Towards Perfect Acetabular Cup Placement in Total Hip Arthroplasty

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Towards Perfect Acetabular Cup Placement in Total Hip Arthroplasty

Op weg naar de perfecte heupkomplaatsing bij totale heupprothesen

(met een samenvatting in het Nederlands)

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CHAPTER 1

General Introduction and Thesis Outline

Hip Osteoarthritis

Hip osteoarthritis (OA) affects millions worldwide, with its prevalence increasing with age and contributing significantly to disability and reduced quality of life.[1–3] Hip OA imposes a substantial burden on individuals and healthcare systems, with escalating global prevalence due to aging populations, rising obesity rates, and improved management of chronic diseases.[1] The condition is irreversible and progresses from mild symptoms, such as joint pain and stiffness, to severe disability in advanced stages. Hip OA has been studied since ancient times, with early descriptions by Hippocrates and significant advances in the 19th century.[4–8] OA involves the degeneration of joint cartilage and subchondral bone remodelling, driven by a complex interplay of mechanical stress, inflammation, and systemic factors, with an ongoing discussion about the pathophysiology.[9–13] The disease progresses through a vicious cycle of cartilage breakdown, joint instability, and muscular adaptation ultimately leading to end-stage OA with an impaired joint function.[14–19] OA is projected to contribute the largest increase in disease burden by 2040 in the Netherlands.[17] In the Netherlands alone, hip OA accounted for €446 million in healthcare costs in 2019.[20] Treatment focuses on symptom management through conservative measures, including pain relief, physical therapy, and lifestyle modifications. However, many patients eventually require total hip arthroplasty (THA) as the disease advances to end-stage joint degeneration.

Total Hip Arthroplasty

Hip replacement began in 1891 with Themistocles Glück's use of ivory to replace damaged femoral heads, evolving through various experimental techniques to modern THA.[21] Sir John Charnley's innovations in the 1950s, including low-friction designs, bone cement, and polyethylene bearings, revolutionized the procedure (Figure 1).[21–24]

Today, advancements in materials, fixation methods, and bearing designs have enhanced durability, wear resistance, and implant stability, significantly improving outcomes for patients with end-stage hip OA and thereby reducing the overall revision rate.[22,24] Nevertheless, there remains a significant need to decrease the burden of revisions as joint registry data shows an overall survival rate of around 75% at 15 to 20 years and only 58% at 25 years.[3,25] According to national joint registries from Australia, Sweden, and the United Kingdom, the main reasons for revision are aseptic loosening, periprosthetic fracture, dislocation/instability, infection, osteolysis, and implant wear. THA dislocation consistently ranks among the top three reasons for revision, accounting for 15 to 21.7% of cases, depending on the registry that is consulted.[26–28]

Figure 1. Radiograph of the pelvis. The right side demonstrates a Charnley low-friction arthroplasty, consisting of a prosthetic cup positioned in the acetabulum and a stem within the femur. The left side shows a native hip with features indicative of osteoarthritis, including joint space narrowing, subchondral sclerosis, cyst formation, and osteophytes.

Total Hip Arthroplasty Dislocation and Impingement

At its introduction in 1962 THA had a dislocation risk of 4.8%.[29] In recent decades the dislocation rate has decreased, likely due to improvements in implant design and surgical techniques such as muscle sparing and alternative approaches. The current dislocation rate after a primary THA is reported to be around 1.7% at 2 years and 2.1% at 6 years postoperatively.[30–33] Dislocations have a severe emotional impact on patients, result in lower quality of life and require more hospital resources.[34,35] Patients who experience dislocations face a significantly increased burden in terms of days in hospital, claims payments for THA hospitalization, and costs for comprehensive outpatient healthcare services compared to those without dislocations.[36] Furthermore, Hermansen et al. using the Danish Hip Register (DHR) data showed that 22.4% of patients experience a re-dislocation after a revision for THA dislocation, probably explaining why THA dislocation is the leading cause of re-revision in the Australian registry[27,37] For the patient it is therefore crucial to get it right in the primary THA.[38]

Understanding the multifactorial aspects of THA dislocation is critical for identifying patients at risk. Risk factors are categorized into patient-, implant-, surgical-, and hospital-related factors.[33] Patient-related risks include high body mass index (BMI), previous spinal fusion which might increase compensatory hip motion, or previous hip surgery compromising muscle tension of the gluteus medius.[33] Additionally, THA indications such as avascular necrosis, rheumatoid arthritis, and inflammatory arthritis elevate the likelihood of dislocation.[33] Implant-related factors associated with reduced risk include correct collum-caput-diaphyseal angles, elevated acetabular liners, dual mobility cups, cemented fixations, specific bearing types, standard femoral neck lengths and larger femoral head diameters which all play a biomechanical role in creation of impingement.[33] The latter improves range of motion and stability but depend on precise acetabular component positioning, emphasizing the critical role of surgical technique.[39–44] Surgical factors, such as approaches like anterolateral or direct anterior, may lower the risk compared to the posterior approach, especially when short external rotators and the posterior capsule in this approach are not repaired.[33] Hospital-related factors include experienced surgeons, high surgical volumes, and preoperative patient education.[33]

While THA dislocation is multifactorial and is sometimes created by impingement, component impingement always has a biomechanical origin. In the long term, component impingement is related to aseptic loosening and component wear, both responsible for 1.8-2.5% and 0.5-0.6% of the THA revisions in recent large scale registries.[26–28,45]
To understand the factors influencing THA stability and component impingement, it is essential to examine the mechanisms of dislocation. Dislocation occurs when joint reaction forces are directed outside the containment of the acetabular cup, primarily through two mechanisms: impingement and excessive femoral stem translation (Figure 2).

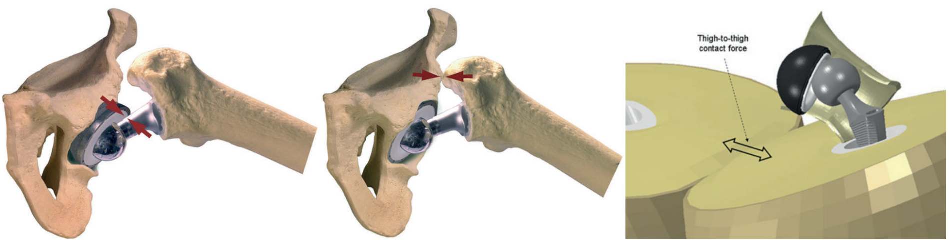

Figure 2. From left to right: implant-to-implant impingement, bone-to-bone impingement, and the generation of a laterally directed force during hip adduction due to thigh-to-thigh contact in patients with a high BMI. All three contributing to the mechanism of total hip arthroplasty (THA) dislocation.

Impingement arises when the femoral head is levered out of the acetabular cup due to anatomical obstruction, often during movements like deep squatting, bending forward, or excessive hip adduction and internal rotation. It can occur between implant components (implant-implant), such as contact between the femoral neck and the acetabular cup, or between bone structures (bony-bony), like contact between the greater trochanter and the pelvis.[46,47] Excessive femoral stem translation, typically seen in obese patients, results from soft tissue contact during flexion and adduction, producing lateral forces that push the femoral head outward.[46–48] Both mechanisms highlight the importance of maintaining proper alignment and muscle tension to prevent dislocation.

The challenge is maintaining joint reaction forces within the containment of the acetabular cup to optimize stability and avoid impingement. Ideal acetabular cup orientation reduces the risk of dislocation, improving patients' confidence in their hip's functionality, enabling the resumption of daily activities, and enhancing overall quality of life. The current recommendation for acetabular cup orientation stems from a 1978 study by Lewinnek, involving 7 cases of dislocation and 300 stable total hip prostheses.[49] The study recommended an orientation with 40° ± 10° inclination and 15° ± 10° anteversion. While the original study standardized the measurement techniques and considers pelvic tilt by the "anterior pelvic plane", subsequent research has introduced diverse methodologies for component orientation measurements, largely driven by CT-based three-dimensional (3-D) assessments. This has resulted in a heterogeneous and inconsistent approach to evaluating acetabular orientation, particularly regarding pelvic positioning and spino-pelvic-femoral motion.

Aim of the Thesis

In order to further improve THA outcomes and lower revisions risk, ideally the joint reaction forces remain within the boundaries of the acetabular cup, irrespective of the patient's anatomy, position, and spino-pelvic-femoral motion, without creating impingement. What surgery-related factors play a role in THA impingement and can this be mitigated with personalized THA 3-D planning strategy? To achieve this ideal placement, we first need to understand what constitutes perfect placement and whether a personalized, perfect orientation can be achieved during surgery. Therefore, the purpose of this thesis is to explore whether an individualized, optimal acetabular cup orientation can be established, accounting for variations in anatomy, motion, and spino-pelvic relationships, to enhance THA stability and avoid impingement. Furthermore, if the ideal cup orientation for an individual patient is unknown, what are the barriers to determining it, and can we provide solutions for some of these barriers?

OUTLINE OF THE THESIS

PART 1

Quantification of Three-Dimensional Total Hip Arthroplasty Cup Orientation

Chapter 2 explores the capabilities and errors of navigation systems in the placement of the acetabular cup compared to freehand placement. It examines whether the use of a navigation system is more precise and accurate, and if it is feasible to achieve presumed perfect acetabular cup placement. Additionally, it investigates whether this precision results in fewer THA dislocations or if it is still limited by certain inaccuracies. Chapter 3 systematically reviews and appraises the literature on the presumed consensus regarding the optimal acetabular cup orientation up to 2017. It also describes the terminology and measurement methods of postoperative acetabular cup orientation. The published studies included different measurement methods but used the same two-dimensional terminology, making it difficult to interpret results, particularly concerning the term "anteversion." Chapter 4, therefore, raises issues with aligning these different anteversion definitions for consistent interpretation, which represent different projectional angles of the acetabular cup in various planes around different axes.

PART 2

Quantification of Three-Dimensional Cup Orientation Dynamics

In Chapter 5, the problems associated with different projectional angles on various planes around different axes are addressed by providing a solution that describes the rigorous 3-D cup orientation, which can be mathematically validated. This 'true' 3-D acetabular cup orientation acknowledges the orientation angle on the sagittal plane around the transverse axis. This neglected plane throughout the history of THA research is important as the main motion of the hip revolves around this axis. When changing from standing to sitting position, the pelvis typically rotates posteriorly around the transverse axis while the hips flex and this affects the femoro-acetabular positions. Throughout the existing literature only simplified models of the effect of motion on acetabular cup orientation exist. Chapter 6 integrates the effect of pelvic motion around the transverse axis into the 'true' 3-D acetabular cup orientation for the individual patient.

PART 3

Towards Functional Three-Dimensional Cup orientation in Total Hip Arthroplasty

Chapter 7 compares our newly defined ("true") 3-D acetabular cup orientation in a case-control study of patients with posterior THA dislocations versus those with stable THAs. It incorporates the individual 3-D acetabular cup orientation and pelvic motion, highlighting differences between these groups, including variations in the sagittal plane. Given the importance of the sagittal angle of the acetabular cup for THA stability, Chapter 8 examines the sagittal angle of the native acetabulum in the normal adult population. Additionally, it explores the relationship between the acetabulum and sagittal spinopelvic characteristics.

Note: This thesis supports the use of three-dimensional (3-D) acetabular cup orientation. While several articles were still under development, no consensus existed on the orientation angle of the acetabular cup in the sagittal plane. Consequently, in Chapters 5 and 6, this angle is referred to as the "sagittal (ante)tilt." With the publication of the article by Eftekhary et al.[50] in 2019—following the establishment of the Hip-Spine Workgroup and its first meeting at the American Academy of Orthopedic Surgeons Annual Meeting in 2018—a consensus was reached. Therefore, in Chapters 7 and 8, this angle in the sagittal plane is referred to as the "sagittal anteinclination."

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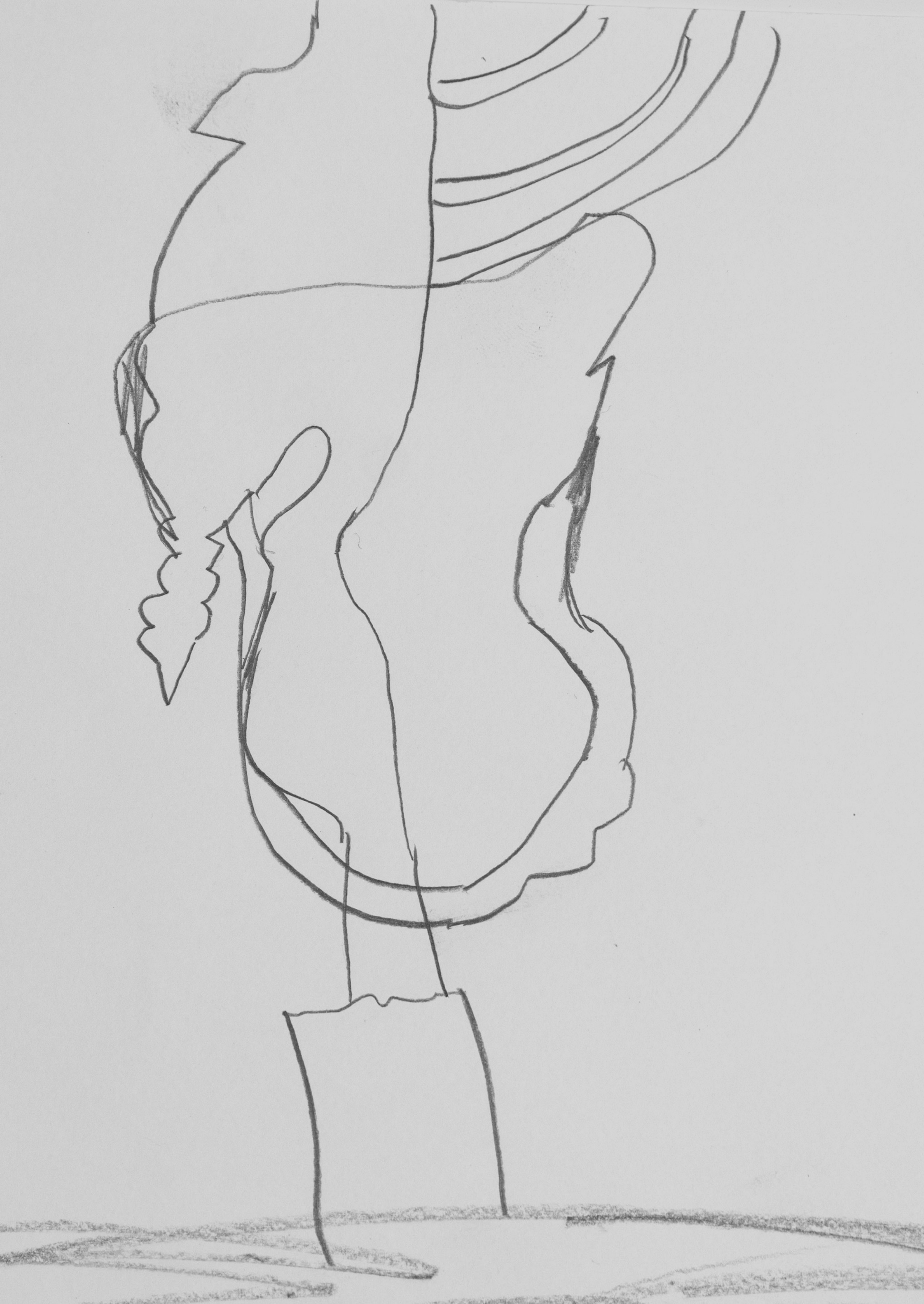
PART 1

Quantification of Three-Dimensional Total Hip Arthroplasty Cup Orientation



CHAPTER 2

Precision and Accuracy of Imageless Navigation versus Freehand Implantation of Total Hip Arthroplasty: A Systematic Review and Meta-Analysis

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ABSTRACT

Background

Total hip arthroplasty (THA) is named the most successful surgical procedure of the twentieth century. To remain a success in the twenty-first century THA should meet the higher demands of patients and society with regard to technical and functional outcome, costs and implant survival. To meet these demands optimal acetabular cup positioning is necessary. An imageless navigation system (NAV) might prevent malpositioning of the acetabular cup in THA. The aim of this study has been to compare the precision and accuracy of the anteversion and inclination of the acetabular cup position after NAV implantation and after freehand implantation of THA.

Methods

A systematic review and meta-analysis was conducted to assess the precision (variance) and accuracy (deviation from the target) from all available high-quality randomized control trials to date.

Results

Six out of seven studies concluded a statistically significant difference in precision in anteversion between the NAV group and the freehand group. Five out of seven studies concluded a statistically significant difference in precision in inclination. There is a significantly better accuracy for the NAV group than for the freehand group for anteversion ($p = 0.002$) and for inclination ($p = 0.01$).

Conclusion

This study showed that NAV placement is more precise and has an improved accuracy for anteversion and inclination than freehand placement of the acetabular cup. However, there is a lack of evidence to support an improved functional outcome and a reduction of complications and revisions.

INTRODUCTION

Total hip arthroplasty (THA) is named the most successful surgical procedure of the twentieth century.[1] In recent decades there have been significant improvements in the design, material and modes of fixation of the prosthesis components of THA.[2] To remain a success in the twenty-first century THA should meet the higher demands of patients and the society with regard to technical and functional outcome, costs and implant survival.[3]

An important factor in meeting those demands has been the optimization of positioning of prosthesis components to increase the range of motion[4], prevent bony impingement and impingement between components[5], prevent instability[6,7], reduce polyethylene wear[8], prevent osteolysis[9] and avert aseptic loosening.[9,10] Several studies showed that 30–60% of the cup and stem positions in the freehand placement are not in the designated target zone.[11–13]This isn't surprising, considering that perioperative estimation of component position by the surgeon is unreliable.[14]

At the beginning of the twenty-first century imageless navigation was developed in order to prevent malpositioning of THA components.[15] Imageless navigation uses optical sensors as 3-D position sensors to track the target bones and surgical tools or implants. In cup placement, the imageless navigation system (NAV) measures the anteversion and inclination angles relative to the anterior pelvic plane (APP). The APP is derived from the anterior superior iliac spines (ASIS) and the pubic tubercles as bony landmarks that are registered by the NAV.

NAV has not yet been broadly implemented by orthopedic surgeons for several reasons. First, it is questionable whether the accuracy and precision of the NAV in vivo is as good as proven on saw bones in vitro.[16] Secondly, there has been a lack of high-quality randomized control trials (RCTs) that prove a superior long-term clinical outcome of NAV compared to freehand implantation of THA. Finally, the extra costs of using such a system might not outweigh the potential benefits.

The main goal of the use of an NAV is to improve precision and accuracy in cup placement in THA. This is expressed in the deviation from the target and the variance respectively for anteversion and inclination in acetabular cup position. The aim of this study has been to compare the precision and accuracy of the anteversion and inclination of the acetabular cup position after NAV implantation and after freehand implantation of THA in all available high-quality RCTs to date.

METHODS

This report mostly follows the recommendations of the PRISMA statement for systematic reviews incorporating network meta-analyses.[17,18]

Search strategy

A Pubmed, Cochrane and Embase search was conducted to identify all relevant articles comparing NAV THA and freehand THA. The search parameters were 'total hip arthroplasty' OR 'total hip arthroplasties' OR 'total hip replacements' OR 'total hip replacement' OR 'total hip prosthesis' AND 'computer navigation' OR 'navigated' OR 'navigation' OR 'navigation based' OR 'computer assisted' OR 'computer based'. The results of the search were exported to a database (RefWorks 2.0) and all duplicate entries were identified and removed. When the inclusion and exclusion criteria were met after reading title and abstract, full-text articles were retrieved. The following predetermined inclusion criteria were used: RCTs between the use of an NAV and freehand THA, reporting on anteversion and inclination as outcome measures. A cross-reference check obtained remaining relevant articles. All studies that failed to meet the inclusion criteria (retrospective, non-imageless, animal, cadaver and saw bones studies, case reports and expert opinions) were excluded. The reasons for excluding trials or publications were documented. Another author was consulted in difficult cases. Agreement was reached in all cases.

NAV gives feedback on inclination and anteversion of the acetabular cup, relative to the APP. Measuring anteversion and inclination should be precise and accurate, thus minimizing the deviation from the target (precision) and with a low variance (accuracy). Therefore, statistical analyses were respectively done on the difference between variance and deviation from the goal of cup anteversion and cup inclination. For each study the F-test was used to test whether there was a difference in variance between the NAV group and the freehand group. A meta-analysis was done for the differences in deviation from goal anteversion and inclination between the NAV group and the freehand group. The statistical heterogeneity for each study was assessed using a standard chi-square test (statistical heterogeneity was considered to be present at $p = 0.1$) and I2 values of 50% were considered to indicate substantial heterogeneity.[19] When comparing trials exhibiting heterogeneity, pooled data were meta-analyzed using a random effects model instead of a fixed model.[20] The Revman version 5.1 software (Cochrane Collaboration, Oxford, UK) was used for the accuracy analyses.

RESULTS

Search and selection

The search yielded a total of 920 articles. After removal of duplicates 437 unique publications remained. Title and abstract of all publications were screened for our predetermined inclusion criteria, after which 26 publications were considered eligible. The full text of these 26 publications was obtained. After applying the exclusion criteria another 19 articles were excluded. Ten articles were retrospective studies, five studies compared a CT-based navigation system, one compared a NAV with an ultrasound navigation system, one was a cadaveric study, one was a case–control study and one only mentioned the clinical outcome.

A total of seven unique publications remained and provided the average anteversion and inclination with their standard deviation, which is needed to compare the difference in variance. All seven were level II evidence. Unfortunately, only four studies defined the deviation from their target goals, which is necessary to calculate the pooled accuracy. Checking the reference lists of all remaining publications yielded no other publications. A flow diagram is provided in Figure 1.

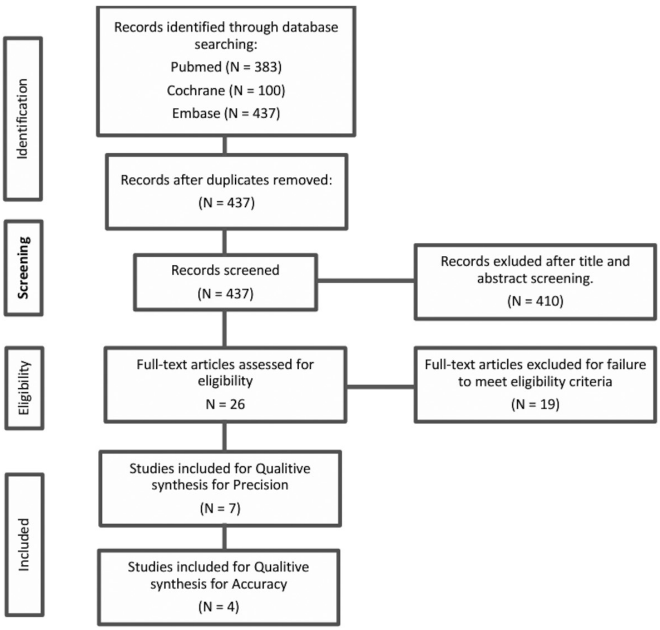

Figure 1. Search diagram

The patient groups were well matched at baseline for the available demographic data. The NAV group consisted of 255 patients with a mean age of 63.0 years and the freehand group comprised 259 patients with a mean age of 64.5 years. The mean BMI in the NAV group was 27.2 kg/m2, compared to 27.0 kg/m2 in the freehand group. The four articles for precision assessment were also well matched. The NAV group consisted of 127 patients with a mean age of 62.4 years and the freehand group comprised 130 patients with a mean age of 64.5 years. The mean BMI in the NAV group and in the freehand group was 27.5 kg/m2. The study of Gurgel had a statistically significant higher number of male patients in the freehand group compared to the NAV group.[21] Table 1 describes the characteristics of these studies.

Table 1. Demographic data

	Fang Lin 2011		Gurgel 2014		Kalteis 2005		Lass 2014		Parratte 2007		Sendtner 2011		Renkawitz 2015	
	N	F	N	F	N	F	N	F	N	F	N	F	N	F
N	25	25	20	20	23	22	62	63	30	30	32	30	66	69
M:F	15:10	13:12	10:10	17:03	08:15	09:13	21:41	29:34	16:14	16:14	13:19	11:19	29:37	35:34
Age	62.1	63.5	51.3	54	63.5	62.4	65.6	68.9	61.2	62.6	68	70	62.5	62.9
BMI	26.5	28.8	27.4	27.5	28	28.7	27.6	27	25.6	25.2	28	26	26.9	27.1

Six out of the seven studies concluded a statistically significant difference in precision in anteversion between the NAV group and the freehand group. Fang Lin (F-test = 4.715 > F-distribution = 2.02)[22], Kalteis (9 > 2.02)[23], Lass (5.11 > 1.52)[24], Parratte (4.55 > 1.84)[25] and Sendtner (8.33 > 1.82)[26] showed a clear improvement in precision for anteversion in the NAV group. Renkawitz (1.66 > 1.5) showed a marginal difference.[27] Gurgel (1.735 < 2.12) showed no difference in precision between the NAV group and the freehand group.[21] See Table 2.

The precision in inclination was statistically significantly improved in the NAV group compared to the freehand group in the studies from Fang Lin (4.719 > 2.02)[22], Kalteis (6.25 > 2.02) [23], Lass (2.086 > 1.52)[24] and Sendtner (2.748 > 1.82). [26] Renkawitz (1.575 > 1.5) showed a slight difference for an improved precision in the NAV group.[27] Gurgel (1.21 < 2.12)21 and Parratte (1.787 < 1.84) showed no statistical difference in precision for the measurement of inclination.[21,25] See Table 3.

A meta-analysis of the four studies, in which a difference in accuracy of anteversion could be determined, showed significant heterogeneity ($\chi 2$ = 10.46, df = 3, I2 = 71%). Using a random effects model, the pooled results indicated that there was a significantly better accuracy for the NAV group than for the freehand group (p = 0.002) for anteversion. See Table 4 and Figure 2.

Table 2. Precision of anteversion, F-test

Study	N Navi.	Mean Navi.	SD Navi.	N freehand	Mean freehand	SD freehand	F-test	F-distribution	Ho
Fang Lin 2011	22	17.7	3.5	25	20.3	7.6	4.715	2.02	Rejected
Gurgel 2014	20	17.4	6.3	20	14.5	8.3	1.735	2.12	Accepted
Kalteis 2005	23	14.4	5	22	24	15	9	2.02	Rejected
Lass 2014	62	19.5	4.6	63	17.3	10.4	5.11	1.52	Rejected
Parratte 2007	30	14.4	4.5	30	16.2	9.6	4.55	1.84	Rejected
Renkawitz2015	66	18.3	6.9	69	17.5	8.9	1.66	1.5	Rejected
Sendtner 2011	32	24.5	6	30	23.8	10.1	8.33	1.82	Rejected

HO = Equal variance, no difference between navigation and freehand

Table 3. Precision of inclination, F-test

Study	N Navi.	Mean Navi.	SD Navi.	N freehand	Mean freehand	SD freehand	F-test	F-distribution	HO
Fang Lin 2011	22	40	2.9	25	42.5	6.3	4.719	2.02	Rejected
Gurgel 2014	20	41.7	3	20	42.2	3.3	1.21	2.12	Accepted
Kalteis 2005	23	45	2.8	22	42.3	7	6.25	2.02	Rejected
Lass 2014	62	38.6	3.6	63	37.7	5.2	2.086	1.52	Rejected
Parratte 2007	30	34	5.7	30	34	7.62	1.787	1.84	Accepted
Renkawitz2015	66	42.5	5.1	69	42.4	6.4	1.575	1.5	Rejected
Sendtner 2011	32	42.3	3.8	30	37.9	6.3	2.748	1.82	Rejected

HO = Equal variance, no difference between navigation and freehand

Table 4. Accuracy of anteversion

	Navigation			Control				Mean difference
Study	Mean	SD	Total	Mean	SD	Total	Weight	IV, random, 95% CI
Fang Lin 2011	3.4	2.7	22	7.3	5.7	25	26.9%	-3.90 (-6.40, -1.40]
Gurgel 2014	5.5	3.8	20	6.6	4.9	20	25.7%	-1.10 -3.82, 1.62]
Kalteis 2005	4	2.9	23	13.7	10.4	22	16.9%	-9.70 [-14.20, -5.20]
Lass 2014	5.5	3.6	62	8.7	6.6	63	30.5%	-3.20 -5.06, -1.34]
Total (95% CI)			127			130	100%	-3.95 -5.06, -1.42]

Random effects; H0 = no difference between navigation and freehand; heterogeneity: $\tau 2$ = 4.53; $\chi 2$ = 10.46, df = 3 (p = 0.02); I2 71%; test for overall effect: Z = 3.07 (p = 0.002).

The four studies showed a significant heterogeneity ($\chi2 = 12.46$, df = 3, I2 = 76%). A random effects model showed a pooled result with a significantly improved accuracy for the NAV group compared to the freehand group (p = 0.01) for inclination. See Table 5 and Figure 3.

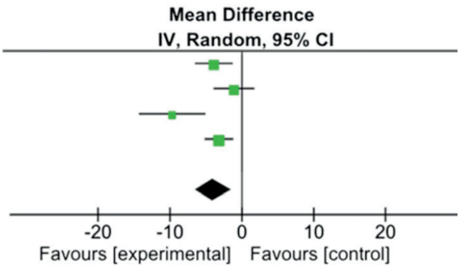

Figure 2. Accuracy of anteversion – Random effects; H0 = no difference between navigation and freehand; heterogeneity: $\tau2 = 4.53$; $\chi2 = 10.46$, df = 3 (p = 0.02); I2 71%; test for overall effect: Z = 3.07 (P = 0.002).

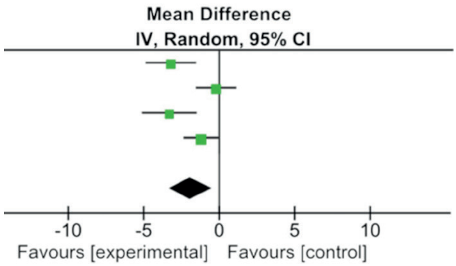

Figure 3. Accuracy of inclination – Random effects; H0 = no difference between navigation and freehand; heterogeneity: $\tau2 = 1.61$; $\chi2 = 12.46$, df = 3 (p = 0.006); I2 76%; test for overall effect: Z = 2.56 (P = 0.01).

Table 5. Accuracy of inclination

	Navigation			Control				Mean difference
Study	Mean	SD	Total	Mean	SD	Total	Weight	IV, random, 95% CI
Fang Lin 2011	2.3	1.5	22	5.5	3.8	25	23.5%	-3.20 -4.82,-1,58]
Gurgel 2014	3	1.8	20	3.2	2.3	20	26.4%	-0.20 [-1.48, 1,08]
Kalteis 2005	2.3	1.6	23	5.6	3.9	22	22.3%	-3.30 -5.06, -1.54]
Lass 2014	3	2.5	62	4.2	3.7	63	27.9%	-1.20 -2.31, -0.09]
Total (95% CI)			127			130	100%	-1.87 -3.31, -0.44]

Random effects; H0 = no difference between navigation and freehand; heterogeneity: $\tau2 = 1.61$; $\chi2 = 12.46$, df = 3 (p = 0.006); I2 76%; test for overall effect: Z = 2.56 (p = 0.01).

Table 6. Results of other meta-analyses

Meta-analysis	Gandhi 2009	Beckmann 2009	Reininga 2010	Moskal 2011	Xu 2014	Li 2014	Liu 2015
Studies	3	5(4)	7	9	8	5	7
Inclination	-	p = 0.59	-	p = 0.57	p = 0.54	p = 0.346	p = 0.83
Anteversion	-	p = 0.59	-	p = 0.97	p = 0.57	p = 0.009	p = 0,89
Outliers	+ effect	p < 0.001	+ effect	p < 0.003	p < 0.0001	p < 0.00	p < 0.001

DISCUSSION

In order to reduce complications from malpositioning and improve functional outcome after THA, correct orientation of acetabular and femoral components is necessary. First of all, this systematic review and meta-analysis showed that NAV is statistically more precise in the placement of the cup concerning the anteversion (6/7 studies) and inclination (5/7 studies). Secondly, this study showed a statistically significant improved accuracy for anteversion and inclination in THA placement with NAV versus freehand placement. Higher precision and accuracy result in smaller deviations from the target and are more consistent in achieving this goal. Nevertheless, a decrease in complications and an improved functional outcome are not influenced solely by an improved orientation of the acetabular component. Factors related to the orientation of the acetabular component, such as head–neck ratio, femoral offset, stem orientation, depth of the acetabular component, muscle tension, comorbidity, surgical approach and the individual anatomy of the pelvis and femur are also involved.[4–6,28–35]

The results of this systematic review and meta-analysis are supported by several other meta-analyses (Table 6).[36–41]

Unfortunately, those meta-analyses had several methodological limitations and an arbitrary sample of studies, which affected their reliability. The meta-analysis of Liu is the only study that compared solely NAV with freehand THA.[39] The other six meta-analyses pooled imageless, fluoroscopic, robotic and CT-based navigation systems to compare them with freehand THA. Those systems have their own types of anatomical registration method with specific errors in their measurements. Secondly, only three out of seven meta-analyses had only RCTs.[37,40,42]

The main conclusion of most of the meta-analyses is the reduction in outliers relative to the safe zone of Lewinnek.[7,36–38,40,42] However, this zone of 15° ± 10° of anteversion and 40° ± 10° inclination is not unquestioned. Rittmeister showed no difference in dislocation rate between cups positioned in and out of the presumed 'safe zone' and Biedermann suggested that there is not a specific safe range for cup position.[43,44] The 'safe zone' of Lewinnek was defined in an underpowered study in 1978 with nine dislocations in 300 patients (3%).[7] Lewinnek used a jig to position the patients' APP equal to the coronal plane, which is not done in the above-mentioned RCTs and meta-analyses.[7] Secondly, the APP is defined by the individual prominence of the ASIS. This prominence has a significant intervariability among patients and does not show a normal distribution.[45] Finally, none of RCTs mentioned in their methodology the correction for pelvic tilt.[46] These factors introduce errors in achieving the target for inclination and anteversion with NAV. The individual variation in prominence of the ASIS, not paralleling the coronal plane to the APP and the lack of correction for pelvic tilt will all introduce errors in postoperative measurements in cup position using x-rays or computer tomography.

