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RESEARCH ARTICLE

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Kinematic pelvic tilt during gait alters functional cup position in total hip arthroplasty

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Abstract

Static pelvic tilt impacts functional cup position in total hip arthroplasty (THA). In the current study we investigated the effect of kinematic pelvic changes on cup position. In the course of a prospective controlled trial postoperative 3D-computed tomography (CT) and gait analysis before and 6 and 12 months after THA were obtained in 60 patients. Kinematic pelvic motion during gait was measured using Anybody Modeling System. By fusion with 3D-CT, the impact of kinematic pelvic tilt alterations on cup anteversion and inclination was calculated. Furthermore, risk factors correlating with high pelvic mobility were evaluated. During gait a high pelvic range of motion up to 15.6° exceeding 5° in 61.7% (37/60) of patients before THA was found. After surgery, the pelvis tilted posteriorly by a mean of 4.0 ± 6.6° ($p < .001$). The pelvic anteflexion led to a mean decrease of −1.9 ± 2.2° ($p < .001$) for cup inclination and −15.1 ± 6.1° ($p < .001$) for anteversion in relation to the anterior pelvic plane (APP). Kinematic pelvic changes resulted in a further change up to 2.3° for inclination and up to 12.3° for anteversion. In relation to the preoperative situation differences in postoperative cup position ranged from −4.4 to 4.6° for inclination and from −7.8 to 17.9° for anteversion, respectively. Female sex ($p < .001$) and normal body weight ($p < .001$) correlated with high alterations in pelvic tilt. Kinematic pelvic changes highly impact cup anteversion in THA. Surgeons using the APP as reference should aim for a higher anteversion of about 15° due to the functional anteflexion of the pelvis during gait.

KEYWORDS

component position, gait analysis, kinematics, pelvic tilt, total hip arthroplasty

This work was performed at Regensburg University Medical Center, Department of Orthopaedic Surgery, Bad Abbach, Germany.

1 | INTRODUCTION

Correct component positioning is crucial for function and outcome in total hip arthroplasty (THA).[1] Pelvic tilt is one parameter affecting functional inclination and anteversion of the acetabular component.[2] For every 5° in change of pelvic tilt a change of 4° in cup anteversion and of 1.5° in cup inclination is observed.[3] The dynamic spinopelvic interaction is complex[4] and thus has been described as one of the unsolved challenges in THA.[5] One aspect is the high interindividual variability of pelvic tilt ranging from −22.5 to 27.0° in the standing position.[6] Furthermore, pelvic tilt differs from the standing to the sitting, the supine and lateral decubitus position.[3,6,7] The clinical relevance of alterations in spinopelvic motion has been highlighted in several studies reporting an increased dislocation rate in patients with spinal fusion.[8–11] A reduction in acetabular anteversion by 5° was observed in the spine fusion group due to changes in pelvic orientation, which may contribute to instability.[12]

During patient positioning in THA, the surgeon aims for a standardized neutral posture of the pelvis. Intraoperatively, this position is used as reference plane for impacting the acetabular component within the intended target zone.[13] Similarly, in computer-assisted surgery the anterior pelvic plane (APP) resembles the neutral orientation of the pelvis.[14] All techniques share the view that the pelvic position is relatively constant from the preoperative to the postoperative situation. However, this has been discussed controversially in literature. Whilst some studies describe the position of the pelvis as steady [15,16] others report relevant pelvic displacements after THA up to 21.7°.[17,18] In addition, activities of daily living reflect dynamic movement sequences including a range of motion of the pelvis. Among these, walking is the most frequently performed activity in daily life. In literature, the variability of pelvic range of motion has been analyzed in gait analysis ranging from 2.7 to 13.6°.[17] The dynamic alteration of the pelvis during gait was even more prominent in osteoarthritis patients.[19] However, to the best of the authors' knowledge no study has evaluated the kinematic changes of cup orientation during walking so far. One reason is that the APP as defined by the two anterior superior iliac spines and pubic tubercles is challenging to track due to the soft tissue over the pubic tubercles resulting in relevant measurement errors. Therefore, as current state of the art a different reference plane is frequently used in gait analysis using the anterior and posterior superior iliac (PSI) spines, which is not automatically transferable to the APP.[17] The aim of the current study was to link the results of kinematic analysis to functional cup position by combining gait analysis with computed tomography (CT)-scans. This enabled after investigation of (1) the variability of pelvic range of motion estimation of (2) functional cup position during gait preoperatively, 6 and 12 months after THA. Furthermore, (3) risk factors for increased pelvic mobility were evaluated.

