Redefining the 3D Topography of the Acetabular Safe Zone

A Multivariable Study Evaluating Prosthetic Hip Stability

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Background: Dislocation is the most common reason for early revision following total hip arthroplasty (THA). More than 40 years ago, Lewinnek et al. proposed an acetabular "safe zone" to avoid dislocation. While novel at the time, their study was substantially limited according to modern standards. The purpose of this study was to determine optimal acetabular cup positioning during THA as well as the effect of surgical approach on the topography of the acetabular safe zone and the hazard of dislocation.

Methods: Primary THAs that had been performed at a single institution from 2000 to 2017 were reviewed. Acetabular inclination and anteversion were measured using an artificial intelligence neural network; they were validated with performance testing and comparison with blinded grading by 2 orthopaedic surgeons. Patient demographics and dislocation were noted during follow-up. Multivariable Cox proportional-hazards regression, including multidimensional analysis, was performed to define the 3D topography of the acetabular safe zone and its association with surgical approach.

Results: We followed 9,907 THAs in 8,081 patients (4,166 women and 3,915 men; 64 ± 13 years of age) for a mean of 5 ± 3 years (range: 2 to 16); 316 hips (3%) sustained a dislocation during follow-up. The mean acetabular inclination was 44° ± 7° and the mean anteversion was 32° ± 9°. Patients who did not sustain a dislocation had a mean anteversion of 32° ± 9° (median, 32°), with the historic ideal anteversion of 15° observed to be only in the third percentile among non-dislocating THAs ($p < 0.001$). Multivariable modeling demonstrated the lowest dislocation hazards at an inclination of 37° and an anteversion of 27°, with an ideal modern safe zone of 27° to 47° of inclination and 18° to 38° of anteversion. Three-dimensional analysis demonstrated a similar safe-zone location but significantly different safe-zone topography among surgical approaches ($p = 0.03$) and sexes ($p = 0.02$).

Conclusions: Optimal acetabular positioning differs significantly from historic values, with increased anteversion providing decreased dislocation risk. Additionally, surgical approach and patient sex demonstrated clear effects on 3D safe-zone topography. Further study is needed to characterize the 3D interaction between acetabular positioning and spinopelvic as well as femoral-sided parameters.

Level of Evidence: Prognostic Level III. See Instructions for Authors for a complete description of levels of evidence.

Since its popularization by Charnley in the 1960s, total hip arthroplasty (THA) has demonstrated excellent efficacy and durability, with established outcomes beyond 30 years of follow-up[1,2]. However, dislocation remains among the most common complications following THA, affecting between 0.3% and 10.0% of patients, with potentially profound repercussions on patient quality of life, pain, repeat dislocation, and revision[3,4]. Given its prevalence, instability is the most common reason for early revision in the American Joint Replacement Registry as well as multiple international registries[5-7].

In 1978, Lewinnek et al. wrote their landmark series on dislocations following primary THA, forming the basis of the acetabular "safe zone."[8] In their paper, the authors recommended ideal acetabular anteversion of 15° ± 10° and inclination of 40° ± 10°.

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While novel at the time, the historic limitations of their methods are impactful. First, their series was limited to 300 THAs that had been performed by 5 surgeons, only 1 of whom repaired the short external rotators. Second, radiographic follow-up was limited to 41% of arthroplasties. Finally, 1 surgeon performed 190 arthroplasties with only 1 dislocation but had a similar proportion of THAs outside the safe zone compared with his colleagues with higher dislocation rates.

Subsequent studies have focused on the position of the acetabular component of dislocating THAs and have highlighted that a large proportion of unstable THAs fall within the Lewinnek safe zone[3,9,10]. These studies have further contributed to the instability literature but remain affected by a set of key limitations. First, the safe zone that was being evaluated was likely imperfect given historic methodological limitations. Second, for papers examining dislocating THAs without a control group of patients without dislocation, it was unclear whether the proportion of patients inside or outside the safe zone was relatively greater, the same, or less than patients who achieved outcomes without dislocation[3]. Third, given the evolution of statistical and surgical methods, nuances in indication based on operative approach, intraoperative soft-tissue tensioning, and proclivity to dislocate support the utility of revisiting the classic acetabular safe zone. Currently, this remains important because of the popularization of the direct anterior (DA) approach in addition to the classic anterolateral (AL) and posterolateral (PL) approaches.