A major bias in the above-mentioned meta-analyses is a lack of uniformity in the pooled data. Several studies used plain x-rays while others used computer tomography. The former method is biased by the divergence of the x-ray beam. The latter is biased by the predetermined slices. Those measurements are not consistent between patients, let alone between studies. Furthermore, those meta-analyses use different definitions of anteversion (radiological or operative) as defined by Murray.[47] Operative anteversion is the angle between the acetabular axis and the sagittal plane. Radiological anteversion is the angle between the acetabular axis and the coronal plane. Those physically represent different angles. Mean radiological anteversion cannot be pooled with mean operative anteversion. Finally, a major limitation is that those meta-analyses compare mean inclination and anteversion between navigation systems and freehand placement. In other words, those meta-analyses just establish whether they are different, not whether they are more precise or more accurate.

There are several limitations to this systematic review and meta-analysis. First of all, the number of studies is limited, especially in the assessment of the accuracy. Unfortunately, most of the RCTs did not mention the deviation from the target. Future RCTs should mention the deviation, otherwise establishing which method is more precise or more accurate is not possible. In spite of the underpowered accuracy group this is the best evidence available to date. Secondly, there are some minor inconsistencies in the methodology of the RCTs between studies. The studies from Fang Lin, Gurgel, Lass and Kalteis used a mechanical tool to assist in cup placement, where other studies did not.[21–24] Another problem is the use of the radiographic anteversion in the studies from Renkawitz, Fang Lin and Paratte.[22,25,27] While Lass and Kalteis converted the operative anteversion to the radiological anteversion using the formula defined by Murray[23,24,47], the studies from Gurgel and Sendter used the operative anteversion.[21,26] To overcome this problem this systematic review and meta-analysis used the method of precision and accuracy to assess the NAV compared to the freehand method. The precision of a value is a measure of the reliability and consistency. The accuracy of a value is a measure of how closely results agree with the true or accepted value. By using this method, it is of less importance which anteversion is used, as long as the goal and final measurement of each study have the same definition. The use of the precision and accuracy is also a superior substantiated method by which to judge a measurement system.[48,49] Despite the use of this method, this study is still comparing NAVs from different companies, namely Brainlab, Stryker and Orthopilot. It is questionable to what extent the data can be pooled to measure the accuracy and precision of different systems. Thirdly, this study could not, like previous meta-analyses, overcome the challenges of the inter-individual variation in pelvic tilt and in the prominence of the ASIS. The included studies did not compensate for this inter-individual variation. Finally, publication bias could have influenced the results of this study because of the small number of available studies. However, to our knowledge this is the best quantifying method used in a meta-analysis and systematic review to date for level II RCTs comparing NAV with the freehand method in THA.

Another limitation of this study is the absence of the evaluation of functional outcome, blood loss, surgical duration, complications and a cost analysis. First of all, this was not done because not all RCTs did a subanalysis of those outcomes. Secondly, the RCT did not always evaluate some of those outcomes at the same moment of follow-up. An exception is surgical duration, which in each study was significantly prolonged for the NAV placement. Also, complications were mentioned by all the studies. Only the studies of Renkawitz and Gurgel had major complications.[21,27] Renkawitz had one dislocation, one deep infection and one periprosthetic fracture in the NAV group and one partial sciatic nerve palsy in the freehand group. Gurgel had one periprosthetic fracture in each group. Functional outcome was mentioned only in the study of Renkawitz and Lass.[24,27]Renkawitz showed an improved functional outcome after six weeks in favor of NAV. This difference was no longer significant after six months and one year. An improved precision and accuracy might not guarantee an improved functional outcome and a reduction in complications. A comparison of the costs was not possible because none of the included studies evaluated costs between NAV and the freehand group.

Despite a higher precision and accuracy in THA with NAV several thresholds are withholding an improvement in functional outcome, a reduction in complications and a reduction in revision surgery: firstly, a lack of knowledge of the perfect cup orientation for an individual patient; secondly, the effect of the individual anatomy towards the reference plane the NAV uses; thirdly, the biases introduced to the reference plane by the individual anatomy in the postoperative measurements of the final cup orientation; and fourthly, the extra financial costs of the use of such a system. None of the abovementioned RCTs published the costs of the use of the NAV. Less is known about the costs of using a NAV per THA. An article by König et al. in 2009 calculated an extra fee of €442 per arthroplasty using a similar ultrasound navigation system.[50] This included the capital costs. So far these costs are not reimbursed by health insurances.

In order to identify the optimal individual cup orientation in the near future and to place the cup in the patient in exactly this position, several recommendations can be made. Firstly, a uniform standardized method of cup measurement is needed in order to compare individual cup orientations and subsequently to pool all the data from several studies. Using such a standardized measuring method could designate anatomical characteristics that influence the optimal cup orientation in an individual patient. Secondly, well-designed and sufficiently powered RCTs, using the method of precision and accuracy, are then needed to evaluate whether NAV is superior in accomplishing such an orientation of the target cup compared to freehand placement. Those RCTs should have a long-term follow up and should include the functional outcome, complications and the costs per THA.

In conclusion, this systematic review and meta-analysis based on the current literature has shown that NAV placement is more precise and has an improved accuracy for anteversion and inclination compared to freehand placement within individual studies of the acetabular cup in THA. However, it is important to emphasize that this does not guarantee a better outcome. There is a lack of evidence supporting an improved functional outcome and a reduction in complications and revisions. This evidence is necessary to warrant the additional costs of a NAV. As this evidence is lacking as yet, one should be cautious of implementing the NAV broadly in THA placement. This research did not receive any specific grant from funding agencies in the public, commercial or not-for-profit sectors.

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CHAPTER 3

Lack of Consensus on Optimal Acetabular Cup Orientation because of Variation in Assessment Methods in Total Hip Arthroplasty: a Systematic Review

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ABSTRACT

Introduction

Dislocation is 1 of the main reasons for revision of total hip arthroplasty but dislocation rates have not changed in the past decades, compromising patients' well-being. Acetabular cup orientation plays a key role in implant stability and has been widely studied. This article investigates whether there is a consensus on optimal cup orientation, which is necessary when using a navigation system.

Methods

A systematic search of the literature in the PubMed, Embase and Cochrane databases was performed (March 2017) to identify articles that investigated the direct relationship between cup orientation and dislocation, including a thorough evaluation of postoperative cup orientation assessment methods.

Results

28 relevant articles evaluating a direct relation between dislocation and cup orientation could not come to a consensus. The key reason is a lack of uniformity in the assessment of cup orientation. Cup orientation is assessed with different imaging modalities, different methodologies, different definitions for inclination and anteversion, several reference planes and distinct patient positions.

Conclusions

All available studies lack uniformity in cup orientation assessment; therefore, it is impossible to reach consensus on optimal cup orientation. Using navigation systems for placement of the cup is inevitably flawed when using different definitions in the preoperative planning, peroperative placement and postoperative evaluation. Further methodological development is required to assess cup orientation. Consequently, the postoperative assessment should be uniform, thus differentiating between anterior and posterior dislocation, use the same definitions for inclination and anteversion with the same reference plane and with the patient in the same position.

INTRODUCTION

Total hip arthroplasty (THA) is a very common surgical procedure which offers high patient satisfaction in terms of reducing pain and improving function and quality of life.[1] The design, quality of materials and method of fixation have all been optimized in recent decades.57 However, in spite of these improvements the total number and percentage of THA revisions is increasing.[3,4] Moreover, there is reason to believe that major limitations in THA are of mechanical and kinematic origin related to mal-placement of the implant components. These limitations include impingement of prostheses components with or without accelerated wear or loosening of components, dislocation of the THA and limitations of range of motion.[5–10] While recently reported short-term dislocation rates, around 0.8% after 1 year postoperative, might indicate a decline in THA dislocations, long-term, high volume cohorts suggest otherwise.[11,12] The Charnley 'low friction' arthroplasty had a dislocation rate of 4.8%, while the latest long-term Medicare cohort shows a dislocation rate of 4.76%.[13,14]

Optimising component orientation could decrease this long-term dislocation rate. Despite the many articles that have been published on this subject, there is still no agreement on optimal THA placement.[9] In particular, there are 3° of freedom during implantation of the acetabular cup and its orientation is easily misjudged by the orthopaedic surgeon due to patient position, acetabular deformation and variable anatomy.[15,16] Concerning the acetabular cup, the 'safe zone' of Lewinnek, from now on 'Lewinneks zone', is widely accepted by surgeons as the correct orientation. This is an inclination zone of 40° ± 10° and an anteversion of 15° ± 10°, based on an underpowered cohort dated from 1978.[17]Several other studies could not confirm Lewinnek's zone and other zones were proposed in various matched case-control studies.[9–11,13] Thus, the matter is far from solved and there is clear evidence that mal-placement of the acetabular cup is still one of the major problems in THA.[18,19] In addition, with the broader use of more precise and accurate navigation systems in the placement of the acetabular cup, reaching consensus about the optimal acetabular cup orientation is necessary for preoperative planning, peroperative placement and postoperative evaluation.[20]

There is only one recently published review evaluating target zones for optimal acetabular component orientation. This review by Seagrave et al. performed a search in the pubmed electronic database to include different types of publications, which directly or indirectly mention the relationship between dislocation and acetabular cup orientation.[21] They could not justify Lewinnek's zone due to variability between studies and the likely multifactorial character of THA dislocation. Therefore, a more comprehensive systematic review that investigates the direct relationship between dislocation and acetabular cup orientation is needed, including a thorough evaluation of the radiological acetabular cup orientation assessment methods that are used.

MATERIALS AND METHODS

Search strategy and selection criteria

A systematic review was conducted to collect all research reporting on the assessment of optimal acetabular cup orientation in THA. Following most of the recommendations of the PRISMA statement, a systematic search was performed in the PubMed, Embase, and Cochrane electronic databases in March 2017.[22] The 1st part of the search syntax was constructed from the term: "total hip arthroplasty", combined with synonyms – in the singular and the plural – using "OR". In the middle part of the search syntax, the term "acetabular cup", combined with synonyms and other names such as "acetabular socket" and "acetabular component" were used, also combined with the "OR" function. In the last part, the term "orientation", with synonyms were used, also combined with the "OR" function. The final search syntax was synthesised by combining the results of the 3 searches performed using "AND". All duplicates were identified and subsequently removed from the database. Only publications written in English, were considered for review.

The titles and abstracts of all unique publications were screened for inclusion criteria. Only studies that reported on orientation of the acetabular cups used in primary THA, with dislocation as a clinical outcome were included. All publications that were considered eligible were retrieved in full text and were screened using our predetermined exclusion criteria. We excluded all studies that failed to meet our inclusion criteria, as well as all animal studies, all studies with an evidence level of 4 and lower, and all studies with a minority of primary osteoarthritis and primary THA. In case of twin studies reporting on a single cohort, only the publication with the longest follow-up was included. Validation studies were also excluded because those studies compare orientation between 2 different treatment methods instead of evaluating the effect of orientation on its own. The study evidence score was judged using the evidence rating scale from the Centre for Evidence-Based Medicine, Oxford, England.[23] Of all remaining articles, the reference lists were checked to search for additional relevant publications. The study selection and the crosschecking of reference lists were done by one of the authors (KW) with direct consultation of other authors (TMS and SMvG) in difficult cases. Agreement was reached in all cases. All data that described acetabular cup orientation was extracted as well as all data concerning the measurement method of acetabular cup orientation.

The following data was extracted from the included articles:

- Postoperative evaluation method (radiographic or Computer Tomography [CT]);
- Definition of inclination;
- Definition of anteversion;
- Differentiation between anterior and posterior dislocation or not;
- Position of patient when radiograph or CT is made;
- Measurements compensation for pelvic obliquity, tilt or rotation;
- Mean acetabular cup inclination;
- Mean acetabular cup anteversion;
- Lewinnek's zone confirmed or not;
- Alternative zone that show statistically significant lower dislocation rates.

The actual close-reading and extraction of relevant data were done by 2 of the authors (TJS and KW).

RESULTS

Search results

Our search generated a total of 792 publications. After removing duplicates, 451 unique publications remained. The titles and abstracts of all publications were screened for the predetermined inclusion criteria, after which 146 publications were considered eligible. These 146 publications were then obtained in full text. After applying our exclusion criteria, a total of 19 unique publications remained. Checking the reference lists of all eligible publications yielded 9 other publications meeting the in- and exclusion criteria as described previously (Figure 1).

Of the 28 studies, 14 were cohort studies and 14 were case-control studies. The 28 studies varied in the reporting methods of acetabular cup orientation making an explicit search question impossible. Therefore, the studies were subdivided by reporting method:

- Mean inclination of the control group versus the dislocation group
- Mean anteversion of the control group versus the dislocation group

- Mean inclination of the control group versus the anterior dislocation group
- Mean anteversion of the control group versus the anterior dislocation group
- Mean inclination of the control group versus the posterior dislocation group
- Mean anteversion of the control group versus the posterior dislocation group
- Dislocation rates outside the Lewinnek's zone versus inside the Lewinnek's zone
- Dislocation rates in alternative zones besides the Lewinnek's zone

Table 1 shows the number of studies reporting on the different reporting methods.

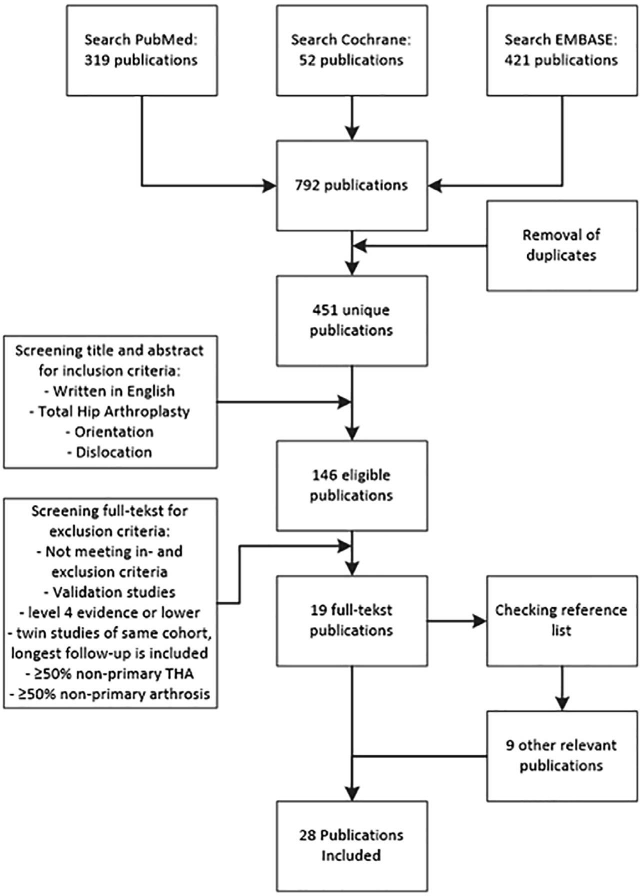

Figure 1. From the 451 unique publications that were found in the literature search, 28 publications were eligible for analysis.

Table 1. Subdivisions in reporting on the acetabular cup orientation.

Reporting methods	
Mean inclination C vs D	19 / 28
Mean anteversion C vs D	17 / 28
Mean inclination C vs AD	4 / 28
Mean anteversion C vs AD	4 / 28
Mean inclination C vs PD	5 / 28
Mean anteversion C vs PD	5 / 28
D inside vs outside LZ	10 / 28
D inside vs outside AZ	6 / 28

C, controls; D, dislocation group; AD, anterior dislocation group; PD, posterior dislocation group; LZ, Lewinnek's zone; AZ, alternative zones.

Acetabular cup orientation

19 studies reported on mean inclination between the control groups and the groups with dislocation.[19,24–37]The study of Sanz-Reig et al.,[38] Sadhu et al.,[39] Li et al.[40] and Garcia-Rey et al.[41] determined a statistically significant difference in inclination between the control group and the group with dislocation, (mean inclination of 43.2 vs. 48.7 ($p = 0.002$), 47.5 vs. 45.1 ($p = 0.01$), 45 vs. 43 ($p = 0.004$), 48.8 vs. 45.6 ($p = 0.003$) respectively).

17 studies reported on mean anteversion between the control groups and the groups with dislocation.[18,19,24,27–30,32,34–36,38,41,42] 3 studies (from Ezquerra-Herrando et al.,[25] Opperer et al.[37] and Sadhu et al.[39]), showed a statistically significant difference between the control group and the group with dislocations, (mean anteversion of 14.19 vs. 11.54 [$p = 0.043$], 16.62 vs. 17.73 [$p = 0.06$], 17.6 vs. 20.5 [$p = 0.04$] respectively).

4 of the 28 included studies differentiated between anterior and posterior dislocations (Table 2).[9,17,27,43] The control group versus the group with anterior dislocation showed a statistically significant difference for mean inclination only in the study from Biedermann et al.[9] (mean inclination of 44.4 vs. 47.9, $p = 0.002$). Mean anteversion was statistically significantly lower in the control group compared to the anterior dislocation group in all 4 studies, (Biedermann et al.[9]; 14.5 vs. 16.8 [$p \leq 0.05$], Fujishiro et al.[27]; 24.5 vs. 37.7 [$p = 0.026$], Lewinnek et al.[17]; 15.6 vs. 33.9 [$p < 0.01$], Masaoka et al.[43]; 15.5 vs. 42 [statistically significant, p value not mentioned]).

Table 2. Values of studies which categorized anterior and posterior dislocations.

		Biedermann	**P**	**Fujishiro**	**P**	**Lewinnek**	**P**	**Masoaka**	**P**	**Garcia**	**P**
Incl	C vs AD	44.4° vs 47.9°	p<0.05	40.9° vs 42.2°	NS	44.4° vs 49.3°	NS	41.5° vs 47°	NS	-	-
	C vs PD	44.4° vs 42.5°	NS	40.9° vs 43.2°	NS	44.4° vs 47°	NS	41.5° vs 46.8°	NS	42.5°±7.5°	P=0.001
AV	C vs AD	14.5° vs 16.8°	p<0.05	24.5° vs 37.1°	p=0.0026	15.6° vs 33°	p=0.01	15.5° vs 42°	S	-	-
	C vs PD	14.5° vs 11°	p<0.05	24.5° vs 20.1°	NS	15.6° vs 18.1°	NS	15.5° vs 4.5°	S	20°±5°	P=0.001

Incl, inclination; AV, anteversion; C, controls; AD, anterior dislocation group; PD, posterior dislocation group; NS, not significant; S, significant.

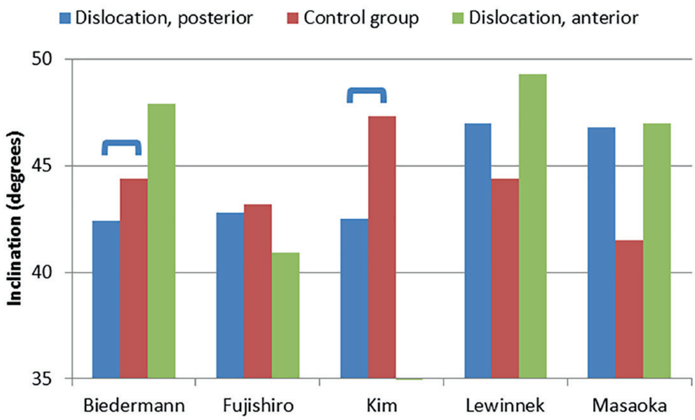

Figure 2. Mean inclination of control group and posterior and anterior dislocation group. Significant differences are indicated by an arc.

Considering the control group versus posterior dislocations subdivision, the study of Kim et al.[44] is included because it had only posterior dislocations, in addition to the 4 above mentioned studies.[9,17,27,43] The study of Kim et al.[44] showed a statistically significant higher inclination in the posterior dislocation group versus the control group with CT and radiographic measurements, (computed tomography [CT]; 46.9 versus 40.8 [p = 0.017], radiographic; 47.3 versus 45.6 [p = 0.003]). On the other hand, higher anteversion in the control group was statistically significant in posterior dislocation group in the studies of Biedermann et al.[9](14.5 versus 11, p < 0.05) and Masaoka et al.[43] (15.5 vs. 4.5, statistically significant, p value not mentioned) and Kim et al.[44] (19.8 vs. 28.9 [p = 0.004] with CT and 20.7 vs. 29.3 [p = 0.002] radiographic)

In 10 studies the dislocation rates were analysed with respect to in and outside Lewinnek's zone.[9,17,18,24,37,39,42,45–47] Lewinnek et al.[17] showed fewer dislocations within this zone versus outside this zone (p = 0.045). Lewinnek's zone was confirmed by 3 out of the 9 studies.[9,18,39] Biedermann et al.[9] confirmed Lewinnek's zone. They showed that 79% of the stable THAs were placed within Lewinnek's zone versus 60% of the dislocated THAs within this zone (p = 0.001). Additionally, Danoff et al.[18] showed that acetabular cup malposition with respect to Lewinnek's zone was an independent risk factor for dislocation (odds ratio [OR] 1.88, p = 0.049). Sadhu et al.[39] showed that 23 of 96 (24%) in primary THA dislocators versus 48 of 96 (50%, p < 0.001) in the control group were in Lewinnek's zone. 6 out of 9 studies could not show a statistically significantly lower dislocation rate in Lewinnek's zone vs outside this zone.[19,24,37,42,45,47] Several other studies rejected Lewinnek's zone without mentioning the statistical proof.[25,27,28,33,34,43,48]

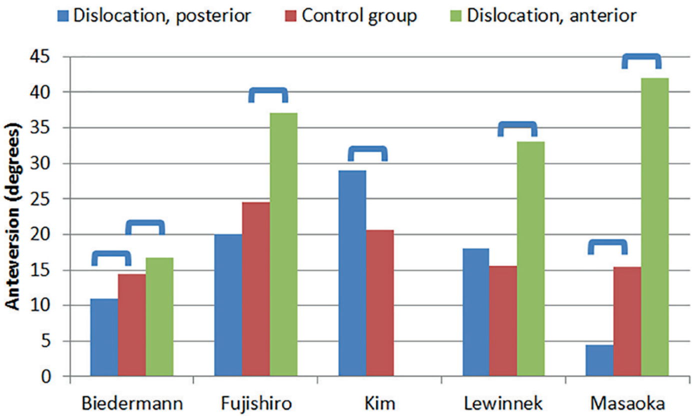

Figure 3. Mean anteversion of control group and posterior and anterior dislocation group. Significant differences are indicated by an arc.

Some authors suggested categorising alternative zones based on the results from their own case-control or cohort studies (Table 3). 1st, based on their results, Biedermann et al.[9] suggest changing the 'safe zone' to 45° ± 10° of inclination and 15° ± 10° of anteversion. This zone included 93% of stable and 67% of unstable hips, proving to be better than Lewinnek's zone with an odds ratio of 6.5 (p = 0.001). 2nd, Danoff et al.[18] proposed the 'posterior approach safe zone' with an inclination of 40° ± 10° and an anteversion of 17.5° ± 7.5° with a multivariate odds ratio of 2.67 (p = 0.009). 3rd, Danoff et al. [18] even defined a 'Sweet Spot Zone' of 41.4° ± 4.3° of inclination and 17.1° ± 4.3° of anteversion. They reported 162 THA within this zone, all without a single dislocation (p = 0.007). 4th Fujishiro et al.[27] proposed a specific zone concerning only an anteversion of 20° ± 10°, (OR 1.9, p = 0.026). 6th, Grammatopoulos et al.[19] showed that a zone of 40° and 15° ± 15° had an odds ratio of 4.1 (p = 0.01) 7th, Sanz-Reig et al.[38] determined an odds ratio of 3.78 for an inclination above 50° (p = 0.003) and an anteversion outside of 15° ± 5° showed an odds ratio of 1.3 (p = 0.044). Lastly, the study of Garcia-Rey et al.[41] showed a statistically significantly higher chance of not having a dislocation when the acetabular cup had an inclination between 35–50° and an anteversion of 15–25° (p < 0.001)

Measurements methods of acetabular cup orientation

Of the 28 studies discussed above, 25 used radiographs to measure postoperative acetabular cup orientation.[9,17–19,24–26,28–30,32–37,39–43,45,47–49] One study used CT ([27]), one study measured it with CT and radiographs ([44]) and one study used CT for the group with a dislocation and

Table 3. Displaying the different alternative safe zones and suggestions.

	Inclinationº	Anteversionº	Calculated:	p
Biedermann	45±10	15±10	C-in AZ vs D-in AZ	p<0.01
Danoff	40±10	17.5±7.5	Odds of dislocation 2.67	p=0.009
	41.4±4.3	17.1±4.3	C-in AZ vs D-in AZ = 162 vs 0	p=0.07
Fujishiro	/	20±10	Odds of dislocation 1.9	p=0.026
Grammatopulous	40±15	15±15	Odds of dislocation 4	p=0.012
Lewinnek	40±10	15±10	D-in AZ vs D-out AZ	p=0.045
Sanz Reig	>50	/	Odds of dislocation 3.78	p=0.003
	/	15±5	Odds of dislocation 1.3	p=0.044
Garcia	42.5±7.5	20±5	C-in AZ vs D-in AZ	P=0.001

C, controls; D, dislocation; AZ, safe zone.

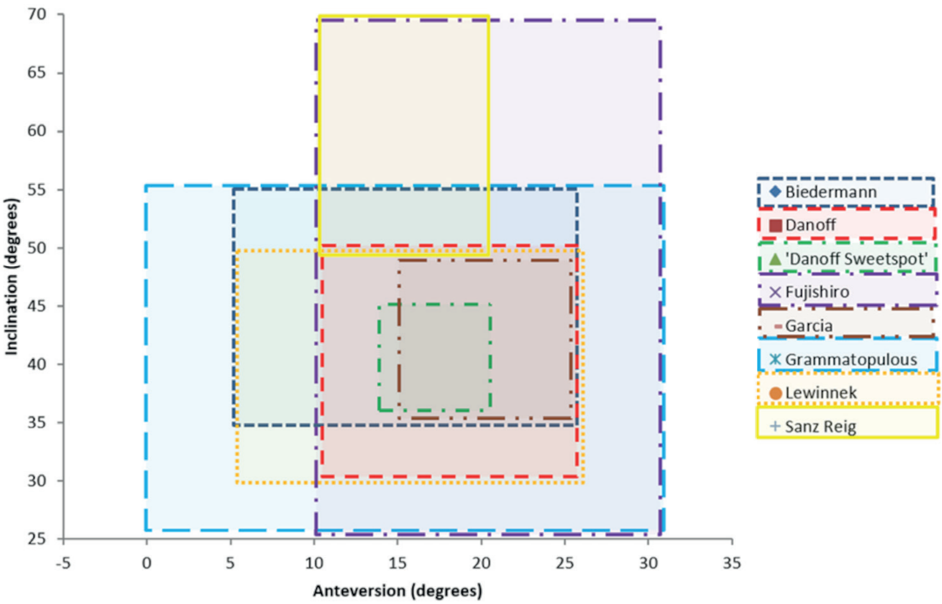

Figure 4. Suggested alternative zones per study.

radiographs for the group without a dislocation.[38] The postoperative imaging was done with the patient in a supine position in 14 studies.[17,19,26–28,30,32,36,40–44,47] In the studies of McCollum et al.[48] and Woolson et al.,[35] the postoperative imaging was done with the patient in a standing position. The postoperative imaging position of the patient was unclear in all other 12 studies.[9,18,24,25,29,33,34,37–39,45,49]

All studies corrected for pelvic obliquity using the measurement of acetabular cup inclination. Fujishiro et al.[27] and Sanz-Reig et al.[38] corrected for pelvic rotation, using CT or measuring anteversion. The studies of Leichtle et al.,[42] McLawhorn et al.[47] and Lewinnek et al.[17] were the only studies that corrected for pelvic tilt. Leichtle et al.[42] used an algorithm to adjust the measured anteversion to pelvic tilt based on a study of Lembeck et al.[50] McLawhorn et al.[47] used an imageless computer-assisted system during surgery, which adjusted anteversion peroperatively. Unfortunately, the postoperative measurements were not corrected for pelvic tilt. Lewinnek et al.[17] positioned the pelvis during surgery such that the anterior pelvic plane was parallel to the table. The postoperative measurements were done on an x-ray of the pelvis in the exact same position.

The measurement of inclination of the acetabular cup was done on anteroposterior (AP) radiographs in 25 studies. The study of Fujishiro et al.[27] measured the inclination on the coronal CT slice showing the largest diameter of the acetabular cup. Sanz-Reig[38] used the same CT method to measure inclination, only for the subjects with a dislocation, contrary to the patients in their control group which were measured on AP radiographs. Kim et al.[44] used the same method with the CT measurements. Their radiographic measurements were done on AP radiographs.

The studies of Jolles et al.,[28] Pollard et al.[32] and Woolson[35] measured anteversion directly on a cross-table lateral radiograph, which approaches the definition of radiographic anteversion of Murray.[51] The studies of Kristiansen et al.,[29] Kim et al.[44] and McCollum et al.[48] used lateral radiographs to measure anteversion directly. This is comparable with the operative anteversion defined by Murray.[51]

There were 4 studies that used CT to measure anteversion directly on the transversal plane.[27,36,38,44] This is anatomical anteversion, according to the definition of Murray.[51] Anteversion was measured on the transversal CT slice showing the largest diameter of the acetabular cup.

19 of the 28 studies tried to establish anteversion indirectly. These studies used the ellipse of the cup seen on the AP radiograph to calculate anteversion with an equation. Different equations were used in these studies. 4 studies used Ein Bild Röntgen Analyse (EBRA, University of Innsbruck, Austria).[9,19,24,47] Danoff et al. [18] and Sadhu et al.[39] used the method of Martell Hip Analysis Suite Version 8.0.4.1 (Martell HAS, Chicago, IL). Dorr et al.[49] used another equation that was based on an algorithm D/C’(arcsin), where C’ is the length at

the widest diameter of the cup and D is the length of a line at the centre and perpendicular to line C', both measured on an AP radiograph. Ezquerra-Herrando et al.[25] and Sanz-Reig et al.[38] used Rithen Pradhan et al.'s equation.[52] Fackler et al. [26] and Lindberg et al.[30] used an equation by McLaren.[53] Leichtle et al.[42] used an equation by Ackland et al.[54] Garcia-Rey et al.[41] used an equation by Widmer et al.[55] These equations are all different variations of an inverse sine function of the ratio between the long and the short axis of the inlet of the acetabular cup. Timperley et al.[33] also used an equation from the software from Orthoview (Southampton, UK), however, the authors converted the outcome to anatomical anteversion with conversion equations described by Murray (Figure 5).[51]

The remaining 4 studies used the equation of Lewinnek.[17,34,37,43] In total, 13 different measuring methods were used for the measurement of anteversion in the 28 studies. The results per article are shown in the supplementary table online.

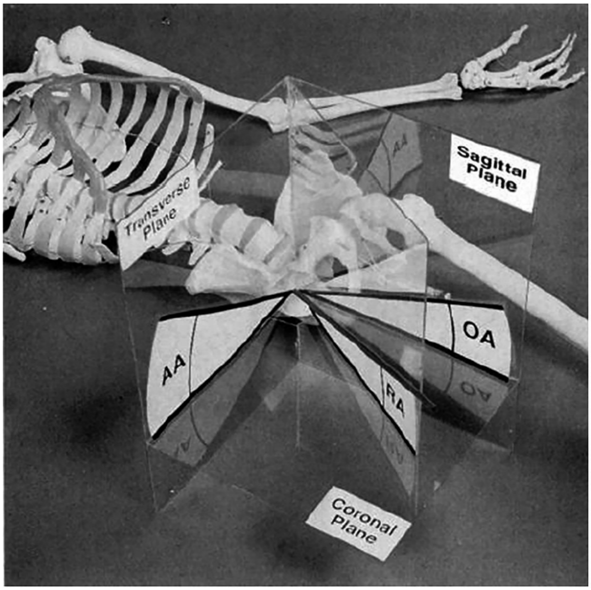

Figure 5. Definitions of anteversion defined by Murray.[51] AA, anatomical anteversion; RA, radiographic anteversion; OA, operative anteversion.

DISCUSSION

This systematic review reveals a widespread lack of uniformity in the measurement methods and reporting of acetabular cup orientation. Consequently, this study could not confirm a consensus for correct acetabular cup placement in order to prevent dislocation in THA. Another consequence of this lack of uniformity is that acetabular cup orientation placed with navigation systems will be inherently flawed, as pre-, per- and postoperative definitions will be different. A recent systematic review from Seagrave et al. has also addressed this lack of uniformity. [21] Our study is methodologically different because we only included studies that primarily investigated the relation between acetabular cup orientation and dislocation. In addition, we performed a more thorough search (Embase, Pubmed and Cochrane) leaving out studies that mention dislocation and acetabular cup orientation secondarily and including more studies investigating this relation directly. For example, Seagrave et al. included studies that evaluate cup orientation preoperatively and even included a meta-analysis of studies investigating manual placement vs navigated placement. Seagrave et al. ignored other meta-analyses that investigated navigated placement vs manual placement, like studies by Reininga et al. and Liu et al.[56,57] Also, unlike the review of Seagrave et al., our study only focused on the postoperative measuring method, as the acetabular cup is fixed in the acetabular socket and the measurement methodology should be uniformly performed.[21]

Mean inclination, 15 out of 19, and anteversion, 14 out of 17, were generally not statistically significantly different between the control and the dislocation group. This contradicts the generally accepted relationship between dislocation and acetabular cup orientation. However, in most studies the amount of mean anteversion of both anterior and posterior dislocations cancel each other out. Thus, anteversion of both dislocations combined will not affect the mean anteversion to a significant extent. Seagrave et al. do not address this important problem.[21] Studies that do differentiate between anterior and posterior dislocations show a statistically significant difference in anteversion between the anterior or posterior dislocations and the control group.[9,17,27,43,44] Thus, higher anteversion angles increase the risk of anterior dislocation. In contrast, too little anteversion increases the risk of a posterior dislocation. This is confirmed by biomechanical and finite element studies and it suggests that there should be a zone in which the likelihood of a dislocation is minimised.[25,48,58] Lewinnek's zone, which is still embraced by many orthopaedic surgeons worldwide, could not be confirmed by 6 out of 9 studies.49 Other zones differed from one another and did not agree on 1 specific zone (Figure 4).