2 | PATIENTS AND METHODS

In the course of a prospective, controlled clinical trial (DRKS 00000739, German Clinical Trials Register) 3D motion-capture gait analysis of the lower extremities was performed in patients undergoing cementless THA before as well as 6 and 12 months after surgery. In addition, 3D-CT scans were obtained after THA. The investigation was approved by the local medical ethics committee (No.: 10-121-0263) and informed consent was obtained before the investigation in all patients. The main outcome of the study dealt with the comparison between conventional and navigation guided THA regarding impingement-free range of motion.[20] Out of the primary study cohort, the gait lab subgroup was chosen (n = 60). The current study is an independent secondary outcome analysis. According to the study protocol, eligible participants were patients between the ages of 50 and 75 with an American Society of Anesthesiologists (ASA) score who were admitted for primary cementless unilateral THA due to primary or secondary osteoarthritis at our Department of Orthopaedic Surgery at Regensburg University Medical Center, Germany. THA in all patients was performed in the lateral decubitus positionusing a minimally invasive anterolateral approach. Press-fit acetabular components and cement-freehydroxyapatite-coated stems (Pinnacle cup, Corail stem; DePuy) with metal heads of 32 mm were used.

A 3D motion-capture gait analysis of the lower extremity (SimiMotion) was performed at three time points (preoperatively, 6 months postoperatively and 12 months postoperatively) as previously described.[21] Only patients that were able to conduct a valid gait experiment (strike one force plate with one foot) were included in the gait analysis. A modified Plug in Gait marker set was used (Figure S1). This bony and anatomical landmark based marker-set consisting of 27 retroreflective markers was previously tested to record the patient-specific gait pattern by means of six digital video cameras with a video sample rate of 70 Hz[22] while the patients walked at self-selected speed on a 10 m walkway. To calculate joint position based on marker data, a static trial was conducted before the gait experiment started, which was followed by a nonlinear scaling algorithm to ensure the patient-specific nature of the kinematic analysis. Before recording, the patients were asked to walk on the walkway three to five times to acquaint themselves with the laboratory situation. Kinematic data was low pass filtered with 6 Hz and an inverse dynamic musculoskeletal modeling software Anybody Modeling System 6.1 (AnyBody Technology A/S) was utilized to compute joint angles and pelvis position.[23] In this analysis soft tissue artefacts are minimized as the system utilizes the optimization algorithm developed by Andersen et al.[24] A plane through the left and right anterior superior iliac (ASI) marker and the middle point between both posterior superior iliac (PSI) markers defines the pelvis orientation. The measured angle between this plane and the ground defines the pelvic tilt (Figure S1). One gait cycle was split into 200 measurements of pelvic position illustrating the kinematic variability of the pelvis during walking. Anatomical landmarks for marker placement were identified by palpation using the most prominent part of the superior iliac spines to enable reproducibility for follow-ups which were obtained by the same experienced examiner. The accuracy of marker positioning for repeated measurements was tested in a previous study with a relative error below 0.5%.[25]

