The Journal of Arthroplasty xxx (2023) 1–8

Contents lists available at ScienceDirect

The Journal of Arthroplasty

journal homepage: www.arthroplastyjournal.org

How to Screen for Lumbar Spine Stiffness in Patients Awaiting Total Hip Arthroplasty

Moritz Innmann, MD, PhD [a, b], Jeroen Verhaegen, MD [a, c], Tobias Renkawitz, MD [b], Christian Merle, MD [b, d], George Grammatopoulos, MBBS, DPhil (Oxon) [a, *]

[a] Division of Orthopaedic Surgery, The Ottawa Hospital, Critical Care Wing, Ottawa, Ontario, Canada
[b] Department of Orthopaedic Surgery, Heidelberg University Hospital, Heidelberg, Germany
[c] Department of Orthopaedic Surgery, University Hospital Antwerp, Edegem, Belgium
[d] Diakonie Klinikum Stuttgart, Stuttgart, Germany

ARTICLE INFO

Article history:
Received 1 December 2022
Received in revised form
30 July 2023
Accepted 1 August 2023
Available online xxx

Keywords:
spinopelvic
hip
spine
arthroplasty
lumbar spine stiffness

ABSTRACT

Background: This study aimed to (1) define the prevalence of spinopelvic abnormalities among patients who have hip osteoarthritis (OA) and controls (asymptomatic volunteers) and (2) identify factors that reliably predict the presence of lumbar spine stiffness.
Methods: This is a prospective, cross-sectional, case-cohort study of patients who have end-stage primary hip OA, who underwent primary total hip arthroplasty (THA). Patients were compared with a cohort of asymptomatic volunteers, matched for age, sex, and body mass index (BMI), serving as a control group. Spinopelvic pathologies were defined as: lumbar spine flatback deformity (difference of 10 or more degrees for pelvic incidence minus lumbar lordosis angle), a standing sagittal pelvic tilt of 19° or more and lumbar spine stiffness (lumbar flexion of less than 20° between both postures).
Results: The prevalence of spinopelvic pathologies was similar between patients and controls (flatback deformity: 16% versus 10%, $P = .209$; standing pelvic tilt >19°: 17% versus 24%, $P = .218$; lumbar spine stiffness: 6% versus 5%, $P = .827$). Age over 65 years-old and standing lumbar lordosis angle less than 45° were associated with high sensitivity and specificity for identifying lumbar spine stiffness (age >65 years: 82% and 66%; standing lumbar lordosis angle <45°: 85% and 73%).
Conclusion: The presence of end-stage hip osteoarthritis was not associated with increased prevalence of adverse spinopelvic characteristics compared to matched, asymptomatic volunteers. Age and $LL_{standing}$ are the strongest predictors of lumbar spine flexion and can guide clinical practice on when to obtain additional radiographs for patients who have hip OA before arthroplasty to identify at-risk patients.
Level of Evidence: II (prospective, cohort study).

Institutions: The investigation was performed at the Heidelberg University Hospital and The Ottawa Hospital.

Funding: The institution of one or more of the authors (Moritz M. Innmann) has received funding from the noncommercial research fund "Stiftung Endoprothetik" Hamburg, Germany performing this study.Each author certifies that there are no other funding or commercial associations (consultancies, stock ownership, equity interest, patent/licensing arrangements, etc.) that might pose a conflict of interest in connection with the submitted article related to the author or any immediate family members.

One or more of the authors of this paper have disclosed potential or pertinent conflicts of interest, which may include receipt of payment, either direct or indirect, institutional support, or association with an entity in the biomedical field which may be perceived to have potential conflict of interest with this work. For full disclosure statements refer to https://doi.org/10.1016/j.arth.2023.08.006.

Ethical review committee statement: The study was approved by the institutional review board of the Heidelberg University Hospital, Heidelberg, Germany and the Ottawa Hospital, Ottawa, Ontario, Canada and conducted as per the Helsinki Declaration of 2008. All participants signed an informed consent. Please, find the letters from the ethical committees attached to the submission.

Location Statement: The work was performed at the Heidelberg University Hospital, Heidelberg, Germany and the Ottawa Hospital, Ottawa, Ontario, Canada.

* Address correspondence to: George Grammatopoulos, MBBS, DPhil (Oxon), Division of Orthopaedic Surgery, The Ottawa Hospital, Critical Care Wing, 501 Smyth Road, K1H 8L6 Ottawa, ON, Canada.

https://doi.org/10.1016/j.arth.2023.08.006
0883-5403/

Spinopelvic characteristics, particularly lumbar spine stiffness, defined as lumbar flexion less than 20°, have been identified as an important factor associated with the risk of revision after total hip arthroplasty (THA) [1–4]. Patients who have lumbar spinal arthrodesis and those who have degenerate, stiff, lumbar spine have been shown to be at increased risk of dislocation following THA [1–4]. These associations highlight the importance of studying the hip–spine association in greater detail.

The femur, pelvis, and spine form an important kinetic chain and work together to allow for efficient movement while transitioning between positions. Data among healthy volunteers and patients have shown great variability in spinopelvic characteristics [5,6]. Patients who have hip osteoarthritis (OA) have increased pelvic motion when transitioning between the standing and seated positions [5,6], which "normalizes" in most patients following hip arthroplasty, as the hip's range of motion is restored [6,7]. To identify patients at risk of complications post-THA due to lumbar spine stiffness, some advocate for the assessment of change in sacral slope between the standing and seated positions [8]. This parameter measures the sagittal motion of the pelvis and has been adopted as a surrogate measure of lumbar spine motion, due to the direct linkage of the pelvis with the lumbar spine. However, the value of the change in sacral slope has been questioned [9].