The lack of confirmation for the use of Lewinnek's zone is not remarkable, because most studies have not compared the exact same measurements. For example, in the studies from Opperer et al.,[37] Grammatopoulos et al.[19] and Esposito et al.[24] it was questionable if the authors had tilted the pelvis in such a way that the anterior pelvic plane was perpendicular to the coronal plane, as Lewinnek et al. did.[17] Leichtle et al.[42] and McLawhorn et al.[47] did correct for pelvic tilt; however, they used a different equation than Lewinnek for the indirect assessment of anteversion. Therefore, unlike Seagrave et al. in their systematic review, we conclude that it is not possible to reject Lewinnek's zone.[17,21]

Most remarkably, 13 different methods of assessment of anteversion could be identified in all the included studies. Murray identifies 3 different definitions of inclination and anteversion based on (i) radiographic view, (ii) anatomical view and (iii) operative view (Figure 5).[51] All anteversion methods used could be categorised in one of these views. The equations and the cross-lateral radiographs try to approximate the radiographic view, the lateral radiograph is categorised in the operative view and the transversal plane on the CT is categorised in the anatomical view. As is shown in Figure 5, these angles have different spatial arrangements. The fundamental difference is that operative anteversion is measured around a transverse axis, anatomical anteversion around a longitudinal axis and radiographic anteversion around an oblique axis.[51]

The equation methods used to establish anteversion pose a particular problem. The equations approximate an angle measured around an oblique axis between the transversal and sagittal planes perpendicular to the inclination. This makes it difficult to reproduce. As shown by the study of Manjunath et al., there are differences between the equations used in various studies, leading to different outcomes.[59] In contrast to the study of Manjunath et al., the position of the patient and correction for pelvic tilt are not even uniform in the studies included here (supplementary Table).[59] Cross-table lateral radiograph of the THA is probably most commonly used postoperatively. Unfortunately, it is difficult to position the patient and the radiological tube in such a way that the projectional plane is reproducible between patients. Furthermore, by lifting the contralateral leg the pelvis is shifted with a slight posterior tilt. Seagrave et al. suggest that the cross-lateral radiograph overestimates anteversion.[21] In fact, it is not an overestimation, it is a spatially different angle compared to the radiographic anteversion of Murray.[51] 2 studies concluded that cross-table lateral imaging is not a reliable method for research purposes.[60,61]

Kristiansen et al. and McCollum et al. used lateral radiographs to assess anteversion, therefore measuring anteversion on the sagittal plane, while in CT it is measured on the transversal plane (Figure 5).[29,48] Thus, the lateral radiograph measurement and CT are considerably different. In addition, measurement on the sagittal plane is directly affected by pelvic tilt, as 1° posterior tilt of the pelvis increases anteversion on the sagittal plane with 1°. Furthermore, 'neutral' pelvic tilt is unknown and patient dependent. This is contrary to pelvic obliquity and pelvic rotation, which can be easily corrected by a horizontal line between the tear drops or anterior superior spina iliaca respectively, because both sides are symmetrical. Correction for pelvic tilt, however, is problematic, because the anterior half of the pelvis is not symmetrical with the posterior half. Therefore, it is necessary to describe the reference plane used to an anatomical landmark. This also affects CT measurements on the transversal plane. Because 'neutral' pelvic tilt is unknown, one cannot see if pelvic position is tilted on a CT image. It could be affected by, for example, spinal deformities. Thus, CT measurements are dependent on the pelvic position because, in contrast to the conclusions of Seagrave et al., 'neutral' pelvic tilt is unknown.[21]

To overcome these problems, several studies have used the anterior pelvic plane as a reference. Unfortunately, this plane is also affected by patient position and anatomical variation.[62,63] It is simply a measurement of the prominence of the anterior superior spina iliaca related to the os pubis. The relation between the anterior pelvic plane and the acetabulum varies in the population. A study of Wan et al. in 619 patients showed that 8.6% of patients had a pelvic tilt parallel to the anterior pelvic plane, 53% had a posterior pelvic tilt and 48.4% had an anterior pelvic tilt.[63] Thus, using the anterior pelvic plane introduces variation in the placement and measurements of the acetabular cup orientation.

The lack of uniformity in the assessment of acetabular orientation is a major flaw in most of the publications studied. In other words, the static position of the acetabular cup is projected in several different manners when assessing orientation. Consequently, this heterogeneity of the included studies ensures that a meta-analysis can never lead to a consensus on the topic concerned. Furthermore, many of the studies included have no exact description of their methodology. The small groups of anterior dislocations in the studies from Lewinnek et al. and Masaoka et al. is another limitation.[17,43] The 14 case-control studies included might introduce a selection bias in the control groups, as they might be not representative of the general population. It is also possible that there is a selection bias in the cohort study groups.

Primary factors like muscle tension, stem anteversion, combined anteversion, head-neck ratio and impingement might cause a dislocation, is spite of a well-positioned acetabular cup.[48,64,65] Secondary factors like increased age, previous surgery, neurological deficiencies and alcohol abuse could, of course, also increase the potential for a dislocation to occur.[66] Furthermore, none of the studies investigated have level 1 or 2 evidence on the rating scale from the Centre for Evidence-Based Medicine, Oxford, UK.[23]

The fact that dislocations occur in all zones and that other factors are related to dislocation, implies that the optimal orientation is patient specific. The lack of uniformity in the studies concerned makes it impossible to identify patient-specific anatomical characteristics that are of influence on impingement and dislocation.[5,63,67] Furthermore, the studies included evaluated acetabular cup orientation in a static situation. While acetabular cup orientation is static in the socket of the acetabulum (and thus the pelvis), the human pelvis in all-day motion is not.88 This motion alters the position of the pelvis and thus the acetabular cup and its position relative to the femoral component. During motion the containment of the femoral head is changed, not only by position, but also by a change in joint reaction forces. After all, muscle tension, bodyweight distribution and muscle recruitment changes in different positions. To determine the relevant anatomical and dynamic factors of concern, it is important that acetabular cup orientation is measured with a uniform methodology. A recent issue is the introduction of reliable navigation systems and robotics in THA. Using such systems, preoperative planning, peroperative surgery and postoperative control imaging should all have the same definitions and reference planes.

This systematic review shows that all available studies assessing acetabular cup orientation use different definitions and measuring methods. This makes it impossible to find a consensus on optimal acetabular cup orientation. Furthermore, using navigation systems for placement of the acetabular cup is inevitably flawed when using different definitions in preoperative planning, peroperative placement and postoperative evaluation. In order to evaluate acetabular cup orientation in relation to dislocation, a methodology should be used that differentiates between anterior and posterior dislocation. This methodology should also use the same definitions for inclination and anteversion with the same reference plane and with the patient in the same position.

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CHAPTER 4

Non-equivalent Results from Different Anteversion Measurements Methods for the Evaluation of the Acetabular Cup Orientation in Total Hip Arthroplasty

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ABSTRACT

Objective

To determine the comparability among 10 radiographic anteversion methods for acetabular cup orientation in total hip arthroplasty (THA) found in the literature and the "gold" standard of assessing the anteversion with CT.

Methods

This is a retrospective study that blindly compares 10 different conventional radiographic anteversion measurements with the "gold" standard, the measurement of anteversion on the transverse plane of the 3-D images made with CT. The patient archiving and communications system (PACS) was systematically searched for subjects that had undergone a CT angiogram of the abdomen and lower extremities, including the pelvis, had at least one THA in situ and had undergone anterior-posterior (AP) and cross-lateral pelvic radiography between January 2013 and August 2016 in the Diakonessenhuis Hospital Utrecht/Zeist, a non-academic institution. CT scans of patients (n = 16) were systematically collected. Three observers independently measured cup anteversion from radiographs, using a total of 10 different methods, and measured the "gold" standard on CT images. The outcomes of the 10 radiographic anteversion were compared in terms of linear correlation with the "gold" standard on CT images.

Results

The correlations of the radiographic measured anteversions with the "gold" standard measured on CT images were 0.528 for the method of Liaw, 0.556 for Wan, 0.562 for the cross-lateral method, 0.586 for Hassan, 0.594 for Dorr, 0.602 for Lewinnek, 0.624 for Widmer, 0.671 for the lateral CT, 0.747 for Ackland, and 0.771 for the method of Riten Pradhan.

Conclusion

Anteversion measurement methods represent different projectional angles of the acetabular cup in different planes around different axes. Therefore, they differ from the "gold" standard and are not interchangeable, as is shown by this study. We consider the anatomical anteversion in the transverse plane rotating around the longitudinal axis as the "gold" standard and recommend avoiding using the term anteversion for other projectional angles in different planes.

INTRODUCTION

Acetabular cup orientation in total hip arthroplasty (THA) is considered of utmost importance to prevent aggravated wear, limited range of motion, and dislocation.[1–7] Over the past four decades, not much progress has been made with respect to optimal acetabular cup orientation, as demonstrated by the constant percentage of long-term THA dislocations in large cohorts.[8,9] Recent systematic reviews indicated that there is still no consensus on optimal acetabular cup orientation, because of mixed terminology and different projectional planes, used with several imaging modalities and different analysis methods.[10,11]

The orientation of the acetabular cup is historically evaluated using two angles: inclination and anteversion. Besides distinct terminology, such as abduction, tilt, flexion or lateral opening, several different definitions exist for inclination and, in particular, for anteversion.[10,11] "Inclination" is mostly measured on anterior–posterior (AP) pelvic radiographs or on coronal plane projections of 3-D imaging modalities and is an angle measured on a coronal plane that rotates around the sagittal axis. Because "anteversion" has been measured on lateral as well as cross-lateral radiographs and on transverse plane projections of CT images, one has to realize that these different definitions are spatial varying angles measured on varying planes around different axes.

First, anteversion measured on lateral radiographs is an angle on the sagittal plane around the transverse axis. Second, the cross-lateral radiograph is measured on a plane in between the sagittal and transverse plane around an axis perpendicular to this plane. Third, the anteversion calculated with several varying algorithms from the ellipse of the acetabular cup projection on an AP pelvic radiograph is also a rotation measured on a plane, which is in between the transverse and sagittal plane with its corresponding perpendicular axis. Finally, anteversion measured on the transverse plane of a CT scan is rotating around the longitudinal axis. These different spatial angles were first described by Murray (Figure 1A).[2,12–15]

The use of various "anteversion" angle definitions that are measured on different projectional planes has not led to comparable results. In our opinion, the 3-D orientation of the acetabular cup, in reference to the anatomical planes, should be considered as the "gold" standard, because this is the anatomical anteversion measured on the transverse plane as described by Murray (Figure 1B).[15]

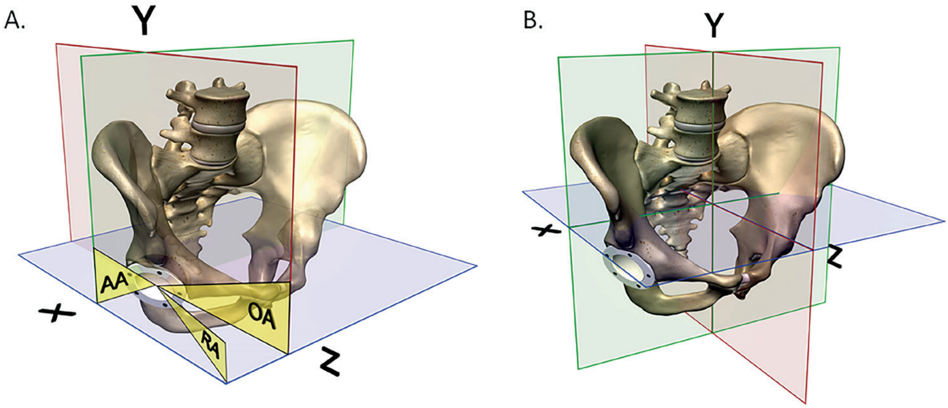

Figure 1. (A) Different spatial anteversion angles, defined by Murray, rotating around different axes11,15. The colored planes show the three anatomical planes. The yellow angels describe the definitions in relation to the three anatomical planes: AA, anatomical anteversion in the transverse plane; OA, operative anteversion in the sagittal plane; RA, radiographic anteversion in a projectional plane. (B) Anatomical planes: green is coronal plane, red is sagittal plane, and blue is transverse plane. X is the transverse axis, Y is the longitudinal axis, and Z is the sagittal axis.

Optimal acetabular cup orientation recommendations should also be reproducible and usable in the preoperative planning, during surgery, and for postoperative evaluation. Therefore, to evaluate cup orientation properly, the definitions should be reproducible and consistent: preferably identical or at least comparable. However, it remains unclear whether the different conventional measurement methods described in the literature are comparable to the "gold" CT-derived standard. The aim of this study is to evaluate the extent to which the different anteversion measurement methods described in the literature represent the "gold" standard.

MATERIALS AND METHODS

Study Inclusion and Exclusion Criteria

After approval from the Institutional Review Board, the patient archiving and communications system (PACS) of the Diakonessenhuis Hospital Utrecht/Zeist, a non-academic institution, was systematically searched for eligible subjects. The subjects were included if: (i) patients underwent a CT angiogram of the abdomen and lower extremities including the pelvis and had at least one THA in situ; (ii) they had undergone an AP and cross-lateral pelvic radiography that enables the measurement of the different radiographic anteversion methods;

and (iii) patients were only included if the imaging was done between January 2013 and August 2016. Exclusion criteria were: (i) previous ipsilateral hip surgery other than primary THA; (ii) malignant disease localized in the pelvis or femur; (iii) image series that were incomplete or with substantial contrast artifacts in the region of interest; and (iv) radiographs and CT scans that were obtained more than 3 months apart from each other.

Study Type

This is a retrospective study that blindly compares 10 different conventional radiographic anteversion measurements with the "gold" standard, the measurement of anteversion on the transverse plane of the 3-D images made with CT.

Study Procedure

During the study period, following the standard protocol, angiographic CT scans were acquired in supine position using a 16-channel multidetector CT system (Siemens Healthcare, Erlangen, Germany; slice thickness 0.5 mm) and intravenous contrast. Following protocol, AP-pelvic radiographs were also taken in the supine position. The cross-lateral pelvic radiograph was carried out in the supine position but with the contralateral hip flexed in 45 and placed on a small stand to keep the position stable. The direction of the radiation beam was parallel to the examination table, 45 to the long axis of the body, and the X-ray film was opposite to the radiation beam16. There were no lateral pelvic radiographs available. Demographic characteristics were collected.

Anteversion Measurement Methods

All non-automated methods for measurement of anteversion as found in two recent systematic reviews were included in this study.[10,11] Studies comparing different anteversion measurement methods were also screened for additional measurement methods. A total of six measurement methods were identified from the systematic reviews.[1,2,6,14,16–19] Three anteversion measurement methods were from other related articles.[3,20,21] The method of McLaren et al., however, was excluded because of a non-reproducible description of the measurement method used.[22] The method described by McCollum et al. performed anteversion measurement on lateral radiographs.[14] In our study, we used sagittal CT images for this method (Figure 2).

In total, 10 manual anteversion measurement methods were included and categorized with respect to the type of plane used for the measurement. Category 1 comprises methods using the anatomical planes, including the "gold" standard and the method of McCollum et al. (Figures 1A and 2).[14,15] Category 2 involves the cross-lateral radiograph (Figure 3).[16]

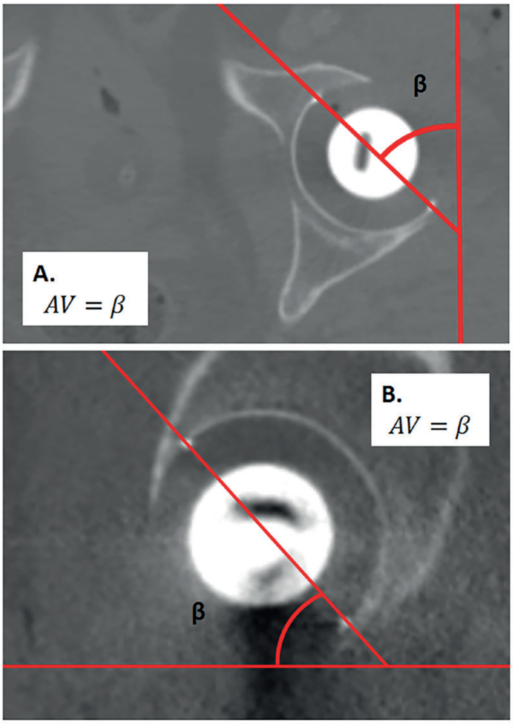

Figure 2. Category 1 methods. Definitions and algorithms of the included anteversion (AV) measurements methods with CT. The angle is measured by the opening of the cup in relation to the axis of the respective plane. (A) Transverse-CT anteversion. (B) Sagittal-CT anteversion.

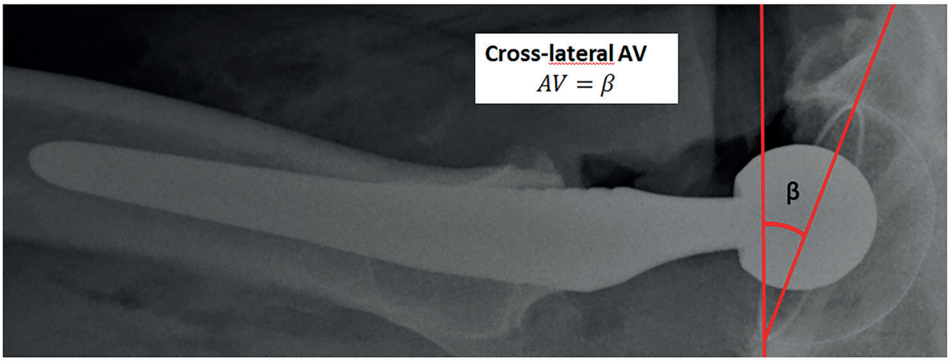

Figure 3. Category 2 method. Definition and algorithm of the included anteversion measurements on a cross-lateral radiograph[16]. The angle is measured by the opening of the cup in relation to the axis of the respective plane. AV, anteversion; β, angle.

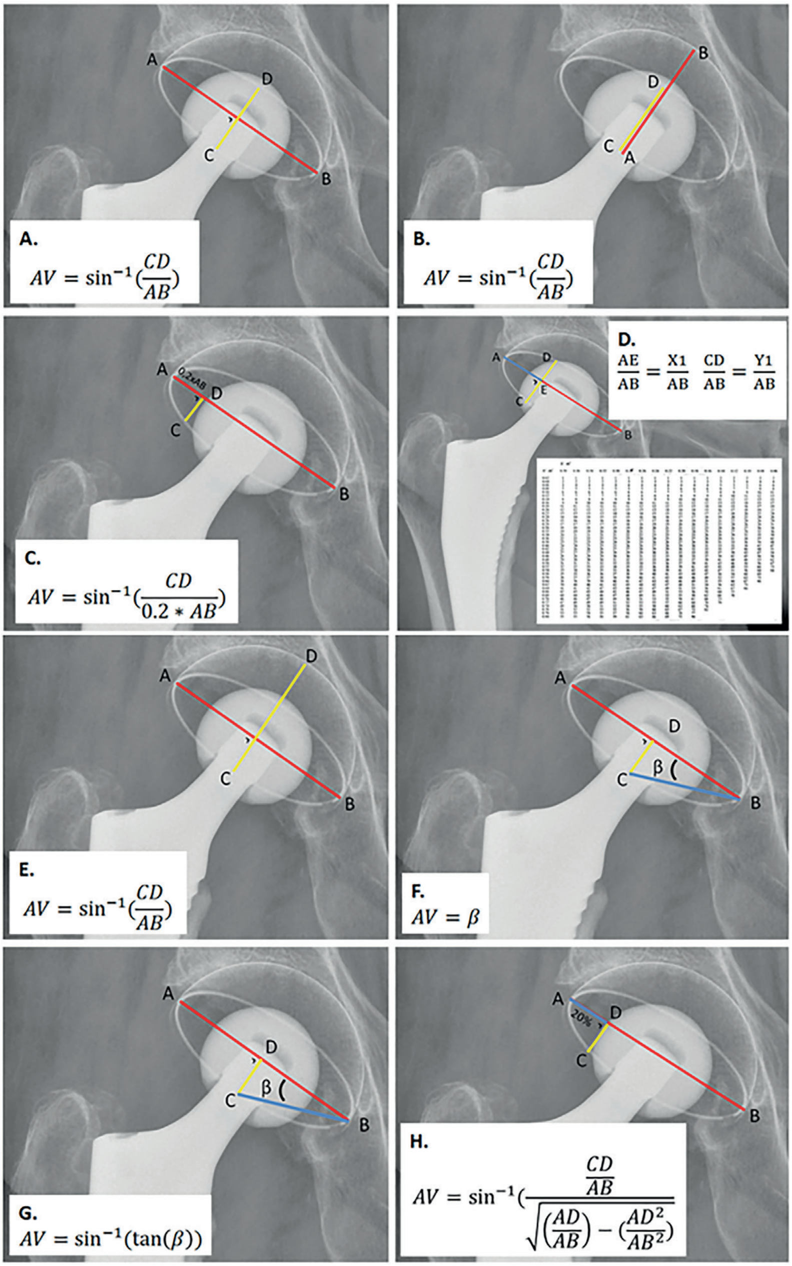

Figure 4. Category 3 methods. Definitions and algorithms of the included anteversion (AV) measurements methods with anterior–posterior radiographs. The respective distances are measured and filled in the respective formulas: (A) Lewinnek et al.[1], (B) Widmer et al.[6], (C) Riten Pradhan[17], (D) Ackland et al.[18], (E) Dorr et al.[19], (F) Wan et al.[20], (G) Liaw et al.[21], and (H) Hassan et al.[3] . β = angle.

The third category includes methods that measure anteversion based on the ratios of the ellipse on an AP pelvic radiograph. These methods try to establish the radiographic anteversion by using different algorithms (Figures 1A and 4).[1,3,6,17–21] The radiographic anteversion is the angle measured on a spatial plane perpendicular to the acetabular cup axis.

Three observers were instructed in using the precise definitions and algorithms of the 11 different measurement methods. For intraobserver reliability, one observer measured the anteversion using the different methods in random order on three separate occasions, with a 2-week interval. For interobserver reliability, all three observers performed the measurements on AP pelvic radiographs, and cross-lateral pelvic radiographs using Rogan View Pro-X (Rogan View Pro-X, version 4.0.8.9, Rogan-Delft B.V., Delft, the Netherlands). Finally, the anteversion method of McCollum et al. was measured on the sagittal plane and the anatomical anteversion was measured on the transverse plane of the CT scans of the pelvis, using HOROS Medical Image Viewer (Horos v2.0.2, Horos project, Annapolis, USA).[14]

Statistical Analysis

Statistical analyses were performed using IBM-SPSS Statistics 23 (SPSS, Chicago, Illinois, USA). Continuous parameters were assessed and presented as mean +/- standard deviation (range). Box plots were used to identify any outliers. For intraobserver and interobserver reliability, measured angles were compared within and between the observers using the intraclass correlation coefficient (ICC), with a one-way random effects model for intraobserver reliability and a two-way mixed effects model with absolute agreement for interobserver reliability. Validity of the different measurement methods was defined as compared to the anatomical anteversion of the acetabular cup on the transverse CT images that we consider to be the "gold" standard. The Pearson correlation coefficient was used for correlation analysis. We considered an alternative method that showed a correlation coefficient >0.80, with the "gold" standard as a good quality method that can be tolerated clinically. The outcomes of the different methods were also tested for differences of the mean using paired student t-tests. The level of statistical significance was set at 0.05.

RESULTS

Population

Sixteen THA on CT scans of 16 patients met the inclusion criteria. The primary THA were implanted between 2002 and 2016. Demographics are shown in Table 1.

Table 1. Demographics.

	n=16
Number of females (%)	11
Age (years)	75.9±7.8 (62-88)
Number of left sided total hip arthroplasty	7 (44%)
Uncemented acetabular component	16 (100%)
Monoblock	16 (100%)
Median cup size in mm (range)	54 (50-60)

All CT angiograms were requested by a local vascular surgeon. All patients had a highly-cross-linked polyethylene uncemented monoblock acetabular cup (RM Pressfit cup, Mathys Ltd. Bettlach, Switzerland).

Anteversion Measurement Results

Measured anteversion data was normally distributed and box plots showed that there were no outliers. The anteversion measurement methods of Riten Pradhan et al. (Figure 4C) and Ackland et al. (Figure 4D) were unable to calculate "anteversion" for two patients, who demonstrated relative high anteversion for the other measurement methods.[17,18] Absolute outcomes of the different anteversion measurement methods are shown in Table 2.

All methods showed excellent intraobserver and interobserver reliability: intraclass correlation coefficients for intraobserver and interobserver reliability varied between 0.921 and 0.997, and 0.871 and 0.996, respectively (Table 3).

Differences of the Mean Outcomes and Linear Correlation Analysis

Three measurement methods (anteversion measured on the sagittal plane with CT, a cross-lateral pelvic radiograph and the method of Widmer et al.) showed no significant difference in mean outcome as compared to our "gold" standard, the anteversion measured on transverse CT scans.[6] The other methods (all on AP-pelvic radiographs) differed significantly from the cup orientation on transverse CT scans (Table 3). Correlation analyses revealed significant linear correlations varying between 0.528 and 0.771 for all methods when compared to the transverse version on CT scans (Table 3) (Figure 5).

Table 2. Outcomes of the different measurement methods and category are shown as mean and standard deviation (SD). CT = computer tomography

Anteversion measurement method	Category	n	mean	SD
Transverse CT(2)	1	*16*	*26.6°*	*±12.6°*
Lateral CT(14)	1	16	25.2°	±12.7°
Cross-Lateral(16)	2	16	27.1°	±11.7°
Lewinnek et al.(1)	3	16	20.4°	±10.4°
Widmer et al.(6)	3	16	32.4°	±13.0°
Riten Pradham et al.(17)	3	14	37.0°	±20.7°
Ackland et al.(18)	3	14	16.6°	±7.9°
Dorr et al.(19)	3	16	38.8°	±7.3°
Wan et al.(20)	3	16	18.5°	±8.4°
Liaw et al.(21)	3	16	20.3°	±10.5°
Hassan et al.(3)	3	16	19.3°	±10.4°

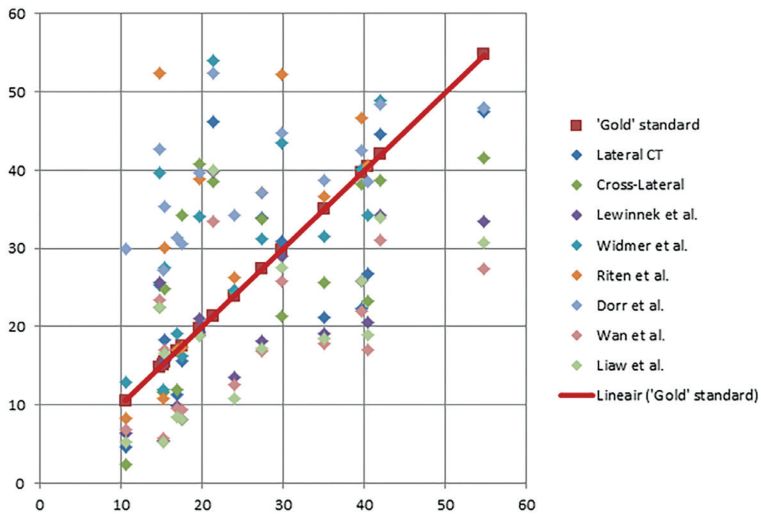

Figure 5. Results per patients for the different anteversion measurement methods on the x-axis versus the "gold" standard on the y-axis.

Table 3. For intraobserver reliability analyses, differences between anteversion measurements were evaluated between multiple measurements of one observer using the ICC. For interobserver reliability analyses, differences between measured angles were evaluated between multiple measurements of three different observers using the ICC. Results of the linear correlation (Pearson correlation coefficient) between the different anteversion measurement methods and the acetabular cup orientation on transverse CT. ICC is shown including the 95% confidence interval. CT = computer tomography. AV = anteversion. * = significant (p=0.05)

Anteversion measurement method	Intraobserver reliability ICC	Interobserver reliability ICC	Absolute agreement (P-value)	Correlation (R)
Transverse CT*(2)*	0.988 (0.973-0.995)	0.871 (0.736-0.948)	-	1
Lateral CT(14)	0.972 (0.938-0.989)	0.993 (0.983-0.997)	0.616	0.671
Cross-Lateral(16)	0.991 (0.980-0.997)	0.984 (0.965-0.994)	0.847	0.562
Lewinnek et al.(1)	0.997 (0.994-0.999)	0.996 (0.990-0.998)	0.032*	0.602
Widmer et al.(6)	0.971 (0.935-0.996)	0.996 (0.991-0.999)	0.054	0.624
Riten Pradham et al.(17)	0.978 (0.946-0.992)	0.988 (0.970-0.996)	0.009*	0.771
Ackland et al.(18)	0.992 (0.981-0.997)	0.992 (0.980-0.997)	0.002*	0.747
Dorr et al.(19)	0.995 (0.988-0.998)	0.990 (0.976-0.996)	0.000*	0.594
Wan et al.(20)	0.947 (0.884-0.979)	0.950 (0.890-0.980)	0.008*	0.556
Liaw et al.(21)	0.921 (0.831-0.969)	0.940 (0.869-0.977)	0.045*	0.528
Hassan et al.(3)	0.980 (0.956-0.992)	0.959 (0.910-0.984)	0.016*	0.586

DISCUSSION

Multiple definitions for acetabular cup anteversion in THA exist. In order to study the relevance of acetabular cup orientation in relation to clinical outcome, it is of major importance that the measured orientation of different studies are comparable and lead to equivalent clinical guidelines for optimal acetabular cup placement. Therefore, this study compared different anteversion measurement methods with the “gold” standard method. In summary, although outcomes of three conventional measurement methods were on average the same as our “gold” standard, individual differences were wide. For this reason, the outcomes are neither directly comparable nor interchangeable (Table 3). This is the first study comparing all non-automated measurement methods for acetabular cup anteversion with a "gold" standard and it provides an explanation as to why there is still no consensus on optimal acetabular cup orientation to date. [10,11]

Our study demonstrates that none of the included methods can function as a substitute for the "gold" standard as they all do not reach the threshold for correlation analyses. Studies investigating so-called "safe zones" for acetabular cup orientation provide recommendations that cannot be applied to other definitions without discrepancies. For example, using cross-lateral radiograph based recommendations as a target during surgery, while changing the anteversion following the operative anteversion definition of Murray will not give the expected result, because it rotates around another axis (Figure 1A).[15] Our results did show that a cross-lateral radiograph, a lateral radiograph, and an AP radiograph were not statistically significantly different from the "gold" standard. This might suggest that these methods could be used as a surrogate. However, it is more likely that this finding is caused by the small number of patients. With a larger study group this effect would probably also be statistically significantly different, because the measurements concerned use different spatial angles.

The differences in these methods lies in the direction of their axis where the angle rotates around. For the "gold" standard the axis of rotation is the longitudinal axis (Y in Figure 1B). Surrogate measurement methods rotate around different axes. The method of McCollum et al. rotates around the transverse axis (X in Figure 1B), while the category 3 methods rotate around an axis perpendicular to a plane between the transverse and sagittal plane.[14] Thus, it rotates around an axis somewhere between the longitudinal (X) and the transverse axis (Y). This specific axis is dependent on the orientation of the acetabular cup. For an example, one could have two patients with both an anteversion of 30^0 with the method of Widmer et al. and have inclinations of 15^0 and 60^0, respectively.[6] If one uses the "gold" standard in both patients, differences in anteversion will be measured. The patient with an inclination of 60^0 will have a relatively low anteversion measured with the "gold" standard, while the patient with an inclination of 15^0 will have a relative high anteversion with the "gold" standard. Thus, compared to the "gold" standard the methods using an ellipse have a relationship with the inclination. Another factor involving the category 3 methods is that it is impossible to define if the acetabular cup has anteversion or retroversion with all methods that use the ellipse on an AP pelvic radiograph (Figure 4).

Limitations

Several other factors could cause diverging measurements and are limitations to our study: measuring error, position of the patient, orientation of the pelvis, position of the radiation beam of the radiograph, and intervariability of the anatomy of the individual patient. The measuring error proved to be small, as shown by the excellent intraobserver and interobserver reliability of all methods (Table 3). Patient positioning may have influenced our results, despite the similar patient positioning for different imaging modalities and that it was defined in protocols. Still, slight deviations cannot be excluded. Standardized orientation of the pelvis is more difficult. For instance, the study of Lewinnek et al. did standardize the pelvic tilt by adjusting the anterior pelvic plane until it was parallel to the table 1.[1] Most other studies and our study did not carry out this adjustment. Patient positioning and adjusting the pelvis so that it is parallel to the table can be changed before measuring the acetabular orientation. This is in contrast to the patients' anatomy, which is fixed. The patients' anatomy determines the reference plane from where the angles are measured.

This study had some other limitations. First, there were some missing values. Using the methods described by Riten Pradhan et al. and Ackland et al., we could not calculate the anteversion for two cases, because these two had relatively increased anteversion.[17,18] This may have introduced a selection bias, which could affect the results. In contrast, this shows that these methods are not suitable for clinical use in a wide range of cup orientations. The second limitation is the relatively small sample size, which introduces a risk for a type 2 error. In our database, there were no more THA patients available with CT angiogram images, cross-lateral pelvic radiographs and AP-pelvic radiographs acquired in the same position. Because of the heterogeneity of our study population, we believe our results generally hold true. However, we do realize that a larger cohort would have given the article more statistical validity. A third limitation is the "gold" standard itself. To our knowledge, there is no study that has validated the "gold" standard. Fourth, with a change in pelvic rotation, tilt or obliquity, a different anteversion is measured. For example, there could be a small change in orientation of the pelvis of the patient in the supine position between the radiographic imaging table and the CT imaging table.[23] Fifth, there might be an increased measuring error with the cross-lateral pelvic radiograph, because the pelvis could tilt posteriorly. This occurs particularly in patients with contralateral osteoarthritis of the hip with a flexion contracture. Finally, including the methods based on a software program that defines the anteversion on an AP-pelvic radiograph would have made this study complete. Unfortunately, these resources were not available. Nevertheless, these methods are based on the ellipse as well and are also subject to the influence of the inclination and possible retroversion of the acetabular cup, as described above.

CONCLUSIONS

This study shows that there is no correlating surrogate anteversion measurement method to substitute the "gold" standard, anteversion measured in the transverse plane around the longitudinal axis on a CT scan. Consequently, studies evaluating acetabular cup orientation with different methods are difficult to standardize and cannot be compared. Therefore, it is difficult to provide a recommendation concerning the optimal acetabular cup orientation.[10,11] We consider the anatomical anteversion in the transverse plane rotating around the longitudinal axis to be the "gold" standard and recommend avoiding using the term anteversion for other projectional angles in different planes.

