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# Femoral Valgus Leads to Earlier Total Hip Arthroplasty Independent of Acetabular Coverage, While Varus Deformity Has a Protective Effect

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ABSTRACT

*Background:* The presence of acetabular dysplasia or femoro-acetabular impingement increases the chance of an earlier total hip arthroplasty (THA). Surprisingly, the influence of femoral and acetabular parameters on the age at which THA is required remains poorly investigated. The aim of this study was to evaluate the radiographic hip morphotype at the time of THA using an artificial intelligence-based analysis to assess potential differences.

*Methods:* Overall, 6,767 patients (mean age 66 years [range, 16 to 99]; women: 60.6%; men: 39.4%) from a single orthopaedic center were included in the final analysis. Images were analyzed using artificial intelligence-powered software. The lateral-center-edge angle and the neck-shaft angle (caput-collum-diaphyseal) were used to determine the nine different hip morphotypes based on the coronal plane alignment of the hip (CPAH, I to IX).

*Results:* Patients who had valgus-aligned femoral necks (CPAH, I, IV, and VII) were significantly younger at the time of THA compared to patients who had femoral varus necks (CPAH, III, VI, and IX), suggesting a potential negative effect of valgus and a protective effect of varus alignment independent of acetabular coverage. Type I hips, defined as acetabular undercoverage in combination with femoral valgus alignment, were on average 16.2 years younger at the time of THA compared to type IX hips with acetabular overcoverage and varus alignment.

*Conclusions:* The hip morphotype had a major impact on the timing of THA. Femoral varus neck alignment demonstrated a protective effect across all age groups, whereas acetabular undercoverage and femoral valgus necks were associated with an earlier need for THA.



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Total hip arthroplasty (THA) is the preferred treatment for end-stage osteoarthritis when conservative management has failed [1]. Positive outcomes have also been observed in patients who had mild to moderate osteoarthritis, where joint-preserving procedures may not be suitable. This is due to the limited correlation between radiographic signs of hip osteoarthritis and pain or functional impairment [2,3]. Although it is widely accepted that conditions such as hip dysplasia and femoro-acetabular impingement necessitate early THA [4], it is surprising that no comprehensive study has yet examined the combined impact of femoral and acetabular parameters on the likelihood of requiring THA.

Altered biomechanical loading patterns in individuals who have various hip morphologies with suboptimal joint positions result in changes within contact areas, increased static loads, and, ultimately, the progression of hip pain and decreased function with the necessity for THA [3,5,6]. These common abnormalities, like acetabular undercoverage or overcoverage, are usually quantified by predefined measures such as the lateral-center-edge (LCE) angle or the acetabular index, whereas the shape of the proximal femur can be quantified with the neck-shaft angle (caput-collum-diaphyseal [CCD]) [7]. Similar to the knee morphotype classification proposed by MacDessi et al. [8], an antero-posterior (AP) coronal plane alignment classification of the hip may provide valuable insight into identifying hips at risk for early THA.

Recent advances in artificial intelligence (AI) have facilitated the rapid evaluation of thousands of radiographic images within minutes [9]. Large-scale analyses of well-established clinical parameters like the aforementioned LCE and CCD angles could reveal previously unrecognized predictive factors associated with an early need for THA that can be easily reproduced in daily clinical practice. These findings could help identify hips at risk and generate future research questions, ultimately contributing to the improvement of treatment algorithms in the foreseeable future.

The aim of this study was to evaluate the radiographic acetabular and femoral morphology at the time of THA using AI-based analysis in a large single-center cohort. We sought to determine whether specific morphological conditions influence the timing of THA. In addition, we aimed to establish an AP coronal plane alignment classification of the hip, consisting of nine distinct hip morphotypes.

## Material and Methods

This retrospective cohort study was approved by the institutional review board (EK47/2020) and was conducted according to the principles of the Declaration of Helsinki (October 2013) and in accordance with the Medical Research Involving Human Patients Act. We analyzed our prospectively maintained institutional arthroplasty registry of our tertiary care academic center of all THAs between September 1, 2008, and May 31, 2021, resulting in 10,823 primary THAs. Posttraumatic hips, patients after pelvic or femoral osteotomies, Perthes disease, and metabolic or genetic bone disease were excluded. A total of 7,765 hips with preoperative radiographs from 6,767 patients were included in the final analysis. There were 4,709 THAs for women and 3,056 THAs for men (men: 39.4%, women: 60.6%). The average age of the patients was 66 years (range, 16 to 99); the mean age for men was 64 years (range, 16 to 92), and the mean age for women was 66 years (range, 17 to 99). The mean body mass index (BMI) of all patients was 27.6 (range, 12.5 to 62.4); of men, 28.2 (range, 12.5 to 48.2) and of women 27.1 (range, 15.2 to 62.4).

Patients undergoing THA receive a standardized pelvic radiograph before surgery. Patients are positioned antero-posteriorly in a standing position with their legs internally rotated by 15°, and the detector is placed in direct contact with the patient's body. The central beam is directed toward the midpoint of the symphysis, and the film focus distance is set at 150 cm. To ensure accurate length measurements, a 25-mm calibration ball is included in each radiograph. Cutoff values for pelvic tilt and rotation are applied based on the threshold values established by Tannast et al. [10]. Radiographs are repeated if these values are exceeded.

