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Complications - Other

Prospective Evaluation of Hip-Spine Dynamics in Patients Who Have a Primary Total Hip Arthroplasty Dislocation: A Matched Case-Control Study

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Background: Understanding of the comprehensive hip-spine relationship may reduce total hip arthroplasty (THA) dislocation. However, the impact of sagittal spino-pelvic dynamics on three-dimensional implant orientation has not been investigated prospectively. This study aimed to assess hip-spine dynamics and changes in three-dimensional implant orientation in patients who have stable and unstable primary THAs.
Methods: In this prospective, case-control study, 23 adults who had a THA dislocation were matched to 23 patients who had a stable implant. Of the 23 dislocations, 17 sustained a posterior, and five sustained an anterior dislocation; one was unknown. Standing anterior-posterior and standing and sitting lateral pelvic radiographs were obtained. Sagittal spinopelvic morphology and orientation parameters, coronal and sagittal acetabular cup, and femoral component orientation parameters were measured. Transverse component orientation parameters were computed. Logistic regressions were conducted to determine the impact of demographics and hip-spine parameters on the likelihood for dislocation.
Results: The unstable THAs had significantly higher pelvic incidence (PI; 60 ± 13° versus 52 ± 10°, $P = 0.015$) and transverse version of the acetabular component (TV_{Cup}; 38 ± 11° versus 32 ± 8°, $P = 0.042$) compared to the stable THAs. Patients who have anterior dislocations had higher sagittal ante-inclination of the acetabular component (SAI_{Cup}) than posterior dislocations (48 ± 5° versus 34 ± 10°, $P = 0.012$). Based on logistic regression analyses, PI, TV_{Cup}, and the approach were significant predictors of THA dislocation.
Conclusions: By assessment of spino-pelvic characteristics, surgeons could identify patients at increased risk for THA dislocation preoperatively based on a high PI. Posterior dislocations seem to occur more in patients who have more TV_{Cup} and a postero-lateral approach, anterior dislocations seem to occur in patients who have more SAI_{Cup}, TV_{Cup}, and a direct anterior approach. This suggests implementing a patient-specific functional safe zone of the acetabular component may further reduce THA dislocation rates.

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Total hip arthroplasty (THA) achieves great success in the treatment of patients who have hip osteoarthritis. Nevertheless, over the last decade, the incidence of instability after primary THA has remained 0.7% [1]. Dislocations are devastating complications and require emergency department visits and sedation for closed reduction [2]. According to Kotwal et al., a first dislocation is associated with a 60% risk of reoccurrence, and 51% of the patients require subsequent revision surgery [3]. Despite patient characteristics, risk analyses, surgical technique, and implant-driven improvements, such as soft-tissue reconstructions, robot-assisted techniques, and dual-mobility implants, the risk for THA dislocation remains a concern for patients and hip surgeons [4].

In 1978, Lewinnek et al. introduced a safe zone to minimize THA instability, recommending $40 \pm 10^\circ$ inclination and $15 \pm 10^\circ$ anteversion in the supine position relative to the anterior pelvic plane [5]. This Lewinnek safe zone, however, has been challenged lately, as many dislocations seem to occur in components placed within this one-size-fits-all safe zone [6]. In the last decade, the large interindividual variation in the shape, orientation, and dynamics of the functional spino-pelvic-femoral unit has become crucial to functional outcomes and mechanical complications in the field of spinal surgery. Similarly, for THA, there is a growing recognition that spino-pelvic dynamics may play an important role in the functional stability of THA during activities of daily living [7,8]. In a recent systematic review, a considerable number of different characteristics of the spino-pelvic unit have been identified to play a role in THA dislocation, for example, previous spinal surgery, lumbar stiffness, standing pelvic orientation, such as a high pelvic tilt (PT $> 19^\circ$), and increased PT changes from standing to sitting [7].

Various studies describe how pelvic dynamics across different body positions affect functional acetabular and femoral component orientation in patients with THA [7–10]. Furthermore, several studies highlight the role of intraoperative imaging, advanced navigation, or robotic systems to assist in accurate positioning of the acetabular cup in a patient-specific orientation [11,12]. However, the clinical impact of sagittal spinopelvic dynamics and resulting three-dimensional (3-D) implant orientation on the stability of primary THA has not been prospectively studied. Understanding the impact of sagittal spino-pelvic dynamics on the 3-D implant orientation and stability could help identify patients who are at risk of THA dislocation and reduce the risk by adjusting the general safe zone to a patient-specific functional safe zone. Evidently, there is a need for a comparative study on spino-pelvic mobility and subsequent dynamics on the 3-D implant orientation in patients who have and do not have a THA dislocation. Therefore, the aim of this prospective study is to investigate hip-spine dynamics and the associated changes in 3-D implant orientation in matched cohorts of patients who have and do not have a THA dislocation.

Methods

Study Population

After approval from the local Institutional Review Board, this prospective, matched, case-control study was conducted from March 14, 2019, to July 14, 2023. All participants provided written informed consent. All adults who randomly presented themselves with a primary THA dislocation at the emergency department of a nonacademic teaching hospital (Diakonessenhuis, Utrecht, the Netherlands) and underwent closed reduction were enrolled and prospectively included in the unstable group. Matching the unstable THAs, the stable group consisted of 23 patients who have had a stable implant between one and five years after primary THA surgery. Patients were matched by age, sex, and American Society of Anesthesiologists score. Only patients who underwent primary THA for hip osteoarthritis were included. Excluded were patients who have bilateral THA (for assessing the side-specific implant orientation on lateral radiographs), dual-mobility implants, indications other than primary osteoarthritis, revision THA, neurologic disability, and dementia. According to the prospective study protocol and sample size calculation (based on a difference in change of PT of 10°), a minimum of 20 cases and 20 controls needed to be included. Patient characteristics as well as surgery and implant information were retrieved.