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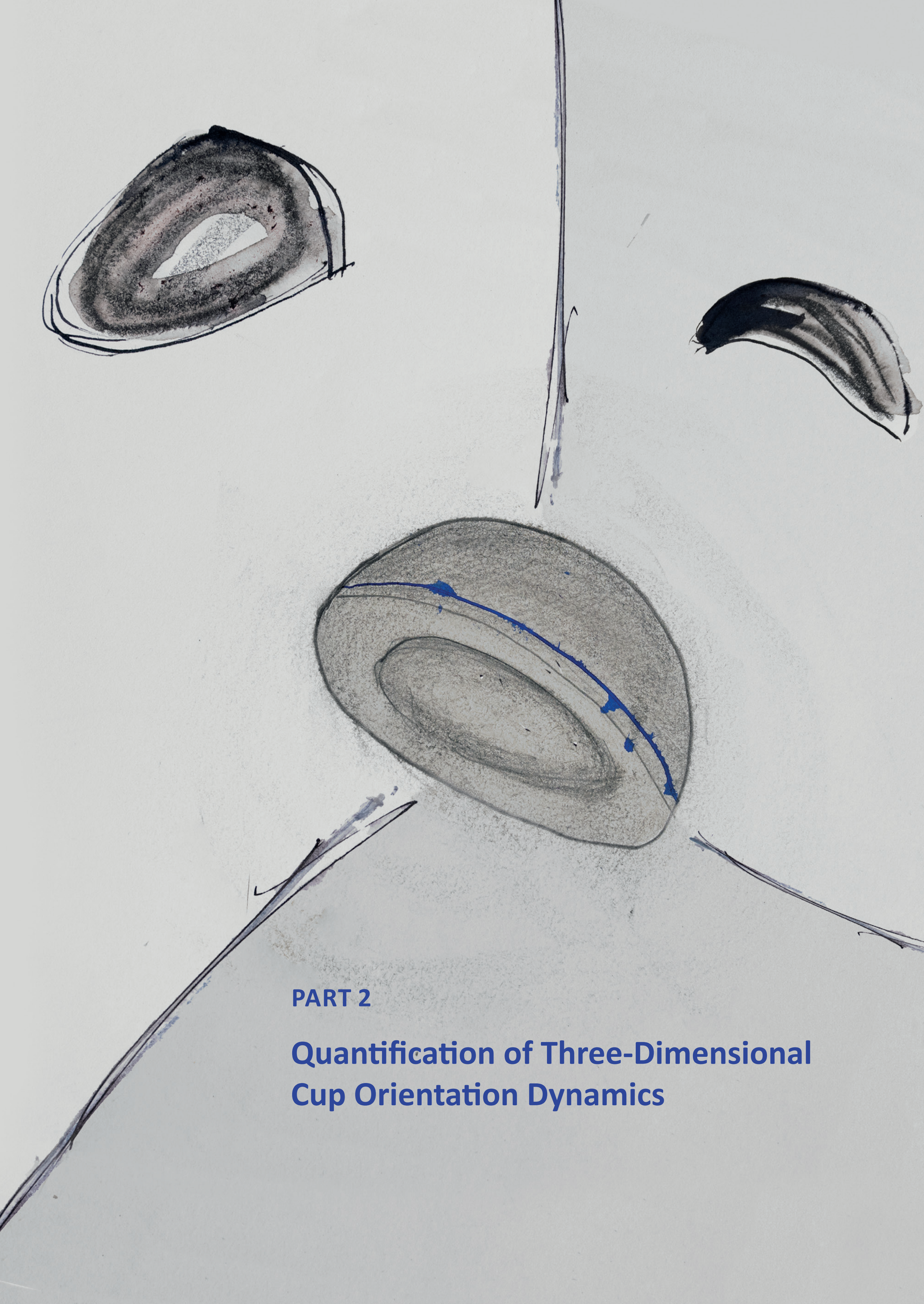

PART 2

Quantification of Three-Dimensional Cup Orientation Dynamics

CHAPTER 5

Trigonometric Algorithm Defining the True Three-Dimensional Acetabular Cup Orientation Correlation between Measured and Calculated Cup Orientation Angles

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ABSTRACT

Background

Acetabular cup orientation plays a key role in implant stability and the success of total hip arthroplasty. To date, the orientation has been measured with different imaging modalities and definitions, leading to lack of consensus on optimal cup placement. A 3-dimensional (3-D) concept involving a trigonometric description enables unambiguous definitions. Our objective was to test the validity and reliability of a 3-D trigonometric description of cup orientation.

Methods

Computed tomographic scans of the pelvis, performed for vascular assessment of 20 patients with 22 primary total hip replacements in situ, were systematically collected. On multiplanar reconstructions, 3 observers independently measured cup orientation retrospectively in terms of coronal inclination, sagittal tilt, and transverse version. The angles measured in 2 planes were used to calculate the angle in the third plane via a trigonometric algorithm. For correlation and reliability analyses, intraobserver and interobserver differences between measured and calculated angles were evaluated with use of the intraclass correlation coefficient (ICC).

Results

Measured and calculated angles had ICCs of 0.953 for coronal inclination, 0.985 for sagittal tilt, and 0.982 for transverse version. Intraobserver and interobserver reliability had ICCs of 0.987 and 0.987, respectively, for coronal inclination; 0.979 and 0.981, respectively, for sagittal tilt; and 0.992 and 0.978, respectively, for transverse version.

Conclusions

The 3-D concept with its trigonometric algorithm is a valid and reliable tool for the measurement of cup orientation. By calculating the transverse version of cups from coronal inclination and sagittal tilt measurements, the trigonometric algorithm enables a 3-D definition of cup orientation, regardless of the imaging modality used. In addition, it introduces sagittal tilt that, like pelvic tilt, rotates around the transverse axis.

INTRODUCTION

The first total hip arthroplasty, introduced in 1962 by Sir John Charnley, had a dislocation rate of approximately 4.8% after 23 years, as reported in a large longterm cohort.[1] Since then, dislocation has remained one of the most common postoperative complications, with reported rates of 0.2% after 3 months, 0.8% after 1 year, and 4.76% after 10 years.[2–4] It is well known that acetabular cup orientation is of substantial importance to a well-functioning and stable total hip replacement.[5–7] Several studies have suggested that cup orientation should be within a specific zone in order to minimize the risk of dislocation. For instance, the widely accepted "safe zone" of Lewinnek is characterized by an inclination of 40 ± 10 and an anteversion of 15 ± 10.[6] However, multiple methods for measuring cup orientation, involving different imaging modalities and various definitions for descriptive angles in different planes, have been introduced.[6,8–10] On the one hand, "inclination" is consistently considered to be the angle that represents cup orientation in the anatomical coronal plane. On the other hand, "anteversion" has been used to describe cup orientation in the anatomical transverse and sagittal planes as well as in different oblique planes.[11] For example, "anteversion" was measured on radiographs in the sagittal plane and on computed tomography (CT) scans in the transverse plane. It was measured on cross-lateral radiographs on a projectional plane or calculated from the ellipse that results from the cup projection on anteroposterior pelvic radiographs. In addition, a combination between the sagittal and transverse angles has been used intraoperatively.[12–15] Several of these methods disregard the fact that these measured angles are projections of a 3-dimensional (3-D) cup on different 2-dimensional (2-D) planes. In a recent study, Snijders et al. showed that a plethora of different definitions of anteversion for cup orientation leads to confusion with respect to guidelines for cup placement.[16] As there is no uniform method for the assessment of cup orientation in 3 dimensions, it is very difficult to compare or pool data from studies on the optimal cup position.[6,7,17] A uniform concept that is applicable with every 2-D and 3-D imaging method could fill this void.
3-D cup orientation can be defined and measured in the coronal, transverse, and sagittal planes (Figure 1).

Each angle rotates around an axis perpendicular to that particular plane. Thus, cup orientation can be defined by angles that describe inclination as the rotation around the sagittal axis in the coronal plane, version as the angle rotating around the longitudinal axis in the transverse plane, and tilt as the angle rotating around the transverse axis in the sagittal plane (Figure 2, Video 1).

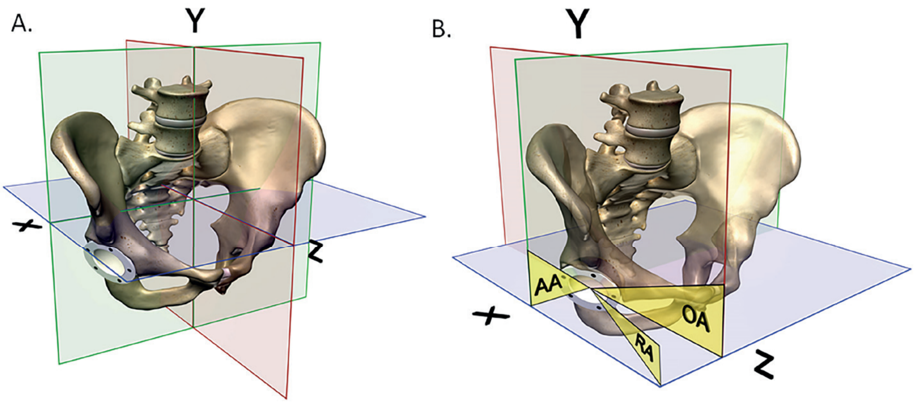

Figure 1. A. Illustration depicting the coronal plane (green), sagittal plane (red), and transverse plane (blue). X indicates the transverse axis, Y indicates the longitudinal axis, and Z indicates the sagittal axis. B. Illustration depicting the different definitions of anteversion introduced byMurray10. AA= anatomical anteversion in the transverse plane, with rotation around the longitudinal axis; OA = operative anteversion in the sagittal plane, with rotation around the transverse axis; and RA = radiographic anteversion in a projectional plane, with rotation around an axis in between the longitudinal and transverse axes.

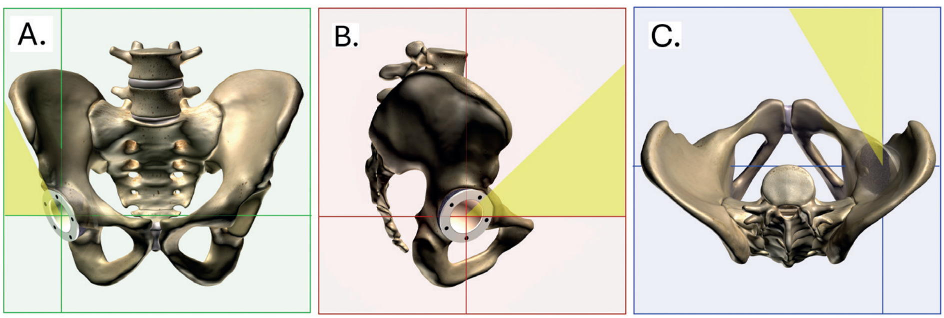

Figure 2. Illustrations depicting coronal inclination (A), sagittal tilt (B), and transverse version (C) of the cup. Video 1 can be viewed here: JBJS Open Access

Evaluation of cup orientation in the sagittal plane is highly recommended. First, adequate inclination and anteversion within the "safe zone" of Lewinnek could still be insufficient in the sagittal plane. Second, high-risk movements for a posterior dislocation often consist of adduction and hip flexion, with the latter movement involving rotation around the transverse axis in the sagittal plane. Third, pelvic tilt also involves rotation around the transverse axis and solely affects relative 3-D cup orientation.

For the present study, we developed a mathematical algorithm that describes the relationships between the 3-D cup-orientation angles in the anatomical planes. Because most modern cups are hemispherical, mathematical modeling could be used to calculate cup orientation in the 3 perpendicular planes. In order to implement this trigonometric mathematical 3-D algorithm, it is necessary to examine the effect of measuring errors on the results of the algorithm. Moreover, because radiographic transverse imaging is impossible to achieve, this algorithm can only be verified with 3-D CT before it can be applied with 2-D radiographic images in daily practice.

The purpose of the present study was to test definitions of cup orientation derived from a trigonometric algorithm defined with respect to the 3 anatomical planes. First, the validity of the algorithm was tested by correlating measured and calculated 3-D cup-orientation angles. Second, we evaluated the intraobserver and interobserver reliability of the 3-D cup-orientation measurements necessary as input for the algorithm.

MATERIALS AND METHODS

Study Procedures

After approval from the institutional review board, the patient archiving and communications system (PACS) was systematically searched for CT angiogram images of the pelvis that were acquired between January 2013 and August 2016 and showed a total hip replacement in situ, a cup with a circumferential reference perpendicular to the cup axis, and complete visualization of the pelvis. The exclusion criteria were previous ipsilateral hip surgery other than primary total hip arthroplasty, malignant disease localized in the pelvis or femur, and images that were part of an incomplete series or that showed substantial contrast artifacts in the region of interest. By protocol, scans were acquired with the patient in the supine position with use of a 16-channel multidetector CT system (Siemens Healthcare; slice thickness, 0.5 mm). Clinical and radiographic charts were reviewed by 1 observer for inclusion and exclusion, and demographic data were collected.

After manual localization of the center of the femoral head of the total hip replacement on the transverse CT images, multiplanar reconstructions were acquired for the coronal, transverse, and sagittal planes with use of MeVisLab (MeVis Medical Solutions). Next, 3 blinded observers independently measured the inclination in the coronal plane, tilt in the sagittal plane, and version in the transverse plane for all cups in random order with use of a HOROS Medical Image Viewer (Horos v2.0.2; Horos project). For interobserver reliability, 1 blinded observer measured the angles at 3 different settings within a 2-week interval. Coronal inclination and sagittal tilt were defined as the angle between the line through the longitudinal axis of the ellipse of the rim of the cup and the horizontal, whereas transverse version was defined as the angle between the longitudinal axis of the ellipse of the rim of the cup and the sagittal axis (Figure 3).

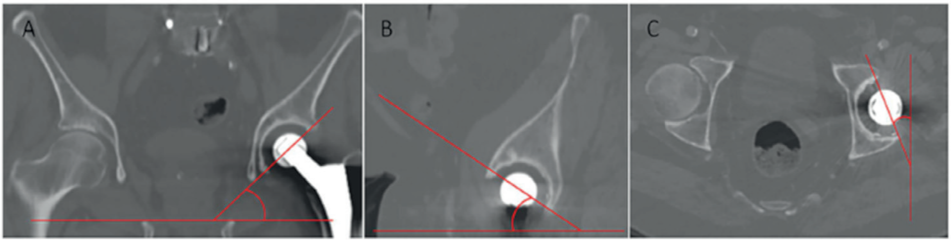

Figure 3. Multiplanar reconstruction of CT scans, illustrating the method of measurement of coronal inclination (A), sagittal tilt (B), and transverse version (C) of the acetabular cup.

Therefore, positive angles represented anterior sagittal tilt (also referred to as antetilt) and anterior transverse version (also referred to as anteversion of the cup). Last, a trigonometric algorithm that was developed inhouse for the assessment of 3-D cup orientation was used for calculation of the 3-D angles (see Appendix). In this algorithm, the angles measured in 2 perpendicular planes were used to calculate the parameter in the third plane. Hence, for each patient, 3 calculations were derived, whereby inclination, version, and tilt were each subsequently determined on the basis of the 2 others. For anteriorly oriented cups, the following equations were used:

1. Inclination = arctan (tan *Version*/tan *Tilt*)
2. Version = arctan (tan (*Inclination*)×tan (Tilt))
3. Tilt = arctan (*tanVersion*/*tanTilt*)

For retroverted and retrotilted cup orientations, the following equations were used:

1. Inclination = arctan (tan *Version*/tan *Tilt*)
2. Version = arctan (tan (*Inclination*)×tan (Tilt))
3. Tilt = 90-arctan (*tanVersion*/*tanTilt*)

Statistical Analysis

For practical purposes and calculation of the different angles with use of the algorithm, data were imported into Excel 2010 (Microsoft). Statistical analyses were performed with use of IBM SPSS Statistics 23 (IBM). The continuous angles were assessed and were expressed as the mean and the standard deviation, with the range in parentheses. Box plots were used to identify any outliers. For validity analysis, differences between the measured and calculated angles per case for the 3 observers were assessed with use of the intraclass correlation coefficient (ICC) and corresponding 95% confidence interval (CI) with a 2-way mixed-effects model for absolute agreement. For intraobserver and interobserver reliability, measured and calculated angles were compared within and between the observers with use of the ICC, with a 1-way random-effects model for intraobserver reliability and a 2-way mixed-effects model for interobserver reliability.

RESULTS

Demographics

Twenty-two total hip replacements on CT scans of 20 patients met the inclusion criteria. All CT angiograms had been requested for vascular assessment. The primary total hip replacements had been implanted between 2002 and 2016. Demographic characteristics and cup types are shown in Table I.

Table 1. Demographic data

No. of patients (no. of hips)	20 (22)
No. of female patients	11 (55%)
Age* (yr)	75 ± 7.1 (62-88)
Left-sided total hip arthroplasty (no. of hips)	13 (59.1%)
Approach	
Direct lateral	9
Posterolateral	7
Anterolateral	3
Unknown	3
Type of cup (no. of hips)	
RM |Pressfit cup (Mathys Bettlach)	17 (77.3%)
PF (Zimmer)	1 (4.5%)
Morscher (zimmer)	1 (4.5%)
Exeter all-polyethylene cup (Stryker)	1 (4.5%)
Monoblock cup of unknown design	2 (9.1%)

Table 1. Continued

Cup fixation (no. of hips)	
Cemented	3 (13.6%)
Uncemented	19 (86.4%)
Cup type (no. of hips)	
Monoblock	22 (100%)
Modular system	0 (0%)
Cup size† (mm)	54 (46-60)

* The values are given as the mean and the standard deviation, with the range in parentheses.
† The values are given as the median, with the range in parentheses.

Validity and Reliability Analyses

Data were normally distributed, and there was only 1 outlier. This outlier was excluded because, in this outlier, 2 angles were around 0. Therefore, the measuring error affected the calculated results to a great extent. The mean coronal inclination, sagittal tilt, and transverse version that were measured on the multiplanar reconstructions for 21 total hip replacements by 3 observers (thus, for 63 measurements), were 42.82 ± 9.18 (range, 25.76 to 64.21), 25.67 ± 11.09 (range, 7.13 to 49.03), and 27.05 ± 12.01 (range, 10.75 to 54.79), respectively. The calculated angles were 42.90 ± 8.95 (range, 26.21 to 65.14) for coronal inclination, 25.55 ± 11.09 (range, 6.53 to 49.19) for sagittal tilt, and 27.26 ± 12.34 (range, 9.62 to 54.74) for transverse version. Tables II, III, and IV show the measured and calculated angles per case and per observer.

Table 2. Measured and Calculated Values of Coronal Inclination*

	Coronal Inclination (deg)					
	Observer 1		Observer 2		Observer 3	
Case	Measured	Calculated	Measured	Calculated	Measured	Calculated
1	30.83	31.87	30.63	31.01	30.31	30.63
2	38.31	39.75	37.81	39.79	39.75	39.27
3	52.22	51.30	51.66	50.76	51.94	50.44
4	64.21	65.14	63.36	63.74	63.20	64.58
5	46.2	44.43	44.24	54.75	46.72	52.39
6	43.23	42.72	44.38	42.06	43.80	44.32
7	38.65	38.77	39.73	39.73	39.26	37.50
8	36.42	32.98	32.46	33.28	31.52	35.42
9	48.16	47.02	48.20	46.39	47.54	47.56
10	45.25	44.85	45.84	46.65	44.00	42.21

Table 1. Continued

	Coronal Inclination (deg)					
	Observer 1		Observer 2		Observer 3	
Case	Measured	Calculated	Measured	Calculated	Measured	Calculated
11	28.69	29.52	29.18	29.47	28.76	28.81
12	37.12	38.74	36.73	29.41	37.23	37.32
13	33.07	34.32	31.96	30.97	32.80	33.48
14	46.72	47.01	43.18	45.79	45.68	46.20
15	54.83	52.08	53.40	49.80	52.05	50.06
16	52.70	52.86	52.74	51.23	53.38	52.32
17	26.08	26.83	26.92	39.38	25.76	26.21
18	44.83	42.87	44.63	41.04	43.75	41.05
19	48.04	48.42	48.56	47.88	47.85	45.89
20†	41.62	37.47	45.43	82.17	42.19	27.70
21	41.80	41.91	41.38	40.92	39.54	41.26
22	49.99	50.53	48.96	49.16	49.41	48.64

* Differences between calculated and measured angles were evaluated with use of the intraclass correlation coefficient (ICC). For coronal inclination, the ICC was 0.953 (95% CI, 0.923-0.971). † Case excluded.

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Table 3. Measured and Calculated Values of Sagittal tilt*

	Sagittal Tilt (deg)					
	Observer 1		Observer 2		Observer 3	
Case	Measured	Calculated	Measured	Calculated	Measured	Calculated
1	27.23	26.29	25.8	25.47	26.75	26.46
2	46.94	45.47	46.46	44.43	46.25	46.74
3	30.34	31.17	30.72	31.54	25.37	26.58
4	28.02	27.03	27.51	27.12	29.12	27.66
5	22.99	24.29	31.53	22.89	25.49	21.31
6	19.59	19.92	19.42	20.92	19.29	18.97
7	48.52	48.40	49.03	49.03	47.4	49.19
8	7.13	8.09	7.66	7.43	7.56	6.53
9	44.1	45.24	43.57	45.38	44.62	44.60
10	20.82	21.09	28.62	27.94	20.08	21.27
11	21.05	20.40	21.3	21.07	21.13	21.09
12	12.33	11.65	10.61	13.92	11.67	11.63
13	12.12	11.57	10.79	11.21	11.35	11.06
14	30.71	30.45	30.71	28.47	30.88	30.42

Table 3. Continued

	Sagittal Tilt (deg)					
	Observer 1		Observer 2		Observer 3	
Case	**Measured**	**Calculated**	**Measured**	**Calculated**	**Measured**	**Calculated**
15	20.99	22.98	18.88	21.26	18.27	19.51
16	34.36	34.21	33.82	35.27	33.87	34.89
17	22.46	21.80	22.77	14.55	22.25	21.85
18	15.01	16.02	15.56	17.53	14.2	15.54
19	25.62	25.33	27.42	27.98	24.6	26.12
20†	-1.5	-1.29	2.76	0.39	-1.39	-1.26
21	16.05	15.99	16.37	16.62	15.55	14.67
22	32.94	32.44	31.66	31.48	31.81	32.51

*Differences between calculated and measured angles were evaluated with use of the intraclass correlation coefficient (ICC). For sagittal tilt, the ICC was 0.985 (95% CI, 0.975-0.991). †Case excluded.

Table 4. Measured and Calculated Values of Transverse version*

	Sagittal Tilt (deg)					
	Observer 1		Observer 2		Observer 3	
Case	**Measured**	**Calculated**	**Measured**	**Calculated**	**Measured**	**Calculated**
1	39.61	40.77	38.81	39.23	40.41	40.77
2	52.15	53.56	51.64	53.60	51.95	51.47
3	25.12	24.40	25.89	25.17	21.39	20.37
4	13.85	14.42	14.41	14.64	14.83	15.72
5	23.4	22.14	23.44	32.21	20.17	24.18
6	21.08	20.74	21.34	19.81	19.72	20.05
7	54.62	54.74	54.18	54.18	54.79	53.07
8	10.91	9.62	11.58	11.94	10.57	12.21
9	42.08	40.95	42.18	40.38	42.06	42.08
10	20.92	20.65	27.25	27.92	21.95	20.73
11	34.2	35.12	34.6	34.92	35.1	35.15
12	15.24	16.11	18.38	14.09	15.16	15.21
13	17.46	18.25	17.62	16.99	16.88	17.30
14	28.97	29.22	30.02	32.33	29.83	30.28
15	16.64	15.13	16.12	14.25	15.45	14.44
16	27.38	27.51	28.28	27.00	27.4	26.51
17	39.26	40.18	27.08	39.58	39.73	40.29
18	16.11	15.10	17.74	15.75	16.2	14.81
19	23.05	23.32	25.13	24.61	23.93	22.51

Table 4. Continued

	Sagittal Tilt (deg)					
	Observer 1		Observer 2		Observer 3	
Case	Measured	Calculated	Measured	Calculated	Measured	Calculated
20†	-1.15	-1.33	0.38	2.72	-0.73	-0.81
21	17.77	17.84	18.72	18.44	17.6	18.63
22	28.08	28.54	28.06	28.23	28.64	27.99

*Differences between calculated and measured angles were evaluated with use of the intraclass correlation coefficient (ICC). For transverse version, the ICC was 0.982 (95% CI, 0.971-0.989). †Case excluded.

Correlation analysis of 63 measured and calculated 3-D angles revealed an ICC of 0.953 (95% CI, 0.923 to 0.971) for coronal inclination, 0.985 (95% CI, 0.975 to 0.991) for sagittal tilt, and 0.982 (95% CI, 0.971 to 0.989) for transverse version (Tables II, III, and IV). The ICCs for intraobserver and interobserver reliability of the measured angles for 21 total hip replacements were 0.987 (95% CI, 0.974 to 0.994) and 0.987 (95% CI, 0.974 to 0.994), respectively, for coronal inclination; 0.979 (95% CI, 0.959 to 0.991) and 0.981 (95% CI, 0.962 to 0.991), respectively, for sagittal tilt; and 0.992 (95% CI, 0.983 to 0.996) and 0.978 (95% CI, 0.956 to 0.990), respectively, for transverse version (Tables V and VI).

Table 5. Results of Intraobserver Reliability Analysis*

Parameter	Measurement 1† (deg)	Measurement 2† (deg)	Measurement 3† (deg)	ICC†
Coronal inclination	0.987 (0.974-0.994)	42.95 ± 9.10 (26.04-64.08)	(27.02-63.55)	0.987 (0.974-0.994)
Sagittal tilt	0.981 (0.962-0.991)	24.39 ± 12.42 (-1.82-48.14)	24.70 ± 12.35 (-0.72-47.17)	0.979 (0.959-0.991)
Transverse version	0.978 (0.956-0.990)	25.79 ± 13.47 (-0.77-53.86)	26.36 ± 13.49 (-0.74-54.16)	0.992 (0.983-0.996)

*Differences between multiple measurements made by one observer were evaluated with use of the intraclass correlation coefficient (ICC). †The values are given as the mean and the standard deviation, with the range in parentheses. The values are given as the ICC, with the 95% CI in parentheses.

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Table 6. Results of Interobserver Reliability Analysis*

Parameter	Measurement 1† (deg)	Measurement 2† (deg)	Measurement 3† (deg)	ICC†
Coronal inclination	43.14 ± 9.16 (26.08-64.21)	42.79 ± 9.05 (26.92-63.36)	42.579.13 (25.76-63.20)	0.987 (0.974-0.994)
Sagittal tilt	24.45 ± 12.41 (-1.50-48.52)	25.13 ± 12.29 (0.38-49.03)	23.91 ± 12.32 (-1.39-47.40)	0.981 (0.962-0.991)
Transverse version	25.76 +13.49 (-1.15-54.62)	26.04 ± 2.76 (2.76-54.18)	25.59 ± 13.68 (-0.73-54.79)	0.978 (0.956-0.990)

*Differences between multiple measurements made by 1 observer were evaluated with use of the intraclass correlation coefficient (ICC). †The values are given as the mean and the standard deviation, with the range in parentheses. The values are given as the ICC, with the 95% CI in parentheses.

DISCUSSION

The present study showed excellent correlation between measured and calculated angles for the assessment of 3-D cup orientation with respect to the 3 anatomical perpendicular planes (Figures. 1 and 2). The proposed trigonometric algorithm can calculate the "true" (gold standard) transverse version in a valid and reliable way on the basis of the coronal inclination and the sagittal tilt. Similarly, coronal inclination can be calculated from sagittal tilt and transverse version, and sagittal tilt can be calculated from coronal inclination and transverse version. Theoretically, the ICC should be 1 in the case of perfect readings, and, in the present study, the ICC approached 1 for all 3 calculated angles (Tables II, III, and IV). The data suggest that the algorithm is usable in everyday practice. The minor measurement error of the readings is clinically irrelevant. An exception in the present study was the outlier case in which both transverse version and sagittal tilt were around 0. In that case, the minor measuring error affected the proportion between the 2 angles greatly, giving a result ranging from 27.70 to 82.17 of coronal inclination (Tables II, III, and IV). Therefore, we recommend using the algorithm with caution in cases in which 2 angles are approaching 0^0.

The validity of this 3-D concept provides improvements for the evaluation of optimal cup positioning in total hip arthroplasty and offers great potential for future comparative studies. The definitions are applicable to both radiographic and CT imaging as long as 2 orthogonal projections can be acquired (radiographs) or simulated (CT). While a craniocaudal radiograph of the pelvis is technically impossible, the algorithm has the potential to accurately calculate the transverse version with use of cup orientation angles on 2 radiographs, allowing for easily accessible postoperative feedback. Anteroposterior and lateral radiographs have to be made following the recommendation of Tannast et al..[18] Specifically, standardized radiographs must be made with the patient in the standing position with the generator at 1.20 m and with the central beam directed to the midpoint between the upper border of the symphysis and the center between both anterior superior iliac spines. The lateral radiograph should be centered on the cranial tip of the contralateral greater trochanter, with the total hip replacement near the detector. After measurement of the sagittal tilt and coronal inclination, the transverse version can be calculated with use of equation number 2 for anteriorly oriented cups, as described in the Materials and Methods section (Figure 4).

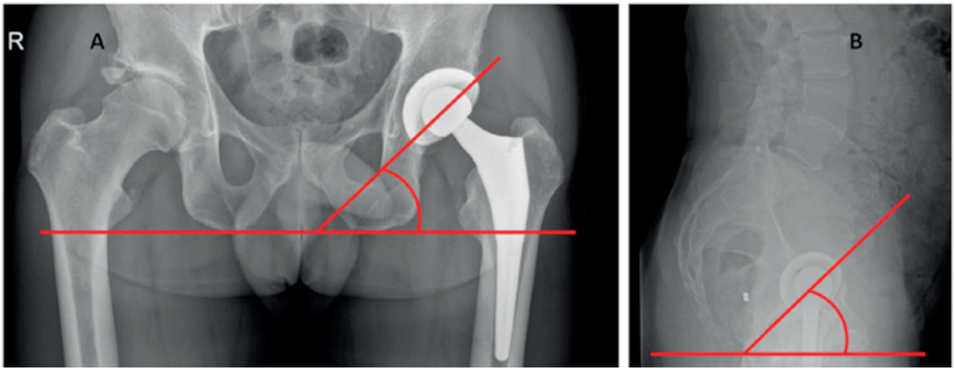

Figure 4. Anteroposterior and lateral radiographs illustrating an example of how to calculate transverse version on the basis of coronal inclination and sagittal tilt according to the equation for anteriorly oriented cups as described in the Materials and Methods section: Version = arctan(tan Tilt · tan Inclination); Version = 39.6 = arctan(tan 39.2 · tan 44.6)

The diverging radiation beam, however, presumably results in a larger measuring error. A future study should validate if the algorithm is also applicable with radiographs. If so, then these practical measurements can be performed without the extra radiation and additional cost of CT imaging, making 3-D evaluation of cup orientation available for large cohorts. Moreover, the 3-D concept could be helpful for establishing a consensus by enabling pooling of different studies that evaluate cup orientation in 2 orthogonal planes.

Murray, in 1993, clearly showed that the definitions for inclination and "anteversion" depend on the evaluation method used (radiographic, anatomical, and direct observation at surgery).[10] Direct comparison of inclination is possible because the definitions introduced by Murray for the 3 perspectives are basically equal. On the contrary, the different definitions of anteversion, which represent distinct spatial angles, are not interchangeable (Figure 1).[10] The transverse "anteversion" angle is a different spatial angle than the sagittal "anteversion" angle. Unfortunately, many previous studies have involved the use of different imaging methods and different definitions for anteversion, making it difficult to compare the recommendations.[6,7,13,14,19–21] Subsequent meta-analyses evaluating cup anteversion pooled these different outcomes of the spatial angles.[22–27] Thus, there is a lack of consensus for optimal cup orientation.[11] A consensus definition for preoperative planning, intraoperative placement, and postoperative evaluation of cup orientation would be useful. We recommend the evaluation of cup orientation in all 3 anatomical planes. These definitions are also applicable intraoperatively. These spatial angles provide unambiguous definitions and are interchangeable between different imaging modalities.

Moreover, there are reasons to believe that malplacement around the transverse axis is important for the mechanism of dislocation. If the cup orientation is in the "safe zone" of Lewinnek for inclination and anteversion, it might not be "safe" enough for sagittal tilt (Figure 5).[6]

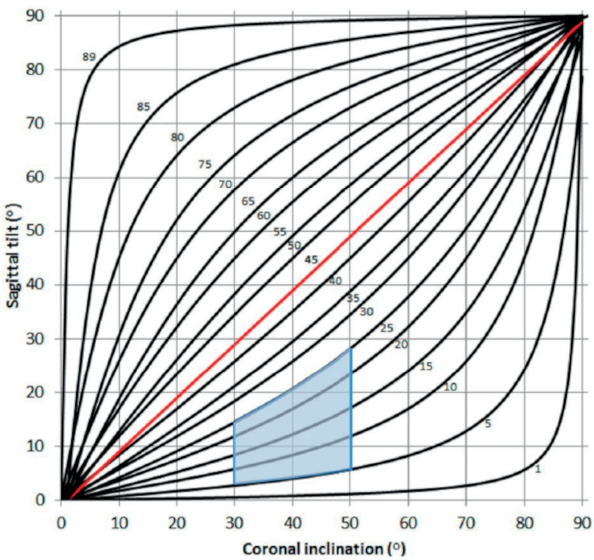

Figure 5. Three-dimensional surface diagram demonstrating the mathematical interrelation between coronal inclination, sagittal tilt, and transverse version. If 1 of the angles is 45_, the other 2 angles are identical. The red line demonstrates the direct comparison of sagittal tilt and transverse version at a coronal inclination of 45. The blue area demonstrates the "safe zone" of Lewinnek.

Most hip and pelvic movements (pelvic tilt as well as hip flexion and extension) take place around the transverse axis. Opposing pelvic movements around the transverse axis could be protective against dislocation during certain hip movements. For example, posterior pelvic tilt enhances the containment of the femoral head when there is also hip flexion. The joint reaction forces remain more opposed to each other. However, there is a wide variety between patients in terms of the dynamics of anterior and posterior pelvic tilt.[28] In addition, the amount of pelvic tilt in particular positions differs widely.[28] Theoretically, 1 of anterior pelvic tilt decreases the sagittal tilt of the cup by 1. In a previous study, Lembeck et al. stated that 1 of pelvic tilt affected anteversion by 0.729.[29] On the basis of our validated algorithm, however, that statement is not correct. Pelvic tilt changes the amount of transverse version depending on the amounts of coronal inclination and pelvic tilt and follows a tangential function (i.e., equation 2 for anteriorly oriented cups as described in the Materials and Methods section) (Figure 5). From a kinematic point of view, there is no argument for neglecting the sagittal tilt. Thus, this 3-D concept has important clinical relevance for defining the orientation around the transverse axis.

