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Original article

# Change in spinopelvic mobility 3 months after THA using a direct anterior approach

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ABSTRACT

*Introduction:* Spinopelvic kinematics, reflected by the change in spinopelvic tilt (ΔSPT) from a standing position to a flexed seated position, has been associated with the risk of prosthetic impingement and hip dislocation. Some studies have suggested changes in spinopelvic mobility after total hip arthroplasty (THA), but none have explored changes in mobility in the first three months following THA using a direct anterior approach.
*Hypothesis:* Our hypothesis was that changes in spinopelvic mobility occur in the first 3 months postoperatively, leading to increased hip mobility and increased spinopelvic kinematic abnormalities.
*Methods:* This retrospective analysis of a consecutive series included 109 patients treated with primary anterior THA by a single senior surgeon. Lateral radiographs taken in standing and flexed seated positions before and three months after surgery were examined to analyze ΔSPT, pelvic femoral angle (PFA), lumbar lordosis (LL), and abnormal spinopelvic mobility (ΔSPT ≥20 °). Secondary objectives included examining the relationship between changes in lumbar flexion and hip flexion, and then analyzing preoperative spinopelvic parameters involved in postoperative pelvic mobility changes.
*Results:* Between the two periods of analysis, the ΔSPT increased on average by 9.53 ° (−34.4/50.3 °), the ΔPFA increased by 7.68 ° (−74/49 °), and lumbar flexion (ΔLL) decreased by 4.26 ° (−20.8/26 °). The rate of ΔSPT ≥20 ° was 22.9% before the operation and 47.7% after the operation (OR = 8.98; CI [2.82; 28.56]; $p < 0.001$). A strong positive correlation was found between changes in ΔSPT and ΔPFA (ρ = 0.76; $r^2 = 0.574$; $p < 0.001$) and no correlation between changes in ΔSPT and ΔLL (ρ=-0.019; $r^2 = 0.005$; p = 0.842). The multivariate analysis demonstrated independent predictors of change in ΔSPT were body mass index (BMI, β = −0.59, [−1.15; −0.03], p = 0.0386), ΔPFA (β = −0.46, [−0.59; −0.34], $p < 0.001$), and ΔLL (β = −0.36, [−0.53; −0.19], $p < 0.001$). No dislocation was observed.
*Conclusions:* Spinopelvic mobility changes occur early on, within 3 months, after anterior THA. Patients with preoperative lumbar stiffness, associated with a stiff hip and lower BMI, should prompt surgeons to the risk of worsening spinopelvic kinematic abnormalities postoperatively.
*Level of evidence:* IV; retrospective study.

## 1. Introduction

Total hip replacement (THA) is a surgical procedure that offers excellent functional results [1], but it is not without risks [2], notably prosthetic impingement [3,4], bone impingement [5], and dislocation [6]. Although various factors can explain these risks [7] (implant size, surgical approach, rehabilitation, etc.), the relationship between the spine and hip is crucial to understanding spinopelvic mobility abnormalities [8–10] and directly linked to these complications.

The impact of spinopelvic risk factors (excessive posterior pelvic tilt, sagittal imbalance, lumbar stiffness and a flat back) on spinopelvic mobility abnormalities has been clearly demonstrated [11], as well as an association with hip stiffness [12]. This has led to the development of classifications [13,14] and algorithms [15] to predict patients at risk, and to guide surgeons in their choice of implant, in order to mitigate these risks. Additionally, abnormal spinopelvic kinematics, measured by >20 ° of anterior rotation of the pelvis from standing to flexed seated, has been associated with a risk of dislocation [12]. Although preoperative analysis of these factors aims to reduce postoperative complications [10,16], some studies have suggested changes in spinopelvic

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kinematics and hip mobility [17,18]. These changes in mobility could potentially affect the risk of impingements and dislocations. While these studies have analyzed mobility beyond 6 months, focusing on relaxed seated positions, the majority of dislocations occur within the first three months after THA [6]. To our knowledge, no study has explored changes in mobility after anterior THA in the first three months after surgery. Our hypothesis was that changes in spinopelvic mobility occur in the first 3 months postoperatively, leading to increased hip mobility and increased spinopelvic kinematic abnormalities. This study aimed to analyze changes in spinopelvic mobility, the rate of abnormal spinopelvic kinematics, change in hip mobility measured by change in pelvic femoral angle (PFA), and change in lumbar flexion (LF) in the pre- and postoperative periods, specifically 3 months after THA via the anterior Hueter-sheath approach. Secondary objectives included examining the relationship between changes in lumbar flexion, hip flexion, and changes in pelvic mobility. Finally, we analyzed the preoperative spinopelvic parameters involved in changes in postoperative pelvic mobility.