Radiographic Assessment

At the first outpatient follow-up, anterior-posterior radiographs in a standing position were prospectively acquired for all subjects with the beam focusing on the pubic symphysis. For the stable THAs, this was performed at the regular 1-year follow-up. Furthermore, lateral pelvic radiographs centered on both femoral heads in standing and neutral sitting position were captured from L5 to the distal femoral component. Coronal and sagittal parameters were divided into the following categories: sagittal spinopelvic morphology and orientation parameters, coronal and sagittal acetabular cup orientation and femoral component orientation parameters, and combined parameters. An overview of the parameters assessed in this study is presented in Table 1 and Figures 1 to 4. The definitions were obtained from previous publications on hip-spine parameters [7–9,13–17]. Presence of spinal stiffness was classified according to the hip-spine classification with a sacral slope (SS) difference of $< 10^\circ$ when changing from standing to sitting position [18]. For the acetabular and femoral components, previously validated trigonometric algorithms were used to calculate the transverse component orientation parameters [14,19]. The combination of trigonometry with biplanar radiographs allowed for reliable assessment of the THA components' orientation in 3-D [9,14]. All sagittal parameters were measured on the standing and sitting radiographs by one orthopaedic researcher using a previously validated method, and changes were calculated [19]. The changes in the 3-D implant orientation from standing to sitting were assessed by combining the standing 3-D orientation parameters with the changes in the sagittal plane [14,20].

Data Analyses

Statistical Package for Social Sciences version 26.0.0.1 (IBM Inc., Chicago, Illinois, USA) was used for data assessment. *Chi*-square tests were applied for categorical parameters, and box-and-whisker plots were created to detect outliers. Shapiro-Wilk tests were used for analyzing data for normal distribution. For normally distributed data, differences between stable and unstable THAs were examined with Student's *t*-tests. Nonnormally distributed data were analyzed using Mann-Whitney *U*-tests. One-way analyses of variance were applied for the subgroup analyses to compare differences between anterior dislocations, posterior dislocations, and stable THAs. When significant differences between groups were detected, pair-wise comparison was conducted with Tukey's *post hoc* analyses. For nonnormally distributed data in the subgroup analyses, the Kruskal-Wallis H tests were used. The level of statistical significance was set at 0.05. Logistic regression analyses were conducted to identify the influence of demographics and hip-spine parameters on the likelihood for dislocation. Significant predictors of dislocation were determined using univariable analyses. Multivariate logistic regressions revealed a formula predicting the probability of dislocation.

Table 1
Definition of Orientation Parameters.

Sagittal Spinopelvic Morphology and Orientation Parameters	
Pelvic tilt (PT)	The angle between a line that is defined by the midpoint of the sacral endplate (S1) and the midpoint of the bicoxofemoral axis, and the vertical in the sagittal plane.
Sacral slope (SS)	The angle between the inclination of S1 and the horizontal in the sagittal plane.
Pelvic incidence (PI)	The angle between the line that connects the center of S1 with the midpoint of the hip axis, and the perpendicular line of S1 in the sagittal plane.
Anterior pelvic plane tilt (APPt)	The angle between a line connecting the midpoint of both anterior superior iliac spines (ASIS) and the pubic symphysis and the vertical in the sagittal plane.
Acetabular cup orientation parameters	
Coronal inclination (CI_{Cup})	The inclination of the acetabular cup and the sagittal axis in the coronal plane.
Sagittal ante-inclination (SAI_{Cup})	The inclination of the acetabular cup and the antero-posterior axis in the lateral plane.
Transverse version (TV_{Cup})	The inclination of the acetabular cup and the longitudinal axis in the transverse plane.
Femoral component orientation parameters	
Coronal inclination (CI_F)	The angle formed by the line that connects the center of the femoral head and center of the neck, and the sagittal axis in the coronal plane.
Sagittal ante-inclination (SAI_F)	The angle created by the line that connects the femoral head with the neck, and the vertical (standing) or horizontal (sitting) in the sagittal plane.
Transverse version (TV_F)	The angle formed by the line that connects the center of the femoral head and midpoint of the neck, and the horizontal in the transverse plane.
Combined sagittal parameters	
Combined anteversion (CA)	The sum of the transverse version of the acetabular and femoral component, a measure for the overall prosthetic alignment.
Pelvic femoral angle (PFA)	The angle between a line connecting the midpoint of S1 and the bicoxo-femoral axis, and the anterior shaft of the proximal femur, which describes the hip flexion in the sagittal plane.
Combined sagittal index (CSI)	$CSI = PFA + SAI_{Cup}$ for information about the functional orientation of the hip joint.
Sacro-acetabular angle (SAA)	$SAA = SS + SAI_{Cup}$ The angle formed by the sacral slope and the inclination of the acetabular cup, and the antero-posterior axis in the lateral plane.

Demographics

A total of 46 patients, 23 patients who had a THA dislocation and 23 controls, were included in this study. Of the 46 primary THA surgeries, 43 were performed by eight different surgeons, applying four different approaches (posterolateral, direct lateral, anterolateral, and direct anterior). The other three patients underwent surgery through the posterolateral approach (PLA) in other Dutch hospitals. Patients' demographics are presented in Table 2. In addition to the matched characteristics, body mass index and laterality matched well between stable and unstable THAs. Surgical approach differed; most of the posterior and anterior dislocations underwent a PLA (94%) and direct anterior approach (DAA; 80%), respectively. Half of the stable THAs had a DAA (48%). There were 17 patients who sustained a posterior, five an anterior, and one a mixed dislocation based on clinical and radiographic findings. This patient was excluded from the subgroup analyses. Except for one patient, the direction of dislocation matched the surgical approach. There were seven dislocations that occurred within 30 days after primary THA and 15 within one year.

Results

Pelvic Morphology and Orientation

As presented in Table 3, the unstable THAs had a significantly higher pelvic incidence (PI) in both the standing (60 ± 13° versus 52 ± 10°, $P = 0.015$) and sitting positions (61 ± 13° versus 52 ± 10°, $P = 0.015$) compared to the stable THAs. PT and SS in the standing and sitting positions were equal for stable and unstable THAs. There were six (35%) posterior and three (75%) anterior dislocations with stiff spines, compared to nine (39%) in the stable group ($P = 0.337$). The subgroup analyses showed that the anterior pelvic plane tilt in the sitting position differed significantly between the posterior dislocation and stable THAs (−20 ± 8° versus −13 ± 9°, $P = 0.044$) and between the posterior and anterior dislocations (−20 ± 8° versus −5 ± 7°, $P = 0.012$).

