Comparison of Native Anatomy with Recommended Safe Component Orientation in Total Hip Arthroplasty for Primary Osteoarthritis

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Background: The adverse consequences of impingement, dislocation, and implant wear have stimulated increasing interest in accurate component orientation in total hip arthroplasty and hip resurfacing. The aims of the present study were to define femoral and acetabular orientation in a cohort of patients with primary hip osteoarthritis and to determine whether the orientation of their native hip joints corresponded with established recommendations for implantation of prosthetic components.

Methods: We retrospectively evaluated a consecutive series of 131 preoperative computed tomography (CT) scans of patients with primary end-stage hip osteoarthritis (fifty-seven male and seventy-four female patients; mean age, sixty years). Patients were positioned according to a standardized protocol. Accounting for pelvic tilt, three-dimensional acetabular orientation was determined in the anatomical reference frame. Moreover, three-dimensional femoral version was measured. Differences in native anatomy between male and female patients were assessed with use of nonparametric tests. Native anatomy was evaluated with reference to the ''safe zone'' as described by Lewinnek et al. and to a ''safe'' combined anteversion of 20° to 40°.

Results: In the entire cohort, the mean femoral anteversion was 13° and the mean acetabular anteversion was 19°. No significant differences in femoral, acetabular, or combined (femoral and acetabular) anteversion were observed between male and female patients. The mean acetabular inclination was 62°. There was no significant difference in acetabular inclination between female and male patients. We did not observe a correlation among acetabular inclination, acetabular anteversion, and femoral anteversion. Ninety-five percent (125) of the native acetabula were classified as being within the safe anteversion zone, whereas only 15% (nineteen) were classified as being within the safe inclination zone. Combined anteversion was within the safe limits in 63% (eighty-three) of the patients. However, only 8% (ten) of the cases in the present cohort met the criteria of both ''safe zone'' definitions (that of Lewinnek et al. and combined anteversion).

Conclusions: Acetabular anteversion of the osteoarthritic hip as defined by the native acetabular rim typically matches the recommended component ''targets'' for cup insertion. There was no specific relationship among native acetabular inclination, acetabular anteversion, and femoral anteversion. Neither native acetabular inclination nor native combined anteversion appears to be related to current implant insertion targets.

Clinical Relevance: The present findings of native acetabular and femoral orientation in patients with primary hip osteoarthritis support intraoperative component positioning for total hip arthroplasty.

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The adverse consequences of dislocation, impingement, and implant wear have stimulated recent interest in optimal component orientation in total hip arthroplasty[1,2] and hip resurfacing[3,4].

On the basis of radiographic analysis, Lewinnek et al.[5] suggested a "safe zone" for the orientation of the acetabular component, with a radiographic cup inclination of 40° (±10°) and cup anteversion of 15° (±10°), to reduce the risk of dislocation. Because both the acetabular and the femoral component orientations determine the functional arc of hip motion, the concept of a "safe" combined anteversion has been introduced[6-8] to minimize the risk of impingement, dislocation, and wear. In clinical practice, these two concepts have gained wide recognition. However, the ranges for safe acetabular and femoral component orientation remain controversial[9], and it is not clear whether native anatomy, such as the acetabular rim[10], the transverse acetabular ligament[11], or the native femoral anteversion[12], should be used as guidance for the insertion of prosthetic components.

Several studies have described the variation in native acetabular and femoral anatomy during the last three decades[13-16]. However, most reported values are limited to either the femur or the acetabulum and were obtained from cadaveric specimens or computed tomography (CT) data of a limited number of individuals with nonarthritic hip joints. We are not aware of any published studies on the native anatomy of the hip in patients with end-stage hip osteoarthritis prior to arthroplasty surgery.

The objectives of the present study were to investigate the variation in femoral and acetabular anatomy in a cohort of patients with primary end-stage hip osteoarthritis and to determine the extent to which osseous landmarks of the osteoarthritic hip can be used intraoperatively to guide component orientation with reference to recommended target zones.