Therefore, the purposes of this study were to (1) determine optimal acetabular component positioning during THA using modern statistical methods and robust patient numbers and (2) determine the potential effect of surgical approach on the topography of the acetabular safe zone and the risk of dislocation.

Materials and Methods

Study Population

All primary THAs that had been performed at a single academic institution from January 2000 to August 2017 were reviewed following institutional review board approval (#20-004702). Inclusion criteria for this case-control study consisted of (1) primary THAs that had been performed from January 2000 to August 2017 and (2) availability of postoperative anteroposterior and lateral radiographs. Exclusion criteria consisted of (1) revision arthroplasty, (2) approaches other than the DA, AL, or PL approaches, (3) tumor indications, and (4) follow-up of <2 years. Throughout the analyzed time period, surgeons sought to recreate native acetabular positioning within the historic safe zone of 15° ± 10° of anteversion and 40° ± 10° of inclination.

Radiographic Measures

Acetabular component orientation was assessed using supine anteroposterior and cross-table lateral hip radiographs. Acetabular inclination was measured on the anteroposterior radiographs by determining the angle between a horizontal pelvic plane and the long axis of the acetabular cup (Fig. 1-A). Subsequently, acetabular anteversion was measured in reference to the vertical plane of the cross-table lateral radiographs using the method described by Woo and Morrey[4] (Fig. 1-B).

Inclination and anteversion were measured using a deep-learning artificial intelligence (AI) model that our group had previously validated[11]. Briefly, 2 cohorts of 600 anteroposterior pelvic and cross-table lateral hip radiographs were used to develop deep-learning models. Cohorts were manually annotated and randomly split into training, validation, and test data sets on an 8:1:1 basis using 2 U-Net convolutional neural network models trained for 50 epochs. Performance was tested on 80 anteroposterior and cross-table lateral radiographs, with primary validation via direct comparison with values that had been measured by a trained orthopaedic surgeon (C.C.W.). The mean difference between human- and machine-level measurements was 1.4° (standard deviation [SD]: 1.1°) and 1.4° (SD: 1.3°) for the inclination and anteversion angles, respectively. Differences of ≥5° between the human and machine measurements were observed in <2.5% of the cases. Secondary validation for the current data set was provided by comparing AI measurements for 60 patients with blinded independent grading by 2 orthopaedic surgeons (M.H. and C.C.W.). This generated high correlation (inclination: 0.89; anteversion: 0.90) and no significant difference between AI and human-measured values (p ≥ 0.15).

Demographics, Approach, and Spinal Pathology

Patients were characterized based on nonmodifiable factors in order to inform acetabular safe-zone analyses. THAs were classified

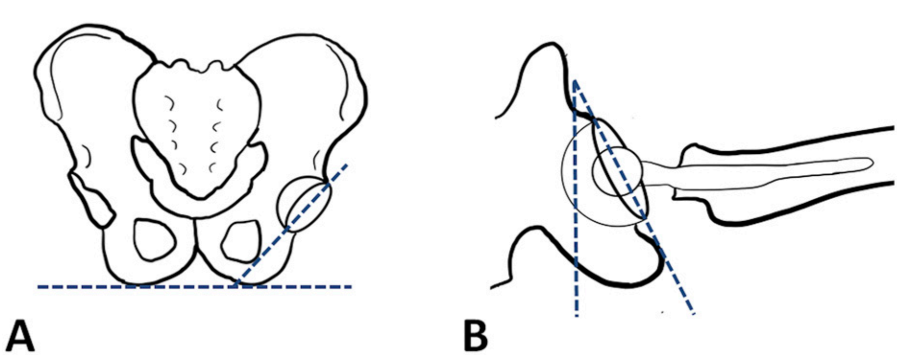

Fig. 1
Measurement technique for acetabular inclination, with use of an anteroposterior radiograph (**Fig. 1-A**), and anteversion, with use of a cross-table lateral radiograph and a vertical reference (**Fig. 1-B**).

based on operative approach (DA, AL, or PL), body mass index (BMI), sex, and femoral head size with the use of institutional total joint registry data and electronic medical records.