3-D Acetabular Cup Orientation

The sagittal and transverse acetabular cup orientations differed significantly between unstable and stable THAs (Table 3). *Post hoc* tests revealed higher standing sagittal ante-inclination (SAI_{Cup}) for the anterior dislocations compared to stable THAs (48 ± 5° versus 35 ± 9°, $P = 0.018$) as well as between the anterior and posterior dislocations (48 ± 5° versus 34 ± 10°, $P = 0.012$). Unstable THAs had a significantly higher transverse version (TV_{Cup}) in the standing (38 ± 11° versus 32 ± 8°, $P = 0.042$) and sitting positions (46 ± 9° versus 39 ± 8°, $P = 0.015$) compared to stable THAs. Based on the analyses of variance test, the three groups differed significantly for sitting TV_{Cup} ($P = 0.035$), without differences in the *post hoc* analyses. Figure 5 shows the box-and-whisker plots of TV_{Cup} and PI in the standing and sitting positions. Standing coronal inclination (CI_{Cup}) was lower in posterior versus anterior dislocations (42 ± 8° versus 48 ± 10°, $P = 0.068$) as well as posterior dislocations versus stable THAs (42 ± 8° versus 48 ± 8°, $P = 0.168$), without statistical significance. The differences in the 3-D acetabular cup orientation between the standing and sitting positions in the coronal, sagittal, and transverse planes were comparable between unstable and stable THAs. In the Lewinnek safe zone, there were four (17%) of the stable THAs and one (4%) of the unstable THAs ($P = 0.045$).

3-D Femoral Component Orientation and Combined Parameters

The 3-D femoral component orientation, combined anteversion, pelvic femoral angle, combined sagittal index, and sacro-acetabular angle are reported in Table 4. There were no significant differences observed between unstable and stable THAs at different positions for these parameters.

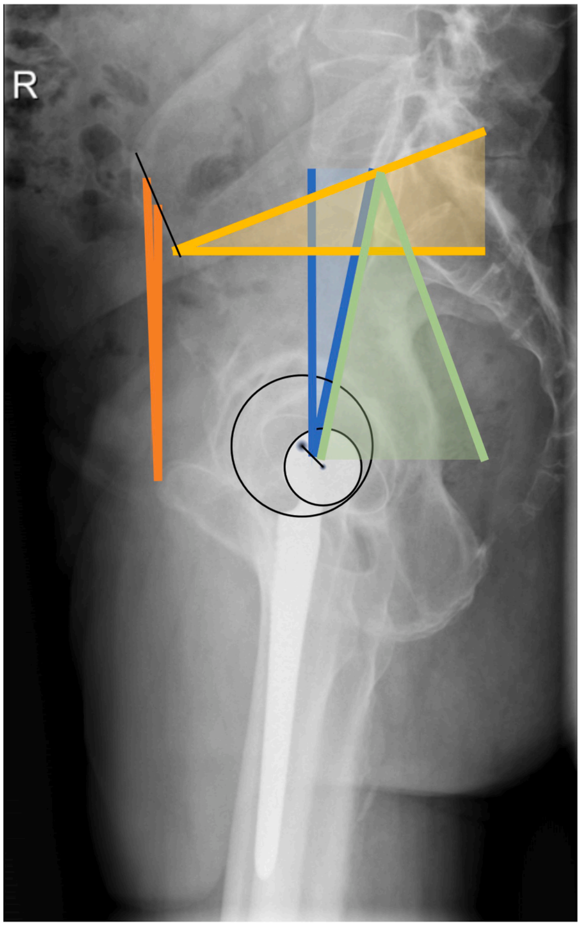

Figure 1. Pelvic morphology and orientation parameters are shown. Blue: pelvic tilt (PT), yellow: sacral slope (SS), green: pelvic incidence (PI), orange: anterior pelvic plane tilt (APPt).

Based on univariable logistic regression analyses, PI, standing and sitting TV_{Cup}, and the approach were identified as significant predictors of dislocation. The logistic regression model was statistically significant ($P < 0.001$). Table 5 presents the results of the model, including β-coefficients, odds ratios, 95% confidence intervals (CIs), and P-values. Using multivariable binary logistic regressions, a formula was derived to determine the likelihood of dislocation (see Equation 1).

Discussion

There is increasing awareness of the large interindividual variation in shape, orientation, and dynamics of the functional spino-pelvic-femoral unit in humans. In several retrospective analyses, it has been shown that spinopelvic dynamics play an important role in the functional stability of THA during activities of daily living [7,8]. This is the first prospective study comparing stable and unstable primary THAs that provides insight into the relevance of sagittal spinopelvic dynamics on 3-D implant orientation and stability. Comparison of the most common sagittal spino-pelvic parameters and the 3-D acetabular cup orientation and femoral component orientation in the standing and sitting positions demonstrated key differences that place patients at risk for dislocation.

The average PI is 49° in the adult population (with a range of 35 to 85°) [21,22]. This study showed higher PI in patients who have unstable THAs compared to the stable THAs (60 ± 13° versus 52 ± 10°, $P = 0.015$). A larger PI indicates a more horizontal orientation of the sacrum within the pelvic ring, and it is well known that in the standing position, this allows for more pelvic retroversion when compensation for spinal kyphotic degeneration is required. These results are in accordance with the study by Dagneaux et al., who reported on higher PI in unstable versus stable THAs (58 ± 13° versus 51 ± 11°, $P = 0.01$) [23]. In this study, however, the standing and sitting PT and SS were not significantly different between stable and unstable THAs. Total hip arthroplasty dislocation generally does not occur statically, but during falls, bending forward to reach feet, or standing up from a deep-flexed seated position [24]. Therefore, the changes between the static standing and sitting radiographs reflect spino-pelvic dynamics but do not adequately reflect the functional pelvic orientations during activities of daily living. Potentially, deep-flexed seated position radiographs may be more relevant for assessment of PT in extreme positions of patients who have a THA dislocation [25].

Sagittal spino-pelvic dynamics lead to changes of the THA components' orientation, especially the acetabular cup. In the sagittal plane, the cup follows the changes of the sagittal spino-pelvic orientation, and this can be assessed on lateral pelvic radiographs. Heckman et al. described a 1:1:1 ratio for changes from standing to sitting in PT, SS, and SAI_{Cup} based on a triangle model for osteoarthritic hips [26]. The effect of sagittal PT on the orientation of the acetabular component in the coronal and transverse planes, however, is more difficult to assess. While coronal and transverse cup orientations can be determined using various methods on standing or supine anterior-posterior radiographs, this is practically not possible in the sitting position with hip flexion. For this reason, in the present study, previously validated trigonometric algorithms were applied to assess the 3-D implant orientation in the standing position. By combining the changes in sagittal orientation of the hemispherical cup from standing to sitting with the 3-D standing orientation, the dynamics of the 3-D orientation of the THA components could be evaluated in the present study. Patients who have anterior dislocations had significantly higher SAI_{Cup} than those with posterior dislocations. As expected, this confirms the acetabular cups in posterior THA dislocations provide less postero-inferior coverage in the sitting position with hip flexion. Consequently, anterior impingement creates a lever effect, which increases the risk of posterior dislocations. Interestingly, the standing and sitting TV_{Cup} were higher in the unstable THAs compared to the stable THAs. The orientation of the acetabular cup in one plane is related to the orientation of the acetabular cup in the other two planes. Due to the trigonometric relation of a hemispheric cup in three anatomical planes, an SAI_{Cup} increase or a CI_{Cup} decrease leads to a TV_{Cup} increase [9]. As a consequence, an increased SAI_{Cup} leads to a higher TV_{Cup} in anterior dislocations. On the other side, a relatively lower CI_{Cup} and a similar SAI_{Cup} compared to stable THAs lead to a higher TV_{Cup} in posterior dislocations.

