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Influence of acetabular and femoral morphology on pelvic tilt

A STUDY OF 388 HIPS

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Aims
The aim of this study was to investigate whether anterior pelvic plane-pelvic tilt (APP-PT) is associated with distinct hip pathomorphologies. We asked: is there a difference in APP-PT between young symptomatic patients being evaluated for joint preservation surgery and an asymptomatic control group? Does APP-PT vary among distinct acetabular and femoral pathomorphologies? And does APP-PT differ in symptomatic hips based on demographic factors?

Methods
This was an institutional review board-approved, single-centre, retrospective, case-control, comparative study, which included 388 symptomatic hips in 357 patients who presented to our tertiary centre for joint preservation between January 2011 and December 2015. Their mean age was 26 years (SD 2; 23 to 29) and 50% were female. They were allocated to 12 different morphological subgroups. The study group was compared with a control group of 20 asymptomatic hips in 20 patients. APP-PT was assessed in all patients based on supine anteroposterior pelvic radiographs using validated HipRecon software. Values in the two groups were compared using an independent-samples *t*-test. Multiple regression analysis was performed to examine the influences of diagnoses and demographic factors on APP-PT. The minimal clinically important difference (MCID) for APP-PT was defined as > 1 SD.

Results
There were no significant differences in APP-PT between the control group and the overall group (1.1° (SD 3.0°; -4.9° to 5.9°) vs 1.8° (SD 3.4°; -6.9° to 13.2°); p = 0.323). Acetabular retroversion and overcoverage groups showed higher mean APP-PTs compared with the control group (p = 0.001 and p = 0.014) and were the only diagnoses with a significant influence on APP-PT in the stepwise multiple regression analysis. All differences were below the MCID. The age, sex, height, weight, and BMI showed no influence on APP-PT.

Conclusion
APP-PT showed no radiologically significant variation across different pathomorphologies of the hip in patients being assessed for joint-preserving surgery.

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Introduction
The morphology of the hip has often been correlated with the position of the pelvis. For example, both dysplasia of the hip and acetabular retroversion have been reported to be linked to increased pelvic tilt (PT).[1-3] It has been suggested that the increased PT in dysplastic hips is caused by a reversible compensatory postural adjustment for insufficient femoral head coverage.[4] Increased PT has been suggested as the cause of the crossover sign on anteroposterior (AP) radiographs in patients with acetabular retroversion.[5,6] If this is true, patients with radiological evidence of complete acetabular retroversion should have either a significantly increased PT or a lumbar lordosis of > 30°.[5,7] However, this is not confirmed by our experience with these patients (Figure 1). In fact, it has been shown that rotation, rather than tilt of the pelvis, has greater influence on the radiological appearance of prearthritic

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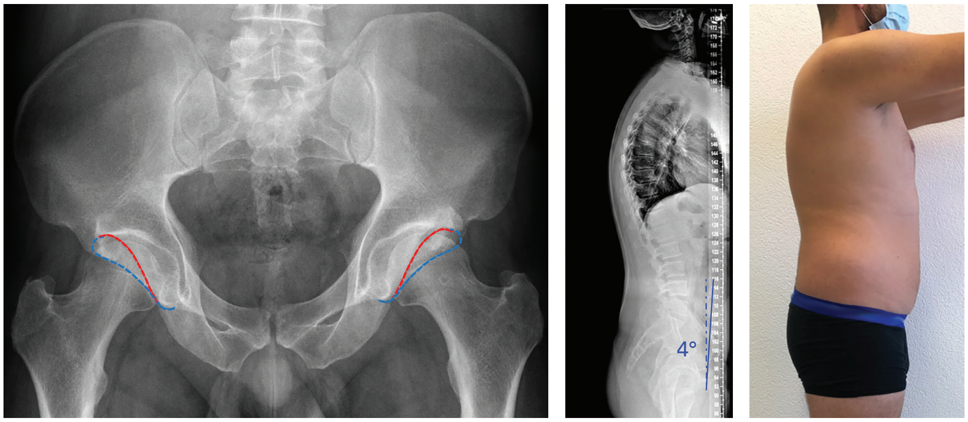