All images were taken either with the Philips DigitalDiagnost (Philips GmbH, Hamburg, Germany) or Siemens Luminos (Siemens Healthcare GmbH, Erlangen, Germany) fluoroscopy system.

### *Hip Measurements*

All measurements were automatically performed with the IBLab HIPPO software (Hip Positioning Assistant 1.03; ImageBiopsy Lab, Vienna, Austria), which was previously validated in clinical and research settings [11]. The software was run containerized using Docker on standard modern hardware with an Intel i7 CPU and 32 GB RAM in the operating system Ubuntu 22.04, with images stored on an external password-protected hard disk drive. All images were further manually checked, and in case of erroneous landmark setting, measurements were repeated with mediCAD v6.0 (Hectec GmbH, Landshut, Germany). A total of 912 radiographs had to be manually remeasured by one of the authors (G.M.S., S.S., J.A.M., or S.H.).

The following parameters were measured: LCE angle, Tönnis angle, Sharp angle, extrusion index, and CCD angle. In addition, the patient's age, sex, height, and weight at the time of surgery from the institutional database were included in the analysis. The following cutoff values for dysplastic hips were used in this study: LCE angle less than 23° [12], acetabular index greater than14° [7], extrusion index greater than 27% [7], and sharp angle greater than 43° [7]. We further categorized the CCD angle into normal 120 to 140°, coxa vara less than 120°, and coxa valga greater than or equal to 140°. To combine both the acetabular and the femoral morphology, we created nine groups based on the LCE and CCD angles appearing on AP pelvic radiographs in the coronal plane (Table 1, Figure 1). As the correlation between radiographic osteoarthritis and clinical osteoarthritis (necessity for THA) is limited, our primary endpoint was the need for THA [2,13].

Data analyses were performed with GraphPad Prism (9.1.0; GraphPad Software Inc., San Diego, California), R (R Foundation for Statistical Computing, Vienna, Austria), and an Excel Sheet (Microsoft Corporation, Redmond, Washington). We used descriptive statistics, including means (M), ranges (range), and percentages. Data were subdivided depending on sex (women/men) and hip morphotype based on LCE and CCD angles. Differences between hip morphotype groups regarding age, sex, and BMI were assessed using one-way analysis of variance.

## Results

### *Sex-Specific Differences*

We observed sex-specific distribution differences in the coronal hip morphotype and therefore displayed them separately. Valgus alignment of the femoral neck, defined by a CCD angle greater than or equal to 140°, was more common in women (men: 3.5; women: 10.5%), whereas varus alignment (CCD less than 120°) was more common in men (men: 17.6; women: 12.7%). The distribution was similar for normally-aligned (CCD 120 to 140°) femoral necks between men (78.9) and women (76.8%). Acetabular undercoverage, defined by LCE less than 23°, was similar for both sexes (men: 24.3; women: 22.4%), whereas acetabular overcoverage was more common in women (men: 29.0; women: 35.2%), and normal acetabular coverage was more common in men (men: 46.7; women: 42.5%).

**Table 1**
Demographic Overview for Each Hip Morphotype Based on the Coronal Plane Alignment of the Hip Classification (CPAH, I to IX).