Spinal mobility is defined as the change in pelvic orientation, classified by the delta SS from standing to sitting more or less than 10° [18]. While the present study was powered on this change, no differences in pelvic mobility were observed between stable and unstable THAs. It should be noted that one patient who developed a posterior dislocation showed a large change in PT from the standing to sitting position and was considered an outlier, as it represented hypermobility of the spino-pelvic unit, which is recognized as another risk factor for THA dislocation [27]. There is

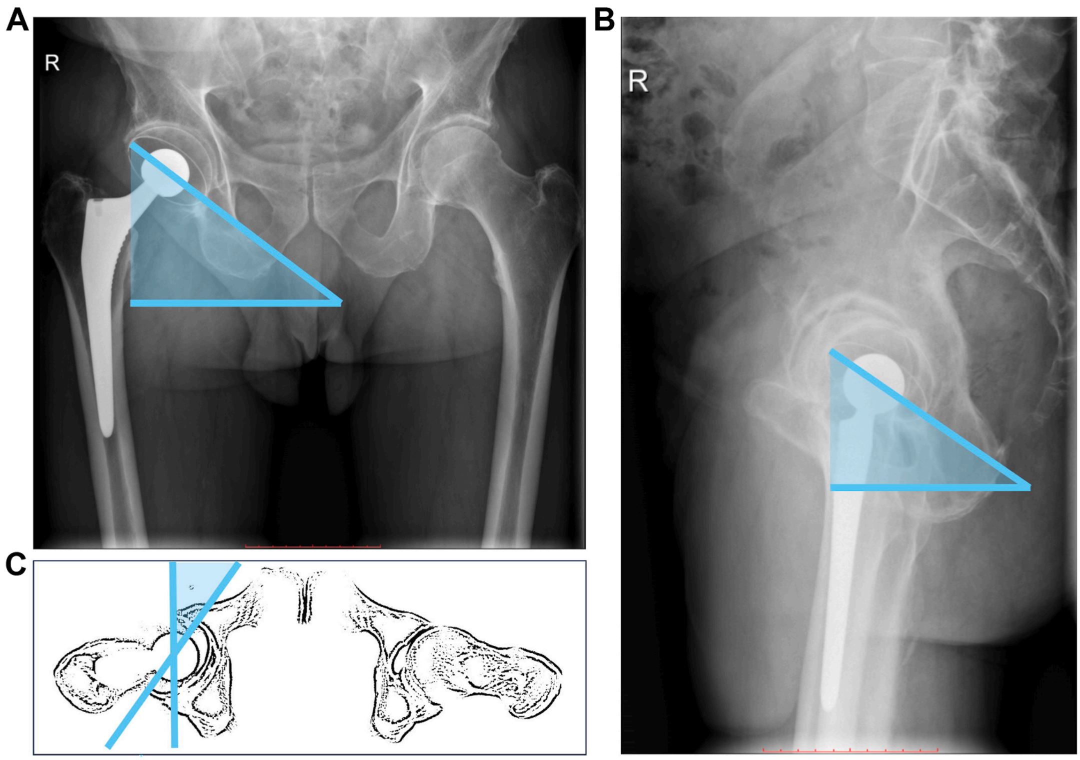

Figure 2. Acetabular cup orientation parameters are shown. Light blue: (A) coronal inclination (CI_{Cup}) and (B) sagittal ante-inclination (SAI_{Cup}). Using the coronal inclination and sagittal ante-inclination, (C) the transverse version (TV_{Cup}) can be determined based on the trigonometric algorithm $TV = arctan\frac{(\tan SAI)}{(\tan CI)}$.