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Fig. 1

a) An anteroposterior pelvic radiograph of a 30-year-old male with complete acetabular retroversion. The red line indicates the posterior wall and the blue line the anterior wall. b) A standing lateral radiograph shows a normal lumbar lordosis and anterior pelvic tilt of 4° with regard to the anterior pelvic plane. c) A clinical photograph of the patient showing a flat-back aspect.

hip pathomorphologies.[2] It is our experience, however, that abnormal acetabular cover, particularly as with retroversion, is frequently attributed to increased PT on conventional radiographs. This potentially inappropriate interpretation can delay or prevent surgical treatment.

These observations, which challenge the conventional understanding of the relationship between PT and hip morphology, led us to question the association between PT and distinct prearthritic hip pathomorphologies. A better understanding of this relationship could help in daily clinical practice to provide the best possible treatment for our patients. In this study, we therefore asked the following questions: is there a difference in PT between symptomatic young patients being assessed for joint preservation surgery and an asymptomatic control group? Does PT vary among distinct acetabular and femoral pathologies? And does PT differ in symptomatic hips based on demographic factors?

Methods

This was an institutional review board (IRB)-approved, single-centre, retrospective, case-control, comparative study. We included 912 consecutive hips in 824 patients undergoing assessment for joint-preserving surgery at a specialized tertiary centre between January 2011 and December 2015. We excluded all patients with incomplete or low-quality radiographs (348 hips), avascular necrosis of the femoral head (five hips), skeletal immaturity (26 hips), post-traumatic deformities (71 hips), and those who had undergone previous surgery (74 hips). This resulted in a study group of 357 patients (388 hips) with a mean age of 26 years (standard deviation (SD) 2; 23 to 29) and with an equal sex distribution (Supplementary Table i).

All patients were assessed radiologically according to a previously described protocol,[8] which included standard supine AP pelvic and axial cross-table radiographs of the affected hip. The pixel size and film focus distance were known for all AP radiographs. All patients also had either CT or MRI scans, being sure to include the distal femur, for the measurement of femoral antetorsion.[9]

Each hip was categorized into a distinct pathological group (Table I). Supine AP pelvic radiographs were analyzed by one observer (AFH) with Hip[2]Norm, a validated image-processing program which provides objective measurements relative to the hips and pelvis.[10,11] We assessed nine radiological parameters (Supplementary Table ii): lateral-centre edge angle (LCEA), Sharp's angle,[12] the acetabular, extrusion, and retroversion indices,[13] centrum-collum-diaphyseal (CCD) angle,[14] and acetabular cover (subdivided into anterior, posterior, and total cover). The α angle and central acetabular version were measured on the CT or MRI scans, as described by Tönnis and Heinecke,[15] and femoral torsion, as described by Murphy et al.[9] Each hip was then placed into one or more subgroups, based on previously published reference values for these measurements.[13] Any hip could be allocated into several subgroups (e.g. developmental dysplasia of the hip and high femoral torsion) based on the measurements.

The hips were compared with 20 asymptomatic hips, which formed an asymptomatic control (Figure 2). This number was based on an a priori power analysis, using a power of 80%, an α error of 0.05, and an overall number of 388 hips in the study. This determined that a sample of 20 controls was sufficient to detect a difference in means with a minimum effect size of 0.65. The control group consisted of patients without hip or low back pain, history of paediatric hip disease, previous surgery, or spinal deformity undergoing CT scans of the pelvis for non-orthopaedic reasons. Based on the CT data, digitally reconstructed radiographs (DRRs) of the pelvis were created in all patients using custom-designed software. This group underwent the same radiological evaluation as the study hips, described above.