Statistical Analysis

A priori analysis was used to determine the sample size that was needed to demonstrate a 5° difference in acetabular inclination and anteversion between arthroplasties with and without dislocation with use of a conservative dislocation rate of 1%. Using published distributions[3], the sample size that was needed for an alpha of 0.05 and a power of 0.95 was determined to be 35 dislocations and 3,521 controls for inclination and 45 dislocations and 4,455 controls for anteversion[12,13].

Demographic data are presented using means, standard deviations, and percentages. We employed Kruskal-Wallis rank-sum testing for nominal values and chi-square testing for proportions. Cox proportional-hazards analysis was used to determine the relationship among demographics, acetabular component positioning, and dislocation, accounting for death and implant revision with competing risk analysis. Subsequently, the RMS package[14] was used to provide visual representation of proportional hazards and acetabular safe-zone topography in relationship to combined acetabular anteversion and inclination. This and other analyses were conducted in R version 4.0.0 (R Foundation for Statistical Computing). P values of <0.05 were considered significant.

Source of Funding

No funding was received for this article.

Results

A total of 9,907 primary THAs that had been performed in 8,081 patients (4,166 women and 3,915 men) with a mean age of 64.1 years (SD: 12.6 years; interquartile range [IQR]: 56.0 to 73.0 years; range: 12.2 to 97.9 years) by 35 orthopaedic surgeons were eligible for inclusion, and the patients were followed for a mean of 5.3 years (SD: 2.7 years; median: 5.1 years; range: 2.0 to 16.2 years; Table I). The mean acetabular inclination was 44° ± 7° and the mean anteversion was 32° ± 9°.

There were 316 THAs (3.2%) that sustained a dislocation at a mean of 1.9 years (SD: 2.6 years; median: 0.4 years; range: 0 days to 13.9 years) postoperatively at an average patient age of 62.9 years (SD: 13.2 years; IQR: 56.2 to 75.1 years; range: 26.0 to 92.5 years), exceeding the required sample sizes from the a priori analysis. Patients without dislocation had a mean anteversion of 31.8° (SD: 8.7°; median: 32.5°; IQR: 25.9° to 37.3°), with the

TABLE I Demographics, THA Characteristics, and Dislocation Rates by Surgical Approach*

Variable	Direct Anterior (N = 810)	Anterolateral (N = 2,944)	Posterolateral (N = 6,153)	P Value
Age in yr				
Overall	64.5 ± 11.3	66.3 ± 11.6	63.1 ± 13.0	
<30	3 (0.4%)	20 (0.7%)	104 (1.7%)	
30-39	19 (2.3%)	50 (1.7%)	258 (4.2%)	
40-49	64 (7.9%)	208 (7.1%)	672 (10.9%)	
50-59	206 (25.4%)	570 (19.4%)	1,298 (21.1%)	
60-69	264 (32.6%)	935 (31.8%)	1,890 (30.7%)	
70-79	205 (25.3%)	900 (30.6%)	1,543 (25.1%)	
80-89	46 (5.7%)	247 (8.4%)	371 (6.0%)	
90+	3 (0.4%)	14 (0.5%)	17 (0.3%)	<0.001
Sex				
Women	413 (51.0%)	1,526 (51.8%)	3,129 (50.9%)	
Men	397 (49.0%)	1,418 (48.2%)	3,024 (49.1%)	<0.001
Laterality				
Right	439 (54.2%)	1,571 (53.4%)	3,307 (53.7%)	
Left	371 (45.8%)	1,373 (46.6%)	2,846 (46.3%)	<0.001
BMI *(kg/m²)*	29.5 ± 5.7	30.4 ± 6.4	30.0 ± 6.1	<0.001
Femoral head size in mm				
<36 mm	307 (37.9%)	1,928 (65.5%)	2,979 (48.4%)	
≥36 mm	503 (62.1%)	1,016 (34.5%)	3,174 (51.6%)	<0.001
Inclination	40.5 ± 6.1°	45.1 ± 7.1°	43.6 ± 7.0°	<0.001
Anteversion	31.7 ± 6.7°	29.1 ± 9.3°	33.0 ± 8.5°	<0.001
Dislocations	6 (0.7%)	71 (2.4%)	239 (3.9%)	<0.001

*BMI = body mass index. Values are given as the mean ± standard deviation or number (%).