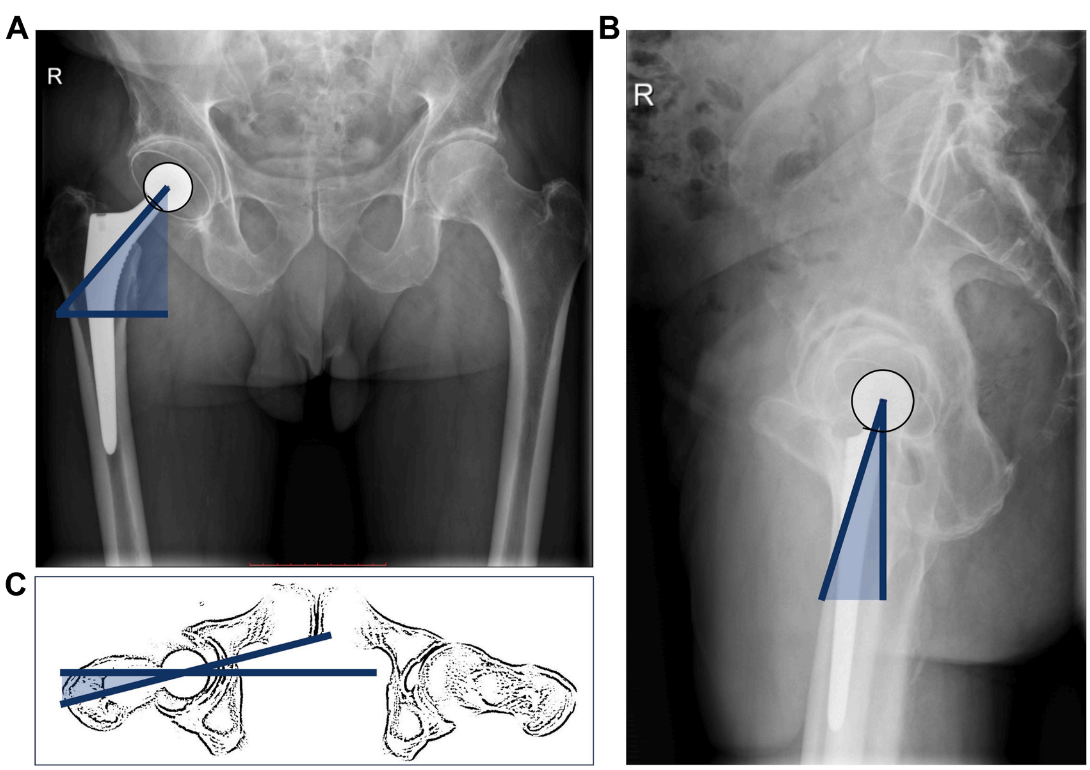

Figure 3. Femoral component orientation parameters are shown. Dark blue: (A) coronal inclination (CI_F) and (B) sagittal ante-inclination (SAI_F). Using the coronal inclination and sagittal ante-inclination, (C) the transverse version (TV_F) can be determined based on the trigonometric algorithm $TV = arctan\frac{(\tan SAI)}{(\tan CI)}$.

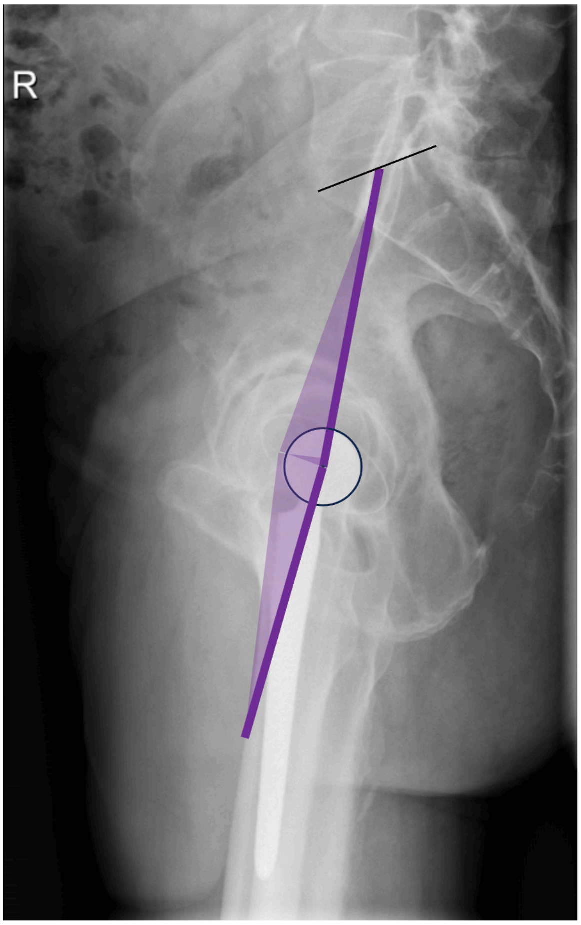

Figure 4. Combined sagittal parameter is shown. Purple: pelvic femoral angle (PFA).

a bimodal distribution of early (within one month) and late dislocations (after one month) between posterior and anterior dislocations. It remains unclear if late dislocations might have normal spinopelvic parameters preoperatively and develop stiffness over time. Nevertheless, these prospective results do not completely support the implementation of the hip-spine classification and suggest that future studies should focus on the effectiveness of specific sagittal spino-pelvic parameters for lowering THA dislocation, impingement, and revision rates. Furthermore, this study shows that a minority of stable THAs are placed within the Lewinnek safe zone, which confirms that the one-size-fits-all safe zone cannot be applied generally.

The question remains whether preoperative screening for spino-pelvic dynamics and eventually changing the THA components' patient-specific functional orientations will decrease the risk of impingement and dislocation. A screening assessment evaluating and interpreting spinopelvic characteristics might help orthopaedic surgeons to minimize the risk for THA dislocation. Preoperatively, where sagittal X-rays are routinely taken, surgeons might identify patients who have a high PI, posing an increased risk for dislocation. Implementing a simple, time- and cost-efficient tool determining the ideal patient-specific functional safe zone of the acetabular component may reduce THA dislocation rates and the need for revision surgery. The optimal screening method on sagittal spinopelvic dynamics that supports surgical planning and execution, however, needs further research.

Several potential limitations of this study should be acknowledged. Total hip arthroplasty dislocation has multifactorial etiology with patient, surgery, and implant-related variables [4]. Matching was performed based on age, sex, and American Society of Anesthesiologists score. According to Berry et al., a larger prosthetic head diameter is related to a smaller dislocation risk [28]. In this study, most of the unstable THAs had a 32 mm prosthetic head (74%), whereas the stable THAs showed an equal

Table 2
Demographic Data of the Stable THAs, Unstable THAs, and Subgroups Who Had Posterior or Anterior Dislocations.

Demographics	Stable THAs ($n = 23$)	Unstable THAs ($n = 23$)	*P*-Value[a]	Posterior Dislocations ($n = 17$)	Anterior Dislocations ($n = 5$)	*P*-Value[b]
Age, mean in years (range)	70 (53 to 83)	70 (54 to 82)	0.921	72 (62 to 82)	66 (54 to 82)	0.442
Women, *n* (%)	11 (48%)	11 (48%)	1	8 (47%)	2 (40%)	0.95
BMI, mean (range)	29.0 (24 to 36)	26.9 (20 to 37)	0.097	26.8 (20 to 35)	28.4 (24 to 37)	0.264
ASA score, *n* (%)			1			1
1	4 (17%)	4 (17%)		3 (18%)	1 (20%)	
2	14 (61%)	14 (61%)		10 (59%)	3 (60%)	
3	5 (22%)	5 (22%)		4 (23%)	1 (20%)	
Left-sided THA, *n* (%)	11 (48%)	11 (48%)	1	8 (47%)	2 (40%)	0.95
Approach, *n* (%)			**0.024**			**0.001**
Direct anterior	11 (48%)	5 (22%)		1 (6%)	4 (80%)	
Anterolateral	3 (13%)	1 (4%)		0 (0%)	1 (20%)	
Direct lateral	2 (9%)	0 (0%)		0 (0%)	0 (0%)	
Posterolateral	7 (30%)	17 (74%)		16 (94%)	0 (0%)	
Cup fixation, *n* (%)			0.55			0.531
Uncemented	22 (96%)	21 (91%)		15 (88%)	5 (100%)	
Cemented	1 (4%)	2 (9%)		2 (12%)	0 (0%)	
Prosthetic head diameter, *n* (%)			0.171			0.383
28 mm, *n* (%)	1 (4%)	1 (4%)		1 (6%)	0 (0%)	
32 mm, *n* (%)	11 (48%)	17 (74%)		13 (76%)	3 (60%)	
36 mm, *n* (%)	11 (48%)	5 (22%)		3 (18%)	2 (40%)	
Time to dislocation (months), mean ± SD (range)		22.4 ± 43.4 (0 to 197)		29.1 4 ± 49.0 (0 to 197)	2.3 ± 1.8 (0 to 5)	0.243
Within 1 months, *n* (%)		7 (30%)		5 (29%)	2 (40%)	
Within 1 year, *n* (%)		15 (65%)		9 (53%)	5 (100%)	