Six weeks postoperatively, a CT scan was obtained from the pelvis down to the femoral condyles (Somatom Sensation 16; Siemens). On the 3D segmented CT reconstructions of the pelvis the angle between the reference plane in the gait analysis (ASIS/PSIS plane) and the APP as defined by the two ASIS and pubic tubercles was calculated with the help of a 3D planning software (MediCAD, Hectec). This enabled conversion of the pelvic tilt angles obtained from gait analysis via the ASIS/PSIS plane to the APP and thus to calculate functional cup positions in relation to the pelvic rotation (Figure S2). The APP is challenging to track in gait analysis due to the relevant soft tissue layer over the pubic tubercles. This harbors a high risk of inaccuracies. Therefore, as current state of the art the pelvic coordinate system is defined by the ASIS/PSIS plane to measure kinematic changes of pelvic tilt.[17] This complicates estimation of functional cup position during gait due to the different reference plane. First, the acetabular component inclination and anteversion were evaluated according to the radiographic definition defined by Murray[26] in the APP and thus independently of pelvic tilt. For cup measurement a 3D image-processing software was used by an independent, external institute (FraunhoferMeVis). Second, the functional cup position during gait was calculated using the converted pelvic tilt angles in relation to the APP according to Wan.[27] This allowed for resolution of the cup positon from the APP to a coronal functional plane that accounted for the patients' pelvic tilt. One patient missed the 6-month follow-up gait analysis. For two patients, no cup position measurements were possible due to software compatibility issues; therefore, component analysis was available for 58 cases. However, these cases were included per intention to treat. In total, 60 datasets were included for final analysis (Figure S3). For each gait analysis 200 measurements were performed per gait cycle leaving 36,000 gait measurement points altogether. Anthropometric characteristics of the study group are shown in Table 1. For statistical analysis, normally distributed continuous data are presented as mean (*SD*). Accordingly, group comparisons were performed by dependent the student's *t* test for two samples and analysis of variance in case of several samples. Absolute and relative frequencies were given for categorical data and compared between groups by χ^2 tests. Statistical testing was performed on a two-sided 5% significance level. IBM SPSS Statistics 24 (SPSS Inc.) was used for analysis.

TABLE 1 Anthropometric and intraoperative characteristics of the study group*

	n = 60
Gender (female)	31 (51.7%)
Age (years)	61.2 ± 7.2
BMI (kg/m^2)	26.5 ± 3.8
Treatment side (right)	34 (56.7%)
ASA 1	13 (21.7%)
ASA 2	33 (55.0%)
ASA 3	14 (23.3%)
Kellgren-Lawrence-Score	8 (5–10)
Cup size	54 (48–62)
Femoral component size	12 (9–16)
Operation time (minutes)	67.1 ± 14.6

Abbreviations: ASA, American Society of Anaesthesiology Score; BMI, body mass index.

*For categorical data values are given as relative and absolute frequencies, for quantitative data values are given as mean ± *SD* or median (range).

TABLE 2 Range of dynamic pelvic tilt during gait cycle

Pelvic tilt	<5°	5–10°	>10°
Pre	38.3% (23)	55.0% (33)	6.7% (4)
6 months	72.9% (43)	23.7% (14)	3.4% (2)
12 months	68.3% (41)	30.0% (18)	1.7% (1)

Abbreviations: pre, preoperatively; THA, total hip arthroplasty.

3 | RESULTS

In the current study, there was high variability of pelvic mobility during gait ranging from 2.4 to 15.6° per gait cycle preoperatively, from 1.3 to 11.5° 6 months after THA and 0.7 to 10.5° 12 months after THA (Table 2). Pelvic mobility showed no correlation to the patients' reported pain level ($r \le .19$, $p \ge .15$). From the preoperative to the postoperative situation, the pelvis tilted posteriorly by a mean of 4.0 ± 6.6° ($p < .001$, preoperatively to 6 months after THA) and by 3.0 ± 8.0° ($p < .001$, preoperatively to 12 months after THA, Figure 1) while walking. In 49.2% (29/59) of patients, the observed change of pelvic tilt was over 5° preoperatively to 6 months after THA and in 43.3% (26/60) preoperatively to 12 months after THA, respectively. This held true for static pelvic tilt which similarly changed by a mean of 4.4 ± 6.0° ($p < .001$, preoperatively to 6 months after THA) and by 4.0 ± 7.3° ($p < .001$, preoperatively to 12 months after THA).

Due to pelvic tilt, the functional cup position differed by a mean of −1.9 ± 2.2° ($p < .001$) for cup inclination and −15.1 ± 6.1° ($p < .001$) for cup anteversion in the preoperative situation, −1.7 ± 2.0° ($p < .001$) for cup inclination and −12.3 ± 6.6° ($p < .001$) for cup anteversion 6 months after THA and −1.7 ± 2.2° ($p < .001$) for cup inclination and −13.0 ± 7.4° ($p < .001$) for cup anteversion 12 months postoperatively in relation to the APP (Figure 2). The difference of pelvic tilt between the supine position during CT and postoperative static pelvic tilt resulted in mean difference of −2.9 ± 2.9° ($p < .001$) for cup inclination and −13.2 ± 5.2° ($p < .001$) for cup anteversion, respectively.