## 2. Material and methods

### 2.1. Participants

A consecutive series of 114 patients who underwent primary THA (including one patient with an old femoral neck fracture, one patient with previous lumbar surgery and no prosthesis on a recent fracture). The average age of the patients was 66.3 years (20–82 years). There were 41 men (37.6%) and 68 women (62.4%), with 61 right hips (56%) and 48 left hips (44%) treated. The baseline characteristics of the entire study cohort are shown in Table 1. Five patients were excluded because they did not meet the criterion of sufficient radiological quality for analysis and thus, 109 patients were included. All eligible patients were operated on by the same senior surgeon, all had lateral functional radiographs (standing and flexed seated) and low-dose CT scans between March 2022 and April 2023.

Preoperative planning using the Optimized Positioning System (OPSInsight, Corin, Cirencester, UK) was implemented for cementless THA with ceramic-ceramic bearing for 77 patients (70.6%) (Meije Dynacup, Corin, Cirencester, United Kingdom) or metal-polyethylene bearing for 32 patients (29.4%) (MobiliT, Corin, Cirencester, United Kingdom). The diameter of the femoral head was determined based on the planned cup size, and the simulated femoral stem version and offset were adjusted to align with the patient's native femoral version and offset.

This study was approved by the local ethics committee, and patients provided informed consent.

**Table 1**
Characteristics of the cohort.

| | Population n = 109 |
|---|---|
| General characteristics | |
| Age (years), average (range) | 66.26 (20/82) |
| Male sex, n. (%) | 41 (37.6%) |
| Right side, n. (%) | 61 (56%) |
| Size (cm), average (range) | 168 (149/186) |
| Weight (kg), average (range) | 72.6 (46/105) |
| BMI (kg/m$^2$), average (range) | 25.6 (17.6/38.1) |
| Femoral version (°), average (range) | 17.9 (-3/48) |
| Implants | |
| Impacted stems, n. (%) | 106 (97.2%) |
| Ceramics, n. (%) | 77 (70.6%) |
| Double mobilities, n. (%) | 32 (29.4%) |
| Lateralized stems, n. (%) | 43 (39.4%) |
| Head sizes (mm), average (range) | 31.6 (22.2/36) |
| Head lengths (mm), average (range) | −0.46 (−4/+4) |

Abbreviations: BMI: Body Mass Index.

Two lateral radiographs were taken for each patient between 3 months and 6 weeks before the operation and 3 months after the operation: one of the upper body while the patient was standing in a relaxed posture, with the feet apart at shoulder width; and another while the patient was in a flexed seated position, with the femurs parallel to the floor.

### 2.2. Spinopelvic mobility parameters

Measurements obtained from lateral radiographs included standing and flexed seated lumbar lordosis (LL) angles, and standing and flexed seated spinopelvic tilt (SPT) angles. For the SPT, anterior rotation was assigned a positive value, and posterior rotation a negative value. Pelvic incidence (PI) was obtained from the bony landmarks on the CT scan.

We examined the PI-LL ratio, defined as the difference between standing PI and LL angles, and lumbar flexion (LF), defined as the difference between standing and flexed seated LL angles (ΔLL).

Parameters included pelvic mobility during the transition from standing to sitting, measured as the difference between standing and flexed seated SPT (ΔSPT). Abnormal spinopelvic kinematics was defined as ΔSPT $\geq 20^\circ$ between standing and flexed seated [7].

All radiological observations were analyzed by two independent observers [19].

The PFA angle in standing and flexed seated positions, defined as the angle between the line from the center of the sacral plate to the center of the femoral head and the second line parallel to the femoral shaft, was measured by two surgeons. Femoral mobility was measured as the difference between standing and flexed seated PFA (ΔPFA) measurements (Appendix 1).

### 2.3. Judgment criteria

The main results focused on spinopelvic mobility (indicated by ΔSPT) between standing and flexed seated positions. We analyzed the rate of abnormality of spinopelvic kinematics ($\geq 20^\circ$) before and 3 months after surgery.