The aims of this prospective case-control study were to (1) Define the prevalence of spinopelvic abnormalities (lumbar spine stiffness, abnormal pelvic tilt, and spinopelvic imbalance) among patients who have hip OA; (2) Test if the prevalence is different to matched healthy volunteers; and (3) Identify factors that reliably predict the presence of lumbar spine stiffness, which can be used as screening tools for patients pre-THA.

Patients and Methods

Study Design

This is a prospective, case-control study of patients who have end-stage hip OA, who underwent primary THA between January 1st 2019 and December 31st 2021 in 2 tertiary academic centers. The patients were compared with a cohort of asymptomatic volunteers, matched for age, sex, and body mass index (BMI), serving as a control group with a 2:1 ratio.

Study Power

Study power was determined as per lumbar flexion. Lumbar spine flexion in patients who have hip OA has been reported to be 40 ± 14°, while lumbar flexion has been reported to be 46 ± 15° for asymptomatic volunteers [9,10]. Therefore, *a priori* sample size calculation was performed in G-power (G*Power Version 3.1.9.2, University of Duesseldorf, Germany) aiming to detect a minimum difference in 6° for the change in lumbar lordosis angle when moving from the standing to deep-seated position between both cohorts [5]. Assuming a 2:1 matching ratio for patients and controls, a minimum of 137 patients and 69 controls was needed to achieve sufficient power (1-β = 0.95, α = 0.05). The study was approved by the institutional review board of the Heidelberg University Hospital, Germany(S-065/2017) and the Ottawa Hospital, Canada (20,200,597-01H) and conducted as per the Helsinki Declaration of 2008. All participants signed an informed consent.

Study Population

Study Group–Hip Osteoarthritis Patients

During the study period, 357 consecutive patients awaiting total hip arthroplasty for primary or secondary hip OA (Kellgren-Lawrence grade 3 to 4), were prospectively recruited [11]. Exclusion criteria were age younger than 18 years, lack of consent, or technical reasons such as poor quality or incomplete radiographs.

Control Group–Asymptomatic Volunteers

During the same study period, a control group of 106 volunteers older than 18 years, who had BMI ≤40, and absence of hip symptoms (Oxford hip score ≥45; 0 to 48 worse-best), radiographic signs of hip osteoarthritis (Tönnis ≤1) [12], and history of spinal or any prior lower limb surgery, were recruited. The volunteers were recruited between March 1st 2018 and November 30th 2021 and were patients that presented to upper limb fracture clinics or healthcare workers, interested in participating in the study after signing an informed consent form.

Matching

A case-control matching was performed for the variables of age (±5 years), sex (identical), and BMI (±3) for each of the hip OA patients and asymptomatic volunteers using a case-control–matching algorithm, resulting in the final study cohort of 140

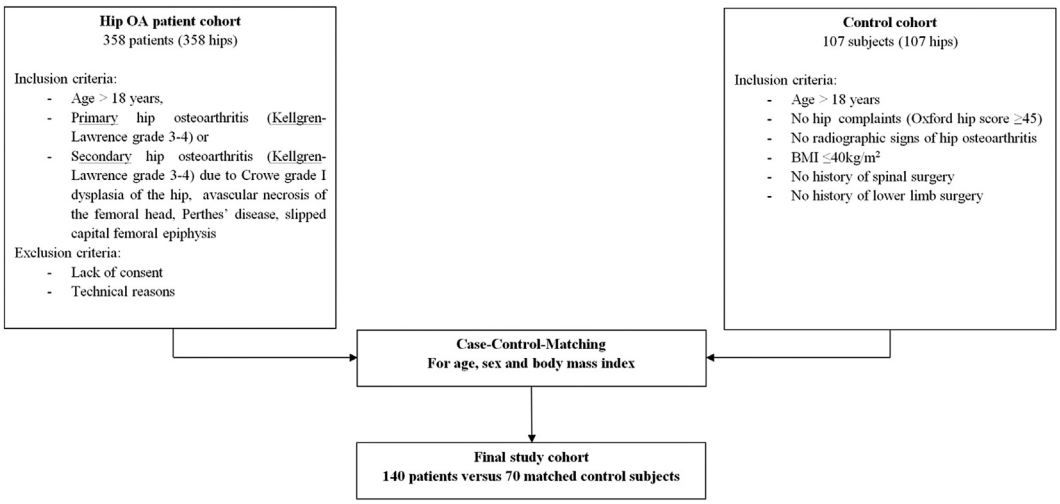

Fig. 1. Flowchart of the cohort included in the study.

Table 1
Demographic and Surgical Data of the Cohort.

Parameter	Overall Hip OA Group (n = 357)	Matched Hip OA Group (n = 140)	Matched Control Group (n = 70)	*P* Value
Mean age (y ± SD [range])	66.8 ± 12.4 (22.5 to 91.3)	59.0 ± 13.1 (22.5 to 87.5)	56.9 ± 15.4 (27.3 to 87.0)	.417[a]
Sex				1.000[b]
Male (n, %)	179 (50.0%)	56 (40.0%)	28 (40.0%)	
Female (n, %)	178 (50.0%)	84 (60.0%)	42 (60.0%)	
Mean BMI (kg/m^2 ± SD [range])	27.7 ± 4.9 (17.4 to 47.7)	27.9 ± 5.6 (17.4 to 40.0)	27.8 ± 5.1 (18.4 to 40.0)	.830[a]

OA, osteoarthritis.
[a] Mann–Whitney *U*-test.
[b] *Chi*-Square test.

patients and 70 matched controls [5] (Figure1). These factors have been shown to influence spinopelvic characteristics [9,10]. Demographic details of the study cohort are outlined in Table 1.