Bolded *P* values indicate statistical significance ($P < 0.05$).
THA, total hip arthroplasty; BMI, body mass index; ASA, American Society of Anesthesiologists.
[a] *P*-values comparing stable and unstable THAs based on the Chi-square tests for categorical and Student's *t*-tests for descriptive variables.
[b] *P*-values comparing stable THAs, posterior dislocations, and anterior dislocations based on Chi-square tests and one-way analyses of variances.

Table 3
Pelvic Morphology and Acetabular Cup Orientation Parameters.

Angle	Stable THAs ($n = 23$), Degrees, Mean ± SD (Range)	Unstable THAs ($n = 23$), Degrees, Mean ± SD (Range)	*P*-Value[a]	Posterior Dislocations ($n = 17$), Degrees, Mean ± SD (Range)	Anterior Dislocations ($n = 5$), Degrees, Mean ± SD (Range)	*P*-Value[b]
Pelvic morphology and orientation parameters						
Pelvic tilt (PT)						
Standing	15.0 ± 7.2 (1.9 to 27.9)	19.8 ± 9.5 (1.9 to 38.1)	0.065	19.5 ± 10.7 (1.9 to 38.1)	21.8 ± 3.7 (18.1 to 26.5)	0.161
Sitting	27.8 ± 10.5 (8.1 to 48.8)	32.0 ± 11.1 (1.0 to 50.9)	0.202	32.3 ± 12.3 (1.0 to 50.9)	30.8 ± 7.1 (21.4 to 37.9)	0.445
ΔPT	−12.8 ± 7.4 (−25.3 to 6.4)	−12.2 ± 7.9 (−35.4 to 2.2)	0.796	−12.8 ± 8.7 (−35.4 to 2.2)	−8.9 ± 4.8 (−14.9 to −3.3)	0.644
Sacral slope (SS)						
Standing	36.5 ± 10.5 (18.3 to 57.7)	39.5 ± 10.2 (22.4 to 62.5)	0.343	38.0 ± 8.8 (22.4 to 52.8)	41.8 ± 14.7 (28.5 to 62.5)	0.624
Sitting	24.4 ± 12.4 (0.3 to 50.3)	28.1 ± 12.0 (10.8 to 53.8)	0.51	25.7 ± 10.9 (10.8 to 45.8)	34.2 ± 13.6 (23.5 to 53.8)	0.328
ΔSS	12.1 ± 7.1 (−9.0 to 24.6)	11.3 ± 8.3 (−5.9 to 33.6)	0.794	12.3 ± 9.1 (−5.9 to 33.6)	7.6 ± 4.3 (1.6 to 11.7)	0.531
Spinal stiffness ΔSS <10°, *n* (%)	9 (39)	10 (46)	0.668	6 (35)	3 (75)	0.337
Pelvic incidence (PI)						
Standing	51.5 ± 9.9 (33.5 to 72.0)	60.3 ± 13.2 (40.6 to 89.0)	**0.015**	58.9 ± 12.5 (40.6 to 77.0)	63.6 ± 18.0 (46.6 to 89.0)	0.062
Sitting	52.2 ± 10.0 (33.7 to 78.9)	61.0 ± 13.3 (40.7 to 88.0)	**0.015**	59.2 ± 12.5 (40.7 to 81.6)	65.0 ± 16.6 (48.3 to 88.0)	0.058
Anterior pelvic plane tilt (APPt)						
Standing	−1.8 ± 7.8 (−19.4 to 10.5)	−5.1 ± 6.7 (−18.2 to 6.6)	0.14	−5.9 ± 6.6 (−18.2 to 2.5)	−3.3 ± 7.7 (−11.1 to 6.6)	0.228
Sitting	−12.6 ± 9.4 (−31.9 to 8.3)	−16.2 ± 9.6 (−37.3 to 4.0)	0.215	−19.5 ± 7.8 (−37.3 to −5.7)	−5.0 ± 6.9 (−11.3 to 4.0)	**0.006; PvsS 0.044; AvsP 0.012;** AvsS 0.248
Acetabular cup orientation						
Coronal inclination cup (CI_{Cup})						
Standing	47.7 ± 7.5 (37.8 to 63.5)	44.3 ± 8.9 (27.7 to 63.9)	0.168	42.1 ± 7.6 (27.7 to 57.4)	48.4 ± 9.9 (39.7 to 63.9)	0.068
Sitting	53.8 ± 8.7 (38.8 to 74.4)	52.1 ± 11.3 (31.1 to 74.4)	0.57	49.8 ± 10.5 (31.1 to 69.0)	56.0 ± 11.6 (43.8 to 74.4)	0.323
ΔCI_{Cup}	−6.1 ± 3.9 (−12.4 to 2.6)	−7.8 ± 5.6 (−21.3 to 1.9)	0.238	−7.7 ± 6.3 (−21.3 to 1.9)	−7.6 ± 3.3 (−10.5 to −2.3)	0.552
Sagittal ante-inclination (SAI_{Cup})						
Standing	34.7 ± 9.3 (17.6 to 48.1)	37.4 ± 10.8 (13.3 to 53.9)	0.365	33.5 ± 9.6 (13.3 to 45.7)	47.5 ± 5.0 (41.5 to 53.9)	**0.013;** PvsS 0.918; **AvsS 0.018; AvsP 0.012**
Sitting	48.3 ± 10.9 (24.2 to 67.2)	52.6 ± 12.0 (30.5 to 68.3)	0.207	49.5 ± 12.2 (30.5 to 68.3)	60.1 ± 4.8 (53.6 to 65.6)	0.103
ΔSAI_{Cup}	−13.6 ± 7.6 (−23.1 to 6.8)	−15.2 ± 8.8 (−39.6 to 4.0)	0.507	−16.0 ± 9.5 (−39.6 to 4.0)	−12.6 ± 7.0 (−22.1 to −3.6)	0.593
Transverse version (TV_{Cup})						
Standing	31.9 ± 7.9 (18.8 to 51.6)	37.9 ± 11.2 (17.2 to 53.9)	**0.042**	36.2 ± 11.0 (17.2 to 49.3)	44.2 ± 11.9 (24.9 to 53.9)	0.064
Sitting	39.2 ± 7.7 (27.7 to 53.4)	45.5 ± 9.3 (24.7 to 58.2)	**0.015**	44.9 ± 9.3 (24.7 to 56.5)	48.5 ± 10.3 (31.6 to 58.2)	**0.035;** PvsS 0.103; AvsS 0.082; AvsP 0.693
ΔTV_{Cup}	−7.2 ± 4.5 (−15.8 to 4.1)	−7.6 ± 5.3 (−23.1 to 2.1)	0.805	−8.7 ± 5.6 (−23.1 to 2.1)	−4.3 ± 2.4 (−6.7 to −1.4)	0.194
Within Lewinnek safe zone, *n* (%)	4 (17)	1 (4)	**0.045**	1 (6)	0 (0)	0.091