All measurements of PT are made with regard to the anterior pelvic plane (APP), as recommended by the Hip-Spine Workgroup,[16] with the following definitions: the APP is defined as

Table I. Definition of study groups based on radiological morphology.

Group	Definition	Hips, n (patients)
Control group	Asymptomatic adult patients having undergone long axis CT angiography for nonorthopaedic reasons	20 (20)
Acetabular pathomorphologies		
Acetabular anteversion	Deficient anterior cover < 14% and excessive posterior cover > 48% with minimum LCEA of 22°, independent from α angle	7 (7)
Acetabular retroversion	Positive crossover sign, positive ischial spine sign, positive posterior wall sign, and retroversion index > 30%, independent from α angle	66 (60)
DDH	LCEA < 22° and/or anterior cover < 14%, or LCEA 22° to 25° and history of PAO for hip instability	63 (59)
Overcoverage	LCEA > 33° to 39° with α angle > 50°, not all retroversion signs positive	31 (27)
Severe overcoverage	LCEA > 39° and/or protrusio acetabuli (defined as femoral head touching or crossing the ilioischial line) and/or total femoral cover > 93%	36 (34)
Femoral pathologies		
Perthes' disease	Documented avascular necrosis of femoral head in childhood	10 (10)
Cam-type FAI	α angle > 50° with neck-shaft angle of 125° to 140° and with normal acetabulum (LCEA 23° to 33°), not all retroversion signs positive	126 (118)
Mixed-type FAI	α angle > 50° and LCEA of 34° to 39°, not all retroversion signs positive	116 (106)
Varus	Neck-shaft angle ≤ 125° independent from acetabular morphology and α angle, without Perthes' disease	52 (46)
Valgus	Neck-shaft angle ≥ 140° independent from acetabular morphology and α angle, without Perthes' disease	46 (40)
High femoral torsion	Femoral torsion > 25° measured according to Murphy et al[9]	106 (98)
Low femoral torsion	Femoral torsion < 10° measured according to Murphy et al[9]	91 (84)

DDH, developmental dysplasia of the hip; FAI, femoroacetabular impingement; LCEA, lateral centre-edge angle; PAO, periacetabular osteotomy.

a plane connecting both anterior superior iliac spines (ASISs) and the pubic tubercles. APP-PT is defined as the angle between the APP and the vertical.[16] At 0°, APP-PT is considered neutral (Figure 3).

The APP was identified, and APP-PT calculated, for all supine AP pelvic radiographs using the previously validated HipRecon software.[17,18] This non-commercial software is based on a 2D/3D deformation reconstruction algorithm using statistical shape modelling. Based solely on a standard AP pelvic radiograph (Figure 4a), pixel size, and film focus distance, HipRecon allows the creation of a patient-specific, virtual 3D model of the pelvis (Figure 4b). In the validation study, the position of the pelvis was verified with regard to the APP on a cadaver model using lateral radiographs. The software proved to be robust, highly accurate, and precise for calculation of APP-PT (0.2° (SD 2.0°)), and had no sex-related bias in its measurements. It also showed the highest correlation with the PT as measured from a lateral radiograph in the controlled-motion cadaveric model, when compared with seven other radiological measurements used to estimate PT on AP radiographs.[18] Once acquired, we then compared APP-PTs between the control group and the whole group, as well as between the control group and each pathological subgroup.

Statistical analysis. Analysis was performed using MedCalc v. 20.217 (MedCalc Software, Belgium). A Kolmogorov-Smirnov test was performed for testing distribution. Normally distributed data were compared using an independent-samples *t*-test for comparison between two groups and analysis of variance (ANOVA) for comparison between multiple groups. Non-normally distributed data were compared using a Mann-Whitney U test for comparison between two groups and a Kruskal-Wallis test for comparison between multiple groups. Both univariate and stepwise multiple regression analyses were performed to examine the relationship between APP-PT and different pathological subgroups. Multiple regression analysis was also used to analyze the relationship between APP-PT and demographic information. We defined the minimal clinically important difference (MCID) in APP-PT as > 1 SD using a distribution-based approach.[19] Significance was set at $p < 0.05$.