Radiographic Assessments

Assessments were performed based on radiographic evaluations, as clinical evaluations have shown limitation in providing clinicians with the pertinent information required to assess spinopelvic characteristics [13]. Cases and controls underwent the following radiographic assessment which included supine anteroposterior radiograph of the pelvis, a lateral radiograph of the symptomatic hip, and lateral radiographs of the lumbar spine, pelvis and femur in the standing and "deep-seated" positions. The "deep-seated" position was defined as a sitting position, with the femora parallel to the floor with the trunk leaning maximally forward [5,8,14]. The deep-seated was chosen for detecting lumbar spine stiffness as per definition in the literature [15]. On the lateral spinopelvic radiographs, the following measurements were performed: lumbar lordosis (LL) angle, sacral slope (SS), pelvic incidence (PI), pelvic tilt (PT), and pelvic femoral angle (PFA) (Figure 2) [8,13,14,16,17]. Radiographic measurements were performed by 2 fellowship-trained arthroplasty surgeons, blinded to each other's measurements (MMI, JV).

The spinopelvic movements were calculated as the difference between the standing and "deep-seated" position for all radiographic spinopelvic parameters as follows (LL, SS, PI, PT, PFA) [5]: $\Delta X_{\text{standing/ deep-seated}} = \Delta X_{\text{deep-seated}} - \Delta X_{\text{standing}}$.

Average-measure correlation coefficients with a 2-way random effects model for absolute agreement were calculated, after performing repeated measurements 2 weeks after the initial radiographic analysis for 10% of randomly selected data sets in a blinded fashion by both reviewers, showing excellent intraobserver and interobserver reliabilities (IORs) (range: 0.858 [95% confidence interval; 0.657 to 0.942] to 0.997 [95% confidence interval; 0.993 to 0.999]).

Definitions of Spinopelvic Pathologies

Spinopelvic pathologies were the following: (1) Flatback deformity on lateral spinopelvic radiographs, defined by a mismatch between the lumbar lordosis angle and pelvic incidence in the standing position (PI-LL $\geq 10^{\circ}$) has been reported to be a

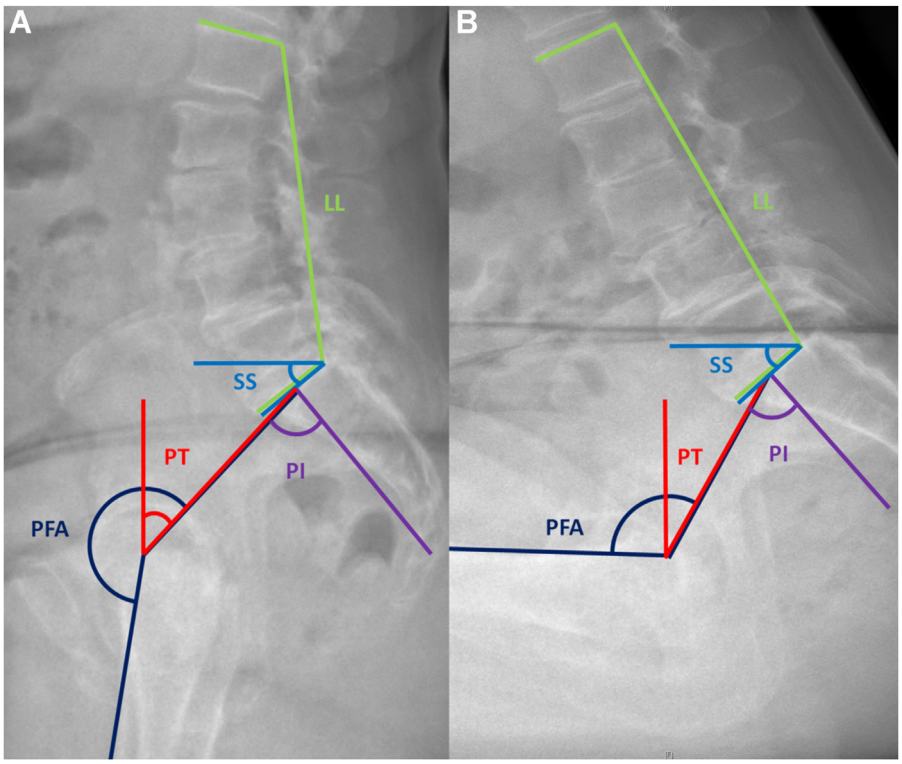

Fig. 2. Illustration of radiographic measurements for the lumbar lordosis (LL) angle, sacral slope (SS), pelvic tilt (PT), pelvic incidence (PI), and the pelvic-femoral angle (PFA) in the (A) standing, (B) deep-flexed seated position.

Table 2
Radiographic Measurements and Prevalence of Spinopelvic Pathologies for all Patients, Matched Patients, and Matched Controls.