This 3-D concept has some limitations when used for the analysis of cup positioning. First, the algorithm cannot be applied to cups that lack a circumferential reference perpendicular to the acetabular axis. Fortunately, almost all modern cups have a circular wire that provides this reference. A second limitation is that the trigonometric algorithm is only applicable for planes that are perfectly orthogonal. Consequently, cross-lateral views cannot be used. On the other hand, innovative biplanar radiography techniques provide opportunities to use this algorithm for the systematic assessment of 3-D cup orientation in patients undergoing THA. Although additional lateral pelvic radiographs expose the patient to a relative high radiation dose compared with cross-lateral pelvic radiographs, this supplementary radiograph is only required one time postoperatively in addition to the standard anteroposterior pelvic radiograph. In addition, most of these patients are >50 years of age, thereby theoretically diminishing the long-term risk of the higher radiation dose. A third limitation is that patient positioning has an impact on 3-D cup orientation as pelvic tilt changes in different positions.[30,31] Kyo et al. established a difference of <10 of pelvic tilt in 83% to 90% of patients between the standing and supine positions.[32] Measuring and calculating the 3 angles with radiographic imaging with the patient in the standing position might give different results than for the 3 angles in the supine position because of this change in pelvic tilt.

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In conclusion, the trigonometric equations provided in the present study can be used to calculate the third 3-D orientation angle with use of the orientation angles in the 2 other anatomical planes. Transverse version is often a dominant factor for stability, and this value can now be calculated from the coronal (inclination) and sagittal (tilt) planes. Thus, this 3-D concept provides unambiguous definitions of cup orientation regardless of the imaging modality, and it could provide the opportunity for easily accessible 3-D postoperative feedback. Future studies are required to determine the reliability of this 3-D concept with anteroposterior and lateral pelvic radiographs and might be beneficial to ultimately guide intraoperative cup positioning.

APPENDIX

An explanation of the trigonometric algorithm rationale and a table showing transverse version for given coronal inclinations and sagittal tilts are available with the online version of this article as a data supplement at jbjs.org (http://links.lww.com/JBJSOA/A50).

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CHAPTER 6

The Effect of Postural Pelvic Dynamics on the Three-Dimensional Orientation of the Acetabular Cup in Total Hip Arthroplasty is Patient Specific

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ABSTRACT

Background

Sagittal pelvic dynamics mainly consist of the pelvis rotating anteriorly or posteriorly while the hips flexes, and this affects the femoroacetabular or THA configuration. Thus far, it is unknown how the acetabular cup of the THA in the individual patient reorients with changing sagittal pelvic dynamics.

Questions

The aim of this study was to validate a method that establishes the three-dimensional (3-D) acetabular cup orientation with changing sagittal pelvic dynamics and describe these changes during functional pelvic dynamics.

Methods

A novel trigonometric mathematical model, which was incorporated into an easy-to-use tool, was tested. The model connected sagittal tilt, transverse version, and coronal inclination of the acetabular cup during sagittal pelvic tilt. Furthermore, the effect of sagittal pelvic tilt on the 3-D reorientation of acetabular cups was simulated for cups with different initial positions. Twelve pelvic CT images of patients who underwent THA were taken and rotated around the hip axis to different degrees of anterior and posterior sagittal pelvic tilt (360°) to simulate functional pelvic tilt in various body positions. For each simulated pelvic tilt, the transverse version and coronal inclination of the cup were manually measured and compared with those measured in a mathematical model in which the 3-D cup positions were calculated. Next, this model was applied to different acetabular cup positions to simulate the effect of sagittal pelvic dynamics on the 3-D orientation of the acetabular cup in the coronal and transverse plane. After pelvic tilt was applied, the intraclass correlation coefficients of 108 measured and calculated coronal and transverse cup orientation angles were 0.963 and 0.990, respectively, validating the clinical use of the mathematical model. Results The changes in 3-D acetabular cup orientation by functional pelvic tilt differed substantially between cups with different initial positions; the change in transverse version was much more pronounced in cups with low coronal inclination (from 50° to -29°) during functional pelvic tilt than in cups with a normal coronal inclination (from 39° to -11°) or high coronal inclination (from 31° to 2°). However, changes in coronal inclination were more pronounced in acetabular cups with high transverse version.

Conclusion

Using a simple algorithm to determine the dynamic 3-D reorientation of the acetabular cup during functional sagittal pelvic tilt, we demonstrated that the 3-D effect of functional pelvic tilt is specific to the initial acetabular cup orientation and thus per THA patient.

Clinical Relevance Future studies concerning THA (in) stability should not only include the initial acetabular cup orientation, but also they need to incorporate the effect of sagittal pelvic dynamics on the individual 3-D acetabular cup orientation. Clinicians can also use the developed tool, www.3d-hip.com, to calculate the acetabular cup's orientation in other instances, such as for patients with spinopelvic imbalance.

INTRODUCTION

Proper acetabular cup orientation and restoration of normal hip dynamics are important factors for the success of THA because they play a key role in implant stability. To date, the acetabular cup's orientation has mostly been studied with patients in the supine or upright static position, although dislocations always occur in dynamic situations (Figure 1A-D).[1,2]

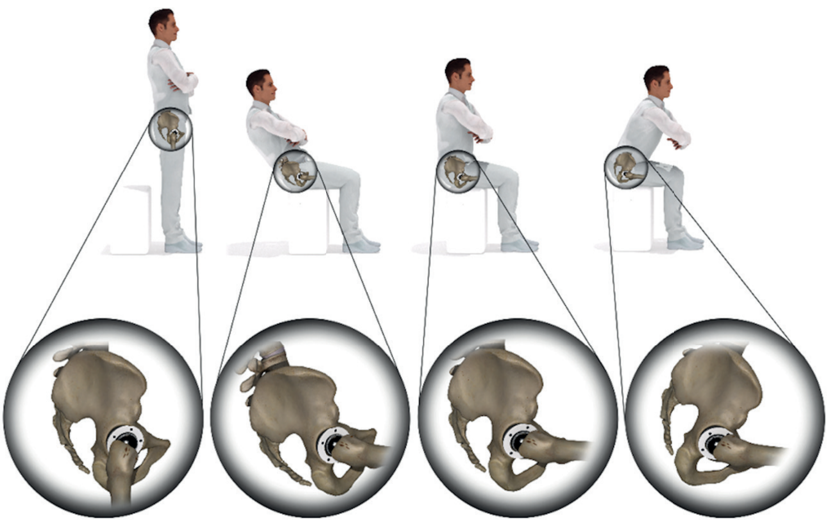

Figure 1. A-D This illustration shows the pelvic tilt and changing acetabular cup orientation in different body positions. (A) The patient is in the standing position. (B) The patient is shown in the sitting position with posterior pelvic tilt. (C) The patient is in the sitting position with neutral pelvic tilt. (D) The patient is in the sitting position with anterior pelvic tilt.

As an example of the importance of spino-pelvic-femoral dynamics, it has been shown that patients undergoing THA who have a history of lumbar spinal arthrodesis often have more rigid pelvic dynamics when moving from standing to sitting, leading to a different acetabular cup orientation in certain body positions. Patients who have undergone lumbar fusion have been shown to have a 3.4-fold higher relative risk of dislocation after THA than do patients who have not had lumbar arthrodesis.[3]

Duval Beaupere et al. were the first to describe that the morphology of the sagittal pelvis differs tremendously between individuals and that the sagittal dynamics of the pelvis, as expressed by the parameters of pelvic tilt and sacral slope, occur around the transverse axis of the hip.[4] An individual's ability to adapt the orientation of the pelvis (pelvic tilt and sacral slope) during functional movements of the human body or when a degenerative spinal condition occurs highly depends on the constant pelvic morphology, often described as pelvic incidence. Patients with a high pelvic incidence are more able to modify their sagittal pelvic orientation than patients with a low pelvic incidence.[5,6] Previous studies showed that the boundaries for functional tilt of the pelvis while an individual changes their body position are from 30° anterior to 30° posterior.[7,8]

Most dislocations after THA seem to occur in the "safe zone" described by Lewinnek et al. and are measured in the standing position.[9,10] In a patient with a posterior dislocation, however, the three-dimensional (3-D) acetabular cup orientation, although adequate while standing, could be inadequate in the sitting position owing to a lack of posterior pelvic tilt. Several studies have already evaluated functional pelvic tilt and the acetabular cup's reorientation when an individual moves through functional positions. However, those studies assumed linear relations close to 1:1 between transverse version and/or coronal inclination.[2,11–16] Simple mathematics applied to any hemispherical shape, however, show that the angles reflecting the orientation of the acetabular cup in relation to three orthogonal planes (Figure 2A-C) follow a sinusoidal relationship rather than a linear one and differ between cups with a different orientation initially.[17]

We therefore sought to validate a method that establishes the 3-D acetabular cup orientation with changing sagittal pelvic dynamics and describe these changes during functional pelvic dynamics.

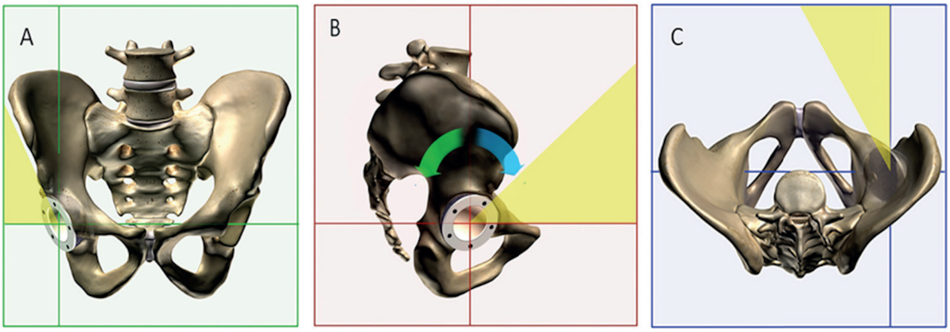

Figure 2. (A) Coronal inclination and (B) sagittal tilt of the cup are measured in relation to the horizontal plane, and (C) the transverse version of the cup is measured in relation to the AP axis. Pelvic tilt is described as rotation around the transverse hip axis. The blue arrow in (B)indicates anterior pelvic tilt; the green arrow in (B) describes posterior pelvic tilt. A change in pelvic tilt of 1° gives a change in sagittal tilt of 1°.

PATIENTS AND METHODS

Study Procedures

After obtaining approval for this study from our institutional review board, we systematically searched our radiologic patient archiving and communications system for CT angiogram images of the pelvis that were acquired between January 2013 and August 2016. The following inclusion criteria were used: THA implant in situ, a hemispherical cup with a circumferential radiologic metal marker that was perpendicular to the cup axis, and complete visualization of the pelvis. Exclusion criteria were previous ipsilateral hip surgery other than primary THA, malignant disease in the pelvis or femur, or an imaging series that was incomplete or with substantial contrast artefacts in the region of interest. According to protocol, CT angiogram images were acquired with the patient in the supine position, using a 16-channel multidetector CT system (Siemens Healthcare, Erlangen, Germany; slice thickness 0.5 mm) using intravenous contrast. Clinical and radiographic records were reviewed by one observer (TES) to determine which patients met the inclusion or exclusion criteria and to extract demographic data.

CT images of 12 hips in 12 patients met the inclusion criteria (Table 1). All CT angiogram images were requested by a local vascular surgeon (SKN) for vascular assessment. The primary THAs were performed between 2013 and 2016. All patients had a highly cross-linked polyethylene, uncemented monoblock acetabular cup (RM Pressfit cup, Mathys Ltd, Bettlach, Switzerland).

Table 1. Demographics and neutral pelvic tilt measurements of all cases in terms of coronal inclination, transverse version and sagittal tilt in degrees.

Factor	Number (n = 12)
% women (n)	50 (6)
Mean $\pm$ SD age in years	75 ± 9
% of left-sided THAs (n)	42 (5)
% Uncemented acetabular component (n)	100 (12)
% Monoblock (n)	100 (12%)
Median Cup size in mm (range)	54 (50-60)
Mean $\pm$ SD Coronal inclination in ^{0}	38 (7)
Mean $\pm$ SD Transverse version in ^{0}	30 (14)
Mean $\pm$ SD Sagittal tilt in ^{0}	25˚ (12˚)

The included CT images were imported into a specially developed software (programmed in MeVisLab, MeVis Medical Solutions, Bremen, Germany). The initial orientation of the pelvis was standardized so that the interteardrop line was horizontal in the coronal plane and the line connecting the anterior-superior iliac spines was horizontal in the transverse plane. Multiplanar reconstructions were created for neutral tilt, which was centered on the femoral head component. Subsequently, the center of rotation of both femoral heads was localized, and the multiplanar reconstruction image was tilted 5°, 10°, 20°, and 30° anteriorly and posteriorly in the sagittal plane around the transverse hip axis passing through the center of both femoral heads to simulate different body positions (Figure 1). New coronal-, sagittal-, and transverse-plane multiplanar reconstruction images of the center of the femoral head were acquired in each tilted position and imported into HOROS Medical Image Viewer (Horos v2.0.2, Horos Project, Annapolis, MD, USA). The coronal inclination, transverse version, and sagittal tilt were manually measured by one observer (TES) following a previously validated technique, with excellent intraobserver and interobserver reliability (Figure 3).[17]

We applied an in-house-developed mathematical model, which allowed us to calculate the 3-D acetabular cup reorientation using a specified pelvic tilt and the initial 3-D cup orientation. This model is based on elementary goniometric formulas and therefore can be mathematically verified (see Supplemental Digital Content 1, http://links.lww.com/CORR/A425). The conducted proof-of-principle study in 12 patients was to verify the practical applicability of the model. We have shown that the orientation of the cup in the three orthogonal anatomic planes (sagittal tilt, transverse version, and coronal inclination) can be represented by the following equations[17]:

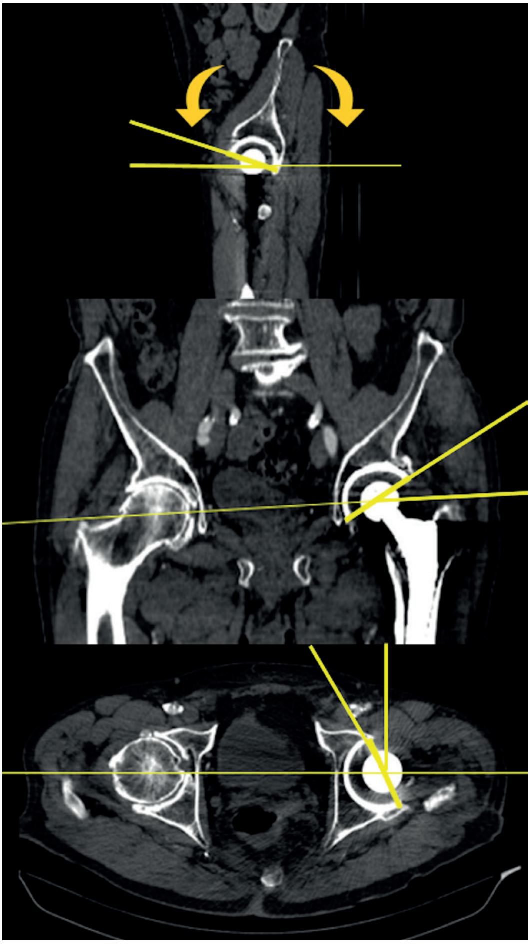

Figure 3. These CT images show the measured angles. Coronal inclination (top) and sagittal tilt (middle) of the cup are measured in relation to the horizontal plane and transverse version of the cup (bottom) in relation to the AP axis. Pelvic tilt is described as rotation around the transverse hip axis. The yellow arrows at the top indicate anterior and posterior pelvic tilt.

$\tan(Version) = \tan(Inclination) \times \tan(Tilt)$ (Equation 1)

Considering rotation of the pelvis around the transverse axis to a new sagittal tilt position (Tilt'), the new coronal inclination (Inclination') and new transverse version (Version') can be determined with the auxiliary variable

$t(inclination, version) = \sqrt{((\tan version)^2 + 1/\tan inclination^2)}$ (Equation 2)

Additionally, the tangent of the other two new angles are given as:

$\tan(inclination') = 1/(t \times \cos Tilt')$ (Equation 3)

$\tan(version') = t \times \sin(tilt')$ (Equation 4)

For practical purposes, the algorithms are an easy-to-use tool in the form of a pre-programmed Microsoft Excel file (Redmond, WA, USA) (see Supplemental Digital Content 2, http://links.lww.com/CORR/A426). The tool that is online available at www.3d-hip.com.

Statistical Analysis

We performed statistical analyses using IBM SPSS Statistics version 23 (SPSS Inc, Chicago, IL, USA). Continuous angles determined in the formulas used for measurement were assessed and are demonstrated as the mean and SD. We used box plots to identify any outliers. For the validity analysis, differences between the measured and calculated angles were assessed using the intraclass correlation coefficient and corresponding 95% confidence interval, with a two-way mixed-effects model for absolute agreement. ‘

Simulation of Different Acetabular Cup Orientations

To simulate cups with different positions, we defined a normal acetabular cup position as 45° of coronal inclination and 20° of transverse version, according to the safe zone for cup placement described by Lewinnek et al..[9] High or low coronal inclination (60° and 30°, respectively), high or low transverse version (35° and 5°, respectively), and combined sagittal and coronal deviations were included. Sagittal tilt was calculated for each cup position using Equation 1. Subsequently, pelvic tilt was simulated by introducing functional AP pelvic tilt from 30° anterior to 30° posterior. These reoriented, tilted positions, which provided the changed Tilt’ and acetabular cup reorientation in the coronal and transverse planes, were determined by calculating the Inclination’ and Version’ using Equations 3 and 4. Because the mathematical model is nonlinear, we assumed that the effect of pelvic tilt is different for varying initial 3-D acetabular cup positions in terms of the original coronal inclination (between 60° and 30°) and transverse version (between 35° and 5°). We compared the effect size of changes in coronal inclination and transverse version between different cup positions using a variance analysis.

Validity Analyses

Data were normally distributed, and there were no outliers. The mean 6 SD coronal inclination and transverse version on the neutral, anterior, and posterior tilted multiplanar reconstructions of the cups were 40 6 9° and 27 6 22°, respectively. The angles calculated with Equations 3 and 4 were 40 6 9° for coronal inclination and 27 6 2° for transverse version. The correlation between 108 measured and calculated angles of cups in the pelvis with different orientations revealed an intraclass correlation coefficient (ICC) of 0.96 (95% CI 0.95 to 0.97) for coronal inclination and an ICC of 0.99 (95% CI 0.99 to 0.99) for transverse version (Table 2).

Table 2. Differences between measured and calculated coronal inclination and transverse version (in degrees). (SD = standard deviation; n = 12)

n = 12	Pelvic tilt	Measured coronal inclination (°), mean (SD)	Calculated coronal inclination, mean (SD)	p (95%CI)	Measured transverse version, mean (SD)	Calculated transverse version, mean (SD)	p (95%CI)
Posterior	30°	49° (10°)	52° (11°)	0.963 (0.946-0.974)	49° (9°)	49° (11°)	0.990 (0.986-0.993)
	20°	46° (10°)	45° (9°)		44° (11°)	44° (9°)	
	10°	41° (8°)	41° (8°)		38° (12°)	38° (8°)	
	5°	40° (8°)	40° (8°)		34° (13°)	34° (8°)	
Neutral	0°	38° (7°)	38° (7°)		30° (14°)	30° (7°)	
Anterior	5°	37° (7°)	37° (7°)		26° (14°)	37° (7°)	
	10°	37° (7°)	36° (7°)		18° (15°)	36° (7°)	
	20°	36° (6°)	36° (7°)		6° (17°)	36° (7°)	
	30°	36° (6°)	36° (7°)		-6° (16°)	36° (7°)	

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We included a dataset wherein we calculated and measured the values of the three angles per subject (see Supplemental Digital Content Material 3, http://links.lww.com/CORR/A427).

RESULTS

3-D Acetabular Cup Reorientation During Pelvic Tilt Simulation

Simulation of the 3-D acetabular cup reorientation during functional pelvic tilt showed there was wide variability between different acetabular cup placements. An initial normal placement according to Lewinnek et al.'s recommendation resulted in changes in transverse version and coronal inclination during 30° anterior to neutral to 30° posterior pelvic tilt (Figure 4, green line).[9]

Transverse version increased from -10° to 20° to 39° and coronal inclination changed from 44° to 45° to 56°. In contrast, the transverse version of an acetabular cup with initially low coronal inclination changed from -29° to 20° to 49° during functional pelvic tilt. Coronal inclination, however, changed from 31° to 30 to 37°. In a cup with high coronal inclination initially, the contrary was observed; transverse version changed from 2° to 20° to 37°, whereas coronal inclination changed from 50° to 60° to 68° (Figure 4). Thus, an initially low coronal inclination was not much affected by pelvic tilt, whereas transverse version

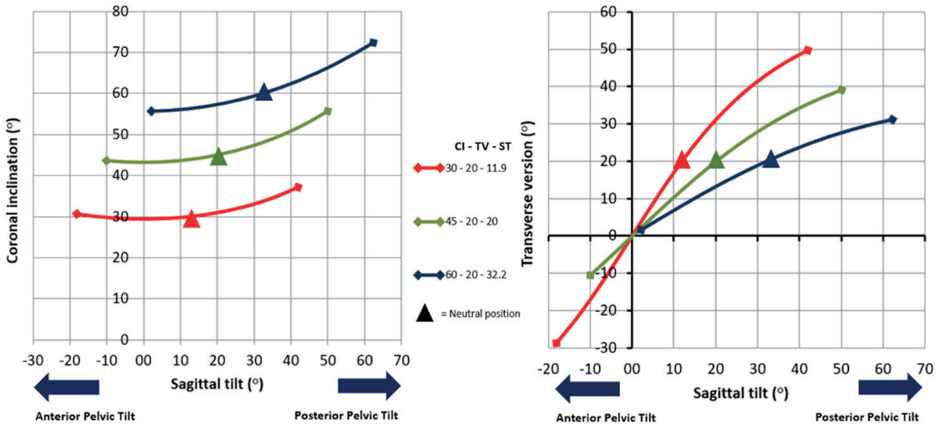

Figure 4. These graphs show changes in coronal inclination and transverse version during functional pelvic tilt (6 30°) for an acetabular cup orientation with 20° of transverse version and low, normal, and high coronal inclination (30°, 45°, and 60°, respectively). The x-axes show sagittal tilt; the y-axes show coronal inclination or transverse version. The green lines indicate normal placement (45° of coronal inclination and 20° of transverse version); D = the triangle on the line is the neutral position of the initial acetabular cup orientation; CI = coronal inclination; TV = transverse version; ST = sagittal tilt.

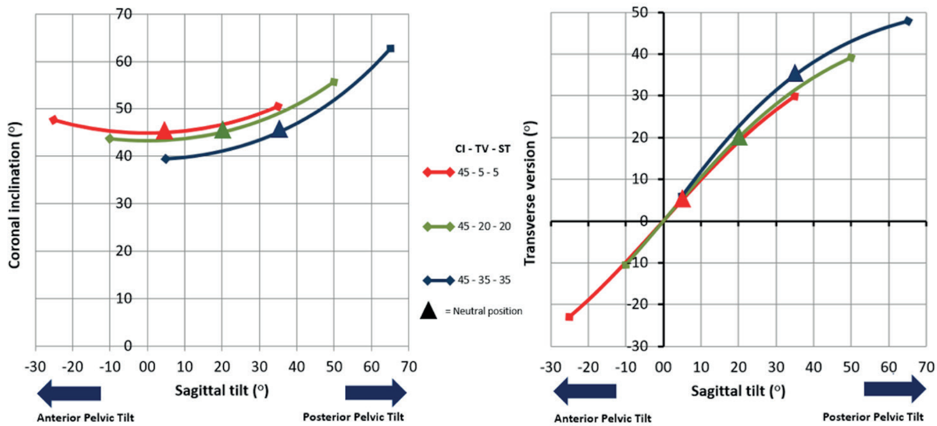

Figure 5. These graphs show changes in coronal inclination and transverse version during functional pelvic tilt (6 30°) for an acetabular cup orientation with 45° of coronal inclination and low, normal, and high transverse version (5°, 20°, and 35°, respectively). The x-axes show sagittal tilt; the y-axes show coronal inclination or transverse version. The green lines show normal placement (45° of coronal inclination and 20° of transverse version); D = the triangle on the line is the neutral position of the initial acetabular cup orientation; CI = coronal inclination; TV = transverse version; ST = sagittal tilt.

was severely affected by sagittal pelvic tilt in a cup with low coronal inclination and vice versa. When the initial acetabular cup orientation differs in transverse version and the coronal inclination remains 45°, there is less variation. Obviously, the acetabular cup orientation with a low transverse version are easily retroverted by pelvic tilt (Figure 5).

Initial acetabular cup orientations varying in transverse version and coronal inclination show that low coronal inclination produce larger changes in transverse version by pelvic tilt compared with initial high coronal inclination (Figure 6). The value of transverse version mainly determines the threshold from when the acetabular cup becomes retroverted (Figure 6).

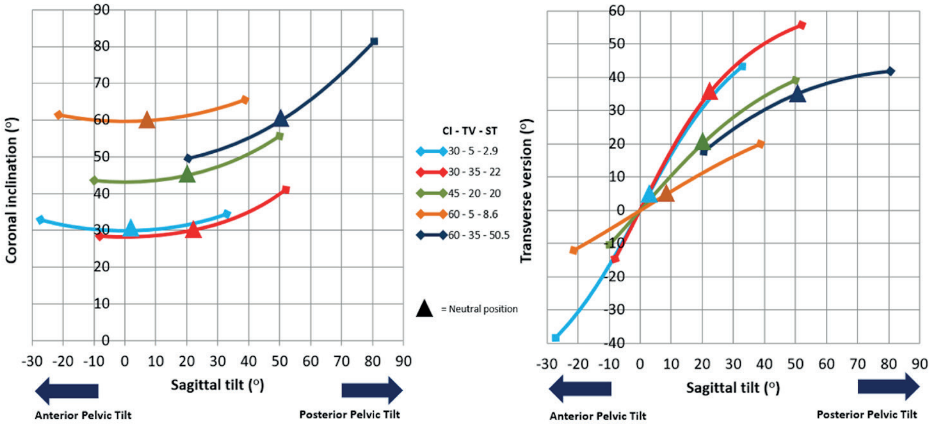

Figure 6. These graphs show changes in coronal inclination and transverse version during functional PT (6 30°) for an acetabular cup orientation with combinations of low and high coronal inclination (30° and 60°, respectively) and low and high transverse version (5° and 35°, respectively) compared with a cup with 45° of coronal inclination and 20° of transverse version. The x axes show sagittal tilt; the y axes show coronal inclination or transverse version. The green lines show normal placement (45° of coronal inclination and 20° of transverse version); D = the triangle on the line is the neutral position of the initial acetabular cup orientation; CI = coronal inclination; TV = transverse version; ST = sagittal tilt.

DISCUSSION

Sagittal pelvic dynamics, consisting mainly of an anteriorly or posterior rotating pelvis, alters the mutual THA component configuration and plays a role in THA stability. Despite being extensively studied in a static position, it is unknown how the orientation of the acetabular cup in the individual patient alters with changing sagittal pelvic dynamics. We conducted this study to demonstrate the effect of sagittal pelvic tilt on the 3-D orientation of acetabular cups in different configurations, described by their positions with respect to the three anatomic planes (coronal inclination, transverse version, and sagittal tilt). This was enabled by a proof-of-principle study of a generally applicable trigonometric formula to assess the effect of pelvic tilt on any 3-D orientation of the acetabular component and any pelvic tilt in patients undergoing THA. These simulations showed that changing the pelvic orientation through functional sagittal tilt creates wide variety in the 3-D acetabular cup orientation, depending on the initial 3-D acetabular cup orientation. The model showed that the effect of pelvic tilt on transverse version is much more pronounced in acetabular cups with low coronal inclination than in those with high coronal inclination. In addition, pelvic tilt has a greater influence on coronal inclination in acetabular cups with high initial transverse version than on coronal inclination in those with low initial transverse version. Furthermore, when the initial transverse version is lower, less pelvic tilt is needed to move the orientation in retroversion.

Limitations

This study has several limitations. First, instability after THA is multifactorial and depends on more factors than 3-D acetabular cup orientation alone. The orientation of the femoral components, which influences the joint's reaction forces, was not considered in this study.[18] Second, the algorithm cannot be applied to acetabular cups that lack a circumferential reference perpendicular to the acetabular axis. Third, orthogonal algorithms are only applicable to planes that are perfectly orthogonal. Consequently, cross-lateral views cannot be used. Fourth, the true spatial orientation of the acetabular cup may also be influenced by pelvic dynamics in other planes, such as during Trendelenburg's gait.[19] Recently, however, Ike et al. demonstrated that 41% of 200 patients undergoing THA had spinopelvic imbalance preoperatively, demonstrating the importance of assessing sagittal spino-pelvic-femoral dynamics in these patients.[20] Although the small number of CT images might be seen as a limitation, one CT image is sufficient for analysis because the model is based on elementary goniometric formulas that can be mathematically verified (see Supplemental Digital Content 1, http://links.lww.com/CORR/A425)

Dislocations occur in dynamic situations, such as when an individual moves from a standing position to a sitting position or bends forward in the sitting position (for posterior dislocations) or extends the hip (for anterior dislocations) (Figure 1).[1] In an individual without spine degeneration, when the individual moves from standing to sitting, the lumbar spine flexes and the pelvis tilts posteriorly, increasing the pelvic tilt, while the femur flexes.[7,15,21,22] Maratt et al. studied pelvic tilt in a computer-simulated anatomic pelvis with a fixed inclination of the acetabular component and without in vivo verification.[14] However, the present study tests a generally applicable and validated formula to assess the effect of pelvic tilt on any acetabular cup orientation (inclination, anteversion, and sagittal tilt) and any pelvic tilt in patients undergoing THA. Therefore, this could be an important advancement in our knowledge of hip-spine dynamics in patients who undergo THA.

3-D Acetabular Cup Reorientation During Pelvic Tilt Simulation

The 3-D acetabular cup reorientation during functional changes in pelvic tilt showed enormous variability between different acetabular cup placements (Figure 6). Because of their primary anatomic orientation, certain cups are very likely to move into positions that render these patients at a high risk of impingement or joint reaction forces outside the boundaries of the acetabular cup, thereby creating a dislocation. For clarification, our study corroborates that increased posterior pelvic tilt functionally increased transverse version of the acetabular cup (Figure 4). The degree of change in transverse version, however, highly depends on the cup's position. Through posterior pelvic tilt, anterosuperior impingement from the femoral component is prevented and the cup's position offers posterior restraint against changing joint reaction forces. In a patient with an initially high coronal inclination, however, variance in transverse version is lower (Table 3).

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Table 3. For simulation analyses, relative acetabular cup orientation with anterior and posterior pelvic tilt was calculated for an acetabular cup with a high and low coronal inclination with normal transverse version (Figure 3). In red is a cup with normal coronal inclination and transverse version. CI = coronal inclination, TV = transverse version, ST = sagittal tilt

Posterior pelvic tilt		**Neutral**		**Anterior pelvic tilt**
30˚	**10˚**	**0˚ (Initial)**	**-10˚**	**-30**
CI / TV / ST	CI / TV / ST	**CI / TV / ST**	CI / TV / ST	CI / TV / ST
35 / 43 / 33	31 / 21 / 13	**30 / 5 / 3**	30 / -12 / -7	33 / -38 / -27
37 / 49 / 42	32 / 33 / 22	**30 / 20 / 12**	30 / 3 / 2	31 / -29 / -18
42 / 55 / 52	34 / 43 / 32	**30 / 35 / 22**	30 / 20 / 12	30 / -14 / -8
51 / 30 / 35	46 / 15 / 15	**45 / 5 / 5**	45 / -5 / -5	48 / -23 / -25
56 / 39 / 50	*47 / 28 / 30*	***45 / 20 / 20***	*44 / 10 / 10*	*44 / -10 / -10*
63 / 48 / 65	49 / 41 / 45	**45 / 35 / 35**	42 / 27 / 25	39 / 6 / 5
65 / 20 / 39	61 / 11 / 19	**60 / 5 / 9**	60 / -1 / -1	61 / -12 / -21
68 / 37 / 62	58 / 30 / 42	**60 / 20 / 32**	52 / 18 / 22	50 / 2 / 2
77 / 52 / 81	44 / 40 / 41	**60 / 35 / 50**	44 / 41 / 40	39 / 25 / 20

This implies that with similar pelvic retroversion during sitting, there is less increase in transverse version. Therefore, these patients may have a greater predisposition to posterior dislocation during posterior pelvic tilt than those with a less-coronally placed cup (Figure 5).[15,23] The same holds true for patients with severe lumbar degenerative disease or those undergoing lumbosacral fusion. Because of pre-existing, increased posterior pelvic tilt, these patients are less able to adjust to posterior pelvic tilt when they move from standing to sitting, and therefore have less increase in transverse version of the acetabular cup, predisposing these patients to posterior dislocation.[24–26]
Another typical dislocation mechanism occurs in a patient who sits and moves forward. In the sitting position, the pelvis is tilted posteriorly and the femur is flexed from 55° to 70°.[22] In this position, the femoral force vectors acting on the acetabulum are directed mostly posteriorly. A patient reaches in front by bending the spine forward, with anterior pelvic tilt in the femoro-acetabular articulation and kyphosis at the lumbosacral junction. We showed that transverse version decreases with anterior pelvic tilt and that with only 10° of anterior pelvic tilt, many acetabular cup orientation combinations are already retroverted in the transverse plane (Table 4).

Table 4. The variance results of relative coronal inclination and transverse version for different initial acetabular cup orientations when functional pelvic tilt (+/-30˚) is applied.

	Variance in coronal inclination			**Variance in transverse version**		
	Coronal Inclination (°)			**Coronal Inclination (°)**		
Transverse version (°)	30	45*	60	30	45*	60
5	2	3	3	805	317	113
20*	6	17	31	730	275	96
35	18	59	110	556	189	64

Moreover, too much transverse version leads to anteromedial impingement, a lack of posterior restraints, or even a lack of inferior restraints. The latter is the mechanism of a drop-out dislocation, first described by Dorr.[27]

Lastly, the mechanism of anterior dislocation was also elucidated in our investigation. In the standing position, the pelvis is normally in an anteriorly tilted position, with high lumbar lordosis. The femoral force vectors acting on the acetabulum are directed superiorly and anteriorly (anteriorly because the femoral stem has approximately 15° of anteversion). In lumbar and/or hip extension, the position of the acetabular component changes, similar to the pattern of posterior pelvic tilt; thus, coronal inclination and transverse version will increase. This could lead to a lack of superior and anterior restraint of the femoral head. Based on our study, we suggest that patients with acetabular components who have high inclination and/or high transverse version are at a greater risk of having anterior dislocation because of this mechanism. Some questions remain: How do we define the best individual and functional 3-D position of the acetabular component? Do we have sufficient surgical accuracy to create this position? The pelvis's position changes from the upright to the supine position, and this deviates between patients with hip osteoarthritis and those without [20]. Therefore, planning the acetabular cup's orientation should be individualized and adjusted to the patient's position during surgery.