Materials and Methods

Study Cohort

We conducted a retrospective cohort study of a consecutive series of 218 white patients who had undergone cementless total hip arthroplasty from April to December 2009. All patients received a cementless custom-made titanium femoral component[17]. The femoral stem was manufactured on the basis of standardized preoperative CT scans of the affected hip.

Patients with a history of trauma (n = 3), infection (n = 2), rheumatic disease (n = 8), hip dysplasia (n = 18), previous pelvic and/or femoral osteotomy (n = 13), osteonecrosis of the femoral head (n = 12), or Legg-Calvé-Perthes disease or slipped capital femoral epiphysis (n = 5) were excluded from the present study. Hip dysplasia was defined as a center-edge angle of <20°[18], an acetabular angle of >42°[19], and/or an acetabular index of <38%[20]. In bilateral cases, only the first hip to undergo total hip arthroplasty was included in the study cohort. Twenty-six cases with inadequate radiographs or CT scans were also excluded. One hundred and thirty-one patients (fifty-seven male and seventy-four female; mean age, sixty years [range, forty-two to seventy-nine years]; mean body mass index, 27 kg/m^2 [range, 19 to 45 kg/m^2]) (see Appendix) with primary end-stage hip osteoarthritis fulfilled the inclusion criteria and were included in the present study. Preoperative radiographs and CT scans were retrieved in generic DICOM (Digital Imaging and Communications in Medicine) format. All patients had provided informed consent for the CT scan with the understanding that the CT scan would be obtained to guide the manufacturing of the femoral component but would not likely alter the planned treatment. The study was approved by our institutional review board (reference S-272/2009).

CT Protocol

All hip CT scans were performed preoperatively with use of a Toshiba Aquilion 16 CT scanner (Toshiba, Tokyo, Japan). Patients were positioned supine with their legs in neutral rotation as confirmed by scout views. The scans were

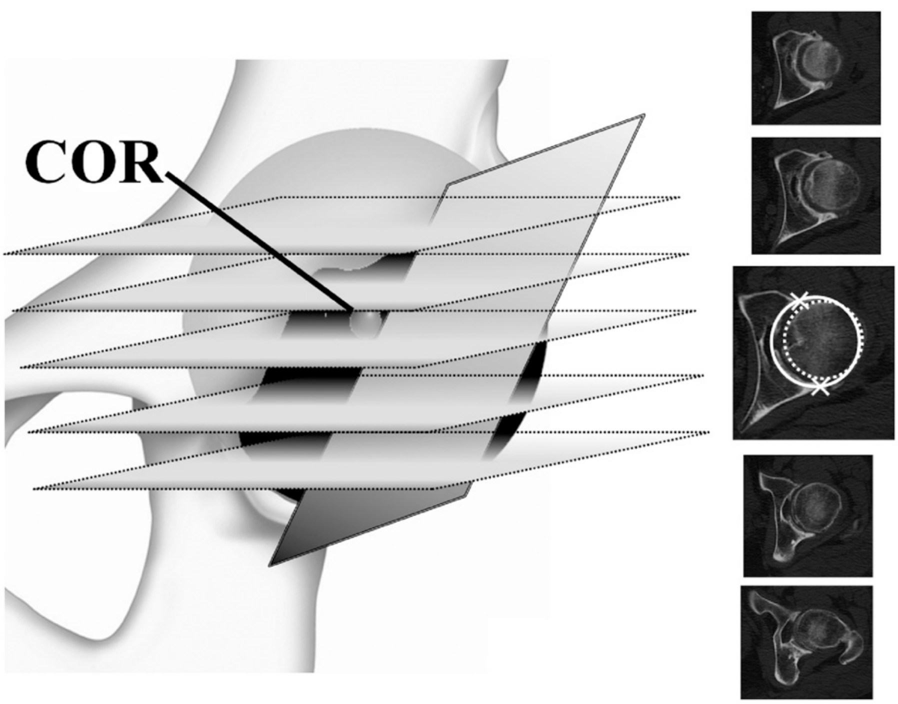

Fig. 1
CT-based model to determine acetabular orientation on five axial slices. COR = center of rotation.