| | Valgus CCD ≥140° | | Normal CCD 120 to 139.9° | | Varus CCD <120° | |
|---|---|---|---|---|---|---|
| | Men | Women | Men | Women | Men | Women |
| CPAH Types | Type I | | Type II | | Type III | |
| Sex-Specific % (N) | 1.3 (40) | 3.9 (186) | 20.3 (620) | 17.0 (800) | 2.7 (82) | 1.4 (67) |
| Undercoverage LCE <23° | | | | | | |
| Age (years) | 53 ± (range, 17 to 78) | 55 (range, 20 to 87) | 61 (range, 27 to 90) | 62 (range, 19 to 89) | 65 (range, 39 to 92) | 65 (range, 26 to 85) |
| BMI | 29.0 (range, 29.7 to 42.1) | 26.6 (range, 17.3 to 52.3) | 27.7 (range, 19.9 to 44.0) | 26.4 (range, 16.1 to 62.4) | 27.4 (range, 19.9 to 44.0) | 26.6 (range, 19.0 to 38.3) |
| LCE (°) | 12.6 (range, −14.5 to 22.2) | 14.9 (range, −15.3 to 22.7) | 17.8 (range, −3.1 to 22.8) | 16.6 (range, −16.0 to 22.9) | 18.6 (range, 3.0 to 22.8) | 16.9 (range, −5.1 to 22.4) |
| CCD (°) | 145.9 (range, 140.0 to 162.7) | 144.6 (range, 140.0 to 166.7) | 127.9 (range, 120.0 to 139.8) | 130.7 (range, 120.0 to 139.9) | 116.4 (range 102.0 to 119.3) | 114.6 (range, 93.0 to 119.9) |
| Extrusion Index (%) | 32.7 (range, 15.0to 58.0) | 30.8 (range, 10.0 to 74.0) | 26.1 (range, 0.0 to 50.0) | 26.7 (range, −6.0 to 58) | 22.5 (range, −3.0 to 46.0) | 22.3 (range, 4.0 to 40,0) |
| Sharp Angle (°) | 42.0 (range, 35.0 to 50.3) | 43.9 (range, 32.5to 63.0) | 39.3 (range, 29.0 to 54.1) | 42.6 (range, 1.4 to 58.5) | 39.5 (range, 21.2 to 52.0) | 42.8 (range, 35.0 to 54.0) |
| Tönnis Angle (°) | 22.3 (range, 7.0 to 37.1) | 21.3 (range, 4.0 to 47.0) | 16.4 (range, 3.0 to 46.2) | 19.5 (range, −1.0 to 43.4) | 16.4 range, 5.0 to 44.8) | 19.3 (range, 9.0 to 32.0) |
| CPAH Types | Type IV | | Type V | | Type VI | |
| Sex-Specific % (N) | 1.3 (41) | 3.7 (174) | 37.4 (1,143) | 34.2 (1,609) | 8.0 (243) | 4.6 (216) |
| Normal Coverage LCE 23-33° | | | | | | |
| Age (years) | 61 (range, 24 to 82) | 64 (range, 40 to 87) | 64 (range, 22 to 92) | 67 (range, 17 to 92) | 66 (range, 35 to 89) | 69 (range, 36 to 90) |
| BMI | 28.6 (range, 16.9 to 39.2) | 27.5 (range 17.0 to 45.1) | 28.3 (range, 16.4 to 46.7) | 27.4 (range, 15.2 to 53.3) | 27.7 (range, 16.4 to 46.7) | 27.8 (range, 18.7 to 49.3) |
| CCD (°) | 144.5 (range, 140.0 to 152.5) | 143.7 (range, 140.0 to 157.4) | 127.0 (range, 120.0 to 139.3) | 129.0 (range, 120.0 to 139.0) | 116.1 (range, 105.0 to 119.6) | 116.0 (range, 100.7 to 119.2) |
| Extrusion Index (%) | 19.8 (range, 1.0 to 34.0) | 17.3 (range, 0.0 to 38.0) | 17.9 (range, −24.0 to 63.0) | 15.0 (range, −6.0 to 57.0) | 16.2 (range, −11.0 to 33.0) | 12.3 (range, −17.0 to 35.0) |
| Sharp Angle (°) | 37.6 (range, 31.0 to 52.0) | 38.9 (range, 31.0 to 50.0) | 36.0 (range, 25.0 to 48.0) | 37.9 (range, 27.0 to 49.0) | 36.2 (range, 24.4 to 45.0) | 37.6 (range, 29.0 to 48.0) |
| Tönnis Angle (°) | 13.6 (range, 3.1 to 37.0) | 13.5 (range, 2.0 to 25.0) | 10.7 (range, −4.0 to 29.0) | 11.9 (range, −2,0 to 35.7) | 11.0 (range, 2.0 to 32.6) | 11.9 (range, 0.0 to 48.0) |
| Types | Type VII | | Type VIII | | Type IX | |
| Sex-Specific % (N) | 0.9 (27) | 2.9 (134) | 21.2 (648) | 25.6 (1,204) | 6.9 (211) | 6.7 (316) |
| Overcoverage LCE >33° | | | | | | |
| Age (years) | 61 (range, 29 to 78) | 64 (range, 17 to 87) | 66 (range, 20 to 90) | 69 (range, 31 to 99) | 69 (range, 16 to 88) | 72 (range, 43 to 96) |
| BMI | 31.3 (range, 19.8 to 42.8) | 26.8 (range, 10.2 to 46.8) | 28.6 (range, 12.5 to 48.2) | 27.3 (range, 15.6 to 50.8) | 28.6 (range, 20.8 to 44.1) | 27.1 (range, 16.0 to 46.1) |
| LCE (°) | 40.9 (range, 33.8 to 67.0) | 40.8 (range, 33.6 to 80.6) | 40.0 (range, 33.2 to 64.0) | 40.0 (range, 33.2 to 76.0) | 39.8 (range, 34.0 to 56.0) | 40.6 (range, 33.2 to 60.0) |
| CCD (°) | 143.4 (range, 140 to 154) | 143.7 (range, 140.0 to 156.2) | 126.3 (range, 120 to 139) | 128.3 (range, 120.0 to 139.7) | 115.4 (range, 104 to 119) | 115.3 (range, 99.0 to 119.6) |
| Extrusion Index (%) | 6.7 (range, −5.0 to 23.0) | 5.6 (range, −11.0 to 31.0) | 9.1 (range, −18.0 to 33.0) | 5.1 (range, −24.0 to 47.0) | 7.0 (range, −13.0 to 27.0) | 2.9 (range, −26.0 to 25.0) |
| Sharp Angle (°) | 32.5 (range, 19.9 to 41.0) | 34.9 (range, 21.0 to 44.0) | 32.9 (range, 18.0 to 45.2) | 34.1 (range, 22.0 to 49.0) | 33.1 (range, 22.1 to 43.0) | 33.9 (range, 24.0 to 46.0) |
| Tönnis Angle (°) | 5.7 (range, −5.0 to 21.0) | 6.6 (range, −8.0 to 20.0) | 5.6 (range, −12.0 to 27.0) | 5.6 (range, −16.0 to 35.0) | 5.1 (range, −10.0 to 18.0) | 5.3 (range, −11.0 to 22.0) |

For each type, the mean age, body mass index (BMI), lateral-center-edge (LCE) angle, caput-collum-diaphyseal (CCD) angle, extrusion index, sharp angle, and Tönnis angle are presented.