Spinopelvic Parameters	Overall Hip OA Cohort	Matched Patients	Matched Controls	*P* Value (Matched Patients versus Controls)
		Mean ± SD (Range)	Mean ± SD (Range)	
LL standing (°)	53 ± 13 (2 to 87)	56 ± 13 (19 to 87)	57 ± 12 (33 to 98)	.480
LL deep-seated (°)	11 ± 13 (−20 to 67)	9 ± 12 (−20 to 55)	9 ± 13 (−14 to 44)	.756
SS standing (°)	40 ± 10 (13 to 69)	41 ± 10 (18 to 69)	40 ± 8 (20 to 61)	.280
SS deep-seated (°)	40 ± 16 (−12 to 90)	40 ± 16 (8 to 88)	47 ± 18 (11 to 87)	.005
PT standing (°)	16 ± 9 (−16 to 55)	14 ± 9 (−10 to 55)	14 ± 8 (−5 to 36)	.802
PT deep-seated (°)	16 ± 17 (−28 to 69)	15 ± 16 (−28 to 46)	6 ± 17 (−33 to 43)	<.001
PI standing (°)	56 ± 12 (25 to 107)	55 ± 12 (25 to 107)	53 ± 11 (26 to 78)	.618
PFA standing (°)	186 ± 12 (154 to 233)	185 ± 12 (155 to 233)	187 ± 9 (167 to 210)	.212
PFA deep-seated (°)	110 ± 17 (70 to 168)	109 ± 16 (70 to 160)	98 ± 15 (60 to 134)	<.001
PI-LL standing (°)	2 ± 13 (−34 to 60)	−1 ± 14 (−34 to 60)	−4 ± 12 (−31 to 33)	.177
Change in Spinopelvic Parameters		Patients Mean ± SD (range)	Controls Mean ± SD (range)	*P* Value
Δ LL standing/deep-seated (°)	−47 ± 15 (−77 to −3)	−47 ± 15 (−77 to −3)	−48 ± 14 (−72 to −14)	.434
Δ SS standing/deep-seated (°)	−1 ± 16 (−42 to 36)	−1 ± 16 (−42 to 36)	8 ± 16 (−23 to 37)	<.001
Δ PT standing/deep-seated (°)	1 ± 16 (−37 to 42)	1 ± 16 (−37 to 42)	−8 ± 16 (−50 to 24)	<.001
Δ PFA standing/deep-seated (°)	−76 ± 19 (−118 to −30)	−76 ± 19 (−118 to −30)	−90 ± 18 (−134 to −53)	<.001
Type/Combination of spinopelvic pathologies		Patients n (%)	Controls n (%)	*P* Value
A) PI-LL ≥10°	60/357 (17%)	23/140 (16%)	7/70 (10%)	.209
B) Standing pelvic >19°	94/357 (26%)	24/140 (17%)	17/70 (24%)	.218
C) ΔLLstanding/deep-seated <20°	20/357 (6%)	7/140 (6%)	4/70 (5%)	.827
A) & B)	39/357 (11%)	16/140 (11%)	6/70 (9%)	-
A) & C)	9/357 (3%)	3/140 (2%)	3/70 (4%)	-
B) & C)	9/357 (3%)	2/140 (1%)	3/70 (4%)	-
A) & B) & C)	8/357 (2%)	2/140 (1%)	3/70 (4%)	-

LL, lumbar lordosis; OA, osteoarthritis; PFA, pelvic femoral angle; PI, pelvic incidence; PT, pelvic tilt; SS, sacral slope.

strong predictor of instability after THA [18]; (2) Standing sagittal pelvic tilt ≥19°, which has been reported to be a strong predictor for hip hypermobility and lumbar spine stiffness [9]; and (3) Lumbar spine stiffness, defined as lumbar spine flexion <20° between standing and deep-seated positions, which has been identified to be a risk factor for dislocation after THA [1–3,15].

Data Analyses

Nonparametric tests were used after exploratory data analysis. *Chi*-square tests were used to test for differences between categorical variables. An independent samples *t*-tests or Mann–Whitney *U*-tests were used to compare demographics and spinopelvic measurements between controls and hip OA patients. Spearman's *rho* (ρ) correlations were performed in order to investigate the association of demographic factors and spinopelvic pathologies. Factors showing a significant and clinically relevant correlation with the previously defined spinopelvic pathologies were added in logistic regression analyses. The logistic regression analyses, were conducted in order to identify predictors for lumbar spine stiffness ($\Delta LL_{standing/deep\text{-}seated}<20°$), having inputted parameters that were shown to have an association with the presence of abnormal spinopelvic characteristics, using univariate correlation analyses. Receiver Operator Curve (ROC) analyses were used to determine the specificity and sensitivity of factors predicting lumbar spine stiffness. Statistical analysis was performed using SPSS v27 (IBM, Armonk, NY). A value of <0.05 was considered significant.

Results

Prevalence of Spinopelvic Pathologies Among Patients

The prevalence of spinopelvic pathologies among patients is detailed in Table 2. There were 6% of patients who exhibited spinal stiffness and 17% showed lumbar spine imbalance. There were no

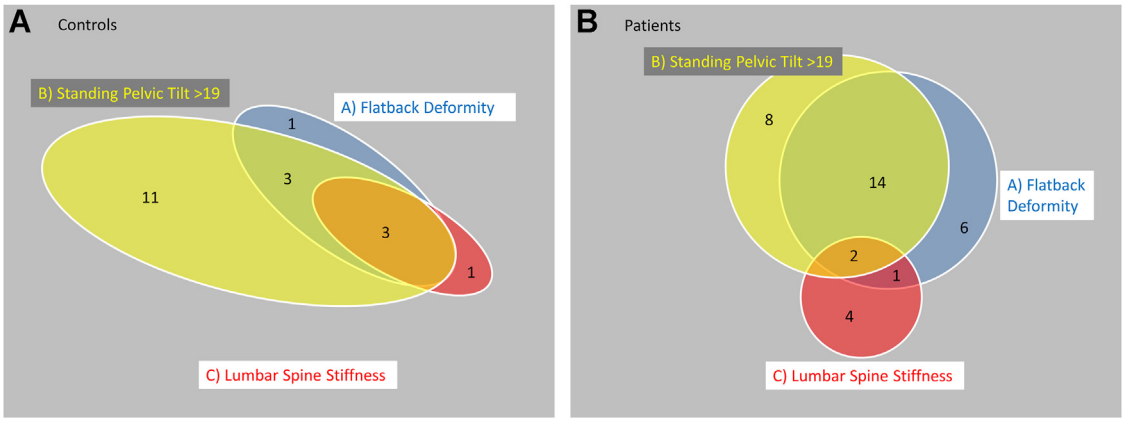

Fig. 3. Venn diagrams illustrating the overlap of the abnormal spinopelvic characteristics for controls (A) and patients (B).