TABLE I Measurements of Native Femoral and Acetabular Anatomy

	Mean ± SD (Range)			P Value for Difference Between Male and Female
	Cohort (N = 131)	Male (N = 57)	Female (N = 74)	
Femoral anteversion *(deg)*	13.3 ± 10.18 (−6.7-56.8)	12.0 ± 8.25 (−3.0-35.9)	14.3 ± 11.40 (−6.7-56.8)	0.239
Head diameter *(mm)*	47.4 ± 4.78 (35.8-62.4)	51.2 ± 3.50 (45.1-62.4)	44.6 ± 3.49 (35.8-57.0)	<0.001
Rim diameter *(mm)*	54.2 ± 5.17 (41.5-69.6)	57.9 ± 3.72 (50.9-69.6)	51.3 ± 4.21 (41.5-69.6)	<0.001
Acetabular inclination *(deg)*	62.1 ± 7.46 (30.2-75.7)	62.0 ± 6.60 (37.1-75.7)	62.1 ± 8.11 (30.2-75.6)	0.573
Acetabular anteversion *(deg)*	19.3 ± 6.98 (0.7-35.1)	18.5 ± 7.10 (0.7-35.1)	19.9 ± 6.89 (4.3-33.2)	0.244
Pelvic tilt *(deg)*	7.7 ± 6.58 (−13.0-26.6)	9.6 ± 6.32 (−6.5-26.6)	6.22 ± 6.42 (−13.0-17.2)	0.008
Combined anteversion *(deg)*	32.6 ± 12.08 (5.7-70.7)	30.5 ± 11.04 (5.7-51.7)	34.2 ± 12.66 (6.4-70.7)	0.146

obtained in three sets: (1) from the cranial aspect of the acetabulum to below the lesser trochanter, (2) from below the lesser trochanter to a point 50 mm distal to the femoral isthmus, and (3) four to six slices of the knee. Slice spacings of 4 mm, 8 mm, and 2 mm were used, respectively. All scans were recorded with a gantry tilt of 0°, 120 kV, and a field of view of 250 mm.

CT Measurements

A validated MATLAB (matrix laboratory) program (version 7.10; The MathWorks, Natick, Massachusetts) was used to perform CT-based measurements. The program enabled the user to select points from preselected axial CT slices and performed vector-based calculations in the three-dimensional coordinate system of the CT scanner.

To determine acetabular orientation, five CT slices were selected (Fig. 1). Thirty points (six on each slice) defined the native lunate surface, ten points (two on each slice) defined the acetabular rim, and thirty points (six on each slice) defined the femoral head. A sphere was fitted to the outline of the subchondral plate of the femoral head to determine the three-dimensional femoral head center and diameter. Acetabular orientation was assessed by fitting a plane to the osseous vertices along the rim, and a sphere was fitted to the subchondral plate of the native lunate surface to represent the center of rotation. The diameter of the rim was calculated with a best-fit circle fitted to the points on the vertices. Acetabular inclination and version were defined by the relationship of the acetabular rim plane to the coordinate system of the CT scanner[12]. To correct for the effects of pelvic tilt on acetabular version for each individual case, the tilt of the anterior pelvic plane was determined on lateral scout views as the plane between the midpoint of the anterior aspect of both anterior superior iliac spines and the midpoint of the most anterior aspect of the pubic tubercles[21]. Pelvic tilt was calculated as the angle between the anterior pelvic plane and the coronal plane, with positive values representing pelvic extension and negative values representing pelvic flexion. For each degree of tilt, anatomical acetabular version values were corrected by 0.7°[22,23].

For the calculation of femoral anteversion, the femoral neck axis was defined with use of the single-slice method described by Sugano et al.[24], and the posterior condylar axis was defined by the most posterior aspect of the lateral and medial condyles. The angle between the femoral neck axis and the posterior condylar axis represented femoral anteversion (Fig. 2). Combined anteversion of the hip was calculated as the sum of acetabular and femoral anteversion.

The standard deviation (SD) of the residuals for the sphere fits was 0.57 mm for the femoral head and 0.73 mm for the lunate surface. The SD of the residuals for the plane fit to the rim was 1.92 mm.