Next, we examined the association between changes in spinopelvic mobility and changes in lumbar flexion (ΔLL) and the pelvic femoral angle (ΔPFA) during the preoperative period until 3 months after surgery.

Finally, we performed an analysis of risk factors influencing changes in spinopelvic mobility, encompassing preoperative spinopelvic parameters (standing SPT, LL, PI-LL, PI, femoral anteversion, PFA), age and body mass index (BMI).

### 2.4. Statistical analyses

Continuous variables are described using means and ranges. Means and proportions were compared between groups using Student's t test, chi-squared test or the Wilcoxon signed rank test.

The normality of changes in ΔSPT, ΔPFA, and ΔLL between preoperative and postoperative scans was assessed with the Shapiro-Wilk test. The Pearson coefficient was used to assess correlations, or the Spearman coefficient if normality was not verified, and the results were categorized as follows: very strong, 1 to 0.9; strong, 0.9 to 0.7; moderate, 0.7 to 0.5; low, 0.5 to 0.3; and very low, 0.3 to 0. Multivariate linear regression was performed to examine the relationship between the change in ΔSPT between preoperative and postoperative scans and the explanatory variables, i.e., preoperative ΔLL, Δ PFA and BMI. Data were checked for multicollinearity with the Belsley-Kuh-Welsch technique. Heteroskedasticity and normality of residuals were assessed by the Breusch-Pagan test and the Shapiro-Wilk test, respectively.

The estimates of the "Intraclass Correlation Coefficient" (ICC) for the measurement of ΔPFA and their 95% confidence intervals were calculated using a random effect model, absolute agreement, with a single evaluator, in order to assess the agreement between Observer 1 and

Observer 2. ICC values less than 0.5, between 0.5 and 0.75, between 0.75 and 0.9, and greater than 0.9 were considered as indicating poor, moderate, good, and excellent reliability, respectively.

We used R software (version 4.0.0, Foundation for Statistical Computing, Vienna, Austria; https://www.R-project.org) and Easy-MedStat (version 3.30.2) for analyses, and probability values <0.05 was considered to indicate statistical significance.

## 3. Results

### 3.1. Analysis of changes in spinopelvic parameters and mobility at 3 months after surgery

An analysis of changes in spinopelvic parameters and mobility at 3 months after surgery for the 109 patients included is provided in Table 2.

Between the two analysis periods, ΔSPT increased on average by 9.53 ° (range: −34.4–50.3 °), ΔPFA increased by 7.68 ° (range: −74 to 49 °), and the ΔLL decreased by 4.26 ° (range: −20.8 to 6 °) (Table 3).

The percentage of patients presenting an abnormality of spinopelvic kinematics ΔSPT≥20 ° was 22.9% preoperatively and 47.7% postoperatively (OR = 8.98; CI [2.82; 28.56]; $p < 0.001$) (Fig. 1).

The average preoperative ΔSPT was 21.2 ° for patients operated on with a dual mobility cup compared to 1.6 ° ($p < 0.001$) for patients with a ceramic insert. Postoperatively the average was 24.8 ° versus 13.9 ° ($p < 0.001$) for patients with and without a dual mobility cup respectively. Regarding hip mobility, the average ΔPFA was 105.2 ° for the dual mobility group compared to 85.7 ° ($p < 0.001$) for the ceramic insert group. Postoperatively the ΔPFA was 102.9 ° compared to 98.5 ° ($p = 0.153$) for patients with and without dual mobility cup respectively.