Table 3
Correlation Analysis for the Association of Demographic Factors (Age and BMI) and Spinopelvic Pathologies in Patients.

Spearman-Rho Correlation Coefficient (*P* Value)	Age (years)	BMI (kg/m^2)	LL Standing (°)	PT Standing (°)	PI-LL Standing (°)	LL Deep-Seated (°)	Δ LL Standing/Deep-Seated (°)
Age (years)							
Controls	1 (−)	0.162(0.246)	−0.237 (0.048)	0.165 (0.172)	0.334 (0.005)	0.500 (<0.001)	−0.695 (<0.001)
Patients	1 (−)	−0.114(0.187)	−0.286 (<0.001)	0.186 (0.028)	0.318 (<0.001)	0.122 (0.151)	−0.430 (<0.001)
BMI (kg/m^2)							
Controls		1 (−)	−0.307 (0.025)	0.037 (0.792)	0.315 (0.022)	−0.069 (0.622)	−0.263 (0.057)
Patients		1 (−)	0.032 (0.714)	0.033 (0.706)	0.032 (0.709)	0.238 (0.005)	−0.126 (0.144)
LL standing (°)							
Controls			1 (−)	−0.067 (0.583)	−0.578 (<0.001)	0.351 (0.003)	0.502 (<0.001)
Patients			1 (−)	−0.2223 (0.008)	−0.576 (<0.001)	0.372 (<0.001)	0.617 (<0.001)
PT standing (°)							
Controls				1 (−)	0.651 (<0.001)	0.221 (0.066)	−0.231 (0.055)
Patients				1 (−)	0.750 (<0.001)	0.090 (0.290)	−0.294 (<0.001)
PI-LL standing (°)							
Controls					1 (−)	0.031 (0.797)	−0.557 (<0.001)
Patients					1 (−)	−0.046 (0.591)	−0.504 (<0.001)
LL deep-seated (°)							
Controls						1 (−)	−0.564 (<0.001)
Patients						1 (−)	−0.440 (<0.001)
Δ LL standing/deep-seated (°)							
Controls							1 (−)
Patients							1 (−)

BMI, body mass index; LL, lumbar lordosis; PI, pelvic incidence; PT, pelvic tilt.

clinically meaningful differences between unmatched and matched patients for spinopelvic mobility and the prevalence of pathologies (Table 2).

Differences in Prevalence Between Matched Groups

No difference in spinal balance was found between patients (23 of 140; 16%) and controls (7 of 70; 10%) ($P = .209$). Similarly, no difference in prevalence of standing pelvic tilt ≥19° (24 of 140; 17% versus 17 of 70; 24%) $P = .218$) and lumbar spine stiffness (7 of 140 [6%] versus 4 of 70 [5%]; $P = .827$) was identified between groups. Most patients had no abnormal spinopelvic characteristics at all (n = 160 of 210; 76%); 40 had one abnormal characteristic (19%), 8 had 2 abnormal spinopelvic characteristics (4%), and only 2 patients (1%) had all 3 abnormal spinopelvic characteristics (Table 2). There were no differences between cases and controls in number of abnormal spinopelvic characteristics detected ($P = .938$) (Figure 3).

Demographic Factors Being Associated With Spinopelvic Pathologies

Age was associated with spinopelvic balance ($\rho = 0.315$; $P < .001$) and lumbar spine stiffness ($\rho = 0.521$; $P < .001$), due to loss of lumbar lordosis in both positions ($LL_{standing}$: $\rho = 0.268$; $P < .001$; $LL_{deep\text{-}seated}$: $\rho = 0.263$; $P < .001$). The BMI and sex did not show any clinically relevant association (Tables 3 and 4). The correlation between age and lumbar spine stiffness and spinopelvic balance was similar between cases and controls (Table 3 and Figure 4).

Table 4
Logistic Regression Analysis Investigating Factors for Lumbar Spine Stiffness ($R^2 = 0.316$).

Parameter	Odds Ratio	95% Confidence Interval	*P* Value
Age at surgery (years)	1.068	0.994 to 1.148	.073
BMI (kg/m^2)	1.102	0.969 to 1.252	.138
Patient versus Control (1/0)	0.847	0.175 to 4.100	.837
LL standing (°)	0.912	0.851 to 0.978	.009
PI standing (°)	1.002	0.930 to 1.079	.966
PFA standing (°)	1.067	0.983 to 1.159	.119

BMI, body mass index; LL, lumbar lordosis; PFA, pelvic femoral angle; PI, pelvic incidence.

Predictors for Lumbar Spine Stiffness

Most patients with stiff spines were older than 65 years (9 of 11) or had $LL_{standing}$ less than 45° (8 of 11). No patient below the age of 55 years-old showed lumbar spine stiffness (Figure 5). The odds ratio of having a stiff spine if older than 65 years with $LL_{standing}$ less than 45° was 4.6 ($P = .036$). Similarly, the logistic regression analyses demonstrated that the standing lumbar lordosis angle was the strongest predictor of lumbar spine stiffness, whereas age showed borderline lack of significance (Table 4).

The ROC analysis illustrated that age over 65 years and standing lumbar lordosis angle of less than 45° degrees, was associated with a high sensitivity and specificity for identifying patients who have lumbar spine stiffness (Figures 5A and B and Table 5). The relationship between age, standing LL, and the presence of a stiff spine is further portrayed in Figure 6.