Safe Zones

Native acetabular and femoral anatomy in the present cohort was assessed with regard to the safe zone for acetabular orientation as described by Lewinnek et al.[5] (inclination of 40° ± 10° and anteversion of 15° ± 10°). It is possible to measure anteversion and inclination with use of three different reference frames: radiographic, anatomical, and operative. Because the Lewinnek angles relate to the radiographic reference frame and the combined angles relate to the anatomical reference frame, it was necessary to convert the data to enable direct comparison. The Lewinnek angles were converted to anatomical values with use of Murray's nomograms[25], resulting in a mean anatomical inclination of 42.3° (range, 30.4° to 54.4°) and a mean anatomical anteversion of 22.6° (range, 6.5° to 43.0°).

Additionally, the native combined anatomical anteversion was evaluated with reference to a safe combined anatomical anteversion of 20° to 40°.

Measurement Accuracy and Reliability

The measurement program was validated according to the following protocol. A hemispheric three-dimensional cup geometry with a 56-mm diameter was virtually implanted into a pelvis model that had been created by the segmentation of CT scans. The cup was inserted at a range of angles (anteversion, from −5° to 25°; inclination, from 35° to 65°). Synthetic CT scans were created from the three-dimensional pelvis model by sectioning the geometric model into slices with a thickness of 2 mm, applying an attenuation algorithm. The synthetic CT scans were then analyzed with use of the measurement software with repeated measurements for cup diameter, version, and inclination.

Intraobserver and interobserver reliabilities of the measurements made by two independent blinded observers for twenty randomly selected patients were evaluated by using single-measure intraclass correlation coefficients with a two-way random-effects model for absolute agreement.

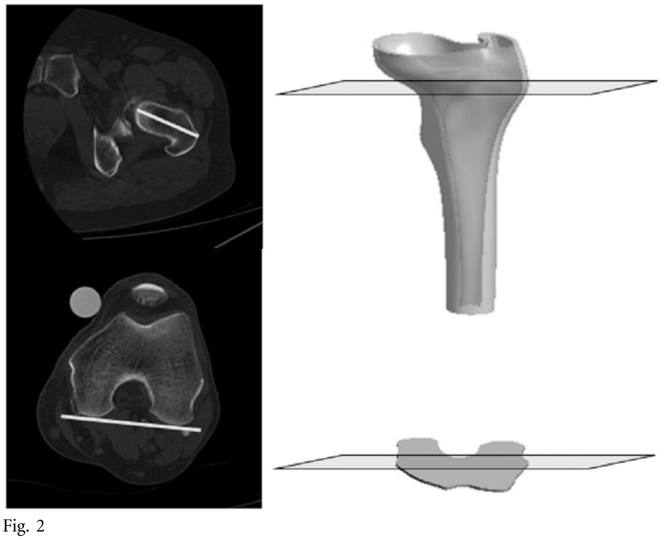

Fig. 2

CT-based measurement of femoral anteversion as described by Sugano et al.[24].