**Table 2**
Preoperative and 3-month spinopelvic parameters.

| | Preoperative n = 109 | Postoperative (3 months) n = 109 | P value |
|---|---|---|---|
| Spinopelvic parameter (°) Average (range) | | | |
| Standing spinopelvic tilt | 0.73 (−19.9/22.8) | −1.71 (−22.5/15) | **<0.001** |
| Seated spinopelvic tilt | 8.09 (−28.1/47.7) | 15.19 (−30.8/45.1) | **<0.001** |
| Standing lumbar lordosis | 57.64 (29.8/85.1) | 53.6 (22.1/84.8) | **<0.001** |
| Seated lumbar lordosis | 5.71 (−21.7/54) | 5.92 (−19.1/53.5) | 0.357 |
| Standing sacral slope | 40.82 (17.2/58.7) | 38.42 (10.9/58.1) | **<0.001** |
| Seated sacral slope | 48.18 (13.1/85.3) | 55.31 (13.6/81) | **<0.001** |
| Standing PFA | 190.1 (161/210) | 188.9 (165/209) | 0.06 |
| Seated PFA | 98.62 (60/137) | 89.83 (56/178) | **<0.001** |
| Mobility from standing to sitting (°) average, (range) | | | |
| ΔSPT | 7.36 (−25.7/41.1) | 16.89 (−35.2/47.7) | **<0.001** |
| ΔLL | 51.93 (21.7/90.6) | 47.67 (21.1/89.4) | **<0.001** |
| ΔSS | 7.36 (−25.7/41.1) | 16.89 (−35.2/47.7) | **<0.001** |
| ΔPFA | 91.44 (52/128) | 99.12 (0/132) | **<0.001** |
| Spinopelvic kinematic abnormality %, (number) | | | |
| ΔSPT ≥20° | 22.9 (25) | 47.7 (52) | **<0.001** |

Abbreviations: SPT, spinopelvic tilt; LL, lumbar lordosis; PFA, pelvic femoral angle; SS, sacral slope.

**Table 3**
Variation in spinopelvic mobility at 3 months.

| Variation between preoperative and 3 months Mean (range) | N = 109 |
|---|---|
| ΔSPT (°) | +9.53 (−34.4/50.3) |
| ΔLL (°) | −4.26 (−20.8/26) |
| ΔPFA (°) | +7.68 (−74/49) |

Abbreviations: SPT, spinopelvic tilt; LL, lumbar lordosis; PFA, pelvic femoral angle.

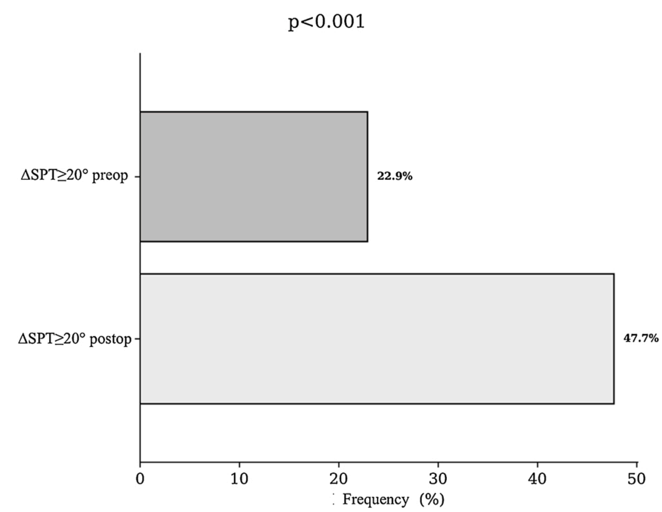


**Fig. 1.** Unfavorable spinopelvic kinetics before and 3 months after total hip replacement.
This figure shows the rate of spinopelvic mobility abnormality (ΔSPT ≥20 °) from standing to flexed seated before and after the operation.
Abbreviations: SPT: spinopelvic tilt

There was an excellent correlation between the ΔPFA measurements between the two observers (ICC: 0.93; 95% CI: [0.893; 0.948]; $p < 0.001$).

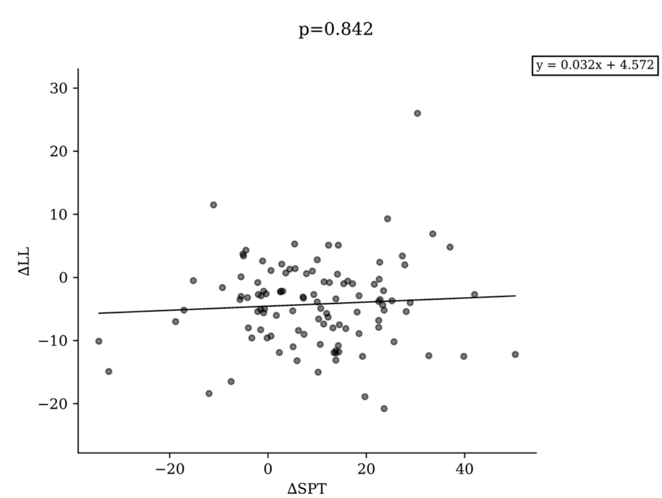


**Fig. 2.** Analysis of the correlation between changes in pelvic tilt and lumbar lordosis.
A lack of correlation was found between the change in pelvic mobility (ΔSPT) and the change in lumbar flexion (ΔLL).
Abbreviations: SPT: spinopelvic tilt; LL: lumbar lordosis

### 3.2. *Analysis of the correlation between changes in ΔSPT and changes in ΔLL and ΔPFA*

A strong positive correlation was found between changes in ΔSPT and ΔPFA ($\rho = 0.76$; $r^2 = 0.574$; $p < 0.001$) (Fig. 2).