In addition, the dynamic change of pelvic tilt during gait resulted in a change of functional cup position up to 2.3° regarding inclination and up to 12.3° regarding anteversion per gait cycle (Figure 3). Comparing functional cup position between the preoperative and postoperative pelvic tilt, change in functional cup inclination ranged from −4.4 to 4.6° and from −17.8 to 17.9° for cup anteversion,

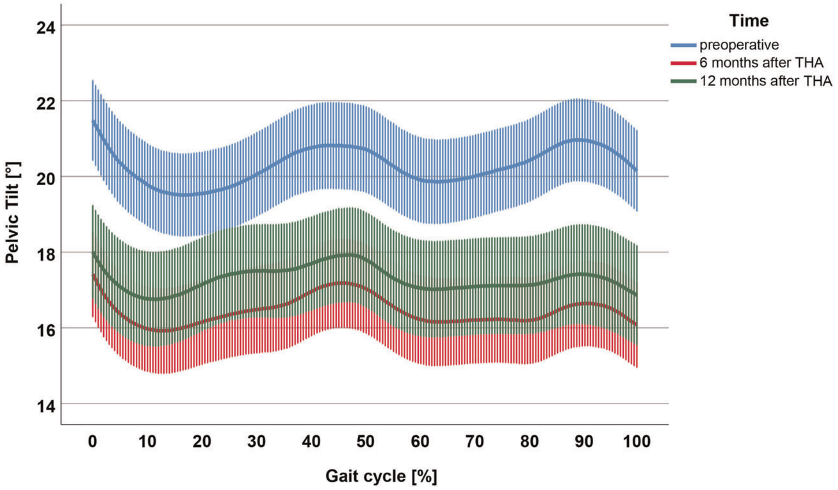

FIGURE 1 Variability of functional pelvic position per gait cycle [Color figure can be viewed at wileyonlinelibrary.com]

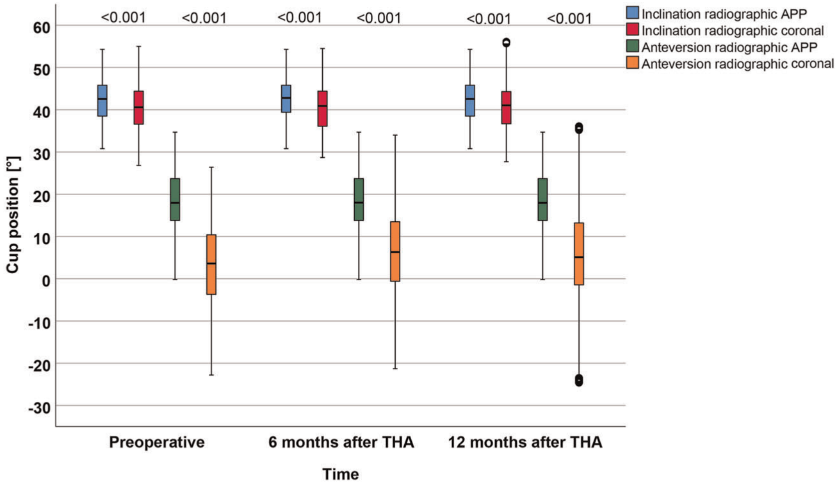

FIGURE 2 Difference of functional cup position due to pelvic tilt and cup position in relation to the anterior pelvic plane (APP) [Color figure can be viewed at wileyonlinelibrary.com]