TABLE II Multivariable Cox Proportional-Hazards Analysis for Predictors of Dislocation*

Variable	Hazard Ratio (95% CI)	P Value
Age, per yr	0.99 (0.98-1.00)	0.15
Sex		
Women	Reference	
Men	0.64 (0.50-0.82)	<0.001
Laterality		
Right	Reference	
Left	1.16 (0.93-1.45)	0.18
BMI, per kg/m²	1.00 (0.98-1.02)	0.77
Femoral head size, per mm		
<36 mm	Reference	
≥36 mm	0.76 (0.59-0.98)	0.03
Surgical approach		
DA	Reference	
AL	2.65 (1.14-6.16)	0.02
PL	4.62 (2.05-10.43)	<0.001

*BMI = body mass index, DA = direct anterior, AL = anterolateral, and PL = posterolateral.

historic ideal anteversion of 15° observed to be only in the third percentile among THAs without dislocation (p < 0.001).

Due to the large sample sizes, significant differences were noted among the surgical approaches in demographic variables, including age, sex, and BMI (Table I). However, these differences were of modest clinical relevance given their small magnitude (e.g., the mean BMI was within a 0.9 kg/m^2 range across the approaches). Of note, large-diameter femoral heads (≥36 mm) were most common in the DA group (62.1%), followed by the PL (51.6%) and AL (34.5%) groups (p < 0.001, Table I).

Multivariable Cox proportional-hazards analysis demonstrated that male sex was protective against dislocation (hazard ratio [HR]: 0.64; 95% confidence interval [CI]: 0.50 to 0.82; p < 0.001; Table II), as was femoral head diameter of ≥36 mm (HR: 0.76; 95% CI: 0.59 to 0.98; p = 0.03). Additionally, in reference to the DA approach, both the AL (HR: 2.65; 95% CI: 1.14 to 6.16) and PL (HR: 4.62; 95% CI: 2.05 to 10.43) approaches demonstrated a significantly (p ≤ 0.02) increased hazard of dislocation, even after accounting for femoral head diameter (Table II).

Optimizing the Safe Zone

The lowest univariate hazard of dislocation was observed at an inclination of 37° (Fig. 2-A). The 20°-wide range that would yield the lowest hazard of dislocation was from 27° to 47°, with a relatively symmetric increase in dislocation hazard with deviation above or below 37°. Outside this range, the dislocation hazard increased rapidly with progressively lower inclination and grew more modestly with higher inclination values (Fig. 2-A). In terms of anteversion, the lowest hazard of dislocation occurred at 27°, with an ideal 20°-wide safe zone of 18° to 38° of anteversion, which was substantially above the historic values of 5° to 25° that had been proposed by Lewinnek (p < 0.001) (Fig. 2-B).

We then proceeded with multidimensional analysis of acetabular component positioning and dislocation risk (Fig. 3). Low values of inclination (<20°) were poorly tolerated in the setting of anteversion of <18°, and, to a lesser extent, anteversion of >38°. While the band of acceptable anteversion was relatively narrow, there was a wide safe zone of inclination from 10° to beyond 50°, provided that anteversion remained within the above values, highlighting the relative importance of anteversion over inclination for dislocation risk.