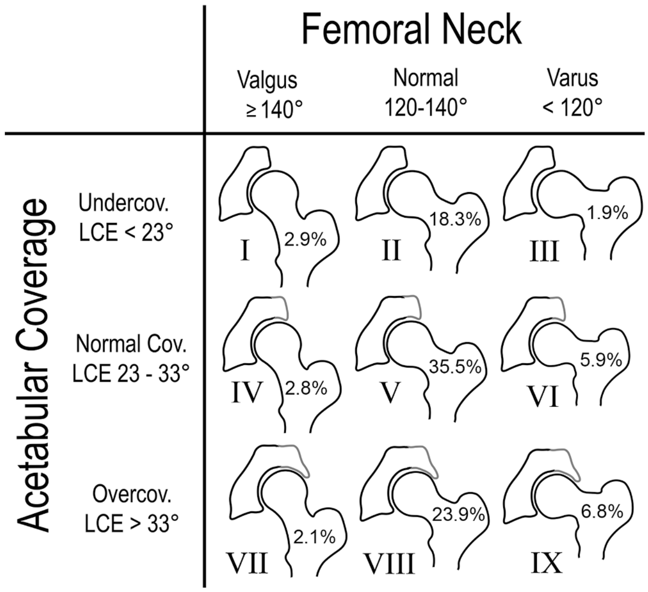


**Figure 1.** Schematic drawing of hip morphotypes based on the coronal plane alignment of the hip (CPAH, I to IX). LCE, lateral-center-edge.

The most common hip morphotype was type V (normal acetabular coverage + normal-aligned femoral neck) for both men (37.4) and women (34.2%), followed by type VIII (acetabular overcoverage + normal-aligned femoral neck, men: 21.2; women: 25.6%) and II (acetabular undercoverage + normal-aligned femoral neck, men: 20.3; women: 17.0%). For men, the least common morphotype was type VII (acetabular overcoverage + valgus-aligned femoral neck, 0.9%), whereas for women, type III (acetabular undercoverage + varus-aligned femoral neck) was the least common (1.4%). Detailed results can be found in Table 1.

Mean BMI values for all groups ranged between 27.0 and 27.8. In general, men had higher values compared to women. Sex differences were significant for type I ($P = 0.01$), II ($P < 0.001$), V ($P < 0.001$), VII ($P = 0.002$), VIII ($P < 0.001$), and IX ($P < 0.001$). The highest differences were found for type VII (men: 31.3; women: 26.8) and the lowest for type VI (men: 27.7; women: 27.8)

*Age-Specific Differences*

We observed significant hip morphotype differences regarding the age at which patients underwent THA ($P < 0.001$). The highest mean age at the time of surgery was found for type IX (acetabular overcoverage + varus-aligned femoral neck; 71 years, range, 16 to 96), and the lowest mean age for type I (acetabular undercoverage + valgus-aligned femoral neck; 54 years, range, 17 to 87). Distribution within men and women was similar, except for type I hips, which were relatively more prevalent under the age of 50 (18.2 versus 3.2%) for women.

The most common hip morphotype under the age of 50 years overall was type II (31.2%, acetabular undercoverage + normal-aligned femoral neck); for men, type V (31.8%, normal acetabular coverage + normal-aligned femoral neck) and for women, type II (31.5%). The least common type overall was type III (2.1%, acetabular undercoverage + varus-aligned femoral neck); for men, type VII (1.4%, acetabular overcoverage + valgus-aligned femoral neck) and for women, type III (1.8%, acetabular undercoverage + varus-aligned femoral neck) and type IX (1.8%, acetabular overcoverage + varus-aligned femoral neck).

In patients aged 50 to 74 years, type V (36.6%, normal acetabular coverage + normal-aligned femoral neck) was the most common type and type III (1.9%, acetabular undercoverage + varus-aligned femoral neck) was the least common. For men, type V (39.4%) was the most frequent and type VII (1.0%, acetabular overcoverage + valgus-aligned femoral neck) was the least frequent. In women also, type V (34.6%) was the most common morphotype, whereas type III (1.5%) was the least common.

For patients 75 years and older, the most common type again was V (overall: 34.9; men: 33.0; women: 35.8%) and the least common was type I (0.9%, acetabular undercoverage + valgus-aligned femoral neck). The least common types for men and women were type I (men: 0.3, women: 1.1%).

Although 29.4% of all type I hips were under the age of 50 years, only 3.0% of type IX hips needed surgery at that age. Contrary to that, the highest relative values for patients 75 years and older were seen for type IX and the lowest for type I: only 7.1% of all type I hips needed surgery after the age of 75 years compared to 38.6% of type IX hips. Detailed results for each type and age group can be found in Figure 2 and Supplementary Table 1.

Patients who had type I hips were significantly younger ($P < 0.001$, mean difference −6.9 years) compared to type II hips, whereas type III hips were significantly older ($P = 0.006$, mean difference +3.5 years). This negative effect of valgus and protective effect of varus-aligned femora on implant-free survival was also seen for hips with acetabular overcoverage and for hips with normal acetabular coverage: Type VII hips were significantly younger ($P < 0.001$, mean difference −4.1 years) compared to type VIII, and type IX were significantly older ($P < 0.001$, mean difference +2.7 years). In patients who had normal acetabular coverage, only the difference between varus and valgus-aligned femora was statistically significant ($P = 0.001$, +4.3 years). The biggest differences were seen between type I and type IX, with type I hips being on average 16.2 years younger at the time of surgery ($P < 0.001$). The corresponding Kaplan−Meier survival analysis can be found in Figure 3.