Bolded *P* values indicate statistical significance ($P < 0.05$).
THA, total hip arthroplasty; PvsS, posterior dislocations versus stable THAs; AvsS, anterior dislocations versus stable THAs; AvsP, anterior versus posterior dislocations; Δ = (value standing − value sitting).
[a] *P*-values comparing stable and unstable THAs based on the Chi-square tests for categorical and Student's *t*-tests and Mann-Whitney U-tests for descriptive variables.
[b] *P*-values comparing stable THAs, posterior dislocations and anterior dislocations using Chi-square tests, one-way analyses of variances and Kruskal-Wallis H tests.

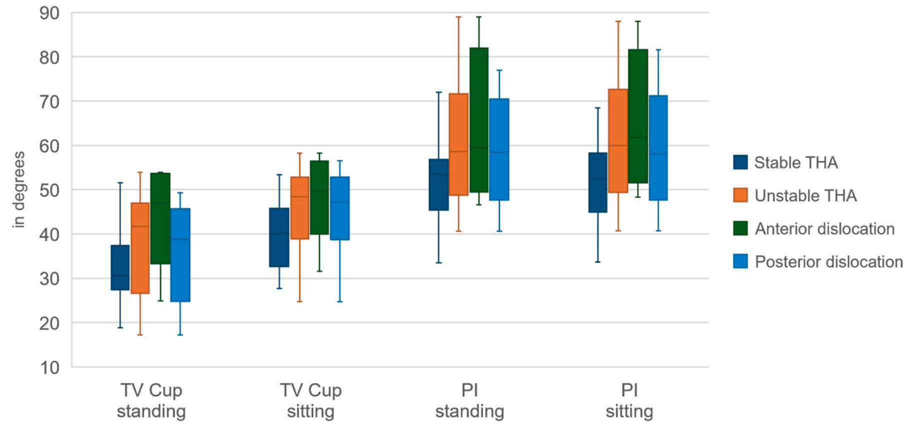

Figure 5. Box-and-whisker plots *of* transverse version of the acetabular component (TV_{Cup}) and pelvic incidence (PI) in the standing and sitting positions demonstrating the distribution of the data and the median.

distribution of 32 mm (48%) and 36 mm (48%) prosthetic heads. In a recent study by Christensen et al., it was shown that the dislocation risk of THAs is slightly lower after DAA compared to PLA (0.7 versus 1.1%) [29]. During the study period, the surgical approach differed between the groups due to a transition from PLA to DAA by most surgeons. For this reason, most of the unstable THAs (74%) had a PLA, whereas half of the stable THAs had a DAA (48%). However, we state that for each THA, despite the confounding factors such as approach and prosthetic head diameter, the risk for dislocation could be further mitigated when the implant is placed within a patient-specific safe zone.

For the logistic regression analyses, many variables may cause lack of statistical power. Validation of the prediction model with a larger sample size is needed. For the confirmation of the different functional component orientations in patients who have a THA dislocation, a prospective study is required to control for surgical

Table 4
Femoral Component Orientation and Combined Sagittal Parameters.