Next, we analyzed the effect of the anterior-based approaches (DA and AL) versus the posterior approach (PL) in determining the acetabular safe zone, combining the DA and AL approaches given their posterior capsular complex-sparing nature and in order to provide statistically robust numbers (Fig. 4). Again, we observed a narrower window of safe anteversion when

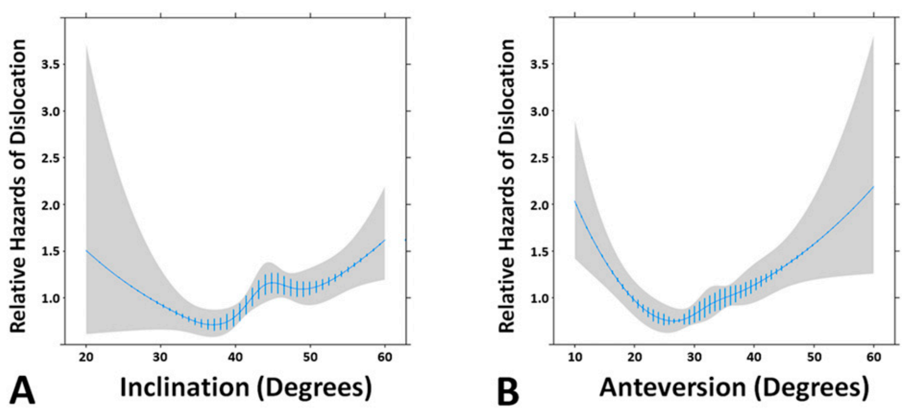

Fig. 2

Univariate continuous Cox proportional-hazards modeling of inclination (**Fig. 2-A**) and anteversion (**Fig. 2-B**) and their relationship to the hazard of THA dislocation. The shaded gray area represents the 95% CI.

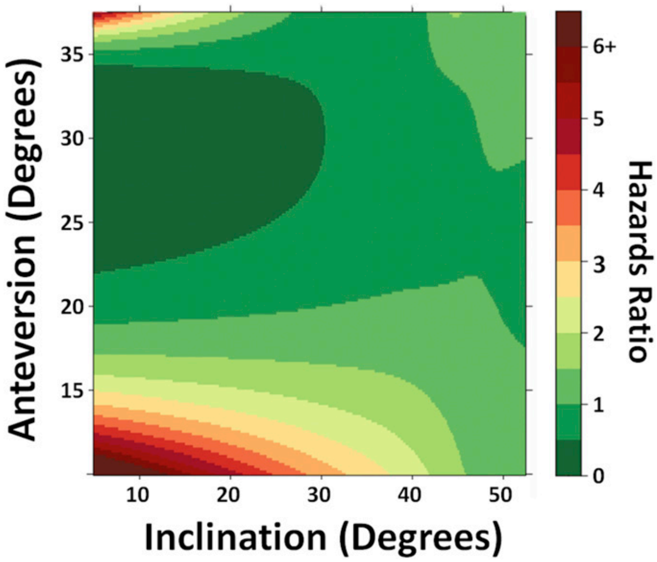

Fig. 3
Hazard of dislocation according to the interaction of anteversion and inclination for all of the analyzed THAs.

compared with inclination for both types of approach, with this being centered at 29° for the anterior-based approaches and 27° for the posterior-based approach. Of note, significant topological differences were found between the anterior and posterior approaches (p = 0.03), with low values of anteversion (<18°) being penalized less in the anterior-based cohorts.

Given the established sex-based differences in dislocation rates, the effect of sex in determining safe-zone topography was also assessed (Fig. 5). Optimal anteversion was centered at 27° for both men and women, with men demonstrating relatively steeper penalties for nonoptimal anteversion (high or low) when compared with women (p = 0.02). For inclination, the lowest dislocation hazard occurred at 37° for men and 42° for women, with men again demonstrating relatively steeper penalties for nonoptimal inclination (p = 0.02). As with the overall and approach-based analyses, both sexes demonstrated a broad range of acceptable inclination from 10° to beyond 50°, provided that satisfactory anteversion was present.

Discussion

The purpose of the present study was to determine optimal acetabular component positioning as well as the effect of surgical approach on acetabular safe-zone topography and dislocation risk. Our hypothesis was supported in that we found that optimal acetabular positioning in our series of 9,907 acetabular components differed from historic values. Additionally, surgical approach and sex were found to substantially influence dislocation risk and safe-zone topography. These findings are clinically relevant in that they guide acetabular positioning and, in doing so, may mitigate dislocation risk in a readily implemented manner.