## Discussion

The present study illustrates differences in the hip morphotype as determined on a plain AP pelvic radiograph for patients undergoing THA. We could demonstrate nine different hip morphotypes based on acetabular coverage and proximal femur shape and their relation to an early or delayed necessity for THA. The most important findings of the present study are different distributions among age groups and the protective effect of varus alignment of the proximal femur, especially in cases of acetabular undercoverage and overcoverage.

With the rise of AI in recent years, large-scale analysis of patient cohorts has been made possible [9]. In the present study, 7,765 preoperative standing pelvic radiographs before THA were evaluated. The most common hip morphotype undergoing THA in the present study was type V hips, which were classified as normal acetabular coverage and a normal CCD angle. Overall, women were more often affected by the need for THA with an increasing relative percentage over their lifespan. The biggest difference in relative numbers between men and women was seen for type I hips, characterized as acetabular undercoverage and valgus neck deformity: 18.2% of all women with THAs under the age of 50 years were type I compared to only 3.2% in men.

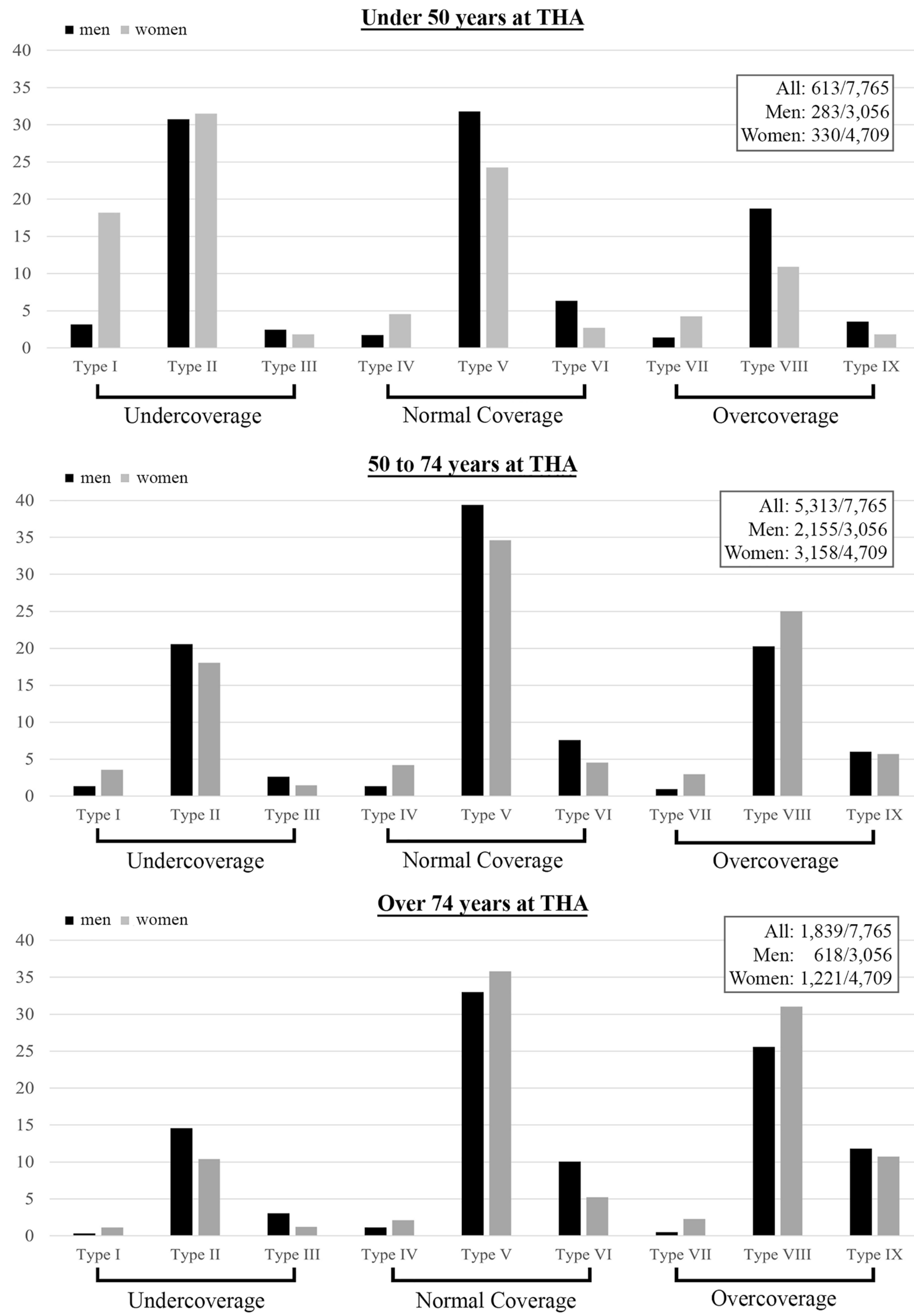


**Figure 2.** Distribution of hip morphotypes based on the coronal plane alignment of the hip (CPAH, I to IX) stratified by age group and sex at the time of total hip arthroplasty (THA).