Angle	Stable THAs ($n = 23$), Degrees, Mean ± SD (Range)	Unstable THAs ($n = 23$), Degrees, Mean ± SD (Range)	*P*-Value[a]	Posterior Dislocations ($n = 17$), Degrees, Mean ± SD (Range)	Anterior Dislocations ($n = 5$), Degrees, Mean ± SD (Range)	*P*-Value[b]
Femoral component`s orientation						
Coronal inclination (CI_F):	48.4 ± 2.9 (43.7 to 54.5)	48.5 ± 4.3 (39.1 to 56.2)	0.873	48.2 ± 4.7 (39.1 to 56.2)	50.1 ± 2.4 (47.1 to 53.5)	0.6
Sagittal ante-inclination (SAI_F):						
Standing	7.2 ± 11.2 (−13 to 27.3)	7.6 ± 11.2 (13.5 to 29.2)	0.911	8.3 ± 11.0 (−6.0 to 29.2)	1.7 ± 12.5 (−17.1 to 17.5)	0.512
Sitting	8.7 ± 13.3 (−15.4 to 38.3)	8.8 ± 11.3 (−15.9 to 30.0)	0.97	6.0 ± 10.8 (−15.9 to 25.7)	18.4 ± 9.6 (9.4 to 30.0)	0.144
ΔSAI_F	−1.5 ± 22.4 (−42.5 to 36.8)	−1.3 ± 17.8 (−28.7 to 37.4)	0.969	2.3 ± 17.0 (−18.6 to 37.4)	−16.7 ± 15.7 (−32.3 to 7.2)	0.182
Transverse version (TV_F)						
Standing	6.4 ± 9.8 (−11.0 to 24.4)	7.0 ± 11.4 (−16.0 to 33.0)	0.835	8.1 ± 11.2 (−5.0 to 33.0)	1.0 ± 11.1 (−16.0 to 14.9)	0.425
Combined parameters						
Combined anteversion	38.3 ± 13.6 (10.7 to 61.2)	45.0 ± 15.2 (19.7 to 78.5)	0.123	44.3 ± 15.9 (19.7 to 78.5)	45.2 ± 14.9 (24.3 to 61.8)	0.372
Pelvic femoral angle (PFA)						
Standing	181.4 ± 8.8 (161.5 to 195.3)	183.0 ± 11.8 (159.5 to 203.5)	0.615	182.2 ± 12.6 (159.5 to 203.5)	187.0 ± 9.5 (177.7 to 196.5)	0.625
Sitting	112.7 ± 13.0 (91.3 to 144.0)	116.6 ± 9.7 (90.3 to 133.9)	0.26	116.2 ± 10.3 (90.3 to 133.9)	117.6 ± 9.4 (111.5 to 131.5)	0.555
ΔPFA	68.7 ± 10.8 (50.6 to 86.5)	66.4 ± 12.1 (39.5 to 83.1)	0.495	65.9 ± 13.2 (39.5 to 83.1)	69.4 ± 8.8 (62.0 to 81.9)	0.727
Combined sagittal index (CSI)						
Standing	216.1 ± 12.6 (191.0 to 241.2)	219.9 ± 17.1 (185.0 to 239.2)	0.271	215.7 ± 17.4 (185.0 to 239.2)	234.2 ± 4.0 (230.0 to 238.0)	0.062
Sitting	161.0 ± 17.7 (117.8 to 195.5)	168.8 ± 17.8 (130.1 to 193.1)	0.148	165.7 ± 18.8 (130.1 to 193.1)	177.2 ± 9.5 (165.1 to 188.3)	0.228
ΔCSI	55.2 ± 15.5 (30.3 to 84.7)	51.1 ± 16.5 (7.3 to 72.5)	0.398	50.0 ± 18.4 (7.3 to 72.5)	57.0 ± 6.7 (49.7 to 64.9)	0.545
Sacro-acetabular angle (SAA)						
Standing	71.2 ± 14.7 (44.7 to 98.8)	76.4 ± 16.6 (47.0 to 107.6)	0.273	71.6 ± 14.1 (47.0 to 92.5)	89.0 ± 14.0 (76.7 to 106.0)	0.076
Sitting	72.7 ± 16.0 (44.2 to 94.9)	80.3 ± 18.1 (52.4 to 119.4)	0.142	75.2 ± 15.0 (52.4 to 102.5)	93.8 ± 18.4 (80.3 to 119.4)	0.058
ΔSAA	−1.5 ± 6.0 (−14.9 to 12.6)	−3.9 ± 4.6 (−13.4 to 4.1)	0.134	−3.6 ± 4.5 (−12.3 to 4.1)	−4.8 ± 5.9 (−13.4 to −0.3)	0.344

THA, total hip arthroplasty; Δ = value standing − value sitting.
[a] *P*-values comparing stable and unstable THAs based on Student's *t*-tests and Mann-Whitney U-tests.
[b] *P*-values comparing stable THAs, posterior dislocations, and anterior dislocations using one-way analyses of variances.

Table 5
Univariable and Multivariable Logistic Regression Analyses of Significant Predictors for THA Dislocation.

Variable	Univariable Analyses		Multivariable Analyses			
	β-Coefficient	*P*-Values	β-Coefficient	Odds Ratio	95% CI	*P*-Values
TV_{Cup} standing	0.064	**0.048**	−0.033	0.968	0.82 to 1.14	0.693
PI standing	0.067	**0.024**	0.092	1.017	1.02 to 1.18	**0.016**
TV_{Cup} sitting	0.087	**0.021**	0.137	1.146	0.96 to 1.37	0.127
Direct anterior approach		0.076				**0.041**
Antero-lateral approach	−0.31	0.808	0.972	2.644	0.13 to 53.51	0.526
Direct lateral approach	−20.414	0.999	−17.559	0.000	0.000	1
Postero-lateral approach	1.676	**0.017**	3.094	22.055	2.48 to 196.51	**0.006**
Constant			−11.464	0.000		**0.003**

Bolded *P* values indicate statistical significance ($P < 0.05$).
THA, total hip arthroplasty; CI, confidence interval; PI, pelvic incidence; TV_{Cup}, transverse version of the acetabular component.

approach, and starting with preoperative spino-pelvic assessments. Because of the low prevalence of THA dislocation, this warrants a large sample size.

Conclusion

By assessment of spino-pelvic characteristics and applying an equation predicting the probability for dislocation, surgeons could identify patients at increased risk for THA dislocation preoperatively based on a high PI. In addition, posterior dislocations seem to occur more in patients who have more TV_{Cup} and PLA, and anterior dislocations seem to occur in patients who have more SAI_{Cup}, TV_{Cup}, and DAA. This suggests that implementation of a patient-specific functional safe zone of the acetabular component may further reduce THA dislocation rates. Spinal mobility and the 3-D femoral component orientation were not different among stable and unstable THAs.

Equation 1. Predicting the probability of THA dislocation based on multivariable linear regression analyses

$$p_{unstable\ THA} = \frac{e^{-11.464-(0.033*TVcup\ standing)+(0.092*PI\ standing)+(0.137*TVcup\ sitting)+(0.972*Anterolateral)-(17.559*Direct\ Lateral)+(3.094*Posterolateral)}}{e^{-11.464-(0.033*TVcup\ standing)+(0.092*PI\ standing)+(0.137*TVcup\ sitting)+(0.972*Anterolateral)-(17.559*Direct\ Lateral)+(3.094*Posterolateral)}+1}$$

THA, total hip arthroplasty; TV_{Cup}, transverse version of the acetabular component; PI, pelvic incidence.

Example:

Patient with THA dislocation: posterolateral approach, TV_{Cup} sitting 39°, PI standing: 46°, TV_{Cup} sitting: 50°,

$$p_{unstable\ THA} = \frac{e^{(-11.464-(0.033*39)+(0.092*46)+(0.137*50)+(0.972*0)-(17.559*0)+(3.094*1))}}{e^{(-11.464-(0.033*39)+(0.092*46)+(0.137*50)+(0.972*0)-(17.559*0)+(3.094*1))}+1} = 0.81 = 81\%\ probability\ for\ dislocation$$

CRediT authorship contribution statement

Christin Trostel: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Joost H.J. van Erp:** Writing – review & editing, Writing – original draft, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Thom E. Snijders:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Harrie H. Weinans:** Writing – review & editing, Visualization, Validation, Supervision, Conceptualization. **Bram Hentenaar:** Writing – review & editing, Resources, Investigation, Funding acquisition, Data curation. **Arthur de Gast:** Writing – review & editing, Supervision, Resources, Funding acquisition, Data curation, Conceptualization. **Tom P.C. Schlösser:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Conceptualization.

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