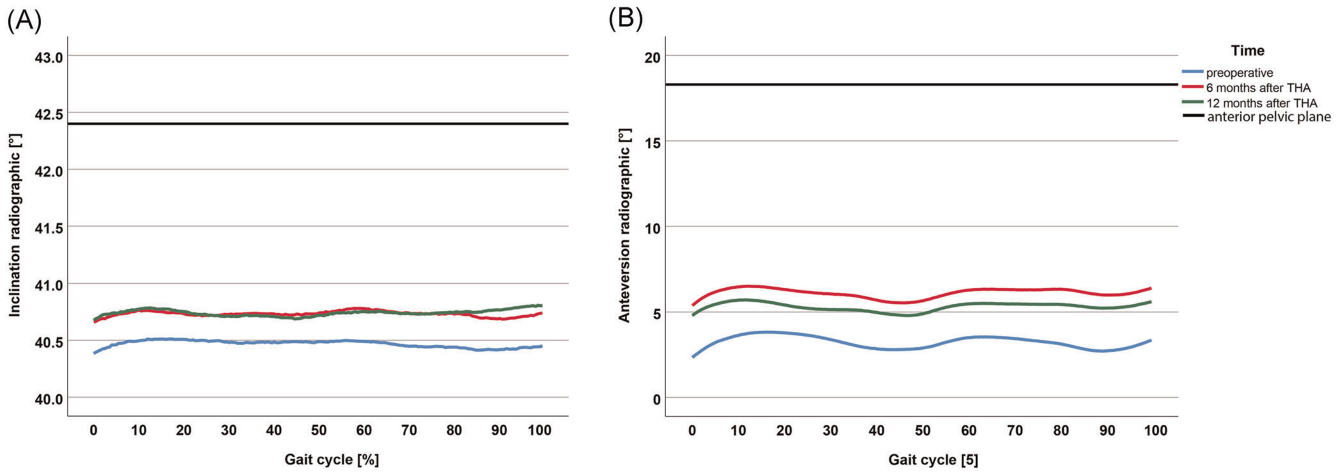

FIGURE 3 Mean change in functional cup inclination (A) and anteversion (B) per gait cycle [Color figure can be viewed at wileyonlinelibrary.com]

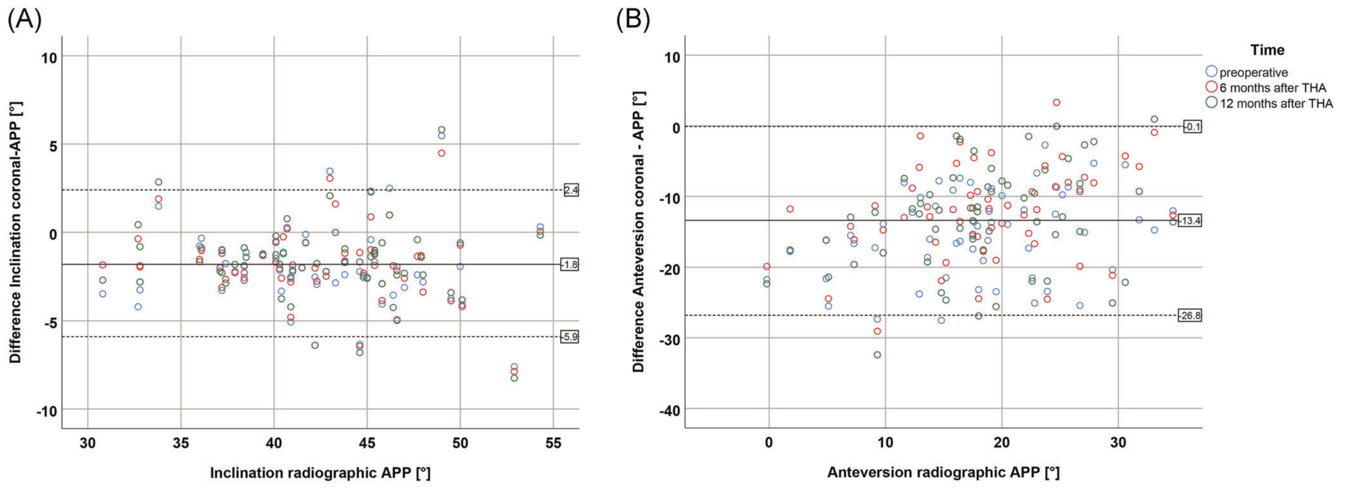

FIGURE 4 Bland-Altman-Plot for individual change in cup inclination (A) and anteversion (B) due to pelvic tilt [Color figure can be viewed at wileyonlinelibrary.com]

respectively. This change was below 5° for all patients regarding cup inclination, whereas for cup anteversion a difference above 5° was observed in 38.3% (23/60) of patients (Figure 4).

