' [42,43]) and 'full navigation' systems are available for use during hip surgery. Whilst large volume data is still pending, early applications of navigated THA suggest consistent improvements in achieving the desired insertion orientation [42] with significantly less ($p<0.001$) deviations from target [40]. Most commercially-available navigation systems reference the APP which provides the frame-of-reference orientation for later angular measurement [8,22] although the paper by Vigdorichik and colleagues (2021) suggests that the perpendicular hip-shoulder-axis may actually be the more accurate and consistent registration plane [41]. The well-performed 2020 prospective randomised control trial by Tanino et al. compared the accuracy of a portable, accelerometer-based navigation system with that of conventional instrumented techniques [40]. While adding an average of 10 operative minutes to each case [40], the use of navigation was associated with

significant improvements in attainment of target cup position [40] - a sentiment supporting the landmark earlier work of Jolles et al. in 2004 [44]. One of the key benefits of contemporary THA navigation [24,40] likely lies in the ability of such systems to track intra-operative pelvic movement and provide 'corrective' measurements [45]. In many cases, the system has the ability to recognise the occurrence and magnitude of pelvic positional changes, even when such movement is below the threshold of unaided surgeon perception. While many authors (and users) feel that intra-operative navigation stands as the best widely available tool for accurate cup implantation [22], such systems do have their own inherent shortcomings including a user learning-curve, system failures, loss of tracker position and poor reliability with increasing pelvic tilt [43]. The integration of EOS imaging applications into intra-operative navigation systems (NAVEOS; VA, USA) is a potentially exciting novel pairing [18] which has been touted to further simplify cup placement with increased accuracy in a lateral decubitus position [18] however this technology needs further, rigorous, validation before wider adoption can be championed.

Discussion

Worldwide, the majority of primary THA is still performed in the lateral position [1] although it has been shown that this position is associated with the greatest degree of unintended intra-operative pelvic movement [23,27,40,46]. Accurate acetabular cup orientation is critical in THA for good clinical results [47] and most authors acknowledge that this can often be a difficult task [4]. Pelvic tilt alters apparent cup position [23] and may subsequently result in suboptimal placement [45]. While the operative approach itself whilst in the decubitus orientation is also an independent consideration for movement (more so with posterior versus anterolateral approaches [25]), failure to recognise changes in pelvic position introduces the potential for erroneous cup placement [25]. Suboptimal acetabular component placement has been linked to a number of post-operative adverse outcomes [6,42] including accelerated bearing wear [2,19,39,48,49] and dislocation risk [2,19,39,40,48,50,51] mechanical impingement [51], decreased functional range-of-movement [12,19,40,48], component migration [39], poor joint function [49], and metal ion toxicity [49]. Regardless of the target orientation, the ability to reliably achieve an optimal acetabular component position is crucial to successful THA [29,31,52].

As discussed previously herein, final cup position is substantially influenced by intra-op patient positioning [2,26], including the initial set up [1,25,29]. Despite the best efforts of surgeons/theatre teams, it remains the case that a pelvis will often move intra-operatively during the performance of a THA [3,25] - in spite of seemingly well applied and tensioned positioning devices. Surgeons must remain cognisant to this reality [32]. While several novel devices have been proposed, to date, there

exists no mainstream, low-risk accepted method for ensuring a 'true' lateral position at the start of a case [17]. Statistically, a pelvis is (far) more likely to roll anteriorly ($p < 0.001$) during a THA in the decubitus set up [3] and this forward tilt is likely progressive across the operation [30]. It has been demonstrated that the greatest source of error occurs when the pelvic sagittal plane is no longer horizontal at time of cup insertion [53]. While it has been proposed that such sequential loss of starting position likely progresses until at least the point of definitive cup and liner insertion, few quantitative data support this at this stage - another inviting opportunity for future research. Pure anterior pelvic roll has been shown to influence cup anteversion to a greater extent than inclination [24]. It is accepted that major pelvic movement will have an effect on the final cup insertion position [33] through perceptual error. Given the common anterior roll mechanism seen, this consequently leads to an underestimation of cup anteversion [30], with the degree of error directly related to the magnitude of pelvic tilt [6,27,50].