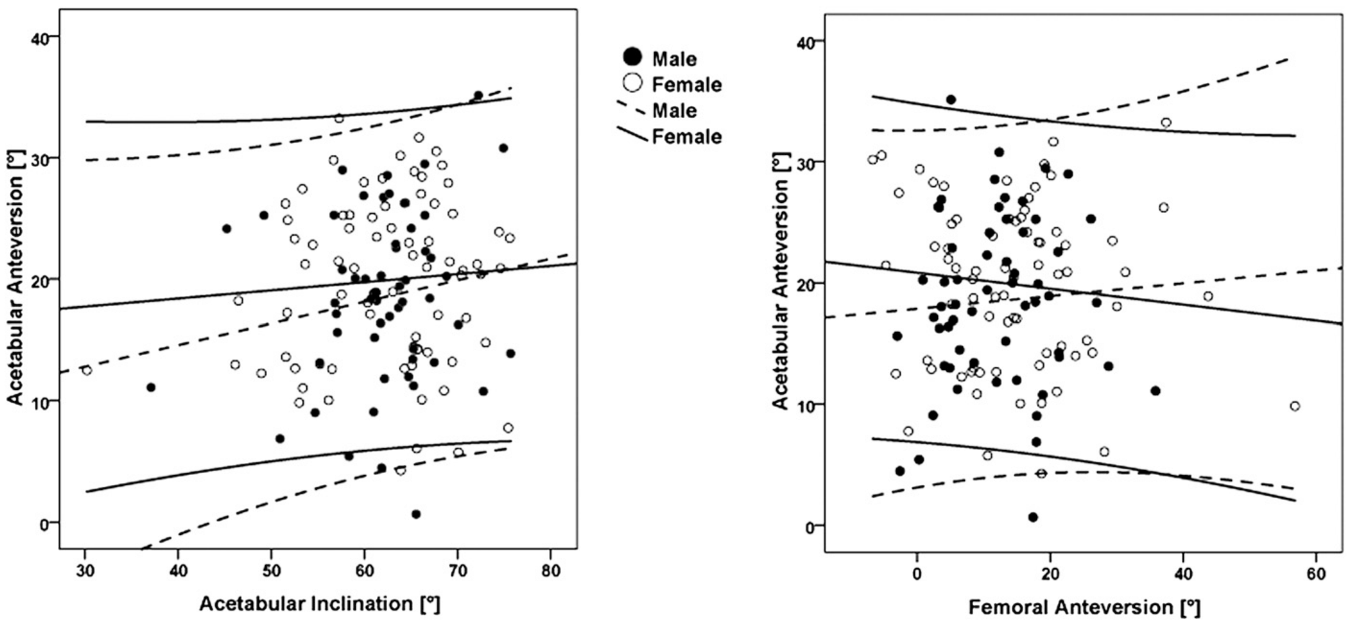

Fig. 3
Scatter plots illustrating no significant correlation between acetabular anteversion and acetabular inclination or femoral anteversion.

Statistical Analysis

For descriptive analysis, absolute mean values and differences were expressed in millimeters or degrees and included SDs. The distributions of variables were examined in exploratory data analysis and were tested for normality with use of Kolmogorov-Smirnov tests. Because not all variables met the criteria for a normal distribution, we used nonparametric tests. Differences in obtained values between male and female patients were analyzed with use of Mann-Whitney U tests for unpaired observations. A Spearman correlation coefficient (r_s) was used to evaluate associations among continuous variables. Results with p values of <0.05 were considered significant. Statistical analysis was carried out with use of PASW Statistics 18 (SPSS, Chicago, Illinois)

Source of Funding

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Results

Measurement Accuracy and Reliability

Repeated measurements of cup diameter of the virtual pelvis model resulted in a mean error of 0.25 mm (SD, 0.62 mm) for a 56-mm cup. The mean measurement error was 0.78° (SD, 0.66°) for cup version and 1.64° (SD, 1.44°) for cup inclination. For CT-based measurements, intraobserver intraclass correlation coefficients ranged from 0.89 to 0.99 and interobserver intraclass correlation coefficients, from 0.87 to 0.99. Pelvic tilt measurements demonstrated intraclass correlation coefficients of 0.93 and 0.84, respectively.

CT Measurements

In the entire cohort, the mean femoral head diameter was 47 mm (SD, 4.8 mm; range, 36 to 62 mm) and the mean acetabular rim