Acetabular coverage, defined as an LCE angle less than 23°, was found in 44.6% of all patients under the age of 50 years, irrespective of the femoral shape, which is in accordance with previous results of smaller studies measuring the Tönnis angle for developmental dysplasia of the hip (40%) [6]. Most of those hips in our study were types I or II, which are characterized by a combination of acetabular undercoverage and valgus or normal femoral neck alignment. We could further see a statistically significant negative effect of valgus-aligned femora: type I hips were on average 6.9 years younger at the time of surgery compared to type II hips. Contrary to that, varus alignment had a protective effect on implant-free survival, and patients were on average 3.5 years older compared to hips with normal alignment and 10.4 years older compared to valgus hips in the case of acetabular undercoverage. Although the high risk of dysplastic hips for early THA has been widely accepted [6], the negative effect of valgus-aligned femora

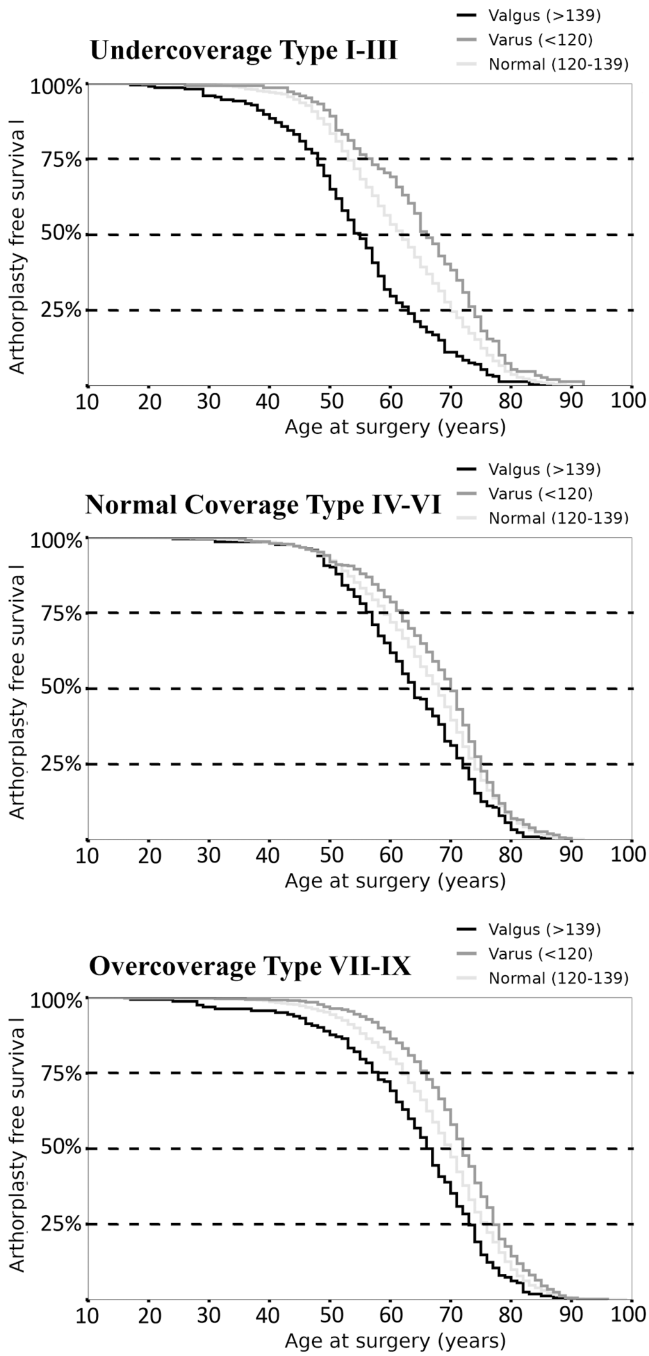


**Figure 3.** Kaplan–Meier analysis based on the coronal plane alignment of the hip (CPAH, I to IX). CPAH classification is defined by combining the lateral-center-edge (LCE) angle and the caput-collum-diaphyseal (CCD) angle. The upper image corresponds to hips with acetabular undercoverage (LCE <23°), the middle image to hips with normal acetabular coverage (LCE 23 to 33°), and the lower image to hips with acetabular overcoverage (LCE >33°). Valgus femora (CCD ≥140°) are marked in dark gray, varus femora (CCD <120°) in medium gray, and normal-aligned femora (CCD 120 to 139) in bright gray.

has only been published for anatomical cohorts [14] and suspected in studies with fewer patients [15].

Among patients aged 50 to 74 years, the most prevalent hip morphotype was type V, characterized by normal acetabular coverage and a normal CCD angle, followed by type VIII. Although dysplastic hips were also present in this age group, their relative frequency nearly halved (23.6%) compared to patients under 50 years of age. The protective or negative effects of varus (type VI) or valgus (type IV) femora were less pronounced in this cohort but remained significant, with valgus femora being, on average, 4.2 years younger. Unlike in the under-50-yage group, the distribution of types was similar for both men and women in this demographic.