How far does an average pelvis move during a routine, primary, THA? Several previous authors have attempted to quantify 'normal' ranges of unintended pelvic movement during THA [23,25,30,33] and then to propose acceptable 'cut offs' to define clinically important variation [24]. Anterior (or posterior) pelvic tilt alters the position of the cup in the sagittal plane [54] which has a direct impact on version perception. In case series' including 67-100 hips [23-25,30,33] previous works have reported median intra-operative pelvic tilt values of >4 degrees [3,30], however mean values and maximum observed tilts ranged broadly between studies - often approaching 20° for the latter [30]. Such studies show 41-57% of cases rolling anteriorly >5 degrees [23,24,29], with 21-38% by >10 degrees [3,24,31]. Otero's 2018 paper reported 15.4% of cases with $10-20^\circ$ of tilt and 2.8% with >20 degrees [31]. In interpreting these errors, Grammatopoulos et al. (2018) suggested that a $>10^\circ$ anteversion error had a 3.5 odds ratio of the final cup position falling outside of the target safe zone [3]. Using widely accepted mathematical conversion factors [54,55], one degree of pelvic tilt results in a $0.7-0.8^\circ$ change in final anteversion. Given the longstanding surgical goal of achieving target anteversion $\pm 10^\circ$ (see Lewinek and others [56]), an unappreciated intra-operative pelvic tilt of just 13° would therefore be enough to see an otherwise perfectly centred cup fall outside of the 'safe' anteversion range. Inconsistency in initial patient set up [25] (i.e. with non-perpendicular 'true' lateral decubitus positioning) linked with a subsequent change in the pelvic position during the operative process (i.e. movement) likely contributes a substantial burden of the variation seen in final cup position [25] despite otherwise technically sound surgical technique. Uniaxial pelvic tilt has been specifically associated with unintended errors in cup version [55]. A high correlation between direct pelvic tilt and version angle ($R^2 = 0.995$, $p < 0.001$) [55] has been confirmed and

is intrinsically linked to the fact that the negative impact of pelvic tilt can be corrected with relative ease using simple (validated) mathematical algorithms with very high precision [55]. Until recently, the challenge however has remained the ability recognise intra-operative pelvic tilt and to accurately quantify its magnitude. While the most common historical methods for determining implantation parameters for acetabular components have included mechanical alignment guides and reference against the TAL [26], both methods have been shown to be unreliable [47] and hinge on precise judgement 'as per the surgeons eye' [57]. Accurate intra-operative determination of anteversion can be difficult [38], even in experienced hands. Technology-assisted surgical options however may provide a solution to the limitations of visual human assessment.

Using standard navigation, it is possible to determine pelvic inclination and tilt by calculating the angular difference between the anatomic frontal plane and true horizontal (i.e. floor) [35]. Modern navigation systems - especially those using accelerometer-based technologies - provide the valuable added benefit of measuring the relative change in the pelvic position independently from data captured from the fixed pelvic tracker(s). Measurement of pelvic tilt during THA allows corrective algorithms to re-calculate the cup insertion angles to correct for the error introduced by pelvic movement and have been shown to improve the accuracy of component placement as per the intended target [54,58]. The large 2010 study by Zhu and colleagues explored the quantitative value of navigation during THA in a cohort approaching 500 hips [54]. While these authors reported a mean intra-operative tilt of just under 5° , the observed range was from 25° of posterior tilt through to 20° of anterior (i.e. a 45° unintended error range) [54]. Over 25% of patients rolled $6-9^\circ$, while over 16% moved more than 10° . It has not yet been definitively established what the perceptual tolerances of visual assessment of pelvic tilt may be by surgeons (or varying levels of experience) although it seems clear that deficiencies in this key skill likely have a negative influence on intended cup implantation position [11].

While much research, attention and interest has centred around pelvic tilt during surgery, the important role of pelvic adduction is rarely assessed or considered [30,59]. Given that the acetabular cup is a 3D element, inserted with intended orientation goals in 3D, it is conceivable that unintended pelvic movement in any direction may have negative consequence on final cup position [31]. Mathematically, unappreciated pelvic adduction can increase radiographic inclination [57] which may have consequences for final bearing stability [59]. In a routine posterior approach to the hip (in a lateral decubitus position) the relatively wider pelvis as compared to the lower limbs tends to see the uppermost hemipelvis drift into adduction [57]. The previous work of O'Neill and colleagues (2018) assessed the pelvic movement

in 270 consecutive primary THAs suggesting that none of their cases showed pelvic abduction with a mean adduction change of 4.4 degrees [59]. This finding was similar to other authors who reported average adduction angles of 2.5-6.7 degrees [30,32]. It is generally felt that these smaller magnitude changes have a lesser impact on inclination than do comparable movements involving pelvic tilt.

Current research would support the notion that anterior pelvic roll occurs incrementally across the case from set up to definitive implant insertion. The descriptive work of Grammatopoulos et al. (2014) suggested a mean angular movement from set up to implant insertion of 9° (sd 6) [25]. Others have suggested similar changes [33]. The later work of Schloemann and colleagues (2019) suggested that more than just 5° of change may be ‘clinically significant’ [37] supporting the suggestion that such unaccounted for angular change may facilitate introduction of critical errors in target cup placement [24,37]. Several authors have recommended that the highest (and most consistent) level of attainment of target cup position may perhaps be achieved using the combination of an assistive anatomical plane (pelvic) positioner and navigation [45,47]. Iwakiri and colleagues (2017) suggested such an approach was reliably simple, consistent, economical and non-invasive [47]. Despite the focus of hip navigation on radiographic outcomes and intra-operative changes, the critical consideration of patient body habitus must be considered. Most authors agree that increasing patient BMI strongly correlates with errors in target cup orientation attainment [29,33] and also intra-operative pelvic positional change [32]. The extended length of bariatric tissue retractors for surgical exposure [32,33] (and sometimes the force applied to them) and direct soft tissue impingement can worsen the magnitude of positional movement [60]. However, high BMI alone cannot be blamed for all of the issues noted with unintended pelvic positional change - the 2019 work of Schloemann et al. showed clinically-relevant anterior pelvic roll in a cohort with a mean BMI of just 20 [37]. Similarly, other authors have suggested no clear association between BMI and pelvic movement [24,30,61]. Regardless, obesity is just one factor so far linked to intra-operative pelvic movement - with evidence to show that low volume surgeons and the approach employed are also recognised cofactors [62].