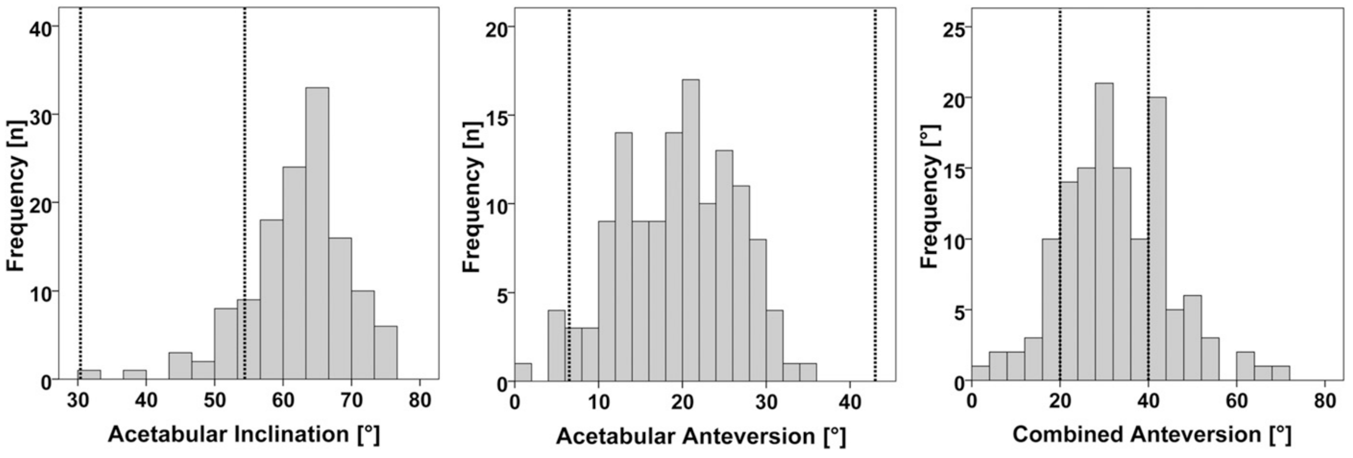

Fig. 4
Bar graphs illustrating the distribution of acetabular inclination, acetabular anteversion, and combined anteversion (all in degrees) with regard to the defined safe zones (shaded areas).

diameter was 54 mm (SD, 5.2 mm; range, 42 to 70 mm). The mean femoral anteversion was 13° (SD, 10.2°; range, −7° to 57°), and the mean acetabular anteversion was 19° (SD, 7.0°; range, 0.7° to 35°). No differences in femoral anteversion, acetabular anteversion, or combined anteversion were observed between male and female patients (femoral anteversion, $p = 0.239$; acetabular anteversion, $p = 0.244$; combined anteversion, $p = 0.146$). The mean acetabular inclination was 62° (SD, 7.5°; range, 30° to 76°). There was no difference between acetabular inclination between female and male patients ($p = 0.573$) (Table I).

We did not observe a correlation between native femoral and acetabular anteversion ($r_s = 0.069$, $p = 0.437$) or between native acetabular inclination and anteversion ($r_s = 0.089$, $p = 0.313$; Fig. 3). Pelvic tilt demonstrated a wide scatter and was significantly higher in male patients (10°) than in female patients (6°, $p = 0.008$; Table I).

Safe Zones

Ninety-five percent (125) of the native acetabula were classified as being within an anatomical anteversion of 6.5° to 43.0°, which corresponds to the radiographic anteversion target zone of 15° ± 10° described by Lewinnek et al.[5]. In contrast, only 15% (nineteen) of the native acetabula were classified as being within an anatomical inclination of 30.4° to 54.4°, which corresponds to a radiographic inclination of 40° ± 10°. Combined anteversion was within the safe limits of 20° to 40° in the anatomical reference frame in 63% (eighty-three) of the patients (Fig. 4). However, only 8% (ten) of the patients had native acetabular and femoral orientation that met the criteria of both "safe zone" definitions (that of Lewinnek et al. and combined anteversion).

Discussion

Component orientation in total hip arthroplasty varies considerably by surgeon, with some advocating the reproduction of native anatomy and others preferring to aim for a predefined target zone. Consequently, a wide scatter of acetabular component orientations has been reported in previous studies, with the percentage of cases within Lewinnek's safe zone ranging from 25% to 80%[26-28]. The clinical relevance of Lewinnek's safe zone remains a matter of debate. Recently, Rittmeister and Callitsis[9] reported that dislocation was not more frequent when the component had been placed outside the safe zone in a retrospective analysis of 500 total hip arthroplasties. Another study showed that, for hip resurfacings, the optimal radiographic target was approximately 45° of inclination and 20° of anteversion. With the accuracy of implantation assumed to be ±10° around this target position, the incidence of pseudotumors in patients whose component had been placed inside this zone was four times lower than it was in patients with a component placed outside this zone[3].