To date, instability remains the most common reason for early THA revision in multiple joint replacement registries, with substantial effects on patient quality of life and function[5-7,15]. While various technologies such as large-diameter femoral heads, dual-mobility articulations, and constrained liners have been introduced to assist in the prevention and management of instability, acetabular component positioning remains a core component of dislocation prevention[16,17]. Furthermore, component positioning can be readily modified and adjusted at the time of surgery, making this an ideal target for risk mitigation efforts. Indeed, many technologies capitalizing on robotics or navigation have emerged with the goal of attaining reproducible acetabular positioning. However, hitting the target is only half of the equation. Surgeons first need to know what the target is to make full use of these technological aids.

Ideal implant positioning is highly dependent on clearly defined targets. While novel at the time, the acetabular safe zone provided by Lewinnek et al. was limited by sample size and the number of cases with radiographic follow-up[8,17]. Additionally, while theoretically attractive, there is no compelling biologic reason to support a square-shaped 20° × 20° safe zone. Therefore, the present study investigated ideal acetabular positioning using modern 3D-

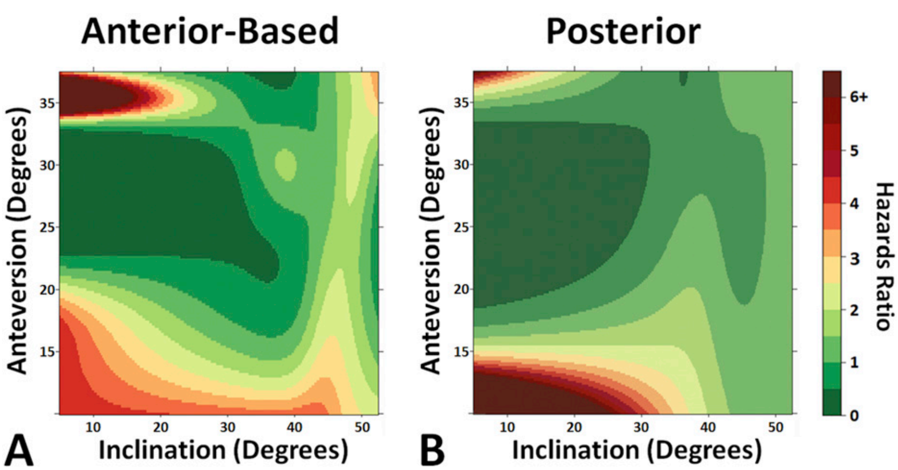

Fig. 4
Hazard of dislocation for anterior-based (**Fig. 4-A**) and posterior-based (**Fig. 4-B**) approaches according to the interaction of anteversion and inclination.

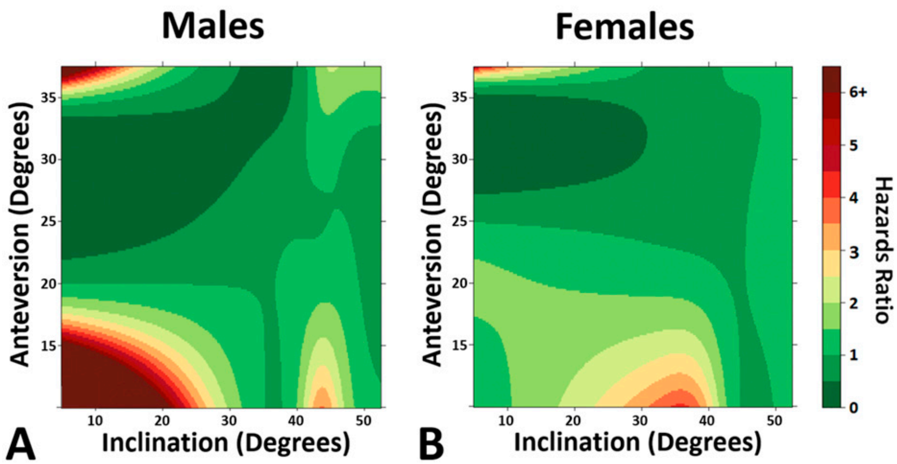

Fig. 5
Hazard of dislocation for men (**Fig. 5-A**) and women (**Fig. 5-B**) according to the interaction of anteversion and inclination.