In the patient cohort over 74 years at the time of THA, there was a further relative decrease in patients who had acetabular undercoverage (14.5%) and an increase in patients who had acetabular overcoverage (42.0%). Again, distributions between sexes were similar, but the protective effect of varus-aligned femoral necks increased statistically to 2.7 years compared to a normal CCD angle and 6.8 years compared to a valgus CCD angle.

### *Clinical Impact*

We demonstrated that both acetabular undercoverage and femoral valgus neck, individually or combined, lead to an earlier need for THA. Although the benefits of periacetabular osteotomies on patient-reported outcomes [16] and the natural history of dysplastic hips are well documented [17], the effectiveness of varization osteotomies of the femoral neck remains unproven. Our findings suggest a positive influence of varus-aligned femoral necks on THA-free survival, which has been previously discussed for complex hip deformities [18]. The role of proximal femur varization osteotomies in preventing early osteoarthritis, however, cannot be answered in the present study and requires further research.

### *Potential Limitations*

Several potential limitations should be considered in this study. Although the LCE and CCD angles are commonly used, these measurements are specific to the coronal plane and may not fully capture potential rotational deformities in the sagittal plane. Due to the overlapping of three-dimensional structures in radiographs, alterations in femoral and acetabular version cannot be fully visualized [10]. Nevertheless, the standard pelvic radiograph remains the imaging workhorse for diagnosis and planning of THA [7]. Both high intrarater and interrater variability in hip measurements are well documented and even minor discrepancies may influence the classification of hip morphotypes. To mitigate this, we used AI software and manually corrected measurements in case of erroneous results in mutual agreement. Furthermore, the study did not quantify radiological evidence of osteoarthritis of the hip joint, as recent literature has shown limited correlation between radiographic findings and clinical manifestations of osteoarthritis [2]. As a result, the primary endpoint of this study was defined as the need for THA. This endpoint, however, also has its limitations, because it is dependent on the informed decision of clinicians and patients and whether they plan to proceed with earlier or later THA. In addition, no radiographs of patients who did not have THA were included in this study, and therefore, we do not have information about hip morphotype distributions in a healthy cohort. Another limitation is the fact that revision rates were not investigated, and no relative risks for each hip morphotype can be inferred. Although statistically significant, the differences in BMI between men and women across some coronal plane alignment of the hip groups were small and most likely attributed to the large sample sizes and not of clinical relevance.

## Conclusions

The present study highlights the major impact of hip morphotype on the timing of THA, with femoral varus neck alignment demonstrating a protective effect across all age groups. In contrast, femoral valgus neck alignment as well as acetabular undercoverage, individually or combined, were associated with an earlier need for THA.

## CRediT authorship contribution statement

**Gilbert M. Schwarz:** Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sebastian Simon:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Jennyfer A. Mitterer:** Writing – review & editing, Investigation, Formal analysis, Data curation, Conceptualization. **Stephanie Huber:** Writing – review & editing, Investigation, Formal analysis, Data curation, Conceptualization. **Sebastian Leder-Berg:** Writing – review & editing, Investigation, Formal analysis, Data curation, Conceptualization. **Jochen G. Hofstaetter:** Writing – review & editing, Validation, Supervision, Methodology, Investigation.