The future for hip arthroplasty appears exciting, especially as appropriately-employed technologies facilitate further improvements in planning, precision and intra-operative execution. Historical two dimensional (2D) templating and planning has already been shown to be far less accurate than modern 3D equivalents [63]. The evolution to more universal 3D standards is likely to incrementally improve surgical planning [64] as such technologies become more mainstream. The cutting edge integration of artificial intelligence algorithms into the

pre-operative decision making pathways may represent further advancement still [65]. Similarly, as intra-operative computer navigation is taken up more broadly many anticipate improved attainment of target cup placement [35] (in a similar fashion to accuracy improvements that were seen during the evolution of TKA navigation). Despite great enthusiasm in some spheres, navigated arthroplasty is not without its inherent problems and limitations. Tracker pin site placement and loosening [46] continue to undermine case-by-case precision with only small positional changes resulting in magnified degradation in accuracy. As with other bony-mounted navigation applications in other parts of the body, site fractures, wound and pin site issues post-operatively also plague use and present technique-specific challenges. Some supporters of technology have suggested that formal (‘full’) hip navigation may be unnecessary, suggesting that less invasive and less time consuming alternatives are already available to improve operative precision. Using a simple off-the-self smartphone with basic accelerometer capability, Peters et al. in 2012 reported a series of 50 THAs suggesting their novel technique was simple, ‘quick and accurate’, reporting that ‘all’ cases were able to achieve less than 5% deviation from the intended pre-operative plan [4]. Similar work by O’Neill et al. (2018) using a simple digital inclinometer reported achieving target cup position within 2.5° in 88% of cases [53] and showed positive statistically-significant differences as compared to conventional instrumented approaches. Contrasting CT-based full navigation with ‘imageless’ accelerometer (mini) navigation however, the recent work by Testsunaga et al. (2020) suggested the latter lacked the accuracy of image-based techniques [46] but it was unclear whether the precision-versus-target cup position translated to meaningful clinical benefit. Equally, the potential improvement in accuracy must be weighed against the time, expense and radiation exposure associated with CT-based pre-op imaging.

Opponents of navigation frequently cite the ‘is the extra angular precision actually worth it’ argument. The now standard use of larger heads, and with increasingly-common selection of dual mobility bearings [66], has arguably improved the stability and mechanical characteristics in many instances perhaps negating the need for such high levels of cup orientation accuracy. Indeed, in their 2013 paper Eilander and colleagues suggested that hip navigation may be an ‘unnecessary’ technical burden, claiming that 82% of the hips included within their comprehensive study had cups within radiographic safe zones using conventional free hand techniques [48]. Finally, the progression to robot-assisted THA surgery [24] may offer further clinical advantages with early science suggesting value, especially in complex cases [67,68] - this area too requires further research to ensure the evidence base underpinning wider uptake stays ahead of the enthusiastic hype.

Conclusions

This comprehensive review of the current literature highlights the following: 1. current techniques and equipment for patient set up in the lateral decubitus position are deficient and, if used poorly, have the potential to cause patient harm. As a result, sagittal plane movement during THAs (i.e. anterior pelvic roll) is currently an accepted shortcoming. Common patterns of sequential pelvic movement during surgery have not been well determined and represent an opportunity for future investigation; 2. the ability of surgeons/surgical teams to visually appreciate (often large) changes in pelvic position with any degree of quantitative precision - in a patient under exclusion draping - is universally unreliable. This is increasingly so in the setting of obesity/high BMI; 3. failure to appreciate such pelvic movement has a direct and tangible effect upon the ability to insert the definitive acetabular component accurately with the intended target position in mind; 4. such unintended component positioning errors likely have a subsequent negative effect on the mechanical parameters of the THA construct and previous evidence would suggest this may lead to increased risk of wear, instability and possibly dislocation (all key determinants of later revision surgery); 5. while the conventional/historical standard for cup insertion has been 'per the surgeon's eye' or using manual alignment jigs, both fail to reliably appreciate intra-operative patient movement. Evidence would suggest that - when used correctly - contemporary navigation systems have the potential to improve the precision of implant insertion versus target orientations by narrowing outlier ranges and by calculation of corrective parameters to compensate for computer-appreciated pelvic positional change; 6. while used widely in some international settings, intra-operative hip navigation (image informed or imageless) has not yet achieved widespread adoption and still requires rigorous scientific validation to confirm its utility in more general settings and to further refine optimised indications for use. The role of robot-assisted approaches in this context show promise but require more generalised validation.

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