Results

The mean APP-PT in the control group was 1.1° (SD 3.0°; -4.9° to 5.9°), and in the overall group was 1.8 (SD 3.4°; -6.9° to 13.2°; p = 0.323, independent-samples *t*-test; Figure 5). Comparison of the control group with the pathological subgroups showed significantly higher anterior tilt in the overcoverage (mean 3.3° (SD 3.0°; -2.2° to 10.1°); p = 0.014, independent-samples *t*-test) and acetabular retroversion groups (mean 3.7° (SD 3.2°; -1.2° to 13.2°; p = 0.001, independent-samples *t*-test); Table II, Figure 5). All statistically significant changes were, however, below the MCID.

Univariate regression analysis identified that five pathological subgroups (overcoverage (p = 0.015), retroversion (p < 0.001), severe overcoverage (p = 0.001), cam-type FAI (p = 0.001), and mixed-type FAI (p = 0.024)) were significantly associated with APP-PT. Stepwise multiple regression, with APP-PT as the dependent parameter and these morphological subgroups as independent parameters, identified that two subgroups (overcoverage (p = 0.001), acetabular retroversion (p < 0.001)) were associated with a significant increase on APP-PT. Given the SD of 3.0 and 3.2° for overcoverage and acetabular retroversion, respectively, the differences in mean APP-PT of these two subgroups compared with the control group were below the MCID.

Multiple regression analysis with APP-PT as the dependent parameter, and demographic parameters as independent parameters, found no significant correlation for age (p = 0.291), sex (p = 0.420), height (p = 0.201), weight (p = 0.179), or BMI (p = 0.157).