The change in pelvic position after THA was more prominent in women with −4.4 ± 9.6° than in men with −1.5 ± 6.1° ($p < .001$). Similarly, body mass index (BMI) correlated with the change in dynamic pelvic tilt after THA compared to the preoperative situation. Overweight (BMI: 25–30 kg/m^2) and obese patients (BMI: >30 kg/m^2) showed less changes in dynamic pelvic tilt with −1.5 ± 8.1° and −1.8 ± 4.7° than normal weight patients with −5.6 ± 9.3° ($p < .001$).

4 | DISCUSSION

The position of pelvis has an impact on functional inclination and anteversion of the acetabular component in THA.[3] In the current study, we combined gait analysis with CT scans to (1) determine how pelvic tilt changes during walking, (2) assess functional cup position when accounting for pelvic position, and (3) to identify risk factors for increased pelvic variability.

There are several limitation of the current study. First, the gait analysis was restricted to the lower extremities and did not allow a quantification of the upper body. Therefore, we were not able to illustrate the complex interactions of spinopelvic mobility during walking.[4] Second, variability of inter-joint coordination for both surgical and nonsurgical limbs have an impact on gait, which we did not measure in our experiment. Third, we tried to account for the influence of soft-tissue artefacts during gait analysis by optimizing the marker positions with an optimization algorithm.[24] This algorithm is capable of reducing the aforementioned effect. However, some assumptions had to be made and could introduce some error. Fourth, the current study focused on walking as the most important activity. However, other activities such as squatting, sitting, and climbing stairs were not evaluated.

To answer the first question of the study, gait analysis revealed a high variability of pelvic mobility while walking from 2.4° up to 15.6° during one gait cycle. The percentage of patients with a stiff pelvis, defined as less than 5° in pelvic range of motion, increased after surgery from 40% in the preoperative situation to 70%. In comparison to the preoperative situation the pelvis tilted posteriorly by a mean of 4° after THA. This might be related to the reduction of hip flexion contractures after to surgery leading to an upright movement of the pelvis. The observed change was over 5° in approximately half of the patients and thus clinically relevant, since functional cup anteversion changes approximately 4° for every 5° of change in pelvic tilt.[3] Our results are in accordance with literature. In a previous study of 21 patients undergoing THA, a change in pelvic tilt up to 13.6° was measured in gait analysis. Thirty-one percent of patients showed a difference between the preoperative and postoperative condition of over 5°.[17] In a much larger cohort of 60 patients undergoing THA, we were able to confirm the high variability of pelvic range of motion during gait and the change of the pelvis in an upright position after THA. In addition, a variety of further studies exists researching into static changes of pelvic tilt. Most of the studies agree that pelvic position shows a high interindividual variability and cup position should be adjusted accordingly (Table 3).[2,3,6,7,15,16,18,28–32] In contrast, the discussion about the change after THA is controversial. While some studies describe a relatively fixed position of the pelvis pre- to postoperatively,[15,16,28] others studies have reported a significant change of pelvic tilt.[17,18] However, except for one study[17] no other studies investigated motion sequences instead of static positions, which may partly explain the opposing results. In our kinematic gait analysis, there was a large change of

TABLE 3 Inerindividual variability of pelvic tilt reported in literature

Study	Standing position	Supine position	Sitting position
Yun et al. (2018)[32]	−28–16°	−18–23°	
Nishiwaki et al. (2018)[18]		−29–27°	
Maratt et al. (2015)[16]	−19–18°		
Grammatopoulos et al. (2014)[7]		−50–29°	
Kanawade et al. (2014)[2]	−15 −26°		−48–5°
Murphy et al. (2013)[15]	−13–13°	−8–21°	
Blondel et al. (2009)[31]	−6–14°		
Babisch et al. (2008)[3]	−12–23°	−3–27°	
Parratte et al. (2007)[17]	−23–14°		
DiGioia et al. (2006)[6]		−22–27°	−64–4°
Lembeck et al. (2005)[29]	−27–3°	−17–3°	
Nishihara et al. (2003)[28]	−46–33°	−37–30°	−62–10°

the pelvic motion after THA when compared to the preoperative condition. Thus, the preoperative position should be regarded with caution as reference for the intraoperative cup position.