With regard to femoral component orientation, data are very limited. Wines and McNicol[29] reported that 71% of femoral components were oriented within 10° to 30° of anteversion. Using computer navigation, Dorr et al.[1] found that 96% of femoral components were within a combined anteversion of 25° to 45°. Although the concept of combined anteversion has been validated in computer modeling[7,8], its clinical relevance remains unclear because no clinical study has yet demonstrated a significant effect of combined anteversion on complication rates or implant survival after total hip arthroplasty. For hip resurfacing, Daniel et al.[30] recently found that component positioning within the target anteversion decreased the risk for developing a pseudotumor.

Whether native anatomy provides a valid intraoperative reference for component positioning when the surgeon is aiming for a defined target zone remains controversial. Some studies have demonstrated that replication of native landmarks, such as the transverse acetabular ligament, can be used to determine intraoperative positioning of the acetabular component[11,31]. In contrast, recent studies have raised questions about the validity of using native anatomy as recommended landmarks for component orientation[10,12].

In the present study, we evaluated the variations in femoral and acetabular anatomy in a cohort of patients with primary end-stage hip osteoarthritis. Then we determined whether their native femoral and acetabular anatomy corresponded to recognized surgical recommendations for safe component orientation in total hip arthroplasty—that is, Lewinnek's "safe zone" and the concept of safe combined anteversion. We found that the native anatomy of the arthritic hip is highly variable, which confirms previous findings, and the mean values for acetabular inclination and version, femoral version, and combined anteversion in the present study cohort compared well with the reported values in the literature[12-14]. Although the values of acetabular and femoral anteversion were slightly higher for the female patients, we did not detect a significant difference in the distribution of the parameters between the sexes, which may be a result of the strict exclusion criteria for all secondary forms of osteoarthritis and the fact that accounting for pelvic tilt reduced differences in acetabular version between male and female patients. The male patients in the present cohort had substantially greater pelvic extension than the female patients, which confirms findings in previous reports[32] and may be attributed to the more severe hip flexion contractures seen in male patients.

The results of the present study indicate that reproducing the native anatomy for acetabular inclination will result in component inclination that is much greater than Lewinnek's "safe zone" value. A reduction of native acetabular inclination by 15° during cup implantation while maintaining acetabular version would have resulted in safe component inclination in 86% (113) of the hips. In contrast, following the osseous landmarks of the native acetabular rim would have resulted in accurate component anteversion in 95% (125) of the cases. This observation is in line with the findings of Murtha et al.[10]. In addition, 63% (eighty-three) of the patients had a native combined anteversion within the defined "safe" limits. In the present study cohort, we found neither an association between acetabular version and inclination nor an association between acetabular and femoral version. The lack of correlation between these parameters suggests that the native anatomy of the osteoarthritic hip is highly variable and thus may be fundamentally different from the placement requirements for a well-functioning artificial joint. Whereas the osseous acetabular rim is of value to determine the anteversion of the cup intraoperatively with reference to Lewinnek's target zone, native acetabular inclination and combined anteversion cannot be considered reliable landmarks because of the lack of correlation and the variability.

The present study has both strengths and limitations. First, the target population consisted of patients with primary end-stage hip osteoarthritis. The irregularity of the native rim and the presence of arthritic osseous alterations may have affected the measurements. We did not exclude specific regions of the acetabulum that have been reported to deviate from planar and spherical representations[10]. The presence of osteoarthritis and associated deformity such as osteophytes or coxa profunda may have influenced the measurements and may explain the relatively large residual values calculated for the planar and spheric fits with regard to the lunate surface and osseous acetabular rim. However, the points were selected at the anterior and posterior vertices of the acetabular rim and the subchondral outline of the lunate surface because these are osseous landmarks that can be well visualized during surgery. The landmarks could also be reliably identified on the CT scans, as evidenced by the intraobserver and interobserver reliability of the CT-based measurements. Moreover, strict exclusion criteria were applied to exclude patients with secondary forms of osteoarthritis and underlying morphological abnormalities. Hence, the present cohort can be considered to be representative of patients undergoing total hip arthroplasty because the leading reason for total hip arthroplasty is primary osteoarthritis[33]. Over the last three decades, cadaver, radiographic, and CT-based studies have demonstrated that the anatomy of the proximal part of the femur and the acetabulum is highly variable[13-15]. However, there is a lack of studies on the native anatomy of patients with osteoarthritis of the hip joint who actually underwent total hip arthroplasty and the native anatomy of patients with osteoarthritis may be different from those of healthy individuals[34].