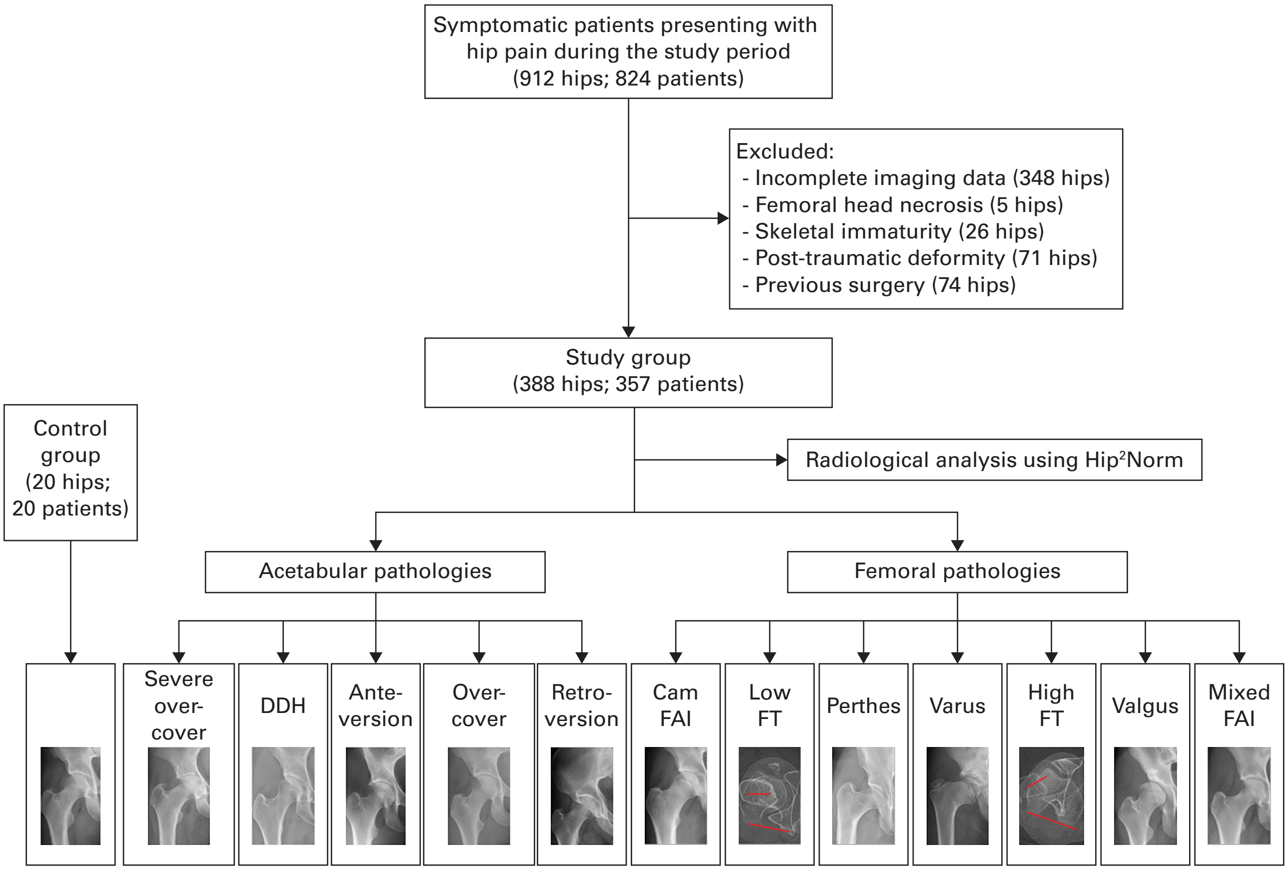

Fig. 2

Study flowchart. DDH, developmental dysplasia of the hip; FAI, femoroacetabular impingement; FT, femoral torsion.

Discussion

There is a debate surrounding whether certain prearthritic deformities of the hip, like acetabular retroversion, are associated with postural alterations or inherent pelvic deformities. A thorough analysis of the relationships between various distinct deformities and APP-PT in the context of hip joint preservation surgery has never been performed. This is the first comprehensive study to analyze the orientation of the APP across a wide spectrum of pathologies in young symptomatic adult patients compared with an asymptomatic control group. Regarding our questions, we found that there was no clinically important difference in the APP-PT between young asymptomatic and symptomatic patients, no clinically important difference in the APP-PT among 11 specific pathologies of the hip, and no association between APP-PT and demographic factors such as age, sex, and BMI.

In relation to the first question, the mean APP-PT of 1° in the control group was consistent with the findings of previous authors (Supplementary Figure a) who have reported mean values ranging from -0.1° to 5°.[20–22] This reinforces the validity of our computer-assisted radiological analysis when compared with commonly used CT-based methods. A consistent finding in our study and in the literature is that there is no clinically relevant change in APP-PT between symptomatic and asymptomatic patients, regardless of whether end-stage osteoarthritis or pre-arthritic changes were analyzed.[22,23] The literature regarding an association of prearthritic deformities with PT is mostly limited to patients with dysplasia or acetabular retroversion.[22,24,25] One possible explanation for this finding could be that the abnormal acetabular morphology on conventional AP pelvic radiographs is not primarily caused by an abnormal PT. Instead, it must be due to other more morphological parameters, such as the rotation of the pelvis, which influences the radiological appearance of the prearthritic hip more strongly, as discussed by Lerch et al.[2]