Discussion

The adverse effects of lumbar spine stiffness on THA outcome have been extensively reported and have raised major awareness among surgeons. However, the pertinent questions of how common adverse spinopelvic characteristics are in a typical arthroplasty clinic and how best to identify lumbar spine stiffness preoperatively has not been adequately addressed, leading to common questions such as “should all patients be screened for the presence of spinal stiffness?” The presence of end-stage hip osteoarthritis was not associated with an increased prevalence of abnormal or adverse spinopelvic characteristics (lumbar spine stiffness, spinopelvic balance, abnormal pelvic tilt), relative to well-matched, well-functioning, asymptomatic volunteers. This possibly implies that the abnormal spinopelvic posture and dynamics due to hip osteoarthritis do not significantly contribute to the degenerative process of the lumbar spine. The identification of spinal stiffness requires dynamic spinopelvic radiographs to accurately assess lumbar motion. However, dynamic radiographs are associated with increased radiation exposure and might be difficult to execute by the hip OA patient due to pain. This raises the question whether it would be possible to obtain the necessary information from a single radiograph. Lumbar spine stiffness

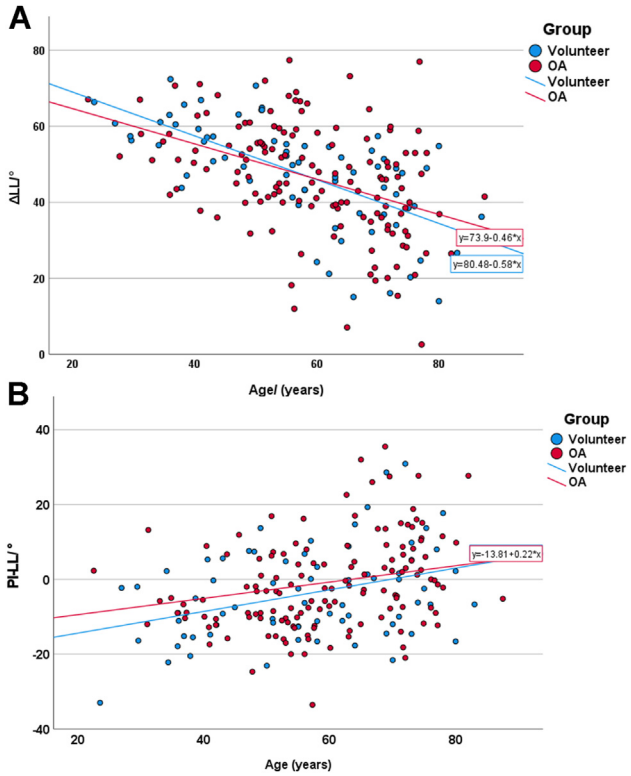

Fig. 4. Scatterplots illustrating the correlation between age and (A) lumbar spine stiffness ($\Delta LL_{standing/deep\text{-}seated}$) and (B) mismatch between PI und LL in the standing position for patients (red) and controls (controls).

exhibited a moderate correlation with age, which was also evident in the ROC analyses; no patient under the age of 55 years-old exhibited spinal stiffness, regardless of $LL_{standing}$. Similarly, $LL_{standing}$ exhibited a strong association with lumbar spine stiffness, and thus a $LL_{standing}$ <45° was identified as an excellent threshold value to use as a screening tool with high sensitivity of 85% and specificity 73%. Based on age and $LL_{standing}$, we were able to identify patients not at risk of adverse spinopelvic characteristics. These patients only require a single standing lateral spinopelvic X-ray (age <65 years, $LL_{standing}$ >45° and no history of spinal pathology) preoperatively, and do not need seated spinopelvic radiographs. This can help reduce radiation exposure while maintaining the ability to use spinopelvic characteristics during preoperative THA planning.

The prevalence of abnormal spinopelvic abnormalities among arthroplasty patients in recent studies has been reported to vary widely between 4% and 53% [19–23]. However, many of these studies have included patients who have lumbar fusions in their cohorts, and defined stiffness using relaxed-seated assessments, which overpredict the presence of spinopelvic abnormalities [9]. In this study of all patients undergoing THA in 2 academic units and having detailed radiographic assessments, the prevalence of spinal imbalance, stiffness, and increased pelvic tilt were 16%, 5%, and 17%, respectively. However, only 4% (6 of 140) of patients showed more than 2 abnormal spinopelvic characteristics. The presence of hip OA was not associated with an increased risk of abnormal spinopelvic characteristics, as evident by the prevalence of these findings in the age, sex, and BMI-matched control group of well-functioning volunteers. Furthermore, the prevalence of abnormal spinopelvic characteristics were similar between matched and unmatched patients. This likely indicates that the hip and spine degenerate independently and that the influence of hip OA on the pathogenesis of spinal degeneration is small, relative to other factors, described to contribute to increased spinal degeneration. However, with advancing age, the incidence of hip-spine syndrome also increases as the incidence of both hip and spine arthritis increase, which are concordant with observations seen in this cohort of advanced age being associated with the presence of abnormal spinopelvic characteristics. These findings are also of important clinical relevance as they illustrate that the proportion of patients who are at increased risk due their individual spinopelvic characteristics is in fact quite low and likely about 10 to 15% of most arthroplasty practices. Thus, it is of importance to define how best to utilize resources to appropriately identify these patients at risk, without over-investigating all patients presenting to clinic.