No correlation was found between changes in ΔSPT and ΔLL ($\rho = -0.019$; $r^2 = 0.005$; $p = 0.842$) (Fig. 3).

### 3.3. *Determinants of change in ΔSPT from standing to flexed seated at 3 months after surgery*

In the multivariate analysis, the independent predictors of change in ΔSPT identified were: BMI ($\beta = -0.59$, [−1.15; −0.03], $p = 0.0386$), ΔPFA ($\beta = -0.46$, [−0.9; −0.34], $p < 0.001$), and ΔLL ($\beta = -0.36$, [−0.53; −0.19], $p < 0.001$), (Table 4 and Fig. 4).

At the last follow-up, we did not observe any complications, including dislocation, infection, or fracture.

## 4. Discussion

The relationship between the spine and the hip plays an important role in understanding spinopelvic kinematics [9,10]. The preoperative analysis of this relationship helps anticipate the risks of impingements and dislocations by proposing an adjustment to implant orientation for a personalized safety zone [14–16,20]. However, a modification of associated mobilities in the postoperative period could lead to a change in this safety zone. This retrospective analysis revealed a statistically significant change in almost all spinopelvic parameters at 3 months postoperatively. By analyzing spinopelvic kinematics, we observed a 9.5 ° increase in pelvic mobility from the standing position to the flexed seated position, i.e. an anterior rotation, and an increase of 7.7 ° in hip mobility, implying notably increased femoral flexion; however, there was no statistically significant change in PFA angle while standing. Regarding lumbar flexion, we identified a decrease of approximately 4 °, mainly due to a loss of standing lordosis (without a statistically significant difference in seated lumbar lordosis) which can be explained by hypercompensation of lumbar lordosis in patients with sagittal imbalance and an adaptive reduction in lumbar lordosis after THA leading to relief of lumbar symptoms [21]. These results demonstrate an early postoperative change in spinopelvic mobility after anterior THA and appear to be in agreement with the results of a study conducted one year after anterolateral THA [18].

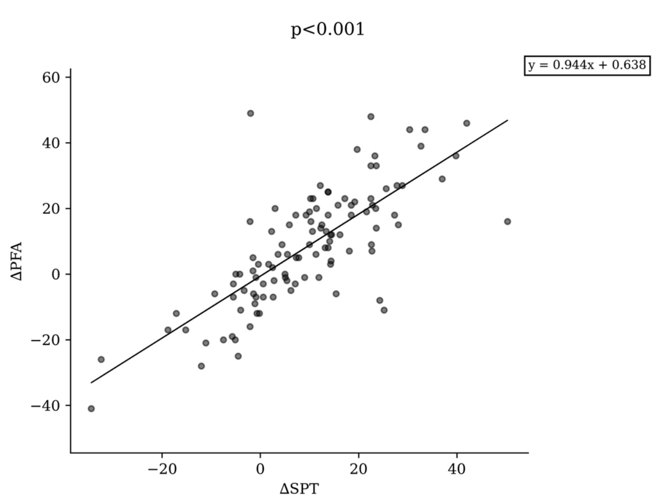


**Fig. 3.** Analysis of the correlation between changes in spinopelvic tilt and hip mobility.
A strong positive correlation was found between change in pelvic mobility (ΔSPT) and change in hip mobility (ΔPFA).
Abbreviations: SPT: spinopelvic tilt; PFA, pelvic femoral angle

**Table 4**
Multivariate analysis of preoperative spinopelvic factors associated with the change in pelvic mobility between the preoperative period and 3 months after surgery.

| | Odds ratio | P Value |
|---|---|---|
| ΔLL | −0.363 [−0.533; −0.192] | **<0.001** |
| ΔPFA | −0.464 [−0.59; −0.337] | **<0.001** |
| BMI | −0.593 [−1.15; −0.0316] | **0.0386** |

Abbreviations: LL, lumbar lordosis; BMI, body mass index; PFA, pelvic femoral angle.