In relation to the second question, we found that acetabular retroversion and overcoverage were the only pathologies related to an increased mean APP-PT, with the difference not being > the MCID of 3°. Moreover, this small difference would not explain the appearance of retroversion as shown in a clinical case (Figure 1).[26] Instead, substantial retroversion is caused by an intrinsic deformity of the pelvis, with an externally rotated hemipelvis and consequently a more anteriorly located sacrum.[27,28] Such a deformity only minimally affects the orientation of the APP but greatly affects pelvic incidence or the sacrofemoral-pubic (SFP) angle.[29] This is further confirmed by an increased pelvic wing angle and a decreased spinopelvic PT (SP-PT) angle in hips with acetabular retroversion. The historical role of APP-PT in the context of acetabular overcoverage in young patients might therefore be more an overinterpreted

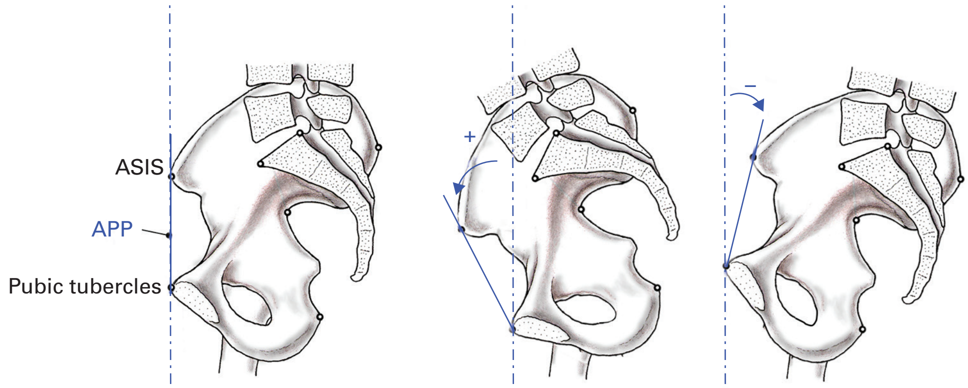

Fig. 3

Definition of pelvic tilt (PT) with regard to the anterior pelvic plane (APP). PT is defined as neutral with the APP in a perfectly vertical position (left). Anterior and posterior PT are defined as rotation of the anterior superior iliac spines (ASISs) anteriorly and posteriorly, respectively. When reporting the APP-PT, a positive value indicates anterior PT and a negative value indicates posterior PT.

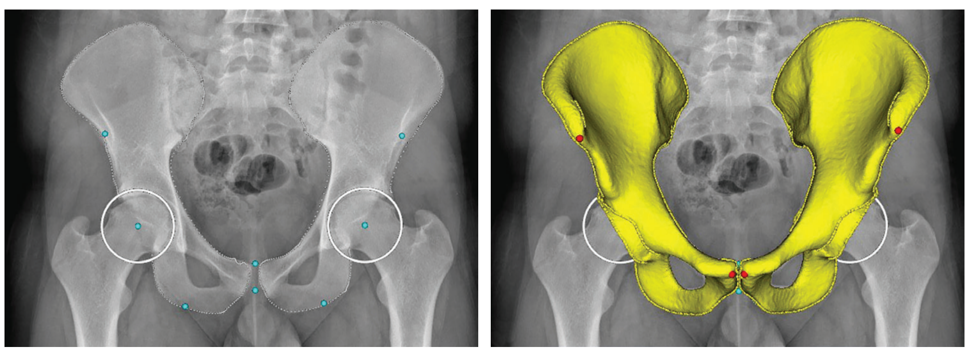

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Fig. 4

HipRecon's 2D/3D deformation reconstruction algorithm allowing the transformation of an a) anteroposterior radiograph into a b) patient-specific 3D model of the pelvis.

myth than a relevant fact confirmed by others.[6] It does not seem to us to be a valuable clinical parameter, particularly since there is no relevant change postoperatively following either periacetabular osteotomy or total hip arthroplasty.[25,30–36] In contrast to previous studies,[22,25] we did not find increased compensatory PT in dysplastic hips (Figure 5).