Regarding our second question, the dynamic variability of pelvic tilt resulted in major changes of functional acetabular component position. In comparison to cup inclination, functional cup anteversion was more prone to alterations due to pelvic tilt. The anterior tilt of the pelvis led to a mean decrease of cup inclination of 2° and of cup anteversion of 15° in relation to the APP. Within the functional change due to the general pelvic tilt, the additional range of pelvic motion per gait cycle during walking caused further alterations in functional cup position ranging up to 2° for cup inclination and up to 12° for cup anteversion. In addition, as pelvic tilt changed from preoperatively to postoperatively, a functional cup position was altered with differences up to 5° for cup inclination and up to 18° for cup anteversion. Altogether, the results of the current study revealed major alterations of functional cup position due to the inter-individually highly variable pelvic position, pelvic range of motion during walking and the changes in pelvic rotation after THA compared to the preoperative situation. In literature, the influence of static pelvic tilt on functional cup position has already been evaluated demonstrating a higher impact on cup anteversion compared to cup inclination which seems more robust.[3] For every degree of anterior pelvic tilt the functional anteversion of the cup has to be adjusted by 0.8°.[33,34] Therefore, correct intraoperative cup positioning is highly challenging due to the strong correlation of cup anteversion and the patient's individual pelvic tilt. Furthermore, differences in pelvic tilt after THA were observed combined with changes in cup inclination up 11° and for cup anteversion up to 33°.[32] Beyond the effect of static pelvic tilt, our study is the first study providing the missing link between kinematic pelvic motion analysis and functional cup position by combining gait analysis with CT scans. This enables a deep insight in the complex interaction of functional pelvic dynamics and its impact on functional cup position during activities of daily living. Besides the known intersubject variability of pelvic tilt this method illuminates an additional high intrasubject variability of pelvic range of motion during activities such as walking and even a time dependent change in pelvic orientation. Due to the high impact of pelvic tilt on especially cup anteversion surgeons using the APP as reference should aim for a higher anteversion of about 15° due to the anteflexion of the pelvis.

When reviewing factors associated with high pelvic mobility, we found women more likely to show a deviation between the preoperative and postoperative pelvic orientation. The observed difference in women was higher by a mean of 3° than in men. Furthermore, the time dependent change in pelvic tilt was more prominent in patients with normal weight by an average of 4° than in overweight or obese patients. In a previous study, a significant higher anterior tilt of the pelvis by 4° was described in women compared to men, whereas no gender-specific differences were seen for changes between prior and after THA.[3] Also further correlations of pelvic tilt and age and contralateral joint are reported in literature.[18] In addition, patients with spine degeneration or fusion might show different patterns of pelvic mobility. However, these data were not available in the current study.

In conclusion, in addition to the high interindividual variability of pelvic tilt, a high intrasubject variability of the pelvic orientation exists consisting of a time dependent change before and after surgery and a kinematic change during activities of daily living in pelvic position. The observed alterations in pelvic tilt have a great impact on functional cup position, particularly cup anteversion and thus should be taken into account to prevent hip dislocation. Especially surgeons relying on the APP should aim for a higher anteversion of 15° due to the anterior tilt of the pelvis. Regarding pelvic tilt variability, normal weight women showed the highest changes in pelvic tilt after surgery in our cohort and thus represent a risk group for impingement and instability.

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AUTHOR CONTRIBUTIONS

Sebastian Dendorfer and Markus Weber originated the idea for the study and led on its design. Tobias Renkawitz and Joachim Grifka supervised the project and were coapplicants on the successful funding proposal. Tobias Renkawitz, Markus Weber, Matthias Meyer, Seth A. Jerabek, Franz Suess, and Joachim Grifka participated in the design of the study and in developing the research protocols. Markus Weber and Matthias Meyer provided statistical consultation. Tobias Renkawitz, Markus Weber, and Joachim Grifka coordinated the trial and were responsible for data acquisition. Franz Suess, Matthias Meyer, and Sebastian Dendorfer performed pelvic tilt measurements. Seth A. Jerabek and Matthias Meyer performed CT analysis. Tobias Renkawitz and Joachim Grifka performed the operations. All authors read and corrected draft versions of the manuscript and approved the final manuscript.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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