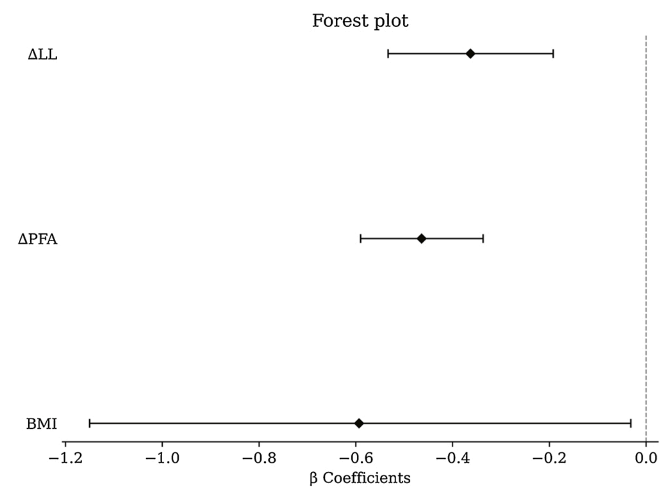


**Fig. 4.** Preoperative factors independently associated with changes in spinopelvic kinematics (ΔSPT) according to multivariate multinomial logistic regression analysis.
Fig. 4 shows the associations of variables included in the final multivariate model with changes in spinopelvic mobility before and after surgery.
Abbreviations: SPT: pelvic tilt; LL, lumbar lordosis; BMI, body mass index; PFA, pelvic femoral angle

The percentage of patients presenting an abnormality of spinopelvic kinematics increased from 22% to 47% at 3 months postoperatively. Spinopelvic mobility analysis allows adjustments in implant positioning, and an *in silico* study showed a 30% risk of preoperative prosthetic impingement with a standard cup position [20]. However, an in vivo study of explants from a consecutive series of revision THA procedures revealed a prosthetic impingement rate of 50% [22]. This could be explained by increased anterior rotation of the pelvis postoperatively, leading to a greater risk of anterior impingement.

However, compared to other analyzes [8,12], the percentage of patients with abnormal spinopelvic kinematics preoperatively in this cohort was high and does not allow extrapolation to the general population. However, if this preoperative threshold of 20 ° constitutes a risk factor for postoperative dislocation [12]; affecting almost one in two patients at 3 months, it seems plausible that this threshold does not represent the postoperative pathological mobility necessary for dislocation. An analysis of spinopelvic kinematics after dislocation should be performed to define a new postoperative threshold associated with the risk of instability.

Analysis of changes in pelvic mobility correlated with changes in lumbar flexion did not reveal a statistically significant association, while increased femoral flexion was statistically associated with increased anterior pelvic rotation. All patients were analyzed in a flexed seated position. Indeed, in this seated position, good hip mobility allows greater anterior rotation of the pelvis accompanying the torso, which requires maximum flexion of the hip. The same results were obtained at 6 months and one year after THA using an anterolateral approach [18]. In addition, some authors have also reported a close relationship between ΔPFA and a change in sacral slope in the relaxed seated position one year after posterior THA, and have defined high-risk patients as those with decreased spinopelvic mobility (ΔSS of from sitting to standing $<10^{\circ}$) [23]. It would appear, however, that the variations in pelvic tilt are less important or even non-significant in the relaxed seated position [18,24] compared to the flexed seated position where patients presenting a higher risk of dislocation or impingement were defined as having excessive anterior rotation of the pelvis $\geq 20^{\circ}$ [12]. This highlights the importance of greater uniformity in the terminology and analysis of spinopelvic mobility [25].