In relation to the third question, we did not find an association between APP-PT and demographic factors. It must be noted that our overall group was younger than comparative studies in the literature (Supplementary Table iii). In previous studies, an age-dependent decrease of PT was associated with an increased lumbar kyphosis. In a recent systematic review, Lukas et al[37] reported that as age increases, an increasing lumbar kyphosis is associated with increased PT. This observation, which seems contradictory, is best explained by the fact that the authors analyzed changes in SP-PT among other spinopelvic parameters and not in APP-PT as in the studies shown in Supplementary Table iii and in our study.[38–42] This highlights the problems that can arise when interpreting the literature on PT and confirms that clear definitions are required in order to avoid misinterpretation. Interestingly, no sex-related difference was found, independent of age, in most of the image-based analyses. This is consistent with our findings and indicates that the APP is a somewhat anatomical constant, and sex-related differences in morphology are mostly in the pelvis and sacrum.

This study had limitations. First, it has the disadvantages associated with its retrospective design, such as a possible selection or indication bias. However, since we analyzed a large consecutive number of hips, this limitation should be minimal. Second, one patient could be allocated to several pathomorphological subgroups, which could influence the analysis of differences among subgroups. However, this reflects clinical practice when patients rarely present with isolated femoral and/or acetabular pathologies but often have many coexisting deformities. Our statistical approach also matches one that has been previously used in the literature.[43] Third, we assessed APP-PT

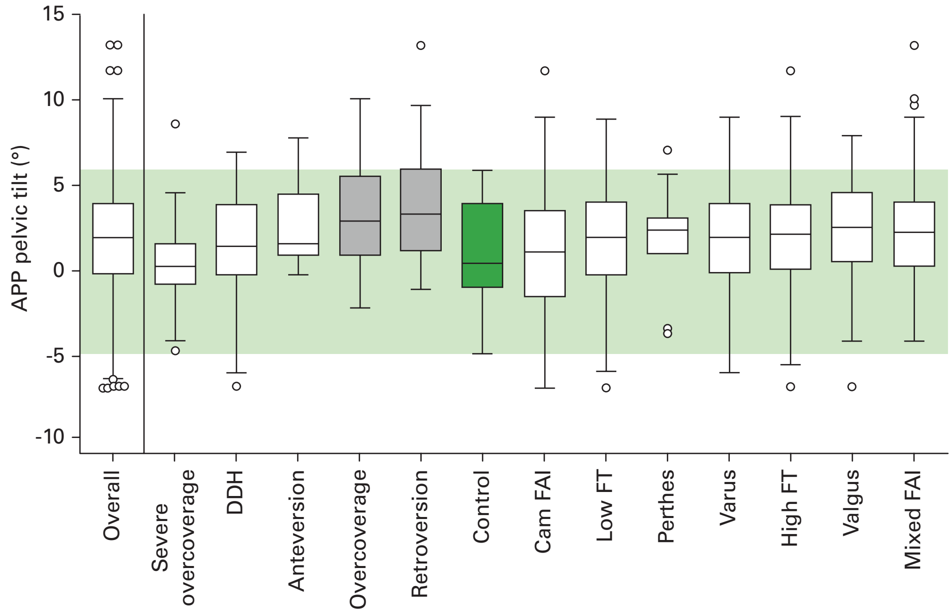

Fig. 5

Box plots of anterior pelvic plane (APP) pelvic tilt for the 12 study groups and the overall group. Values are presented as median and 95% confidence intervals. The boxes represent interquartile range, and circles represent outliers. Boxes shaded in grey (overcoverage and retroversion groups) indicate significantly higher mean pelvic tilt compared with the control group (green). DDH, developmental dysplasia of the hip; FAI, femoroacetabular impingement; FT, femoral torsion.

Table II. Pelvic tilt of the different study groups in comparison to the control and overall group.