## References


[1] Gorur A, El-Othmani MM, Xu W, Herndon CL, Cooper HJ, Geller JA. Primary total hip arthroplasty outcomes for labral tears are comparable to advanced osteoarthritis. J Arthroplasty 2024;40:431–6.
[2] Agricola R, Reijman M, Bierma-Zeinstra SMA, Verhaar JAN, Weinans H, Waarsing JH. Total hip replacement but not clinical osteoarthritis can be predicted by the shape of the hip: a prospective cohort study (CHECK). Osteoarthritis Cartilage 2013;21:559–64.
[3] Agricola R, Heijboer MP, Roze RH, Reijman M, Bierma-Zeinstra SMA, Verhaar JAN, et al. Pincer deformity does not lead to osteoarthritis of the hip whereas acetabular dysplasia does: acetabular coverage and development of osteoarthritis in a nationwide prospective cohort study (CHECK). Osteoarthritis Cartilage 2013;21:1514–21.
[4] Greber EM, Pelt CE, Gililland JM, Anderson MB, Erickson JA, Peters CL. Challenges in total hip arthroplasty in the setting of developmental dysplasia of the hip. J Arthroplasty 2017;32:S38–44.
[5] Ganz R, Parvizi J, Beck M, Leunig M, Nötzli H, Siebenrock KA. Femoroacetabular impingement: a cause for osteoarthritis of the hip. Clin Orthop Relat Res 2003;417:112–20.
[6] Muddaluru V, Boughton O, Donnelly T, O'Byrne J, Cashman J, Green C. Developmental dysplasia of the hip is common in patients undergoing total hip arthroplasty under 50 years of age. SICOT J 2023;9:25.
[7] Tannast M, Hanke MS, Zheng G, Steppacher SD, Siebenrock KA. What are the radiographic reference values for acetabular under- and overcoverage? Clin Orthop Relat Res 2015;473:1234–46.
[8] MacDessi SJ, Griffiths-Jones W, Harris IA, Bellemans J, Chen DB. Coronal Plane Alignment of the Knee (CPAK) classification. Bone Joint J 2021;103-B:329–37.
[9] Huber S, Mitterer JA, Vallant SM, Simon S, Hanak-Hammerl F, Schwarz GM, et al. Gender-specific distribution of knee morphology according to CPAK and functional phenotype classification: analysis of 8739 osteoarthritic knees prior to total knee arthroplasty using artificial intelligence. Knee Surg Sports Traumatol Arthrosc 2023;31:4220–30.
[10] Tannast M, Zheng G, Anderegg C, Burckhardt K, Langlotz F, Ganz R, et al. Tilt and rotation correction of acetabular version on pelvic radiographs. Clin Orthop Relat Res 2005;438:182–90.
[11] Schwarz GM, Simon S, Mitterer JA, Huber S, Frank BJ, Aichmair A, et al. Can an artificial intelligence powered software reliably assess pelvic radiographs? Int Orthop 2023;47:945–53.
[12] Tonnis D, Heinecke A. Acetabular and femoral anteversion: relationship with osteoarthritis of the hip. J Bone Joint Surg Am 1999;81:1747–70.
[13] Kinds MB, Welsing PMJ, Vignon EP, Bijlsma JWJ, Viergever MA, Marijnissen ACA, et al. A systematic review of the association between radiographic and clinical osteoarthritis of hip and knee. Osteoarthritis Cartilage 2011;19:768–78.
[14] Tu L-A, Weinberg DS, Liu RW. The association between femoral neck shaft angle and degenerative disease of the hip in a cadaveric model. HIP Int 2022;32:634–40.
[15] Doherty M, Courtney P, Doherty S, Jenkins W, Maciewicz RA, Muir K, et al. Nonspherical femoral head shape (pistol grip deformity), neck shaft angle, and risk of hip osteoarthritis: a case-control study. Arthritis Rheum 2008;58:3172–82.
[16] Tønning LU, O'Brien M, Semciw A, Stewart C, Kemp JL, Mechlenburg I. Periacetabular osteotomy to treat hip dysplasia: a systematic review of harms and benefits. Arch Orthop Trauma Surg 2023;143:3637–48.
[17] Wyles CC, Vargas JS, Heidenreich MJ, Mara KC, Peters CL, Clohisy JC, et al. Natural history of the dysplastic hip following modern periacetabular osteotomy. J Bone Joint Surg Am 2019;101:932–8.
[18] Ganz R, Horowitz K, Leunig M. Algorithm for femoral and periacetabular osteotomies in complex hip deformities. Clin Orthop Relat Res 2010;468:3168–80.

## Appendix

**Supplementary Table 1**
Demographics of Hip Morphotypes Based on the Coronal Plane Alignment of the Hip (CPAH, I to IX) According to the Age at Total Hip Arthroplasty (THA).

| CPAH Type | Under 50 Years | | | 50 to 74 Years | | | 75 Years and Older | | | Total N |
|---|---|---|---|---|---|---|---|---|---|---|
| | Men | Women | N, % | Men | Women | N, % | Men | Women | N, % | |
| Type I | 9 | 60 | 69 | 29 | 112 | 141 | 2 | 14 | 16 | 226 |
| | 3.2 | 18.2 | 11.3 | 1.3 | 3.5 | 2.7 | 0.3 | 1.1 | 0.9 | |
| Type II | 87 | 104 | 191 | 443 | 569 | 1,012 | 90 | 127 | 217 | 1,420 |
| | 30.7 | 31.5 | 31.2 | 20.6 | 18.0 | 19.0 | 14.6 | 10.4 | 11.8 | |
| Type III | 7 | 6 | 13 | 56 | 46 | 102 | 19 | 15 | 34 | 149 |
| | 2.5 | 1.8 | 2.1 | 2.6 | 1.5 | 1.9 | 3.1 | 1.2 | 1.8 | |
| Type IV | 5 | 15 | 20 | 29 | 133 | 162 | 7 | 26 | 33 | 215 |
| | 1.8 | 4.5 | 3.3 | 1.3 | 4.2 | 3.0 | 1.1 | 2.1 | 1.8 | |
| Type V | 90 | 80 | 170 | 849 | 1,093 | 1942 | 204 | 437 | 641 | 2,753 |
| | 31.8 | 24.2 | 27.7 | 39.4 | 34.6 | 36.6 | 33.0 | 35.8 | 34.9 | |
| Type VI | 18 | 9 | 27 | 163 | 143 | 306 | 62 | 64 | 126 | 459 |
| | 6.4 | 2.7 | 4.4 | 7.6 | 4.5 | 5.8 | 10.0 | 5.2 | 6.9 | |
| Type VII | 4 | 14 | 18 | 20 | 93 | 113 | 3 | 28 | 31 | 162 |
| | 1.4 | 4.2 | 2.9 | 0.9 | 2.9 | 2.1 | 0.5 | 2.3 | 1.7 | |
| Type VIII | 53 | 36 | 89 | 437 | 790 | 1,227 | 158 | 379 | 537 | 1853 |
| | 18.7 | 10.9 | 14.5 | 20.3 | 25.0 | 23.1 | 25.6 | 31.0 | 29.2 | |
| Type IX | 10 | 6 | 16 | 129 | 179 | 308 | 73 | 131 | 204 | 528 |
| | 3.5 | 1.8 | 2.6 | 6.0 | 5.7 | 5.8 | 11.8 | 10.7 | 11.1 | |