Several patient- (age and BMI) and static radiographic- factors ($LL_{standing}$, PI-LL, $PT_{standing}$, LL_{seated}) were found to be associated with spinal flexion. However, due to significant association and collinearity between these factors, the 2 factors that were the strongest predictors of spinal flexion/stiffness were age and $LL_{standing}$. ROC analysis of these 2 factors enabled the description of relevant thresholds (age >65 years-old and $LL_{standing}$ <45°) that can be used in the clinical setting to predict the presence of spinal stiffness by considering patient age and performing measurements from a single radiograph ($LL_{standing}$ <45°). Furthermore, no patient below the age of 55 years-old exhibited spinal stiffness, nor spinopelvic imbalance, but 5 had high $PT_{standing}$. Thus, to minimize

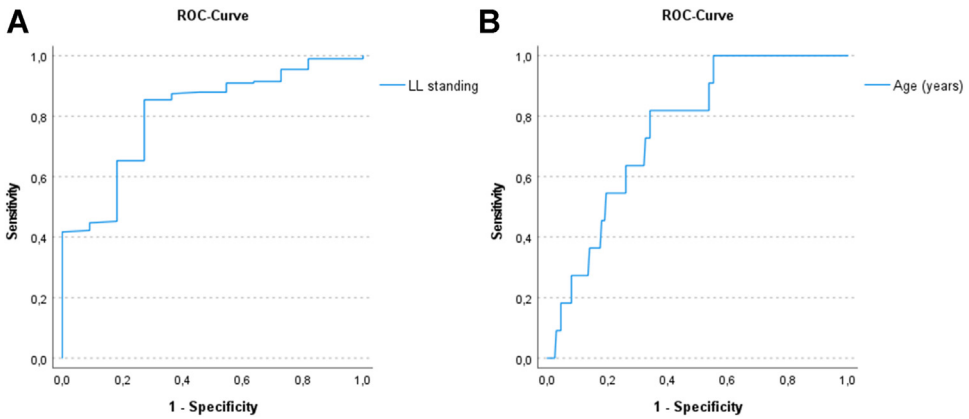

Fig. 5. Receiver operating characteristic (ROC) curve analysis for lumbar spine stiffness and the factors (A) standing lumbar lordosis angle and (B) age.

Table 5
Output of Receiver Operator Curve (ROC) for Lumbar Spine Stiffness.

Factor	Area Under the Curve	Optimum Threshold	Sensitivity	Specificity
Age	0.756	65 y	82%	66%
Standing lumbar lordosis angle	0.808	45°	85%	73%

radiation and cost, if a surgeon solely wishes to identify patients at risk, and does not plan as per sagittal characteristics, no sagittal profile radiographs are necessary for patients younger than 55 years-old without spinal pathology. For patients older than 55 years-old, we would recommend a single standing spinopelvic view to measure $LL_{standing}$, PI-LL and $PT_{standing}$ to identify at-risk patients. Furthermore, static characteristics change little post-operatively, which makes them more reliable in preoperative planning of cup orientation than dynamic characteristics, which are subject to change post-THA [18].

This study has several potential limitations. All assessments were performed using radiographs. Such assessments may thus suffer from variability in the execution of the technician's command by the patients. Also, the study was appropriately powered to detect a 6° difference in LL, which has been reported to be a clinically relevant difference. However, if less of a difference is found to be clinically relevant in the future, this study may suffer for Type II bias. However, there were no large differences between unmatched and matched patients for spinopelvic mobility and the prevalence of pathologies. Furthermore, a much larger cohort would be needed to detect small differences in the distribution of spinopelvic pathologies between groups. A larger cohort would also allow for testing for nonlinear association between age and spinal characteristics as it may be plausible that the relationship present among the young may not be applicable for patients older than 70 years-old. Furthermore, prospective longitudinal assessments would assess the effect of hip OA on lumbar stiffness more accurately. A cross-sectional study may suffer from selection biases that may not be accounted for as part of the study design. To overcome such limitations, we accounted for case controls matched for demographic factors previously considered to affect spinopelvic dynamics.

In conclusion, the presence of at least 1 abnormal spinopelvic characteristic can be found in 1-in-6 patients awaiting THA. Spinal stiffness increases with age and the presence of hip OA is not associated with an increased risk of adverse spinopelvic characteristics. Age and $LL_{standing}$ are the strongest predictors of spinal flexion and important thresholds can be defined that can guide clinical practice on when to obtain additional radiographs prior to surgery. Young patients under the age of 55 years-old did not exhibit spinal stiffness. A single, static lateral spinopelvic view would suffice in hip OA patients above the age of 65 years-old with a relevant $LL_{standing}$ threshold of 45° as it would provide with all data sufficient for screening for adverse spinopelvic characteristics. These evidence-based recommendations help surgeons stratify radiation exposure and reduce cost while incorporating spinopelvic imaging in preoperative THA planning.

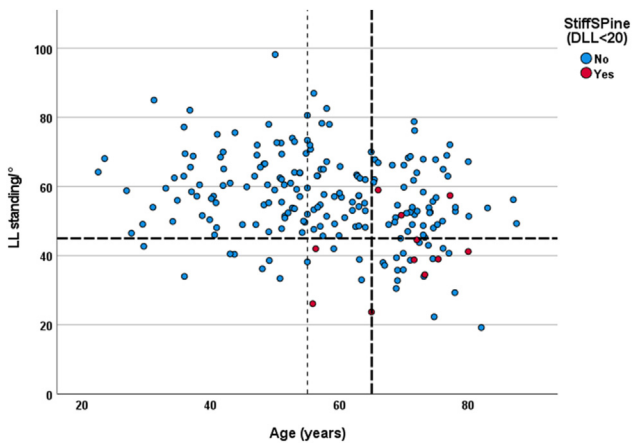

Fig. 6. Scatterplot illustrating the correlation between age and (A) lumbar spine stiffness ($\Delta LL_{standing/deep\text{-}seated}$) and (B) mismatch between PI und LL in the standing position.

Acknowledgments

We thank the noncommercial research funds Stiftung Endoprothetik (Hamburg, Germany) and Canadian Institute of Health Research for supporting this study.