based methods to define safe-zone topography. Our findings are novel in that they suggest that the ideal acetabular anteversion is substantially higher than historic values, with a goal of 27° (range: 18° to 38°). Our findings are also supported by recent studies investigating native acetabular orientation. Namely, computed tomography (CT) studies assessing native anatomy consistently have provided anteversion values of >15°, with Tohtz et al. observing a mean anteversion of 22.7° in 336 native hips[18], Merle et al. observing a mean anteversion of 19.3° in 131 patients[19], and Maheshwari et al. reporting a mean anteversion of 19.1° in 172 hips[20]. Of note, topographic analysis demonstrated that the band of acceptable anteversion was relatively narrow whereas there was a wide safe zone of inclination from 10° to beyond 50°, provided that anteversion remained near the optimal value of 27°. This suggests that surgeons should aim for anteversion as close as possible to the ideal value, understanding that slight deviations toward increased anteversion are better tolerated than deviations in the opposite direction.

It is biomechanically intuitive that recreating native anatomy may enhance stability and decrease dislocation risk. This is supported by previous studies that have demonstrated the importance of anatomic posterior capsular repair at the time of THA[21,22]. Our findings are also supported by approach-based alterations to soft-tissue restraints. Namely, we observed that anterior-based approaches better tolerate lower-than-ideal anteversion values. In contrast, the posterior-based approach demonstrated a rapid increase in dislocation risk as anteversion decreased, probably due to reduced posterior soft-tissue restraints to internal hip rotation and posterior hip dislocation, in at least some patients, after the posterior approach.

Our sex-based analyses supported similar acetabular positioning for men and women. It is noteworthy that while men had an overall lower risk of dislocation, they demonstrated different 3D safe-zone topography, with steeper relative increases in dislocation hazard with nonoptimal positioning. This may be due to a multitude of differences, including sex-specific variations in pelvic anatomy[23], gait biomechanics[24,25], and soft-tissue laxity[26,27], and merits future investigations that are focused on determining the potential etiology of such differences. Regardless, surgeons can be informed by the fact that ideal anteversion and inclination are similar for both sexes at the time of arthroplasty.

Our study has important limitations. First, while our focus was on acetabular cup positioning, other factors, including age, acetabular liner configuration (e.g., elevated-rim liners), femoral component version, spinopelvic mobility, and leg length play a role in stability and merit further investigation. We excluded age and spinopelvic mobility from our analysis as they are nonmodifiable and have been previously established in the literature to affect the risk of dislocation. Regarding acetabular liner design, it has been previously shown that elevated-rim and face-changing-configuration liners may alter dislocation risk. However, adjusting for the effect of such liners remains challenging because the degree of lateralization provided by the liners varies not only among manufacturers but also among liner sizes from the same manufacturer. Furthermore, offset and rim height also vary among non-neutral liners. Additionally, surgeon-dependent intraoperative rotation and positioning of the lipped apex of the liner varies and is difficult to quantify. Second, while dislocation is the most common reason for early THA revision, instability remains relatively rare. Therefore, comprehensive characterization of the interactions that predispose to dislocation are limited by the number of events available for analysis in any given database. Nevertheless, we believe the present study is among the largest of its size in terms of analyzed acetabular components. Third, given the volume of images to be measured, we elected to automate this process with AI and expand our statistical power. While limited by the nonhuman nature of these measurements, we believe that we have robustly tested and validated our methodology, including validation with blinded grading by 2 orthopaedic surgeons. Finally, with additional future data, it may be possible to evaluate the effects of femoral anteversion and discrete spinal measurements, with the understanding that combined anteversion and spinopelvic motion may cause alterations in the location as well as the width of the safe zone on a patient-specific basis.

In conclusion, optimal acetabular positioning differs significantly from historic values, with increased anteversion providing decreased dislocation risk. Additionally, surgical approach and patient sex demonstrate clear effects on 3D safe-zone topography. Further study is needed to characterize the 3D interaction between acetabular positioning and spinopelvic as well as femoral-sided parameters. ■

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