The tested mathematical model was incorporated into an easy-to-use tool (www.3d-hip.com and Supplemental Digital Content 1, http://links.lww.com/CORR/A425) and enables us to calculate the dynamic acetabular cup orientation for each patient. As a clinical example, in a patient with a posterior dislocation after THA, when the patient is in a sitting position, the tool can be used to establish the 3-D orientation of a well-placed cup. A clinician could obtain standing biplanar pelvic radiographs (AP and lateral) and a sitting lateral pelvic radiograph. By determining the coronal and sagittal cup angles in the standing position and the change in pelvic tilt between the two lateral radiographs and applying them to the tool, the clinician could evaluate the coronal, sagittal, and transverse cup orientation with the patient in the sitting position. The 3-D orientation in the sitting position might be inadequate because of limited posterior pelvic tilt, leading to hip dislocation in maximum flexion.[28] As another example, the same parameters can be used to evaluate differences in the cup's orientation between the preoperative and standing position in patients with sagittal spinopelvic imbalance and a retroverted pelvis.

CONCLUSION

In summary, this mathematical model advances the present knowledge of 3-D acetabular cup orientation in patients who undergo THA because it enables us to exactly determine the 3-D acetabular cup orientation subjected to spinopelvic dynamics for every patient undergoing THA. Clinically, by combining the individual sagittal orientation of an acetabular cup on two lateral radiographs in different body positions, this model allows us to determine the exact changes in acetabular cup orientation in all three anatomic planes during pelvic dynamics. Future studies could compare functional pelvic motion and functional 3-D acetabular cup orientation in patients with stable and unstable implants.

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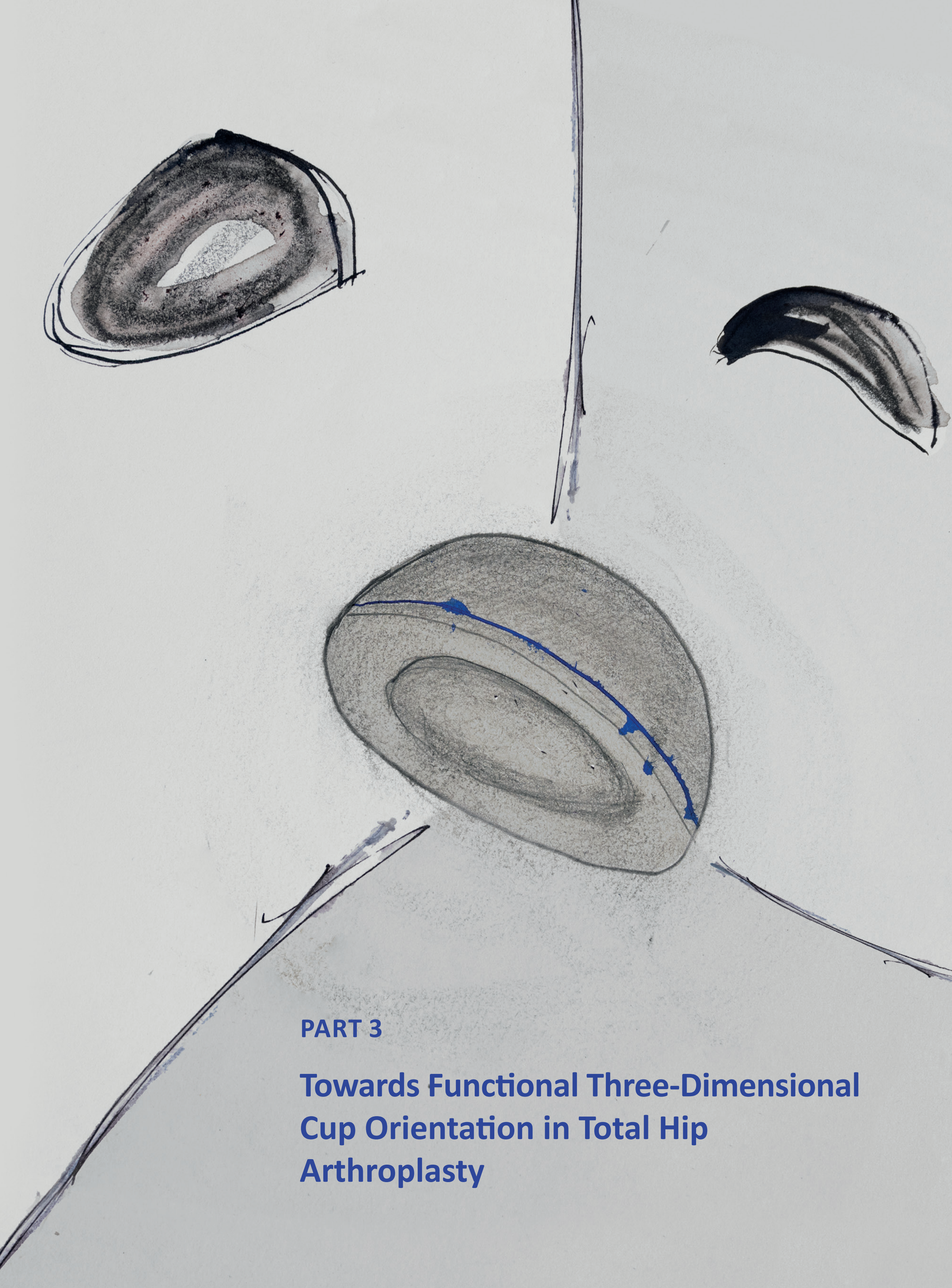
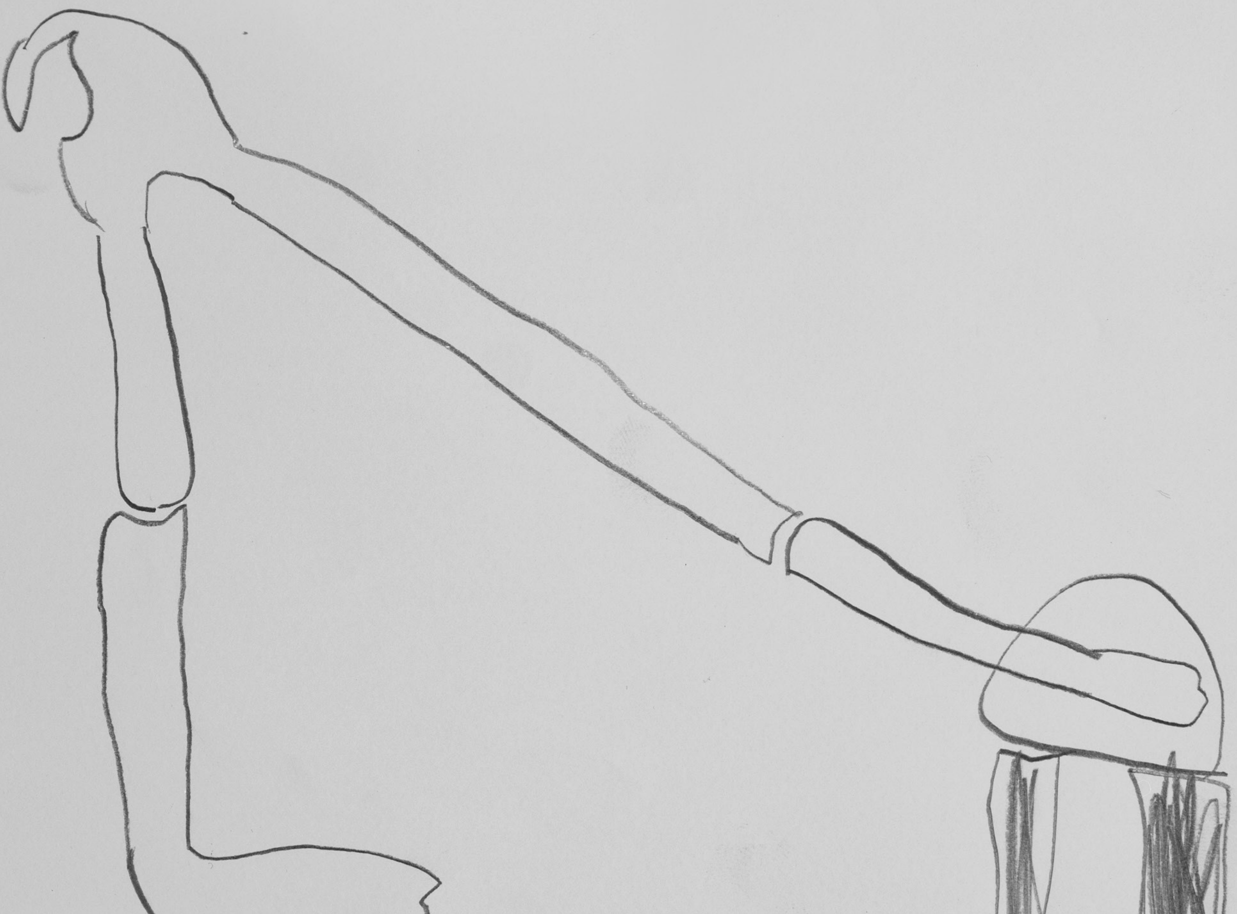


PART 3

Towards Functional Three-Dimensional Cup Orientation in Total Hip Arthroplasty



CHAPTER 7

The Effect of Functional Pelvic Tilt on the Three-Dimensional Acetabular Cup Orientation in Total Hip Arthroplasty Dislocations

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ABSTRACT

Background

Anterior and posterior pelvic tilt appears to play a role in total hip arthroplasty (THA) stability. When changing from the standing to the sitting position, the pelvis typically rotates posteriorly while the hips flex and this affects the femoro-acetabular positions. This case-control study compares changes in 3-D acetabular cup orientation during functional pelvic tilt between posterior THA dislocations vs stable THAs.

Methods

Standing and sitting 3-D cup orientation was compared between fifteen posterior dislocations vs 233 prospectively followed stable THAs. 3-D cup orientation was calculated using previously validated trigonometric algorithms on biplanar radiographs. Those algorithms combine the angles in the three anatomical planes (coronal inclination, transverse version, and sagittal ante-inclination) in the standing position with the change in sagittal pelvic tilt from standing to sitting to calculate the 3-D orientation in the sitting position.

Results

The standing cup orientation of the dislocated THAs was only characterized by a lower coronal inclination (P ¼ .039). Compared with the controls, from standing to sitting, they showed less posterior pelvic tilt ($P < .001$). This led to a significant lower coronal inclination ($P < .001$) and sagittal anteinclination ($P < .001$) in the sitting position but similar transverse version (P ¼ .366).

Conclusions

Comparing posterior THA dislocations to stable THAs, there is a lower increase of all three orientation angles from standing to sitting. This leads to a decreased sitting coronal inclination and sagittal ante-inclination which may lead to an increased risk of impingement ensued by THA instability. By contrast, the transverse version was not significantly different in both positions. This confirms the importance of biplanar data on functional cup orientation.

INTRODUCTION

For more than four decades, the “safe zone of Lewinnek”, for acetabular cup placement, which is based on supine pelvic radiographs, has been implemented to limit the dislocation rate.[1] Recently, however, this has been called into question because most total hip arthroplasty (THA) dislocations seem to occur within this proposed “safe zone”.[2] Furthermore, recent studies stated that sagittal pelvic dynamics could play a significant role in the stability of THAs.[3–6]

The normal posterior pelvic tilt from standing to sitting results in an opening of the acetabulum anteriorly so it can accommodate flexion of the femur. With degenerative spinal pathology, the pelvis is most often already retroverted because lordosis is lost and if pelvic mobility is stiff, further posterior tilt is restricted during postural change from standing to sitting.[7–11] To date, it has been recognized by multiple studies that variations in sagittal pelvic dynamics potentially play a role in implant stability in THAs.[9–13] Owing to the hemispherical shape of most acetabular cups, anterior and posterior pelvic tilt in the sagittal plane will also change the orientation in the other two anatomical planes, the coronal and transverse plane.[13] For better understanding the relevance of spino-pelvic-femoral dynamics in THA implant stability, the purpose of this study is to describe the effect of functional pelvic tilt on the 3-D acetabular cup orientation for posterior THA dislocations vs a cohort of stable THAs. We postulate that posterior dislocated THAs will have a reduction in pelvic tilt from standing to sitting and a decrease in functional acetabular cup position.

MATERIALS AND METHODS

Study Population

Patients who presented with a posterior dislocation of a THA to our practice between 2011 and 2017 were included in this study. Posterior dislocations are defined as a posterior position of the femoral head relative to the acetabular cup.[14,15] Fifteen patients with a posterior THA dislocation were included. The control group consisted of 233 subjects of a prospective cohort of 238 THA patients enrolled between 2011 and 2017 with complete postoperative radiographic data at three months; 5 of the 238 had a dislocations within the first year. Patients who received a dual mobility cup or where the data were not complete were excluded. In the fifteen dislocated and 233 control patients, the THA was placed by a posterolateral approach. Previously, these patients were included in the publications by

Heckmann et al. and Tezuka et al., but assessment of the exact 3-D reorientation of the acetabular cup during functional pelvic tilt was not previously performed.[10,16] Institutional review board approval was obtained before the data collection.

Functional 3-D Acetabular Cup Orientation

Patients from the prospective cohort study (controls and early dislocations) underwent standing and sitting lateral spine-pelvis-hip radiographs as well as a supine anteroposterior pelvis radiograph including the proximal femur with the beam centered on the symphysis 3 months postoperatively, as previously described.[4] For the late dislocations, the same radiographs were collected at the first outpatient follow-up after the late dislocation. The 3-D acetabular cup orientation (coronal inclination (CI), transverse version (TV), and sagittal ante-inclination (AI)) was calculated for the supine, standing, and sitting positions. These mathematical models were previously validated for pelvic tilt using multiplanar 3-D reconstruction on pelvic CT scans in multiple orientations and had an interobserver reliability of 0.953 for CI, 0.982 for TV, 0.985 for AI, 0.963 for CI' and 0.990 for TV'.[13,17] These algorithms combine the orientation of the hemispherical acetabular cup in the three anatomical, orthogonal planes in the supine position plus the sagittal change in pelvic tilt to calculate the 3-D acetabular cup orientation in the standing and sitting body positions. The algorithms can be seen in the supplemental material or can be used with the developed tool available at www.3d-hip.com. (Supplemental material) For evaluation of the supine pelvic and acetabular cup orientation a mean difference of 5.5 of posterior pelvic tilt between standing and supine was used, based on the studies of Buckland et al. and Pierrepont et al..[18,19] In accordance with the decisions of the Hip-Spine Workgroup, the following definitions were used to describe the sagittal pelvic parameters and acetabular cup orientation and dynamics in the three anatomical planes (Figure 1)[6]:

- Pelvic incidence (PI): the angle between one line connecting the center of the femoral heads and the center of the sacral plate, and a second line perpendicular to the sacral plate.
- Sacral slope (SS): the angle between a horizontal reference line and a line parallel to the sacral plate.
- Coronal inclination (CI): the rotation of inclination of the cup around the anterior-posterior axis in the coronal plane.
- Sagittal ante-inclination (AI): the sagittal angle of the cup that includes inclination and anteversion that changes with posterior and anterior tilt of the pelvis.
- Transverse version (TV): the anteversion angle of the cup around the craniocaudal axis in the transverse plane.

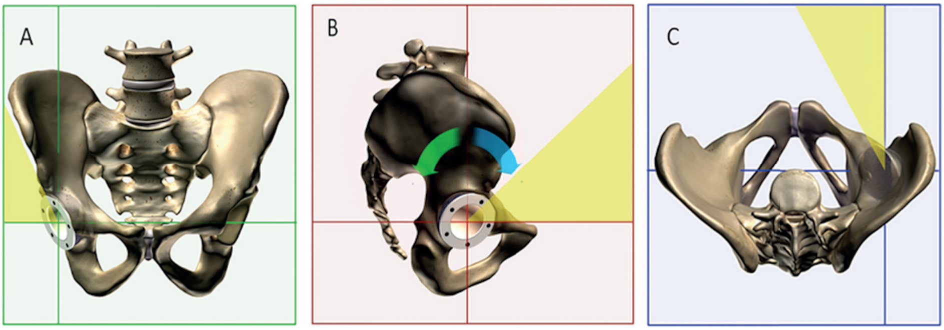

Figure 1. Coronal inclination (a) and sagittal ante-inclination (b) of the cup are measured in relation to the horizontal plane and transverse version (c) of the cup in relation to the anterior-posterior axis. Pelvic tilt is described as a rotation around the transverse hip-axis. The blue arrow in B describes anterior pelvic tilt; the green arrow in B describes posterior pelvic tilt. A change of 1° of pelvic tilt, gives a change of 1° of the sagittal ante-inclination of the cup.

Statistical Analysis

Statistical analyses were performed using IBM-SPSS Statistics 23 (SPSS Inc., Chicago, Illinois). Chi-squared test was used for categorical parameters. For the continuous parameters (follow-up, PI, SS, body mass index (BMI), CI, AI, and TV in standing and sitting position), box plots were used to identify any outliers and Kolmogorov-Smirnov test to test for normality. In non-normality parameters the Mann-Whitney U test was used and in normality the independent t-test. The level of statistical significance was set at 0.05.

RESULTS

Five of fifteen posterior dislocations occurred within one year postoperative (mean 2.3 months, range 0.3-4 months). Ten of fifteen occurred past 1 year (mean 52.2 months, range 12-108 months). Comparing both groups in terms of BMI, PI, and SS showed no significant differences (P = .711, P = .760, P = .474, respectively).

Standing CI, TV, and AI showed no significant differences (P = .165, P = .956, P = .326, respectively). Sitting CI, TV, and AI showed also no significant differences (P = .051, P =.530, P = .059, respectively). Hips with posterior dislocation differed significantly from stable THAs by a lower BMI (P = .047), lower PI (P = .010), and lower SS (P = .004) (Table 1).

Table 1. Demographics. age in years, body mass index in kg/m^2, follow-up in years, pelvic incidence in degrees, sacral slope in degrees (measured in the standing position).

	Stable THA (n=233)	**Late posterior dislocations (n=15)**	**P**
Mean Age (range)	62.6 (27 – 85)	66.1 (39 – 94)	0.342
Male or Female (M : F)	119 : 114	10 : 5	0.380
Right or Left (R: L)	131 : 102	6 : 9	0.221
Mean Body Mass Index (range)	28.1 (16.7 – 51.5)	25.6 (18.3 – 36.3)	0.047*
Mean follow-up (range)	3.3 (2.85 – 3.87)	5.0 (0.01-18)	0.674
Mean pelvic incidence (range)	54.5 (25 – 87)	48.1 (36 – 60)	0.010*
Mean Sacral Slope in degrees (range)	38.5 (10 – 62)	32.8 (24 – 44)	0.004*

* indicates P<0.05, a statistically significant difference between the posterior dislocation group and the stable THAs.

The change of SS and PT from standing to sitting was significantly different between the posterior dislocations and the stable group (11.5 vs 21.1, P = .000 and 11.2 vs 21.1, P = .000, respectively). In the standing position, the posterior dislocations had a lower statistical CI compared to the stable THAs (43.5 vs 46.3, P = .039). (Table 2, Figures. 2 and 3).

Table 2. Standing 3-D acetabular cup orientation.

	Stable	**Posterior dislocations**	**P**
CI	46.3˚±4.9˚	43.5˚±5.9˚	0.039*
TV	33.5˚±6.5˚	36.3˚±10.7˚	0.133
SI	34.8˚±8.0˚	34.9˚±9.6˚	0.805

CI = coronal inclination, TV = transverse version, SI = Sagittal ante-inclination. * indicates P<0.05, a statistically significant difference between the dislocation group and the stable THAs.

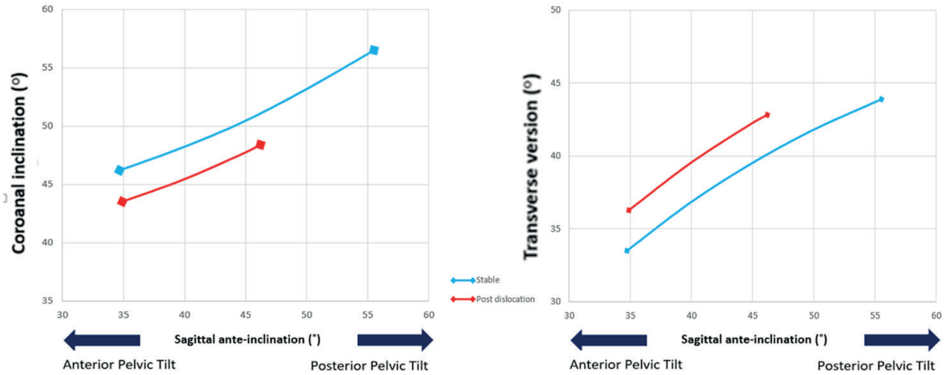

Figure 2. Functional 3-D acetabular cup orientation from standing to sitting in stable THAs or THA with a late posterior dislocation.

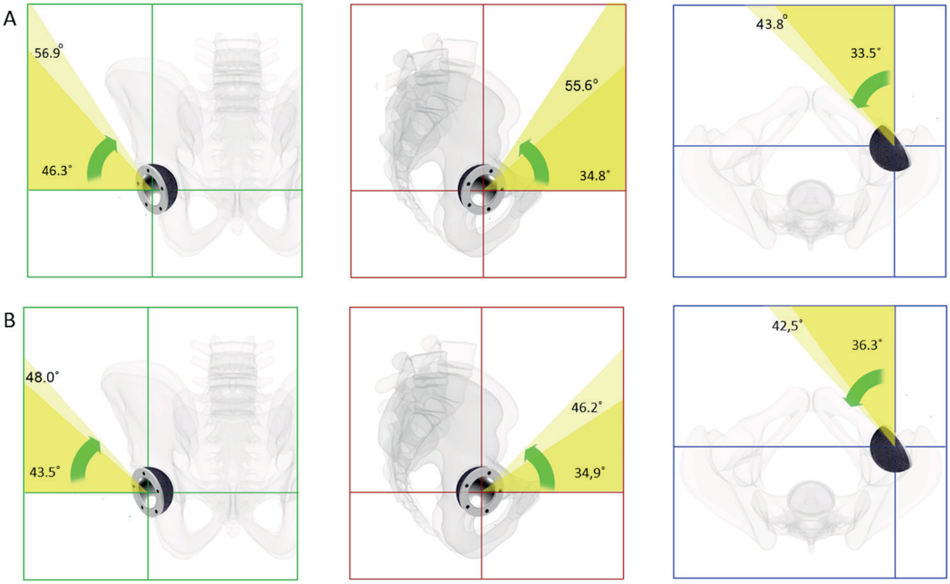

Figure 3. The mean 3-D acetabular component in the standing (dark yellow) and sitting (light yellow) position in the two groups: A. patients with a stable THA, B. patients with a posterior dislocated THA. Green, coronal inclination; red, sagittal ante-inclination; blue, transverse version.

In the sitting position, dislocated hips had a statistically significant lower CI and AI, but similar TV as compared with stable THAs (Table 3, Figures. 2 and 3).

From standing to sitting, the posterior dislocations had both statistical and clinically significant less posterior pelvic tilt reflected by the change in AI (+11.3 vs +20.8, P = .000). These were similar to the change in SS and PT of both groups. The reduced posterior pelvic tilt thus results in decreased sitting CI with a consequent lesser increase in AI (+11.3 vs +20.8, P = .000) (Table 4) which represents the functional acetabular cup position.

Table 3. Sitting 3-D acetabular cup orientation.

	Stable	Posterior dislocations	P
CI	56.9±7.3˚	49.0˚±9.7˚	0.000*
TV	43.8˚±5.2˚	42.5˚±8.7˚	0.366
SI	55.6˚±9.1˚	46.2±12.1˚	0.000*

CI = coronal inclination, TV = transverse version, SI = Sagittal ante-inclination. * indicates P<0.05, a statistically significant difference between the dislocation group and the stable THAs.

Table 4. Functional 3-D acetabular cup orientation; Difference between standing and sitting. CI = coronal inclination, TV = transverse version, SI = Sagittal ante-inclination.

	Stable	Posterior dislocations	P
CI	+10.7˚±5.7˚	+5.5˚±6.2˚	0.000*
TV	+10.3˚±5.0˚	+6.2˚±3.4˚	0.002*
SI	+20.8˚±9.3˚	+11.3˚±7.2˚	0.000*

* indicates P<0.05, a statistically significant difference between the dislocation group and the stable THAs.

DISCUSSION

Dislocation of a THA can be either by implant-implant (stem-cup) impingement, by bone-bone (femur pelvis) impingement or implant-bone impingement. Posterior pelvic tilt from standing to sitting accommodates flexion of the femur. Whether a lack of pelvic tilt, an increase of hip flexion, malposition of acetabular or femoral implant, or a combination of these lead to one of the forms of impingement during postural change, depends on the amount of reorientation in 3-D.[3,12,13,16,20] Although the Lewinnek safe zone is based on static coronal and transverse plane cup orientation in the supine position, recent studies demonstrated the importance of functional sagittal pelvic tilt and sagittal cup reorientation for THA stability.[3,8,9,16] We studied the changes in the orientation of the acetabular cup in all three orthogonal anatomical planes during functional pelvic tilt in THA patients with posterior dislocations compared with stable THAs. It demonstrates that the 3-D orientation of the acetabular cup changes with changing body position, but degree of changes and 3-D orientation in the sitting position differs between stable and unstable THAs.[8–10] Compared with stable THAs, hips with posterior dislocations had less difference between standing and sitting in CI, TV, and AI because of reduced pelvic mobility.[10,18,21] With less pelvic mobility, less increase in AI enlarges the risk of impingement, especially in patients with spinal pathology with pre-existent pelvic retroversion and diminished pelvic mobility.[7–10,16,20] The altered spinal pelvic mechanics in patients with a dislocation could have been developed years after THA placement. A lower PT from standing to sitting could be a result of progressive degenerative pathology of the spine, combined with muscle atrophy in the aging patient making them prone for a dislocation. Otherwise, there could also be patients who already have a degenerative spine with coexisting muscle atrophy when the THA is placed. Both patients might benefit from optimizing acetabular cup orientation by increasing the AI in the sitting position, preventing anterior impingement.

A recent study established the mathematical relationship between the orientation angles of the acetabular cup on the three orthogonal, anatomical planes (ie, CI, TV, and AI).[17] In this study, 1of pelvic tilt around the hip-axis equals 1of change in the cup orientation (AI) in the sagittal plane.[10] In contrast to earlier assumptions in the literature, the degree of change in CI and TV, however, is not linearly related, because it is dependent on an individuals' pelvic mobility as well as the initial 3-D cup positioning.[22–24] The effect of sagittal pelvic tilt on the TV is much greater in acetabular cups with relatively low CI compared to high CI, and vice versa.[13] This explains the comparable TV in the sitting position in contrast to CI and SI in this study. Hips with posterior dislocation have less CI in the standing position, so with less pelvic tilt from standing to sitting compared with stable THAs, TV still changes considerably.[13] Thus, each acetabular cup responds differently to an individuals' functional spino-pelvic-femoral dynamics based on its initial position, and could create significant risk for implant impingement/instability.

The lower standing and sitting AI, found in this study, is consistent with a lower functional sagittal safe zone which signifies risk of dislocation. The finding that TV, which does not differentiate in the standing or in the sitting position in both groups, is not the most important angle is an important contribution of this study. This finding confirms the data from two plane measurements studies by Stefl.[16,25] Therefore, the cup in the CI and AI position, implanted by the surgeon, is important for controlling impingement risk.

From the spine literature, it is well known that individuals with a sagittal pelvic morphology characterized by a low PI (a more vertical position of the sacrum within the pelvic ring and the femoral heads under the sacrum) normally have more pelvic retroversion (lower SS) because of less lumbar lordosis. With spinal imbalance and stiffness, there is less increase in acetabular opening as expressed by our data of CI and AI in hips with a dislocation which means more hip flexion is needed that increases the risk of bony impingement.[8,16] Our data does not include the femur but previous studies of femur mobility can be interpolated with our 3-D cup data. Because the hip functions as a joint, our 3-D cup data are important additional knowledge for the orthopedic surgeon in understanding stability of the joint. It is also important because it confirms 2-D findings, thereby confirming the validity of these previous studies.[3,4,8,9,16]

We had limitations. Although we observed clear associations of altered pelvic-femoral dynamics, changes in implant orientation and THA stability, this study did not investigate other factors involved in THA dislocation, such as surgical approach and technique, muscle tension, femoral head size, femoral component orientation, combined anteversion, long-term wear, head-neck ratio, and impingement. All of these factors do have a role in dislocation in spite of a well-positioned acetabular cup.[26–28] Long-term wear of the bearing has also been described as having a role in THA dislocation.[29,30] Another limitation is that this study did not address factors involved in impingement, like individual differences in bony anatomy, extreme range of motion of the hip, protrusion of the acetabular cup or stem positioning. Despite the different confounders that certainly play a role in the onset of different types of dislocations, we believe that our observations of associations of altered pelvic-femoral dynamics and the consequent changes in implant orientation with THA stability hold true.

CONCLUSION

In patients with a posterior THA dislocation, restricted pelvic tilt combined with a lower PI, results in a lower increase of CI, TV, and AI from the standing to the sitting position. Our data show that stability is dependent on a decreased orientation of CI and AI, in contrast to TV. In hips with dislocation, the 3-D orientation of these angles reveals a compromised functional safe zone which increases the risk of impingement and instability. Dependent on the initial operative cup position, the risk can be increased by reduced posteroinferior acetabular restraint.

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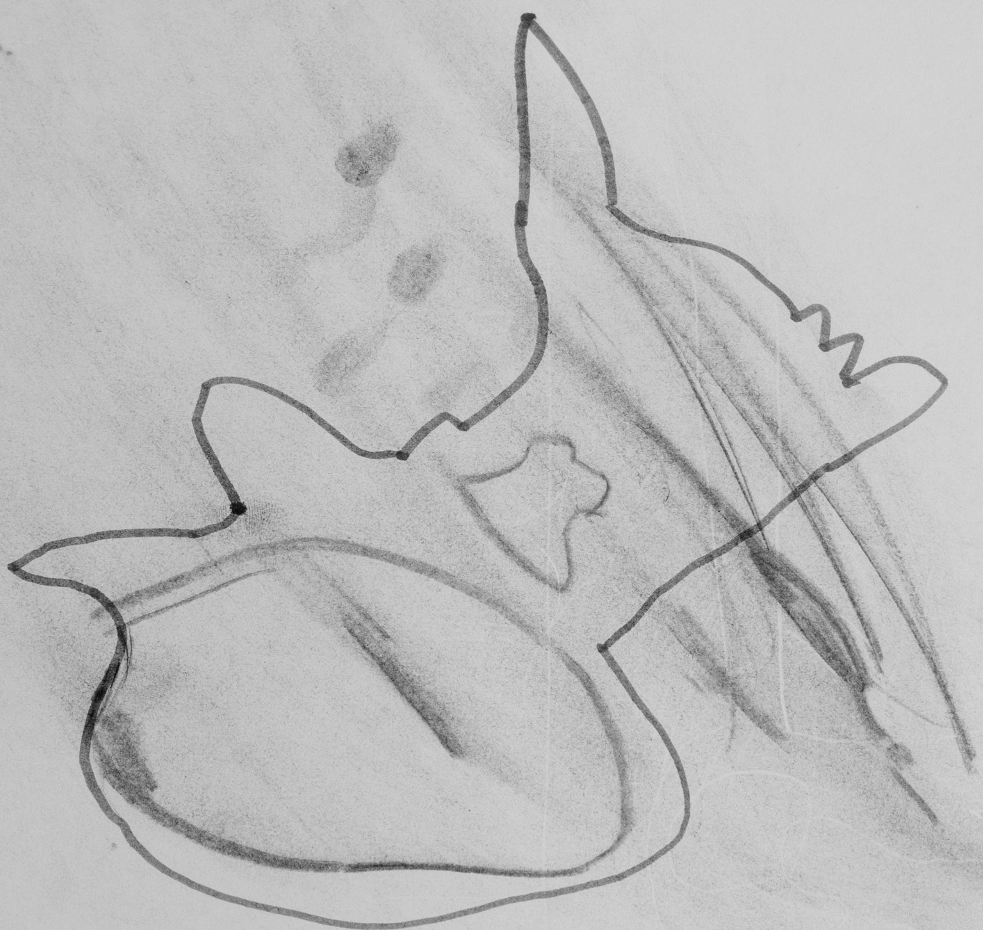

CHAPTER 8

Variability in Acetabular Orientation in Relation to Morphological, Mechanical and Functional Spinopelvic Characteristics in the Normal Adult Population

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ABSTRACT

Background

Functional mechanics of the acetabular cup is important in THA stability. The implantation orientation of the cup is often based on the native acetabulum, as it is the visual reference during surgery. However, there is wide variation in sagittal spino-pelvic morphology within the population and functional pelvic tilt will change the 3D orientation of the cup. This study's aim is to quantify the relationships between normative acetabular orientation and sagittal morphology, as well as the mechanical and functional alignment of the spino-pelvic unit in a typical adult population.

Methods

True sagittal images of the pelvis were reconstructed from a CT database of 308 adults (18-87 years). To characterize pelvic morphology and orientation, the following parameters were determined: pelvic incidence (PI), ischio-iliac angle (IIA), sacro-acetabular angle (SAA), sacral slope (SS), pelvic tilt (PT) and anterior pelvic plane tilt (APPt). For acetabular orientation, coronal inclination (CI), transverse version (TV) and sagittal ante-inclination (SAI) were measured with the pelvis supine, in neutral mechanical tilt (PT = 0˚), SAI in neutral morphological tilt (APPt=0˚) and a normative functional position (). Correlation analyses were performed between the acetabular and pelvic parameters.

Results

The interindividual variation was largest for SAI (mean ±sd 17˚±9˚), compared to CI (40˚±4˚) and TV (14˚±6˚). SAI was significantly larger in females (22˚ vs. 12˚, p<0.001), and left and right hips were comparable. Mean SAI changed from 27˚ to 17˚, 33˚ and 28˚ in the supine, neutral mechanical, neutral morphological and normative functional position respectively. Functional SAI correlated most with the SAA (r=0.78, P<0.001) and weakly with PI (r=0.22, p<0.001), SS (r=0.30, p<0.001) and APPt (r=0.13, p<0.001).