Group	Hips, n	Mean pelvic tilt, ° (SD; range)	p-value*
Control group	20	1.1 (3.0; 4.9 to 5.9)	
Overall	388	1.8 (3.4; 6.9 to 13.2)	0.323
Severe overcoverage	36	0.3 (2.6; 4.7 to 8.6)	0.344
Cam-type FAI	126	1.0 (3.6; 6.9 to 11.7)	0.954
DDH	63	1.5 (3.1; 6.8 to 6.9)	0.628
Low femoral torsion	91	1.8 (3.2; 6.9 to 8.9)	0.347
Perthes'	10	1.9 (3.4; 3.6 to 7.1)	0.492
Varus	52	2.0 (3.4; 6.0 to 9.0)	0.295
High femoral torsion	106	2.0 (3.2; 6.8 to 11.7)	0.220
Valgus	46	2.4 (3.0; 6.8 to 7.9)	0.097
Mixed-type FAI	116	2.4 (3.4; 4.1 to 13.2)	0.096
Acetabular anteversion	7	2.6 (2.8; 0.2 to 7.7)	0.238
Overcoverage	31	3.3 (3.0; 2.2 to 10.1)	0.014
Acetabular retroversion	66	3.7 (3.2; 1.2 to 13.2)	0.001

*Independent-samples *t*-test.
DDH, developmental dysplasia of the hip; FAI, femoroacetabular impingement; SD, standard deviation.

on supine radiographs of the pelvis but could not simultaneously assess the SP-PT as we did not have lateral radiographs of the pelvis and our software algorithm does not reconstruct the sacrum. This is also the reason why no other spinopelvic parameters were included in our analysis, limiting the ability to draw global conclusions about the hip–spine relationship. In addition, no dynamic comparison was made between radiographs in the standing, sitting, and/or supine positions. However, there is considerable evidence in the literature that the pelvis tends towards a consistent posterior tilt by a few degrees during the transition from supine to standing. This finding has been reported in various pathologies of the hip, ranging from dysplasia to acetabular retroversion,[25,44–46] and has also been reported in normal controls.[47] Although we did not report position-dependent changes in APP-PT, as this was beyond the scope of the study, posterior PT from supine to standing should be considered in daily clinical practice. Some authors advocate assessing PT on both supine and standing pelvic radiographs (the functional PT), especially in those with acetabular retroversion, to avoid inappropriate surgical correction in one positional extreme or another after an anteverting PAO.[44] Fourth, the control group was significantly older than the overall group, and measurements were performed with DRRs rather than on conventional AP radiographs of the pelvis. There may be some bias from these differences, but it is difficult to interpret.[48]

In addition to ensuring that there is agreement and consistency in how we interpret and report on PT, recognizing and quantifying the effect of age and modality on its measurement should be a priority for research workers in this area.

In conclusion, we found that APP-PT was not a distinguishing factor between pathological subtypes in patients being evaluated for joint-preserving surgery of the hip. Future studies should focus on a comprehensive, methodologically clear analysis of the relationship between APP-PT and SP-PT, morphological parameters such as external rotation of the iliac wing, and dynamic spinopelvic parameters, to quantify the flexibility of the lumbar spine in these young patients.

Take home message

- In hip preservation surgery, pelvic tilt (PT) has become an increasingly discussed topic, as it affects the radiological and biomechanical properties of the hip joint.
- To date, the relationship between PT and distinct pathomorphological subgroups is not well delineated, and methodological differences in measurement have complicated, rather than clarified, our understanding.
- We provide a retrospective analysis of anterior pelvic plane (APP)-PT in a consecutive series of symptomatic patients with a comprehensive spectrum of diagnoses compared to an asymptomatic control group.
- We assessed APP-PT in all patients with the previously validated HipRecon software.

Supplementary material

Tables showing the characteristics and radiological parameters of the study groups, as well as a literature table comparing the reported influence of demographic factors on pelvic tilt, with a forest plot showing the mean anterior pelvic plane pelvic tilt values (hedges) reported in the literature compared with those in the current study.

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