Analysis of spinopelvic parameters has proven useful in assessing the risk of prosthetic impingement and dislocation and has led to the creation of various classifications [13,15] and software [26] to adjust the position and orientation of implants. However, these approaches do not make it possible to anticipate changes in postoperative spinopelvic mobility or the optimal orientation of the implant to reduce the risk of impingement postoperatively. Multivariate analysis of preoperative spinopelvic parameters associated with pelvic mobility changes identified ΔLL, ΔPFA and BMI as independently linked factors. Lumbar flexion is directly linked to spinopelvic mobility abnormalities and has been shown to be one of the main risk factors [11,27,28]. Given the increased hip flexion after THA in osteoarthritis patients, it appears clear that a preoperative stiff hip increases the risk of postoperative changes in spinopelvic kinematics; on the contrary, a higher BMI limits hip flexion and pelvic mobility [29]. Patients presenting with a sagittal balance disorder and/or lumbar stiffness with unfavorable spinopelvic kinematics before surgery could present with a worsening of this after surgery, thus this change seems linked to hip mobility, which may be limited by soft tissues in obese patients. This raises the question of whether hip mobility should be taken into account in preoperative analyzes to determine implant orientation, considering femoral flexion gains, or rather move towards the use of an independent classification system or algorithm for these modifiable factors early in the postoperative period.

Our study has several limitations. First, although this is a retrospective analysis, the series was consecutive. A prospective analysis would be desirable. In addition, five patients could not be included in the analysis due to insufficient quality of postoperative radiographs for spinopelvic parameter analysis; Radiology radiographers also need special training on correct patient positioning.

Additionally, all patients had surgery with the prosthetic femoral version planned like the native femoral version. However, recent studies have shown variation in postoperative version using uncemented quadrangular stems [30,31]. This imprecision does not allow a formal evaluation of the effect of the femoral version on changes in mobility. Although it may seem unassociated in our work, another study uses the femoral version to anticipate changes in femoral flexion associated with BMI at five years after THA [32].

Furthermore, in our study, despite the changes in mobility, we did not observe any cases of dislocation. However, all patients underwent surgery with a cup orientation adaptation system based on an analysis of spinopelvic mobility, reducing the risk of prosthetic impingement from 30% to 10% in the standard position [20]. by making it possible to avoid biases linked to imprecise positioning of the pelvis on an orthopedic table [33]. In addition, taking into account the analysis of preoperative spinopelvic mobility, patients with a stiff spine or sagittal imbalance and abnormal spinopelvic kinematics received a dual mobility cup, representing nearly 30% of patients. These implants have demonstrated a reduction in the risk of dislocation with excellent long-term results [34,35]. This method explains the significant difference in pre- and postoperative spinopelvic mobility between patients operated on with or without a dual mobility cup. On the other hand, the analysis of hip mobility between these two groups highlighted a significant difference in ΔPFA preoperatively but a synchronization postoperatively due to the gain in hip mobility, which confirms the importance of hip mobility in pelvic mobility abnormalities. Considering this, it was not possible to analyze the risk of dislocation associated with changes in mobility in our population. Furthermore, we have not analyzed the functional results of the patients, in particular the impact of changes in spinopelvic mobility on lower back pain nor the rate of prosthetic impingements that cannot be analyzed *in silico* postoperatively as well as the risks of wear that this could cause.

Additionally, some patients in our study presented with a reduction in spinopelvic mobility with reduced hip flexion. It is possible that other factors should be considered in spinopelvic mobility changes, such as rehabilitation or pain, which may limit postoperative hip flexion.

Finally, previous studies analyzing mobility changes were conducted at 6 months and/or one year after surgery [17,18,24,32]. We chose an earlier assessment of 3 months for analysis due to the high incidence of dislocations in the first 3 months after THA [6]. It is possible that mobility will continue to change over the following years. Thus, additional research is needed to pursue this analysis, mainly to anticipate the risk of long-term impingements given the current lifespan of prostheses and the risks of late dislocations [36].

## 5. Conclusions

Spinopelvic mobility changes occur early, at 3 months after anterior THA in a flexed seated position. Patients with preoperative lumbar stiffness associated with a stiff hip and lower BMI should alert surgeons to the risk of worsening spinopelvic kinematic abnormalities postoperatively.

## CRediT authorship contribution statement

TA designed the study and wrote the manuscript. TA and AH interpreted the data. TA performed the analyses. TA, AH, CV, and LL participated in data interpretation and critically reviewed the manuscript. All authors revised the manuscript for important intellectual content.

## Declaration of Generative AI and AI-assisted technologies in the writing process

No artificial intelligence systems were used for this work.

## Funding

None.

## Clinical trial registration

IDRCB 2023-A01390-45, MR004 2225508.

## Declaration of competing interest

TA and LL are consultants for the companies CORIN, Amplitude and Lape Medical. TA is a consultant for the Depuy company. The measurements of spinopelvic mobility were carried out by engineers from the CORIN company.

## Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.otsr.2025.104169.

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