Conclusion

Significant variability in sagittal acetabular orientation exists within an adult population, with larger SAI in women. The SAI is only strongly related to the SAA. This supports consideration of the individual's SAA (i.e. SAI and SS) for determining physiological, patient-specific cup orientation, as it includes information about pelvic motion, morphology and position, all relevant to THA stability.

INTRODUCTION

Total hip arthroplasty (THA) is very successful for the treatment of end-stage hip pathology. Nevertheless, THA dislocation remains a common complication with a profound impact on patient well-being. Many studies emphasized the importance of the dynamics of the spino-pelvic-femoral complex for stability.[1–8] Several morphological and orientation parameters of the pelvis, acetabulum and femur in standing and sitting position have been demonstrated to be relevant, and can be used to identify a patient at risk for a dislocation.[9] For the acetabular cup, its sagittal-plane orientation has been found a distinguishing risk factor for posterior dislocations.[10]

While pelvic morphology and orientation are mostly determined by the patient's pre-existing anatomy and potential spinal or hip pathology, the acetabular and femoral implant orientation can be manipulated by the surgeon. For this, historically, surgeons rely on palpable anatomical landmarks of the anterior pelvis as a reference for the pelvic orientation combined with the frequently described 'safe-zone' for anteversion and inclination.[11] Currently, many surgeons also include visual reference of the native acetabular orientation and transverse ligament to find the optimal cup orientation for an individual patient.[,12–14] As restoration of a patient's natural biomechanics plays a crucial role in minimizing the risk of dislocations, the next step may involve taking into account the patient's distinct pelvic morphology and orientation.

In the field of spine surgery, many studies have described the interindividual variation in pelvic morphology and orientation in the sagittal plane within the normal adult population.[,15–18] For the hip as well, a significant variation in 3D acetabular orientation has been described.[12,19–23] As surgeons commonly utilize native anatomy to orient their cup, this may lead to large variations in functional position of the cup. The native mean inclination and anteversion have been described by several studies as being between 49˚-62˚ and 8˚-25˚ respectively, depending on different reference planes and sex.[12,19–23] Unfortunately, there is limited knowledge available regarding the range of sagittal orientations of the native acetabulum, sagittal ante-inclination (SAI), and its correlation with the diverse sagittal spino-pelvic morphology. This knowledge gap persists, even though it is well-established that sagittal pelvic tilt directly impacts the functional alignment of the cup.[8,10]

The connection between a patient's distinct native acetabular orientation, the visual and tactile landmarks of the pelvis, and the patient's pelvic morphology, along with their corresponding functional pelvic alignment, remains to be fully understood. Given the potential significance of this understanding in further reducing dislocation rates, this study's aim is to quantify the relationships between the normative acetabular orientation and sagittal morphology, as well as the mechanical and functional alignment of the spinopelvic unit in a typical adult population.

MATERIAL AND METHODS

Study Population

The population consisted of all adults included in an existing database, previously used for assessment of the spinopelvic morphology.[24] All patients had undergone CT examination of the abdomen for acute abdominal pathology or trauma screening in an academic center in the Netherlands between June 2005 and December 2012. The scans were acquired with Philips Brilliance 16 and 64 scanners (Philips Medical Systems Nederland BV, Best, The Netherlands) in the supine position, and consisted of axially reconstructed images with 0.4–1.0 mm pixel size and 3.0–4.0 mm slice thickness. Clinical and radiographic medical charts were reviewed to rule out (pre-)existent (spinal) pathology. These patients were excluded. CT scans without complete visualization of the pelvis, femoral heads and L5, or with severe artifacts were excluded as well.

Image analysis

True sagittal CT images of the pelvis were reconstructed based on the line connecting the midpoints of both femoral heads, representing the hip axis. The midpoint of the femoral heads were localized by the exact centers of the spheres that best fit between the 3-D edges of the femoral heads.[25] The multiplanar reconstructions of the pelvis in supine position were reoriented to represent neutral mechanical tilt (PT = 0˚), neutral morphological tilt (APPt = 0˚) and a theoretical normative functional position (Figure 1).

The functional orientation of the pelvis was calculated by according to Vialle et al. and used to correct the SAI into the functional standing body position.[26]

The 3D acetabular orientation angles were measured in the supine and neutral mechanical position, using a previously validated technique on the respective reconstructions depicting

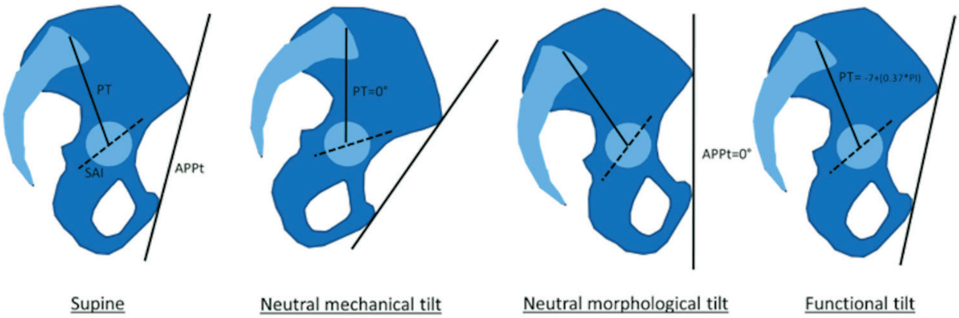

Figure 1. The multiplanar reconstructions of the pelvis in supine position were reoriented to represent neutral mechanical tilt (pelvic tilt = 0˚), neutral morphological tilt (APPt = 0˚) and the functional standing position.

the center of rotation of the native acetabulum on the coronal, transverse and sagittal plane.[27] The following definitions were used to describe the pelvic parameters and acetabular orientation (Figure 2 and 3).[8,24,27,28]

- Pelvic incidence (PI): angle between a line connecting the center of the femoral heads and the midpoint of the sacral plate, and a second line perpendicular to the sacral plate.
- Ischio-iliac angle (IIA): angle between the ischium and ilium, defined as the mean angle between the axis of the left and right ischium, and the same line connecting the midpoint of the sacral endplate to the hip axis.
- Pelvic tilt (PT): angle between the vertical and a line connecting the center of the femoral heads with the center of the S1 endplate.
- Sacral Slope (SS): angle between a horizontal line and a line parallel to the sacral plate.
- Sacro-acetabular angle (SAA): a pelvic constant produced by the sum of the SAI and the SS.
- Anterior pelvic plane tilt (APPt): angle between the plane created by the anterior superior iliac spines and the pubic symphysis and the coronal plane. Negative APPt is posterior pelvic tilt.
- Coronal inclination (CI): angle of the native acetabulum around the anterior-posterior axis in the coronal plane.
- Transverse version (TV): angle of the native acetabulum around the cranio-caudal axis in the transverse plane.
- Sagittal ante-inclination (SAI): angle of the native acetabulum around the hip axis in the sagittal plane.

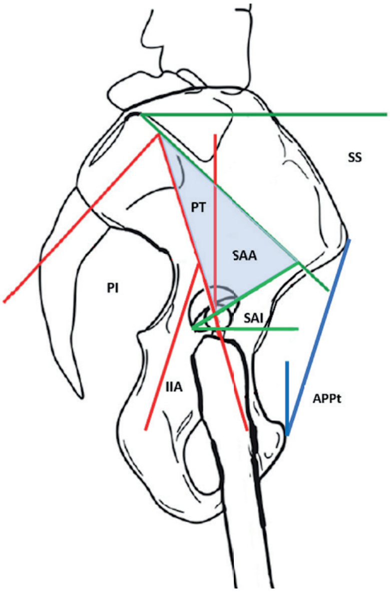

Figure 2. Sagittal pelvic parameters included in this study are shown. Abbreviations: sacral slope (SS), pelvic tilt (PT), pelvic incidence (PI), ischio-iliac angle (IIA), sacro-acetabular angle (SAA), sagittal ante-inclination of the acetabulum (SAI), anterior pelvic plane tilt (APPt).

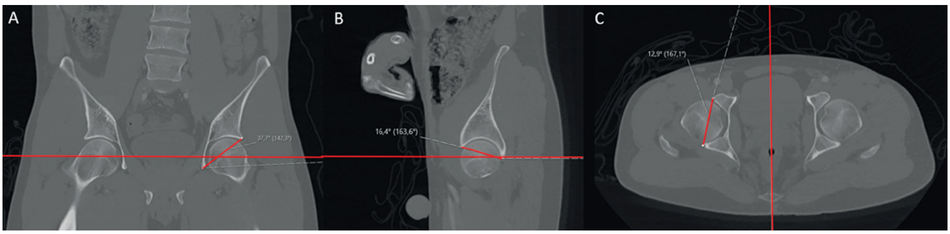

Figure 3. Coronal inclination (a) and sagittal ante-inclination (b) of the acetabulum are measured in relation to the horizontal plane and transverse version (c) of the acetabulum in relation to the anterior-posterior axis.

Measurement accuracy and reliability

Measurement properties of CT based sagittal pelvic parameter measurements were investigated in previous studies by Vrtovec et al. and Schlösser et al..[24,25] Intraobserver and interobserver reliability analysis of the 3D acetabular orientation measurement in the neutral mechanical and functional position was performed by two observers on a randomly selected subset of 23 CT-scans.

Statistical analysis

Statistical analyses were performed with use of IBM SPSS Statistics 23 (SPSS Inc., Chicago, Illinois). Descriptive statistics were computed, providing the mean, standard deviation (SD) and range. The Kolmogorov-Smirnov test was used to test for normality. For reliability analyses of the acetabular measurements the mean absolute difference (MAD) and the Intraclass Correlation Coefficient (ICC) were used, with a two-way mixed effects model for intraobserver and interobserver reliability. In case of normally distributed data the independent t-test was used to test for statistical differences between sexes and sides of the acetabular measurements. If the data was not normally distributed the Mann-Whitney U test was used. Pearson's correlation analysis determined the correlation coefficient between parameters. The level of statistical significance was set at 0.05 and the Bonferroni-Holm method was used to adjust for the multiple comparisons (63 hypotheses).

RESULTS

Population

Out of 310 subjects, 308 were included in this study.[24] Two were excluded, as it was impossible to generate the multiplanar reconstruction in which the acetabular rim could be assessed properly. The mean age of the cohort was 44.3±17.6 years (range 18.0-87.0), 149 (48%) were females. Descriptive morphological pelvic parameters are also shown in table 1. PI was 48°±11°, ranging between 20-77°. SAA was significantly lower in males and did not differ between sides.

Table 1. Age and descriptive pelvic parameters in males and females. Data is shown as (mean ± standard deviation, range).

	Total population (n=308)	Males (n=159)	Females (n=149)	p
Age in years	44±18 (18-87)	44±17 (18-87)	45±18 (18-82)	0.47
Pelvic morphology parameters				
PI	48±11 (20-77)	48±10 (25-77)	48±11 (20-75)	0.67
IIA	26±7 (9-46)	25±7 (9-42)	26±6 (12-46)	0.22
SAA	70±13 (38-102)	65±12 (39-92)	76±11 (47-102)	<0.001*
Pelvic orientation parameters (supine position)				
PT	10±6 (-7-28)	10±6 (-2-27)	11±6 (-7-28)	0.3
SS	38±8 (7-58)	38±7 (19-58)	37±9 (7-58)	0.17
APPt	-6±4 (0- -20)	-5±4 (0- -20)	-6±4 (0- -17)	0.06

Normative acetabular orientation

Descriptive acetabular orientation parameters are shown in Table 2. ICC for intraobserver and interobserver reliability of the acetabular measurements were 0.948 and 0.982, respectively, with a MAD of 0.3˚ and 0.4˚. All data was normally distributed except for the supine PT, TV and SAI and neutral mechanical SAI of the left acetabulum. There were no differences between sides, they were combined for further analyses. The three anatomical acetabular orientation angles were significantly different between males and females in every pelvic orientation (*p*<0.001, Table 2).

Table 2. 3-D acetabular orientation in the supine, neutral and functional positions in males and females. Data is shown as (mean ±standard deviation, range).

	Total population (n=308)	**Males (n=159)**	**Females (n=149)**	**p**
Supine position				
CI	40±4 (26-52)	38±3 (27-48)	41±4 (26-52)	<0.001*
TV	20±6 (1-41)	18±5 (1-41)	22±6 (8-38)	<0.001*
SAI	27±9 (5-54)	22±7 (5-44)	32±8 (9-54)	<0.001*
Neutral mechanical position				
CI	40±4 (25-60)	39±4 (26-60)	41±5 (25-52)	<0.001*
TV	14±6 (-2-32)	12±5 (0-31)	17±6 (-2-32)	<0.001*
SAI	17±9 (0-41)	12±7 (0-29)	22±7 (0-41)	<0.001*
Neutral morphological position				
SAI	33±10 (10-68)	27±8 (10-52)	39±8 (13-69)	<0.001*
Functional position				
SAI	28±9 (6-50)	23±7 (6-43)	32±7 (11-49)	<0.001*

Changes in acetabular orientation by pelvic tilt

PT changed from 10˚ ±6˚ (-7˚ - 29˚) supine, to 0˚ in the neutral mechanical, to 16˚±7˚ (3˚-44˚) in the neutral morphological, to 11˚ ±4˚ (0˚- 22˚) in the functional position (P<0.001). Reciprocal changes in SAI and APPt are shown in Table 3.

Relation of acetabular orientation with pelvic parameters

In the sagittal plane, the functional SAI correlated most with the SAA (r=0.78, *p*<0.001), more in females than in males (Table 4, Figure 4a-c).

Table 3. Changes in pelvic and acetabular orientation parameters with the pelvis supine, in neutral mechanical tilt, in neutral morphological tilt and the functional standing position.

Orientation parameter	Supine position	Neutral mechanical position	Neutral morphological position	Functional position
PT (°)	10±6	0	16	11
SAI	27±9	17	33	28
APPt	-6±4	-16	0	-5

Table 4. Correlation analyses between 3-D acetabular orientation in the supine, neutral and functional positions, compared to spinopelvic parameters. Only correlation coefficients are shown for statistically significant correlations. n.s. = nonsignificant.

	PI	IIA	SAA	SS_{supine}	PT_{supine}	$APPt_{supine}$
Supine position						
CI	n.s.	n.s.	0.21	n.s.	n.s.	n.s.
TV	0.19	0.14	0.40	n.s.	0.30	n.s.
SAI	0.22	0.13	0.66	n.s.	0.40	n.s.
Neutral mechanical position						
CI	-0.20	-0.22	0.34	n.s.	-0.24	0.13
TV	n.s.	n.s.	0.13	n.s.	n.s.	n.s.
SAI	-0.23	-0.22	0.48	n.s.	-0.28	0.18
Neutral morphological position						
SAI	0.17	n.s.	0.74	n.s.	0.29	0.45
Functional position						
SAI	0.22	n.s.	0.78	0.30	n.s.	0.13

Functional SAI correlated weakly with PI ($r=0.22$, $p<0.001$), SS ($r=0.30$, $p<0.001$), APPt ($r=0.13$, $p=0.001$) and not with IIA and PT. SAI_{Supine} showed similar correlations with PI and SAA ($r=0.22$ and 0.66, $p<0.001$) and also weakly with IIA ($r=0.13$, $p=0.001$), PT ($r=0.40$, $p<0.001$), and not with SS and APPt.

In the transverse plane, correlation analysis showed weak correlations of TV_{supine} with PI, IIA, SAA and PT, and not with SS or APPt. $TV_{neutral\ mechanical}$ showed only a weak correlation with SAA. In the supine coronal plane, there was only a weak correlation with SAA. The neutral mechanical CI, had a weak significant positive correlation with SAA and APPt and a weak negative correlation with PI, IIA and PT.

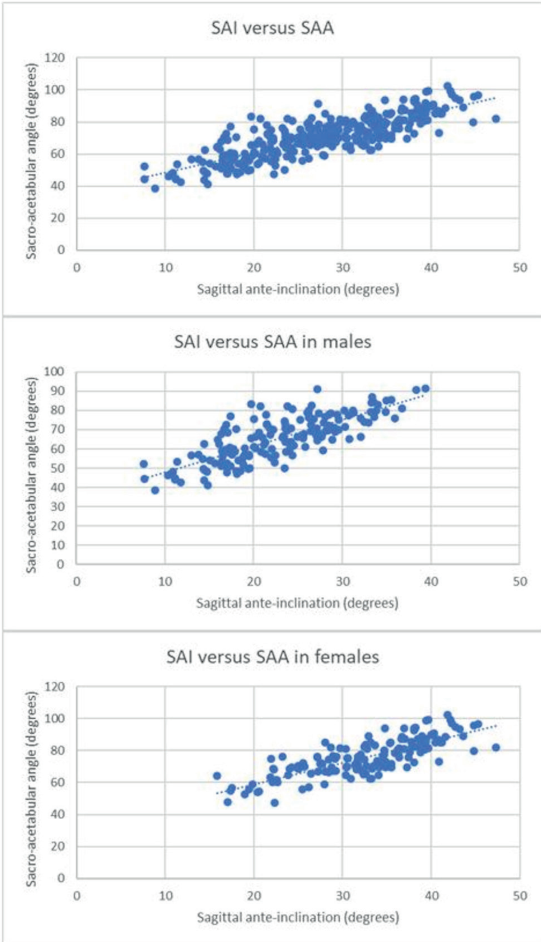

Figure 4. Plots demonstrating the linear relation between sagittal ante-inclination and the sacro-acetabular angle in the total population (a), males (b) and females (c) are shown.

DISCUSSION

In the last decade there has been an increasing recognition of the importance of the sagittal spino-pelvic-femoral dynamics in relation to the clinical outcome after THA surgery. In this work, the variation in 3D acetabular orientation was studied in relation to the sagittal pelvic morphological and orientation parameters in 308 adults of a normal population in order to understand to which extent native acetabular orientation and the APPt are linked to an individual's unique pelvic morphology and functional pelvic orientation. It can be concluded that there is wide variation in native acetabular orientation within the human adult population, mostly in the sagittal plane, with significant variation between men and women. For the common intra-operative references plane 'APPt' and the anatomical pelvic parameter 'PI' were found to be only weakly related to the individual's acetabular orientation. Several studies have described the native acetabular orientation in the coronal and transverse plane. The present study did not establish a significant difference between the left and the right acetabulum (left *versus* right, mean CI 39.9˚ *versus* 39.3˚ and TV of 19.9˚ *versus* 20.0˚). However, the study did identify statistically significant differences between the sexes (p< 0.001), aligning with findings in a study by Thelen et al..[23] That contrasts with other research, as these studies only detected gender disparities in the transverse plane [19–21], while others failed to observe a significant difference between sexes at all.[12,22] The TV, 18.2˚ for males and 21.8˚ for females, correspond to previous studies.[19–23,29,30] The CI, male 38.3˚±3.4˚ and female 41.0˚±4.1˚, however, were lower than previously published studies ranging from 50.5˚ to 62.0˚ for males and 52.1 to 62.1˚ in females.[12,19,29,30] Most likely, this was the consequence of definition of the reference plane, pelvic positioning and exclusion of end-stage osteoarthritic hips.

Our study describes a wide variation in the sagittal acetabular angle, with a mean of 27˚ ± 9˚. This suggest that the role of the SAI might outweighs the role of abovementioned historically used CI and TV.[6,10] Variation in position of the pelvis aggravates this variability of the observed SAI as it is directly affected by a 1 to 1˚ of pelvic motion around the hip axis, compared to the CI and TV were this has less effect. Higgins et al. was the first who measured the SAI in a large normal cohort.[29] They found a SAI of 28˚±8˚ in 88 males and 33˚±9˚in 112 females with CT imaging. Stefl et al. only described it for seven 'normal' patients.[31] These 'normal' patients, measured as a SS of 40˚±10˚, had a mean preoperative SAI of 48.4˚ compared to the functional SAI of 28˚±9˚ in this study. The difference could be explained by measuring it in the standing position, with lateral radiographs and patients with end-stage osteoarthritic hips. They were using the APPt as reference, which increases the SAI in this study as well (28˚ *versus 32*˚). Suzuki et al. described the SAI in a large normal Japanese cohort.[32] They showed a SAI of 25˚±8˚ in males and 30˚±8˚ in females which approximates our results of 22.9˚±7.1˚ and 32.4˚±7.3˚. Suzuki et al. was also using the APPt. Mehkael et al. measured the SAI in a control cohort of 68 patients with more females than males.[30] They measured a SAI of 25.5˚ and it was correlated with the PT. They also showed that the SAI is increased in patients with spinal deformities who stand with their knees flexed (SAI =33˚), implying an increased posterior pelvic tilt is needed to maintain sagittal balance in the upright position.

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Normally, when a subject sits down, the spine straightens and the pelvis tilts posteriorly around the hips while opening the acetabulum anteriorly and providing more clearance for the femur.[33] Leaving more clearance decreases the chance for anterior impingement and allows for more hip flexion. When a subject stands, the pelvis tilts anteriorly, giving clearance for the femur posteriorly and balances the weight of the trunk above the femoral heads. As any degenerative spinal disorder is kyphogenic, patients with a spinal deformity need more posterior pelvic tilt in order to maintain sagittal balance in the upright position. They can increase their SAI, until the hips end in relative extension. With further spinal decompensation or in order to further extend the hips for forward locomotion, knee flexion is required to avoid for impingement at the posterior acetabular rim or ischial bone. Based on the present results, it is expected that the wide variability in SAI is also linked to the compensatory capacity of relative hip extension for spinopelvic compensation. For instance, patients exhibiting minimal pelvic lordosis (i.e., a low ilio-ischial angle), low PI and/or high sacral angle inclination. In these cases, the acetabulum is inherently situated in a relatively extended position during neutral standing, with the ischial and sacral bones vertically aligned. Consequently, such hip configurations are more prone to experiencing posterior impingement with (relative) extension. The exact anatomical mechanism of bony or soft-tissue impingement of the hips in extension in a neutral *versus* compensated pelvic position, however, cannot be derived from the present study.

The common intra-operative reference plane, the 'anterior-pelvic plane' and the morphological pelvic parameter "pelvic incidence" are only weakly related to the individual's acetabular morphology. The SAA shows a strong correlation with the SAI. Obviously, as the SAA consist of the algebraic sum of SS and the SAI of the individual patient, an increased SAI gives a direct effect on the SAA. The SAA might therefore be a better morphological reference for preoperative cup orientation planning then APPt and PI. APPt is affected by patient position and anatomical variation. It introduces an extra variable as the plane is a measurement of the prominence of the anterior superior spina iliaca related to the os pubis and varies in the population.[34,35] In our study this is corroborated by the increased standard deviation in SAI_{app} versus SAI supine, neutral and functional (respectively ±10.0˚ *versus* ±8.6˚, ±8.6˚, ±9.0˚). In addition, APPt remains difficult to control during surgery, except when a preoperative 3D imaging system with navigation is used. PI reflects the relative (horizontal) offset and endplate inclination of the sacral plateau (S1) in relation to the center of the hip axis, without including the orientation of the femoral heads, pubic or ischial bones.[15,17] For this reason, PI does not represent the mechanical hindrance that could lead to posterior femoro-acetabular or femoro-ischial impingement and therefore THA dislocations.

CONCLUSION

This is the first study to quantify the 3D orientation of the native acetabulum in relation to pelvic mechanical parameters in a large adult cohort from a normal human population. A significant variability in sagittal acetabular orientation exists, with larger SAI in women. The sagittal acetabular orientation is only weakly related to the APPt, PT and PI, but is strongly related to the SAA. This supports consideration of the individual's SAA (i.e. SAI and SS) for determining physiological, patient-specific acetabular implant orientation in THA, as it includes information about the expected pelvic motion, morphology and position, all relevant in THA stability.

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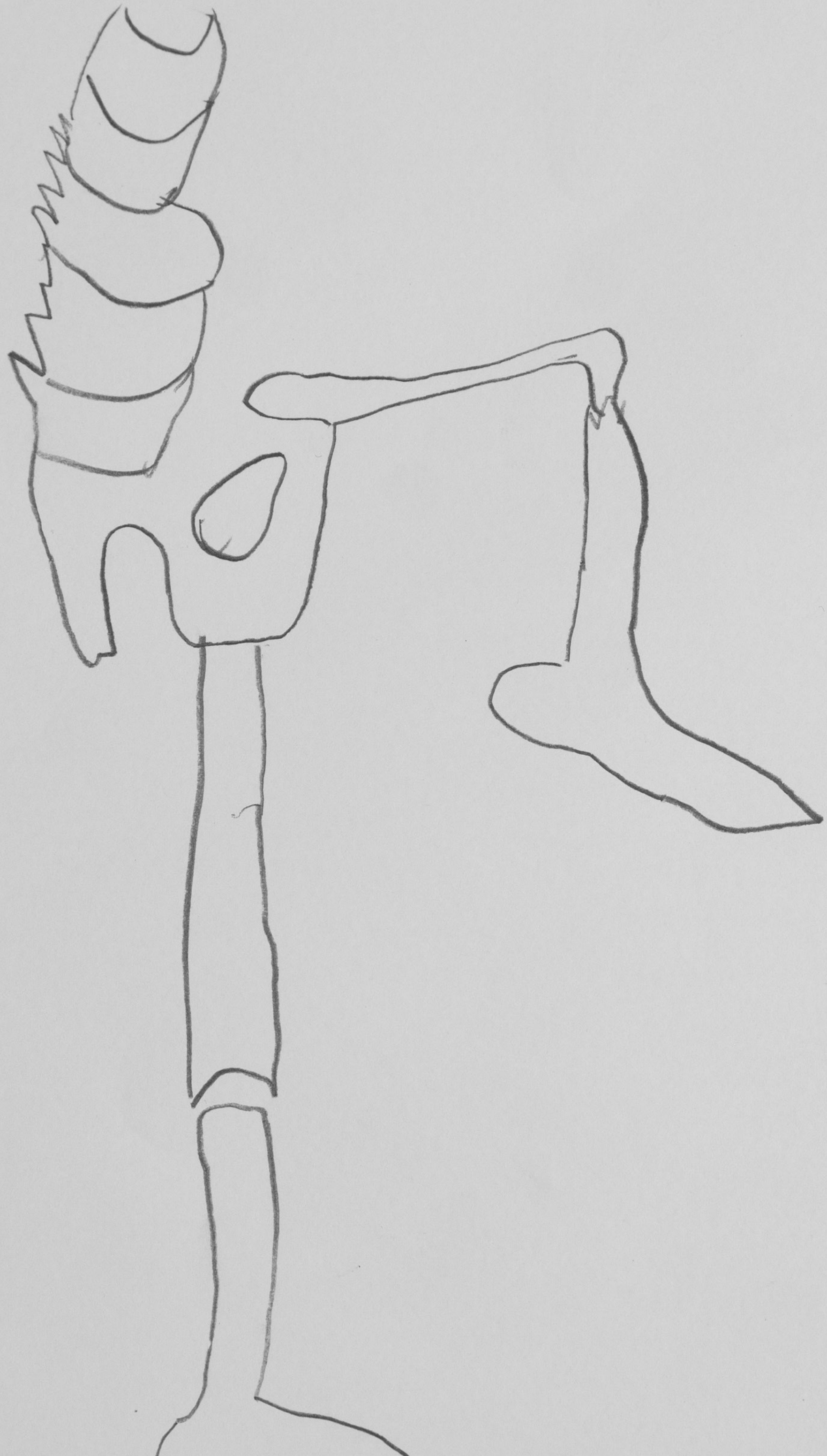

CHAPTER 9

General discussion and Future Perspectives

The success of total hip arthroplasty (THA) is often quoted as the "operation of the century".[1] In the majority of cases, older adults with hip osteoarthritis (OA) who present with significant hip pain and functional limitations that have not improved with conservative management are effectively treated with total hip arthroplasty (THA). Despite its overall very good, long-term results for patients, further reduction of revision burden in THA remains critical for further improvement of the quality of life of patients with hip OA. Joint registry data demonstrates an overall survival rate of the implants of approximately 75% at 15 to 20 years and 58% at 25 years.[2,3] These statistics underline the importance of addressing factors contributing to THA failure. Among the complications, THA dislocation is a significant concern, with reported rates of approximately 1.7% at 2 years, increasing to 2.1% at 6 years postoperatively.[4–7] Dislocation consistently ranks as one of the top three causes of revision THA, accounting for 15% to 21.7% of revision cases.[8–10] In the latest Dutch annual reports, a rising trend is reported for younger age groups, particularly those between 45 and 60 years of age.[10–13]

Besides patient-related biological factors, optimal outcomes in THA depend on maintaining joint reaction forces within the containment of the acetabular cup, for which the patients anatomy, posture, and spino-pelvic-femoral motion should be taken into account. Achieving this goal while avoiding impingement remains a significant challenge. This thesis *explores whether an individualized, optimal acetabular cup orientation can be established, accounting for variations in anatomy, motion, and spino-pelvic relationships, to enhance THA stability and avoid impingement.*

Critical barriers to determining the ideal, functional, patient specific cup orientation are identified and strategies are proposed to mitigate these challenges, aiming to enhance THA outcomes and reduce revision rates.

PART 1

Quantification of Three-Dimensional Total Hip Arthroplasty Cup Orientation

The findings presented in *Chapter 2* indicate that navigation systems achieve greater precision and improved accuracy to Lewinnek's safe zone (inclination of 45° ± 10° and anteversion of 15° ± 10°) in acetabular cup orientation, when compared to freehand placement in THA.[14] This conclusion aligns with evidence from several other meta-analyses.[15–20] Most importantly, it also shows that there is insufficient evidence to substantiate a correlation between the use of navigation systems and better functional outcomes, as well as a reduction in complications or revision rates. A notable limitation of the studies included in our meta-analysis, as well as those referenced in other meta-analyses, is the lack of uniformity in the pooled data, which introduces potential bias. This raises an important concern regarding whether similar biases are present in the foundational studies upon which the current consensus is based. Before comparing methods on targeting the optimal acetabular cup orientation in THA surgery, a critical reassessment of how "optimal acetabular cup placement" is defined and can be quantified, is necessary.

The systematic review in *Chapter 3* reveals a widespread lack of uniformity in the measurement methods of the acetabular orientation in relation to dislocations. Many studies, for instance, fail to differentiate between anterior and posterior dislocations, resulting in values that effectively cancel each other out. In contrast, studies that do make this distinction reveal a statistically significant difference in anteversion between anterior or posterior dislocations and control groups.[14,21–24] These findings suggest the potential existence of a safe zone for acetabular cup orientation; however, the widely cited "Lewinnek safe zone" could not be validated by most studies.[14]

Further complicating matters, the methodologies employed across studies exhibit significant variation. Differences include supine versus standing positions, with or without pelvic tilt correction, and diverse measurement techniques for acetabular cup orientation—all while using the same two-dimensional terminology. For anteversion specifically, methods ranged from cross-lateral radiographs to lateral radiographs, transverse CT images, and indirect measurements on anteroposterior pelvic radiographs, resulting in 13 distinct measurement approaches. This methodological heterogeneity fundamentally undermines the ability of meta-analyses to establish a consensus on optimal acetabular cup orientation. It also precludes the identification of patient-specific anatomical factors that may influence impingement and dislocation.[25–27] Additionally, most studies evaluate acetabular cup orientation in static scenarios, whereas the dynamic nature of the human pelvis during daily activities introduces further complexity. Although the acetabular cup is fixed within the pelvis, the pelvis itself is constantly in motion. This dynamic aspect of acetabular orientation represents a major challenge and will be addressed in detail in part 2. *Chapter 4* reveals that different anteversion measurement methods, despite utilizing identical terminology, produce varying results when compared to the 'gold standard'. The "transverse anteversion angle" is a different spatial angle than the "sagittal anteversion" angle. This inconsistency highlights the critical need for standardized measurement protocols to ensure reliable comparisons and meaningful conclusions in future research. To simplify, description of orientation based on the six-degrees of freedom and anatomical planes can standardize and uniform the quantification of implant orientation independent of imaging modality. Therefore, the anatomical anteversion in the transverse plane, rotating around the cranio-caudal longitudinal axis, can be considered the gold standard and avoiding using the term anteversion for other projectional angles in different planes is recommended.

PART 2

Quantification of Three-Dimensional Cup Orientation Dynamics

To address the issue of non-uniformity identified in previous studies, a comprehensive 3D model was developed that accurately describes acetabular cup orientation across all three anatomical planes, each rotating around its respective axis. In this model described in *Chapter 5*, coronal inclination is defined as rotation around the anteroposterior axis, transverse version as rotation around the longitudinal axis, and sagittal ante-inclination as rotation around the transverse axis. *(Figure 1)*

These standardized definitions are universally applicable during surgery and across all imaging modalities, provided two orthogonal projections can be obtained (radiographs) or simulated (CT scans). While a craniocaudal radiograph of the pelvis is technically impossible, for a hemispheric cup, the trigonometric algorithm developed can precisely calculate transverse version using cup orientation angles derived from the two other radiographic projections. This enables an easily accessible method for postoperative quantification of cup orientation in 3-D. Additionally, the lateral pelvic radiograph required,

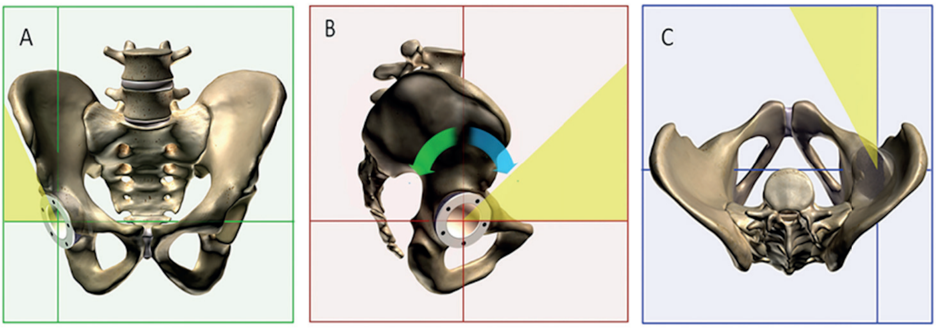

Figure 1 A-C (A) Coronal inclination and (B) sagittal tilt of the cup are measured in relation to *the horizontal plane, and (C) the transverse version of the cup is measured in relation to the AP axis. Pelvic tilt is described as rotation around the transverse hip axis. The blue arrow in (B) indicates anterior pelvic tilt; the green arrow in (B) describes posterior pelvic tilt. A change in pelvic tilt of 1° gives a change in sagittal tilt of 1°.*

not only facilitates the measurement of sagittal ante-inclination of the cup, but can also be used for assessment of individual sagittal pelvic morphology and orientation by measurement of pelvic incidence, sacral slope and pelvic tilt. 1° of anterior pelvic tilt around the hip-axis decreases the sagittal tilt of the acetabular cup by 1°. Given the substantial variability in anterior and posterior pelvic tilt among patients[28], this 3-D model provides a robust framework for incorporating pelvic tilt into future cup orientation analyses.