References

[1] Grammatopoulos G, Gofton W, Jibri Z, Coyle M, Dobransky J, Kreviazuk C, et al. 2018 frank stinchfield award: spinopelvic hypermobility is associated with an inferior outcome after THA: examining the effect of spinal arthrodesis. Clin Orthop Relat Res 2019;477:310–21.
[2] Buckland AJ, Puvanesarajah V, Vigdorchik J, Schwarzkopf R, Jain A, Klineberg EO, et al. Dislocation of a primary total hip arthroplasty is more common in patients with a lumbar spinal fusion. Bone Joint J 2017;99-B:585–91.
[3] Bedard NA, Martin CT, Slaven SE, Pugely AJ, Mendoza-Lattes SA, Callaghan JJ. Abnormally high dislocation rates of total hip arthroplasty after spinal deformity surgery. J Arthroplasty 2016;31:2884–5.
[4] Dhawan R, Bare JV, Shimmin A. Modular dual-mobility articulations in patients with adverse spinopelvic mobility. Bone Joint J 2022;104-B:820–5.
[5] Innmann MM, Merle C, Phan P, Beaule PE, Grammatopoulos G. Differences in spinopelvic characteristics between hip osteoarthritis patients and controls. J Arthroplasty 2021;36:2808–16.
[6] Innmann MM, Verhaegen JCF, Reichel F, Schaper B, Merle C, Grammatopoulos G. Spinopelvic characteristics normalize 1 year after total hip arthroplasty: a prospective, longitudinal, case-controlled study. J Bone Joint Surg Am 2022;104:675–83.
[7] Sculco PK, Windsor EN, Jerabek SA, Mayman DJ, Elbuluk A, Buckland AJ, Vigdorchik JM. Preoperative spinopelvic hypermobility resolves following total hip arthroplasty. Bone Joint J 2021;103-B:1766–73.
[8] Stefl M, Lundergan W, Heckmann N, McKnight B, Ike H, Murgai R, Dorr LD. Spinopelvic mobility and acetabular component position for total hip arthroplasty. Bone Joint J 2017;99-B(1 Suppl A):37–45.
[9] Innmann MM, Merle C, Phan P, Beaule PE, Grammatopoulos G. How can patients with mobile hips and stiff lumbar spines Be identified prior to total hip arthroplasty? A prospective, diagnostic cohort study. J Arthroplasty 2020;35:S255–61.
[10] Verhaegen JCF, Innmann M, Alves Batista N, Dion CA, Horton I, Pierrepont J, et al. Defining "normal" static and dynamic spinopelvic characteristics: a cross-sectional study. JB JS Open Access 2022;7:e22.00007.
[11] Kellgren JH, Lawrence JS. Radiological assessment of osteo-arthrosis. Ann Rheum Dis 1957;16:494–502.
[12] Kovalenko B, Bremjit P, Fernando N. Classifications in Brief: tonnis classification of hip osteoarthritis. Clin Orthop Relat Res 2018;476:1680–4.
[13] Innmann MM, Merle C, Gotterbarm T, Ewerbeck V, Beaule PE, Grammatopoulos G. Can spinopelvic mobility be predicted in patients awaiting total hip arthroplasty? A prospective, diagnostic study of patients with end-stage hip osteoarthritis. Bone Joint J 2019;101-B:902–9.
[14] Esposito C, Miller T, Kim H, Barlow B, Wright T, Padgett D, et al. Does degenerative lumbar spine disease influence femoroacetabular flexion in patients undergoing total hip arthroplasty? Clin Orthop Relat Res 2016;474:1788–97.
[15] Langston J, Pierrepont J, Gu Y, Shimmin A. Risk factors for increased sagittal pelvic motion causing unfavourable orientation of the acetabular component in patients undergoing total hip arthroplasty. Bone Joint J 2018;100-B:845–52.
[16] Heckmann N, McKnight B, Stefl M, Trasolini N, Ike H, Dorr L. Late dislocation following total hip arthroplasty: spinopelvic imbalance as a causative factor. J Bone Joint Surg Am 2018;100:1845–53.
[17] Legaye J, Duval-Beaupère G, Hecquet J, Marty C. Pelvic incidence: a fundamental pelvic parameter for three-dimensional regulation of spinal sagittal curves. Eur Spine J 1998;7:99–103.
[18] Grammatopoulos G, Falsetto A, Sanders E, Weishorn J, Gill HS, Beaule PE, et al. Integrating the combined sagittal index reduces the risk of

dislocation following total hip replacement. J Bone Joint Surg Am 2022;104:397–411.
[19] Vigdorchik J, Sharma A, Buckland A, Elbuluk A, Eftekhary N, Mayman D, et al. 2021 Otto Aufranc Award: a simple Hip-Spine Classification for total hip arthroplasty : validation and a large multicentre series. Bone Joint J 2021;103-B(7 Suppl B):17–24.
[20] Vigdorchik JM, Sharma AK, Madurawe CS, Pierrepont JW, Dennis DA, Shimmin AJ. Prevalence of risk factors for adverse spinopelvic mobility among patients undergoing total hip arthroplasty. J Arthroplasty 2021;36:2371–8.
[21] Pierrepont J, Hawdon G, Miles BP, Connor BO, Bare J, Walter LR, et al. Variation in functional pelvic tilt in patients undergoing total hip arthroplasty. Bone Joint J 2017;99-B:184–91.
[22] Gu YM, Kim W, Pierrepont JW, Li Q, Shimmin AJ. The effect of a degenerative spine and adverse pelvic mobility on prosthetic impingement in patients undergoing total hip arthroplasty. J Arthroplasty 2021;36:2523–9.
[23] Buckland AJ, Ayres EW, Shimmin AJ, Bare JV, McMahon SJ, Vigdorchik JM. Prevalence of sagittal spinal deformity among patients undergoing total hip arthroplasty. J Arthroplasty 2019;35:160–5.