Second, preoperative CT scans were performed for use in the manufacturing of the cementless femoral component employed in this cohort, and the CT protocol aimed to minimize radiation exposure and metallic artifacts of a contralateral total hip arthroplasty. Thus, CT data were limited to the affected hip joint, and geometric calculations could not be performed with reference to the osseous coordinate system, such as the anterior pelvic plane. It has been reported that orienting osseous landmarks in the direction of an external coordinate system is prone to error, mainly because of the difficulty in controlling patient positioning and pelvic tilt[22]. To account for this, we confirmed the patient position in the scanner according to a standardized protocol and excluded patients with pelvic obliquity or rotation. Additionally, we corrected for effects of pelvic tilt by assessing differences between the anterior pelvic plane and the coronal plane on lateral scout views.

Third, the three-dimensional models of acetabular orientation and size were built by fitting a plane to the vertices of the acetabular rim and a sphere to the native lunate surface. This may have simplified the true three-dimensional acetabular anatomy. The true native rim is irregular and has a waveform[35]; consequently, each generated plane and the resulting acetabular orientation is relative to exactly where and how many points are measured. Thus, the generated plane is artificial and hence the present model is potentially prone to measurement errors. We did not perform any validation measurements in cadaveric specimens, which would again pose the question of what true version and inclination are. However, we have clearly demonstrated that the implemented measurement protocol is able to accurately and reliably measure the predefined orientation of a virtual cup of known inclination and version in synthetic CT scans of a pelvic model.

It is also evident that hips with end-stage osteoarthritis have rim osteophytes. Intraoperatively, many surgeons trim away osteophytes or at least resect any bone that clearly appears vestigial. Although the native vertices of the anterior and posterior aspects of the native rim could be reliably identified on the CT scans used in our study, the individual judgment of the osseous rim and of the extent of osteophytes are other factors that may have led to potential inaccuracy and variability in the values reported for the orientation of the native arthritic hip.

Last, the true axis of the femoral neck used to evaluate three-dimensional femoral version can be determined only by means of a three-dimensional reconstruction of the neck portion, which was limited with the present CT protocol because a 1-mm slice interval is required for this purpose. However, the selected single-slice method chosen in the present study has demonstrated sufficient accuracy for femoral anteversion measurements when the slice chosen for determining the femoral neck axis is just below the femoral head.

The data from the present study do not allow us to establish the orientation of a healthy, nonarthritic hip joint and cannot answer the question of whether we should replicate a physiologic anatomy or aim for predefined target zones. Rather, the aim of the study was to determine to what extent the osseous morphology of the arthritic hip that we encounter during surgery may be useful to guide intraoperative component placement.

In conclusion, the present study highlights the great variability in native acetabular and femoral anatomy in patients with primary hip osteoarthritis. If individual patient anatomy had been reconstructed in the total hip arthroplasties, only ten (8%) of the cases in the present cohort with primary osteoarthritis would have had component orientation that met the criteria of both "safe zone" definitions. Acetabular anteversion in the osteoarthritic hip as defined by the native acetabular rim typically matches the recommended component targets for cup insertion. There was no specific relationship among native acetabular inclination, acetabular anteversion, and femoral anteversion. Neither native acetabular inclination nor native combined anteversion appears to be related to current implant insertion targets.

Appendix

eA A table showing patient demographic characteristics is available with the online version of this article as a data supplement at jbjs.org. ■

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