Finally, THA dislocations occurs in dynamic situations, such as when an individual moves from a standing position to a sitting position, when bending forward in the sitting position (for posterior dislocations) or with maximum hip extension (for anterior dislocations).[29] In *Chapter 6* we validated a generally applicable formula to assess the effect of pelvic tilt on any acetabular cup orientation (coronal inclination, transverse anteversion, and sagittal ante-inclination) and any pelvic tilt in patients with a THA. Clinically, by combining the individual sagittal orientation of an acetabular cup on two lateral radiographs in different body positions, this model allows us to determine the exact changes in acetabular cup orientation in all three anatomic planes during pelvic dynamics.

The 3-D analysis of acetabular cup reorientation during functional changes in pelvic tilt revealed significant variability based on initial cup orientation. Notably, the model demonstrated that the effect of pelvic tilt on transverse version is considerably more pronounced in acetabular cups with low coronal inclination compared to those with high coronal inclination. Similarly, pelvic tilt has a greater influence on coronal inclination in cups with high initial transverse version than in those with low initial transverse version. Furthermore, the model highlighted that when the initial transverse version is lower, a smaller degree of pelvic tilt is required to shift the orientation into retroversion. This variability underscores the clinical significance of individual cup orientation and its interaction with pelvic dynamics. Certain acetabular cup positions, due to their primary anatomical orientation, are predisposed to unfavorable reorientations during pelvic motion. These reorientations can result in impingement or joint reaction forces that fall outside the boundaries of the acetabular cup, increasing the risk of dislocation. Understanding these dynamics provides valuable insights into patient-specific risks and highlights the importance of considering functional pelvic motion when planning and evaluating THA procedures.

PART 3

Towards functional Three-Dimensional Cup Orientation in Total Hip Arthroplasty

In *Chapter 7*, the previously validated 3-D models for quantification of cup orientation static as well as dynamic are applied to clinical practise. In a case-control study patients with posterior THA dislocations are compared to those with stable THAs. In general, the variation in sacral slope was 5.7 degrees and the variation in pelvic dynamics was 9.5 degrees, demonstrating the heterogeneity of the mobility of the spino-pelvic unit in THA population. This study integrated individual 3-D acetabular cup orientation and pelvic motion, revealing that the degree of positional change and 3-D orientation in the sitting position differs significantly between the two groups. Hips with posterior dislocations exhibited markedly reduced pelvic mobility, resulting in less change in coronal inclination, transverse version, and sagittal ante-inclination compared to stable THAs. In line with other recent studies, the patients with reduced pelvic mobility (at the lumbosacral junction), can be considered "hip-users".[30–33] Consequently, the change in acetabular cup orientation from standing to the sitting position differed substantially in these cases as compared to patients with normal pelvic mobility ("spine-users"). [30–33] The spine literature highlights that individuals with sagittal pelvic morphology characterized by a low pelvic incidence (a more vertical sacrum within the pelvic ring, with femoral heads positioned beneath the sacrum) typically exhibit greater pelvic retroversion (lower sacral slope) due to reduced lumbar lordosis. In cases of spinal imbalance and stiffness, there is limited increase in acetabular opening, as reflected by our data on coronal inclination and sagittal anteversion in hips with dislocations. Consequently, these individuals require greater hip flexion, which heightens the risk of bony impingement.[34,35] These observations emphasize the critical role of both pelvic dynamics and spinal morphology in optimizing acetabular cup orientation to minimize the risk of dislocation.

Reduced sagittal pelvic tilt from standing to sitting may be attributed to progressive degenerative spinal pathology, spinal fusion and/or pelvic retroversion combined with muscle atrophy in aging patients that had previous THA, predisposing them to late increased risk for dislocation or impingement.[36] Alternatively, some patients may already present with a degenerative spine, spinal fusion and/or pelvic retroversion and coexisting muscle atrophy at the time of THA implantation.[32,37] For the latter, the optimal cup orientation probably needs to be adjusted to the patient's functional spino-pelvic anatomy, to avoid increased dislocation or impingement in the early postoperative phase. Both groups could potentially benefit from individualized acetabular cup orientation.

Insights from *Chapter 6* elucidate that sagittal pelvic tilt has a more pronounced effect on transverse version in acetabular cups with relatively low coronal inclination compared to those with high coronal inclination, and vice versa. This coupled reorientation explains why transverse version appears comparable in the sitting position across the two groups, despite differences in the cup orientation in the other planes. Notably, hips with posterior dislocations tend to exhibit lower coronal inclination in the standing position. Thus, even with reduced pelvic tilt during the transition from standing to sitting, transverse anteversion still undergoes considerable change. However, transverse version alone does not differ significantly between dislocated and stable THAs in either the standing or sitting position. This finding suggests that coronal inclination and sagittal ante-inclination are more critical orientation factors influencing dislocation risk, potentially explaining the lack of consensus on acetabular cup orientation in previous studies reported in *Chapter 3*.

Chapter 8 expands on this understanding by analysing the 3-D acetabular orientation in relation to sagittal pelvic morphology in a cohort of 308 adults from the general population. This investigation aimed to determine the extent of the relationship between sagittal pelvic morphology and the native acetabular orientation in 3-D.*(Figure 2)*

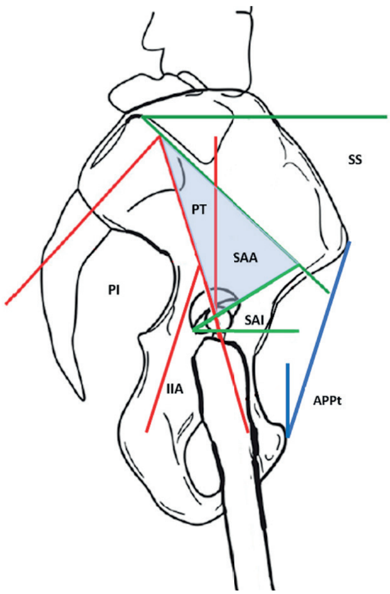

Figure 2. Sagittal pelvic parameters included in this study are shown. Abbreviations: sacral slope (SS), pelvic tilt (PT), pelvic incidence (PI), ischio-iliac angle (IIA), sacro-acetabular angle (SAA), sagittal ante-inclination of the acetabulum (SAI), anterior pelvic plane tilt (APPt).

The findings revealed substantial variability in native acetabular orientation within the adult population, with remarkably the most pronounced variation occurring in the sagittal plane (27˚ ± 9˚). Notably, the main finding was a significant differences in mean functional sagittal acetabular orientation between the genders (22° in men versus 12° in women). With relevance to THA surgery, this study shows that following the individual's native acetabular orientation will result in large variation in functional 3-D cup orientation. The study also demonstrates that other commonly used intraoperative reference planes, such as the anterior pelvic plane (APPt), and anatomical pelvic parameters, such as pelvic incidence, were only weakly correlated with individual acetabular orientation. By contrast, the sagittal ante-inclination of the native acetabulum was obviously closely associated with the sacral acetabular angle (SAA), which represents the algebraic sum of sacral slope (SS) and sagittal ante-inclination. Essentially, it describes the orientation and position of the hip joints and lumbo-sacral junction to each other. As the SAA accounts for pelvic morphology, position, and motion—key factors influencing THA stability. This supports critical consideration of an individual's SAA for determining physiological, patient-specific acetabular implant orientation in THA.[33]

Hypothetically, a patient with a low SAA would exhibit a relatively horizontal acetabulum (morphology) and greater pelvic retroversion (position) in the sagittal plane. This configuration reduces the compensatory retroversion capacity of the pelvis (motion), potentially leading to a reduced anterior acetabular opening when the patient is seated. As a result, it can be hypothesizes that patients with low SAA are at heightened risk of anterior impingement and, consequently, posterior dislocation. These findings underscore the necessity of incorporating individual sagittal pelvic morphology into preoperative planning to enhance the stability and functional outcomes of THA.

CONCLUSION

This Thesis identifies and addresses the primary barriers to determining the optimal acetabular cup orientation for preventing THA dislocation, namely:

- Methodological heterogeneity: Variability in measurement methodologies undermines the current consensus on the "optimal" acetabular cup orientation for individual patients.
- The relationship between acetabular cup orientation and the positional dynamics of the pelvis, lumbar spine, and femur has not been adequately incorporated into existing frameworks.
- Unclear relationship between pelvic motion and acetabular orientation: The effect of pelvic motion on relative acetabular cup orientation remains insufficiently understood.

These barriers are effectively addressed by the development of a 3-D trigonometric model capable of precise measurement and calculation of coronal inclination, sagittal ante-inclination, and transverse version. Notably, the model integrates sagittal ante-inclination with the sacral acetabular angle, thereby accounting for the pelvic position and its relationship with surrounding anatomical structures. The model enables assessment of the impact of pelvic motion on relative acetabular cup orientation, facilitating the evaluation of cup positioning during high-risk movements, such as deep seating. This capability provides a critical framework for optimizing acetabular orientation to maintain joint reaction forces within the boundaries of the acetabular cup while avoiding impingement, irrespective of individual patient anatomy, positioning, or spino-pelvic-femoral motion. By enabling patient-specific adjustments to acetabular cup orientation, this approach aims to improve THA outcomes, reduce the risk of dislocation, and lower revision rates. Ultimately, it allows for the early identification of high-risk patients and supports precise adjustments to ensure correct acetabular cup orientation during the initial procedure, fostering long-term success.

Future studies on THA stability or impingement, should consider the impact of spino-pelvic mobility as a relevant confounding factor and standardize the method for implant orientation quantification. To date, this can be assessed easily with the trigonometric algorithms provided in this thesis. Ultimately, however, the relevance of personalized assessment of spino-pelvic and THA dynamics to the patient and society are studied in more large scale studies, in which for example, also dynamic simulations of activities in daily life are included.

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APPENDICES

Supplementary Materials

Summary

Dutch Summary

Acknowledgements (Dankwoord)

List of Publications

About the Author

SUPPLEMENTARY MATERIALS

Supplementary material of the article

Lack of consensus on optimal acetabular cup orientation because of variation in assessment methods in total hip arthroplasty.

Appendix of the article:

Trigonometric algorithm defining the true three-dimensional acetabular cup orientation correlation between measured and calculated cup orientation angles.

Supplementary material of the article

The effect of functional pelvic tilt on the three-dimensional acetabular cup orientation in late total hip arthroplasty dislocations.

SUPPLEMENTARY MATERIAL OF THE ARTICLE

Lack of Consensus on Optimal Acetabular Cup Orientation because of Variation in Assessment Methods in Total Hip Arthroplasty: a Systematic Review

Measurement methods	Biedermann 2005 (1)	Danoff 2016 (2)	Dorr 1983 (3)	Dudda 2010 (4)	Esposito 2014 (5)	Ezquerra 2014 (6)	Fackler 1979 (7)
Study type	Case-control	Cohort	Case-control	Case-control	Cohort	Case-control	Case-control
Reference Plane	Frontal plane	APP	APP	?	?	APP	Frontal plane
Imaging	Radiographic	Radiographic	Radiographic	Radiographic	Radiographic	Radiographic	Radiographic
Position	?	?	?	?	?	?	Supine
Position correction	Pelvic Obliquity	Pelvic Obliquity	Pelvic Obliquity	?	Pelvic Obliquity	Pelvic Obliquity	Pelvic Obliquity
Inclination	AP	AP	AP	?	AP	AP	AP
AV	AP	AP	AP	?	AP	AP	AP
AV Method	EBRA	Martell	D/C'(arcsin)	?	EBRA	Rithen Pradhan	McLaren

Measurement methods	Fujishiro 2016 (8)	Garcia 2016 (9)	Grammatopoulos 2015 (10)	Jolles 2002 (11)	Kristiansen 1985 (12)	Kim 2009 (13)	Leichtle 2013 (14)
Study type	Cohort	Cohort	Cohort	Case-control	Case-control	Cohort	Case-control
Reference Plane	Frontal Plane	?	?	?	Frontal plane	?	?
Imaging	CT	Radiographic	Radiographic	Radiographic	Radiographic	Radiographic and CT	Radiographic
Position	Supine	Supine	Supine	Supine	?	Supine	Supine
Position correction	Pelvic Obliquity	Pelvic Obliquity	Pelvic Obliquity	Pelvic Obliquity	Pelvic Obliquity	Pelvic Obliquity	Pelvic Obliquity and Tilt
Inclination	CT (Frontal) and AP	AP	AP	AP	AP	Frontal/AP	AP
AV	Transversal	AP	AP	Lateral crosstable	Lateral	Transversal/AP	AP
AV Method	Transversal	Widmer	EBRA	-	-	Transversal/Lateral	Ackland

Measurement methods	Li 1999 (15)	Lewinnek 1978 (16)	Lindberg 1982 (17)	Masaoka 2006 (18)	McCollum 1990 (19)	McLawhorn 2015 (20)	Minoda 2006 (21)
Study type	Cohort	Cohort	Case control	Cohort	Cohort	Cohort	Cohort
Reference Plane	?	APP	?	?	?	APP	APP
Imaging	Radiographic	Radiographic	Radiographic	Radiographic	Radiographic	Radiographic	Radiographic
Position	Supine	Supine	Supine	Supine	Standing	Supine	?
Position correction	Pelvic Obliquity	Pelvic Obliquity and Tilt	Pelvic Obliquity	Pelvic Obliquity	Pelvic obliquity and tilt	Pelvic Obliquity	Pelvic Obliquity
Inclination	AP	AP	AP	AP	AP	AP	AP
AV	-	AP	AP	AP	Lateral	AP	AP
AV Method	-	Lewinnek	Mclaren	Lewinnek	-	EBRA	Lewinnek

Measurement methods	Opperer 2016 (22)	Pierchon 1994 (23)	Pollard 1995 (24)	Sadhu 2017 (25)	Sanz-Reig 2014 (26)	Timperley 2016 (27)	Woolson 1999 (28)
Study type	Case-control	Case-control	Cohort	Case-control	Case-control	Case-control	Cohort
Reference Plane	APP	?	?	?	?	?	Frontal plane
Imaging	Radiographic	Radiographic and CT	Radiographic	Radiographic	Radiographic and CT	Radiographic	Radiographic
Position	?	Supine	Supine	?	?	?	Standing
Position correction	Pelvic Obliquity	Pelvic Obliquity	Pelvic Obliquity	Pelvic Obliquity	Pelvic Obliquity	Pelvic Obliquity	Pelvic obliquity and tilt
Inclination	AP	AP	AP	AP	AP and frontal	AP	AP
AV	AP	Transversal	Lateral crosstable	AP	AP	AP	Lateral
AV Method	Lewinnek	Transversal	-	Martell	Pradhan	Orthoview	-

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APPENDIX OF THE ARTICLE

Trigonometric Algorithm Defining the True Three-Dimensional Acetabular Cup Orientation Correlation between Measured and Calculated Cup Orientation Angles

Three-dimensional (3D) geometrical acetabular cup orientation can be defined in the anatomical planes by coronal inclination, transverse version, and sagittal tilt of the cup (see Figs. 1 and 2 in article). In modern total hip arthroplasty, most cups are almost a perfect hemisphere and have a circular metal wire inserted at the outer circumference of the cup. This wire or the outer rim of the cup is visible on computed tomography (CT) or radiographic imaging of the cup.
Because the shape of the cup is hemispherical, with a constant diameter, and these angles are measured in 3 perpendicular planes, these are trigonometrically related to each other. This supplement describes the trigonometric formulas of these angles, which defines the orientation of the cup in a unique manner.

Definitions and Abbreviations

Three-dimensional coordinate system:
Mediolateral (transverse) axis (X)
Craniocaudal (longitudinal) axis (Y)
Anteroposterior (sagittal) axis (Z)
Opposite (O)
Adjacent (A)
Diameter of the cup (S)

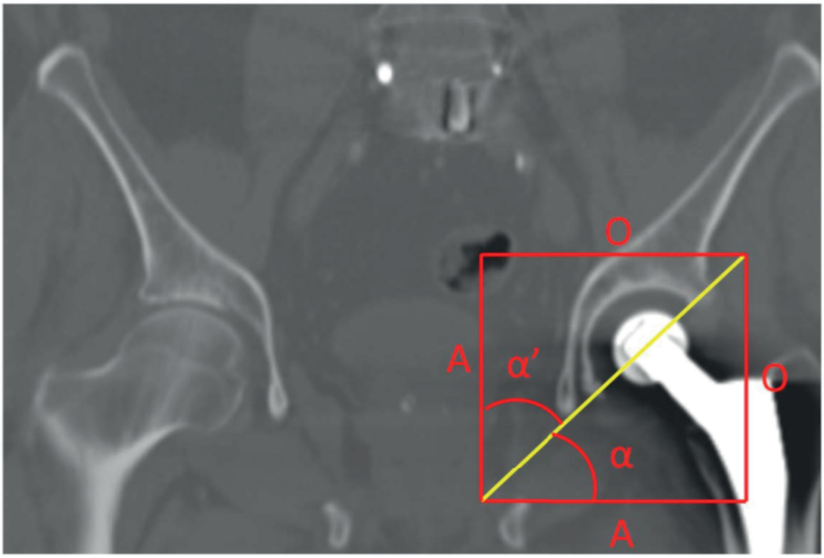

Figure E-1A. Coronal Inclination (Fig. E-1A).
Coronal inclination (α) is defined as the spatial angle between the transverse axis (X) and the cup in the coronal plane at the center of the femoral head. The coronal inclination has a complementary angle (α'), which is the angle between the longitudinal axis (Y) and the cup. The sum of those 2 angles is 90°.

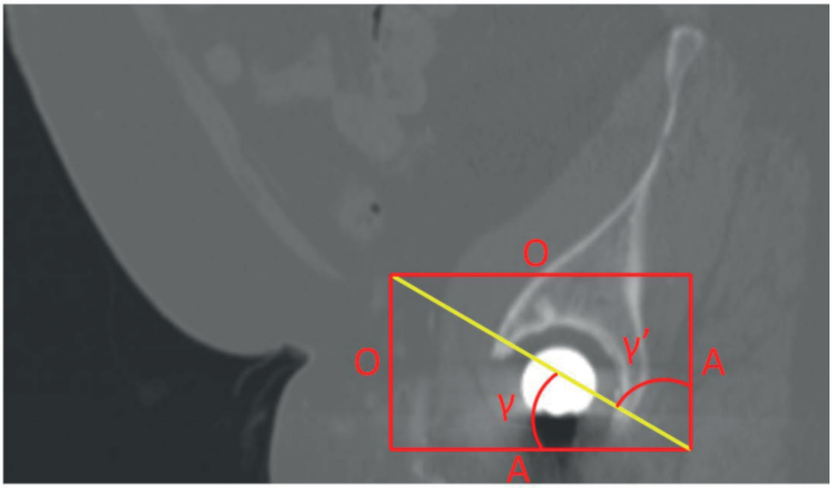

Figure E-1B. Sagittal Tilt
Sagittal tilt (γ) is defined as the spatial angle between the sagittal axis (Z) and the metal wire projected onto the sagittal plane at the center of the femoral head. The sagittal tilt has a complementary angle (γ'), which is the angle between the longitudinal axis (Y) and the metal wire. The sum of those 2 angles is 90°.

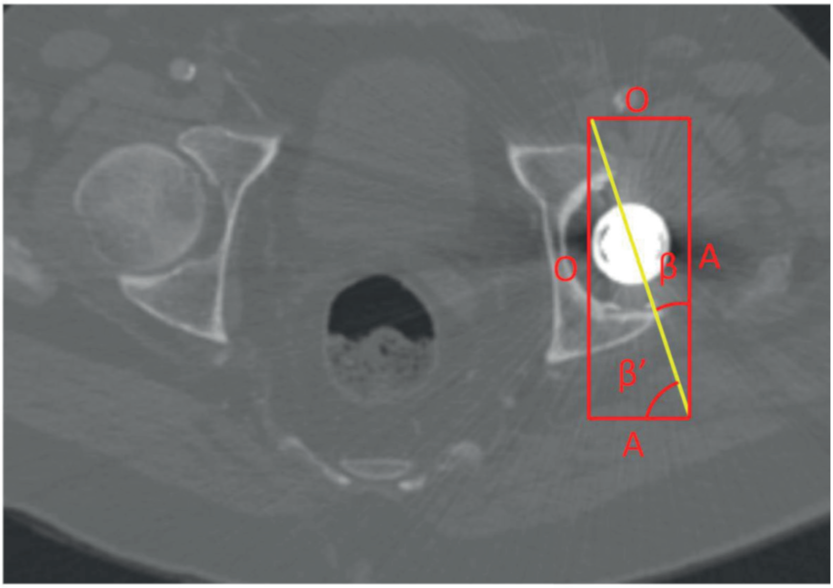

Figure E-1C. Transverse Version
Transverse version (β) is defined as the spatial angle between the sagittal axis (Z) and the metal wire projected onto the transversal plane at the center of the femoral head. The transverse version has a complementary angle (β'), which is the angle between the transverse axis (X) and the metal wire. The sum of those 2 angles is 90°.

Mathematical Rationale of the Trigonometric Algorithm

The orientation of the cup can be described as a vector:

$$\overrightarrow{\text{Acetabular cup orientation}} \quad \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

The vectors of the cup orientation projected onto the coronal, sagittal, and transversal planes are, respectively:

$$\overrightarrow{\text{Inclination}} \begin{bmatrix} X \\ Y \\ 0 \end{bmatrix} \qquad \overrightarrow{\text{Version}} \begin{bmatrix} X \\ 0 \\ Z \end{bmatrix} \qquad \overrightarrow{\text{Tilt}} \begin{bmatrix} 0 \\ Y \\ Z \end{bmatrix}$$

By using the trigonometric equations, those angles could be described as follows, including their complementary angles:

Inclination (α):

$$\tan\alpha = \frac{O}{A} = \frac{Y}{X}$$
$$\sin\alpha = \frac{O}{S} = \frac{Y}{S}$$
$$\cos\alpha = \frac{A}{S} = \frac{X}{S}$$

Version (β):

$$\tan\beta = \frac{O}{A} = \frac{Y}{X}$$
$$\sin\beta = \frac{O}{S} = \frac{Y}{S}$$
$$\cos\beta = \frac{A}{S} = \frac{X}{S}$$

Tilt (γ):

$$\tan\gamma = \frac{O}{A} = \frac{Y}{X}$$
$$\sin\gamma = \frac{O}{S} = \frac{Y}{S}$$
$$\cos\gamma = \frac{A}{S} = \frac{X}{S}$$

Complementary inclination (α'):

$$\tan\alpha' = \frac{O}{A} = \frac{Y}{X}$$
$$\sin\alpha' = \frac{O}{S} = \frac{Y}{S}$$
$$\cos\alpha' = \frac{A}{S} = \frac{X}{S}$$

Complementary version (β'):

$$\tan\beta' = \frac{O}{A} = \frac{Y}{X}$$
$$\sin\beta' = \frac{O}{S} = \frac{Y}{S}$$
$$\cos\beta' = \frac{A}{S} = \frac{X}{S}$$

Complementary tilt (γ'):

$$\tan\gamma' = \frac{O}{A} = \frac{Y}{X}$$
$$\sin\gamma' = \frac{O}{S} = \frac{Y}{S}$$
$$\cos\gamma' = \frac{A}{S} = \frac{X}{S}$$

The cup is a circular hemisphere with a constant diameter. Therefore, mathematically seen, one is able to change the diameter by 1. This gives the opportunity to give an equation by which, if 2 angles are known, the third one could be calculated. These equations describe the relationship between the 3 angles (α, β, and γ; see Table I and Figure 5 in article):

$$\mathit{Inclination} = \arctan\left(\frac{\tan \mathit{Version}}{\tan \mathit{Tilt}}\right)$$

$$\text{Version} = \arctan\left(\tan(\mathit{Inclination}) \times \tan(\text{Tilt})\right)$$

$$\text{Tilt} = \arctan\left(\frac{\tan \mathit{Version}}{\tan \mathit{Tilt}}\right)$$

Practical Considerations and Potential Pitfalls

- Mathematically, this trigonometric algorithm can be used for a symmetrical, hemispherical cup.
- Measurement should be performed by consistently using the circular metal wire around either the cup or the acetabular rim.
- The anatomical planes should be used because these are exactly perpendicular to each other. Multiplanar reconstructions acquired using 3D imaging modalities or images acquired with use of biplanar radiography seem most suitable.
- We recommend using the algorithm with caution in cases in which the sagittal tilt and transverse version are approaching 0°. A small measuring error affects a small positive

or negative tilt and version to a great extent. This could have an influence on the proportions between them, affecting the outcome of the algorithm.

- For negative values of transverse version (retroversion), sagittal tilt is negative as well (retrotilt), and vice versa. Furthermore, if negative sagittal tilt and negative transverse version are present, the following equations are required:

$$Inclination = \arctan\left(\frac{\tan Version}{\tan Tilt}\right)$$

$$\text{Version} = \arctan\left(\tan(Inclination) \times \tan(\text{Tilt})\right)$$

$$\text{Tilt} = 90 - \arctan\left(\frac{tanVersion}{tanTilt}\right)$$

TABLE E-1 Transverse Version for Given Coronal Inclinations and Sagittal Tilt*

Calculated transverse version	Inclination								
Sagittal tilt	0°	1°	15°	30°	45°	60°	75°	89°	90°
0°	0	0	0	0	0	0	0	0	—
15°	0	0.3	4.1	8.8	15	24.9	45	86.3	—
30°	0	0.6	8.8	18.4	30	45	65.1	88.3	—
45°	0	1	15	30	45	60	75	89	—
60°	0	1.7	24.9	45	60	71.6	81.2	89.4	—
75°	0	3.7	45	65.1	75	81.2	85.9	89.7	—
90°	—	—	—	—	—	—	—	—	—

*All values are given in degrees.

SUPPLEMENTARY MATERIAL OF THE ARTICLE

The Effect of Functional Pelvic Tilt on The Three-Dimensional Acetabular Cup Orientation in Total Hip Arthroplasty Dislocations

The 3-D acetabular cup orientation can be defined by the following angles according to the definitions of the Hip-SpineWorkgroup[1]:

- Coronal inclination (CI): the rotation of inclination of the cup around the anterior-posterior axis in the coronal plane.
- Sagittal ante-inclination (AI): the sagittal angle of the cup that includes inclination and anteversion that changes with posterior and anterior tilt of the pelvis.
- Transverse version (TV): the anteversion angle of the cup around the cranio-caudal axis in the transverse plane.

Two of these angles measured on biplanar radiographs can be used to calculate the third by using previously validated trigonometric algorithms.[2,3]

The first algorithm is based on an equation that the orientation of the hemispherical cup given in the three orthogonal anatomical planes in a static situation is given by:

$$\tan(\mathit{Version}) = \tan(\mathit{Inclination}) \times \tan(\mathit{Tilt}) \qquad \text{(Equation 1)}$$

With the second algorithm, the standing and sitting 3-D cup orientations can be calculated, considering that sagittal pelvic tilt is a rotation of the pelvis and acetabular cup around the transverse hip-axis and that 1^0 change of sagittal pelvic tilt equals 1^0 of change in the sagittal orientation of the cup. Therefore, a new AI position (AI'), is related to a new CI (CI') and new TV (TV') by:

With the auxiliary variable:

$$t(inclination, version) = \sqrt{(\tan version)^2 + \frac{1}{taninclination^2}} \qquad \text{(Equation 2)}$$

Additionally, the tangent of the other two new angles are given as:

$$\tan(inclination') = \frac{1}{t \times cosTilt'} \qquad \text{(Equation 3)}$$

$$\tan(version') = t \times \sin(tilt') \qquad \text{(Equation 4)}$$

The algorithms are incorporated in a developed tool available at: www.3d-hip.com.

SCAN ME

SUMMARY

Towards Perfect Acetabular Cup Placement in Total Hip Arthroplasty

Exploring whether an individualized, optimal acetabular cup orientation can be established, accounting for variations in anatomy, motion, and spino-pelvic relationships, to enhance Total Hip Arthroplasty (THA) stability and avoid impingement.

In order to further improve THA outcomes and lower revisions risk, ideally the joint reaction forces remain within the boundaries of the acetabular cup, irrespective of the patient's anatomy, position, and spino-pelvic-femoral motion, without creating impingement. What surgery-related factors play a role in THA impingement and can this be mitigated with personalized THA 3-D planning strategy? To achieve this ideal placement, we first need to understand what constitutes perfect placement and whether a personalized, perfect orientation can be achieved during surgery.

This thesis identifies and addresses the key obstacles in determining the optimal orientation of the acetabular cup to prevent dislocations after THA namely:
Methodological heterogeneity: Variations in measurement methods undermine the current consensus on the 'optimal' acetabular cup orientation for individual patients.
Insufficient integration of pelvic, lumbar, and femoral dynamics: Existing frameworks do not adequately account for the relationship between the orientation of the acetabular cup and the positional dynamics of the pelvis, lumbar spine, and femur.
Uncertain relationship between pelvic movement and acetabular orientation: The effect of pelvic movement on the relative orientation of the acetabular cup is still not sufficiently understood.

These obstacles are effectively addressed by the development of a 3D trigonometric model capable of accurately measuring and calculating coronal inclination, sagittal ante-inclination, and transverse version. Notably, the model integrates sagittal ante-inclination with the sacral-acetabular angle (SAA), thus taking into account pelvic position and its relationship to surrounding anatomical structures. This approach enables assessment of how pelvic movement impacts the relative orientation of the acetabular cup, facilitating evaluation of cup positioning during high-risk movements such as deep sitting.

This functionality provides a crucial framework for optimizing acetabular cup orientation so that joint reaction forces remain contained within the cup and impingement is avoided—

regardless of individual anatomy, positioning, or spino-pelvic-femoral motion. By allowing patient-specific adaptations in cup orientation, this approach aims for improved THA outcomes, a reduced risk of dislocation, and lower revision rates. Ultimately, it enables early identification of high-risk patients and supports precise adjustments to ensure correct acetabular cup orientation during the initial procedure, thereby contributing to long-term success.

NEDERLANDSE SAMENVATTING

Deze scriptie identificeert en adresseert de belangrijkste obstakels bij het bepalen van de optimale oriëntatie van de acetabulum cup ter preventie van dislocaties na totale heupprothesen (THA), te weten:

- Methodologische heterogeniteit: Variatie in meetmethoden ondermijnt de huidige consensus over de 'optimale' oriëntatie van de acetabulumcup voor individuele patiënten.
- Onvoldoende integratie van bekken-, lumbale en femorale dynamiek: De relatie tussen de oriëntatie van de acetabulum cup en de positionele dynamiek van het bekken, de lumbale wervelkolom en het femur is niet adequaat opgenomen in bestaande kaders.
- Onzekere relatie tussen bekkenbeweging en acetabulumoriëntatie: Het effect van bekkenbeweging op de relatieve oriëntatie van de acetabulum cup wordt nog onvoldoende begrepen.

Deze obstakels worden effectief aangepakt door de ontwikkeling van een 3-D trigonometrisch model dat in staat is coronale inclinatie, sagittale ante-inclinatie en transversale versie nauwkeurig te meten en te berekenen. Opmerkelijk is dat het model de sagittale ante-inclinatie integreert met de sacral-acetabular angle (SAA), waardoor rekening wordt gehouden met de bekkenpositie en de relatie met omringende anatomische structuren. Het model maakt het mogelijk om de impact van bekkenbeweging op de relatieve oriëntatie van de acetabulumcup te beoordelen, wat de evaluatie van de cup positionering tijdens risicovolle bewegingen, zoals diep zitten, faciliteert.

Deze functionaliteit biedt een cruciaal kader om de acetabulumcup oriëntatie te optimaliseren, zodat de gewrichtsreactiekrachten binnen de grenzen van de cup blijven en impingement wordt voorkomen, ongeacht de individuele anatomie, positionering of spino-pelvic-femoral beweging. Door patiëntspecifieke aanpassingen in de oriëntatie van de acetabulumcup mogelijk te maken, streeft deze benadering naar betere THA-resultaten, een verminderd risico op luxatie en een lagere revisiegraad. Uiteindelijk maakt dit het mogelijk om risicopatiënten vroegtijdig te identificeren en ondersteunt het precieze aanpassingen om tijdens de initiële procedure de juiste oriëntatie van de acetabulumcup te waarborgen, wat bijdraagt aan langdurig succes.

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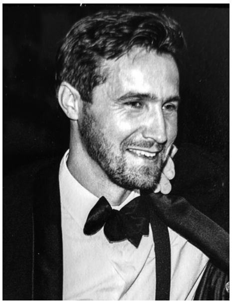
ABOUT THE AUTHOR



Thom Edgar Snijders was born on 9 December 1984, in a family of 7, in the village of Sint Willebrord, Noord-Brabant, where his father served as a General Practitioner. Thom originates from a family primarily composed of physicians, with ancestral roots in the province of Limburg. He attended primary school at OBS Het Palet in Rucphen and, in 2003, graduated from the Atheneum at Norbertus College in Roosendaal, after which he was admitted to the Medicine program at the University of Groningen.

Following a challenging start to his undergraduate studies, he commenced his junior internships at Isala Hospital in Zwolle. During this period, he pursued a Social Medicine and Emergency Department internship at Stanger Hospital in South Africa. In 2012, he moved to Amsterdam for his final internship and to undertake a research project at the Department of Orthopedics at the Diakonessenhuis in Utrecht/Zeist. His interest in Orthopedic Surgery grew significantly during this time. His Master's thesis culminated in a publication, marking the beginning of his research career in Orthopedic Surgery.

In 2013, he completed his medical degree and began work as a surgical resident at the Surgery Department of Erasmus MC. In 2014, Dr. Arthur de Gast invited him to rejoin the Orthopedic Department at the Diakonessenhuis, a position he accepted with great enthusiasm. He remained there for four years, initially serving as an Orthopedic resident and later as a researcher at the Clinical Orthopedic Research Center – mN. During this period, he produced several publications and presented at international conferences—including EFORT, and Eurospine. In 2016, he began his doctoral studies at UMC Utrecht under the supervision of Prof. R.M. Castelein.

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In 2018, he was accepted into the Orthopedic Surgery Residency Program at UMC Utrecht. After completing several residencies, he concluded his Orthopedic Surgery training in 2024 at Antonius Hospital under the guidance of Dr. M. van Dijk. In September 2024, he began a Spine Surgery fellowship at OLVG Amsterdam and the Amsterdam UMC. He also served as a board member of the Dutch Spine Society and is a member of the medical staff of the professional football club AZ Alkmaar. He currently resides in Weesp and, in his free time, enjoys spending time with his two sons, Olivier and Joep, as well as playing field hockey and cycling.