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The Impact of Pelvic Incidence on Spinopelvic and Hip Alignment and Mobility in Asymptomatic Subjects

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Background: The influence of pelvic incidence (PI) on spinopelvic and hip alignment and mobility has not been well investigated. The aim of this study was to evaluate the influence of PI on spinopelvic and hip alignment and mobility, including the pelvic-femoral angle (PFA) and motion (ΔPFA), in functional positions in a cohort of asymptomatic volunteers.

Methods: This was a single-center, prospective, cross-sectional study. We included 136 healthy volunteers (69% female; mean age, 38 ± 11 years; mean body mass index, 22 ± 3 kg/m^2) divided into 3 subgroups on the basis of their PI: PI $< 45°$ (low PI), $45° \leq$ PI $\leq 60°$ (medium PI), and PI $> 60°$ (high PI). We made full-body lateral radiographs in free-standing, standing with extension, relaxed-seated, and flexed-seated positions. We measured the sacral slope (SS), lumbar lordosis (LL), and PFA. We calculated lumbar (ΔLL), pelvic (ΔSS), and hip (ΔPFA) mobilities as the change between the standing (i.e., standing with or without extension) and sitting (i.e., relaxed-seated or flexed-seated) positions.

Results: There were significant differences between some of the 3 subgroups with respect to the LL, SS, and PFA in each of the 4 positions. There were no significant differences in ΔLL, ΔSS, or ΔPFA between the 3 groups when moving from a standing to a sitting position. PI had an inverse linear correlation with $\text{PFA}_{\text{extension}}$ ($R = -0.48$; $p < 0.0001$), $\text{PFA}_{\text{standing}}$ ($R = -0.53$; $p < 0.0001$), $\text{PFA}_{\text{relaxed-seated}}$ ($R = -0.37$; $p < 0.0001$), and $\text{PFA}_{\text{flexed-seated}}$ ($R = -0.47$; $p < 0.0001$). However, PI was not correlated with $\Delta\text{PFA}_{\text{standing/relaxed-seated}}$ ($R = -0.062$; $p = 0.48$) or $\Delta\text{PFA}_{\text{extension/flexed-seated}}$ ($R = -0.12$; $p = 0.18$). Similarly, PI was not significantly correlated with ΔLL or ΔSS in either pair of positions.

Conclusions: This study confirmed that spinopelvic and hip parameters in functional positions were affected by PI, whereas lumbar, pelvic, and hip mobilities did not depend on PI. These findings suggest that hip surgeons should consider the PI of the patient to determine the patient's specific functional safe zones before and after total hip arthroplasty.

Level of Evidence: Prognostic Level II. See Instructions for Authors for a complete description of levels of evidence.

Hip mobility is important in the sagittal flexion and extension of the whole coordinated kinematic chain of the spine, pelvis, and lower limbs[1]. This movement occurs in the femoroacetabular articulation. The motion of the femur relative to the pelvis can be estimated with use of the pelvic-femoral angle (PFA), which is the angle of the femur in relationship to the sacrum. This angle helps to define hip mobility (ΔPFA) between postural changes with use of lateral spinopelvic radiographs. Recent studies have utilized lateral radiographs to focus on spinopelvic parameters, including the PFA, in functional positions such as standing and sitting. These studies found that abnormal spinopelvic and hip alignment and mobility impact postoperative outcomes after total hip arthroplasty (THA)[1-5].

Pelvic incidence (PI) is a constant morphological parameter. It is defined as the angle between the line orthogonal to the sacral plate and the line that connects the middle of the sacral plate to the acetabular axis (the P-line)[6]. PI is a radiographic measurement that represents the biomechanical relationship between the lumbar spine and the pelvis in patients with differing pelvic anatomy, which may lead to different patterns of spinopelvic alignment and compensation during daily activities performed by

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patients with physiological and pathological conditions such as hip osteoarthritis[7-9]. Recent studies have demonstrated a relationship between PI and postoperative compensation and dislocation following THA[8,10-13]. However, conflicting results were found for sagittal pelvic morphology[14]. Furthermore, the role of PI in a patient's risk of instability following THA is not well understood.

A prior study demonstrated a correlation between PI and pelvic tilt ($PT = -7 + 0.37 \times PI$; $R = 0.66$)[15]. However, the relationship between PI and PFA has not been well investigated despite its potential importance, both before and after THA, in the kinematics of the femur relative to the pelvis when moving between standing and sitting positions. Furthermore, it is not yet clear whether and how PI is associated with normal spinopelvic and hip alignment and mobility during functional activities.

The aim of the present study was to evaluate the influence of PI on spinopelvic and hip alignment in functional positions involving standing and sitting, and on spinopelvic and hip mobility in moving between those positions, with use of radiographic spinopelvic and hip parameters in a cohort of asymptomatic volunteers. We hypothesized that spinopelvic and hip parameters, including the PFA, would be affected by the PI.

Materials and Methods

Cohort

This was a single-center, prospective, cross-sectional study. We recruited 151 volunteers between March 2022 and August 2022. We included 136 healthy volunteers in the study, comprising 94 (69%) women and 42 (31%) men, with a mean age and standard deviation (SD) of 38 ± 11 years (range, 23 to 64 years). The mean body mass index (BMI) was 22 ± 3 kg/m^2 (range, 17 to 31 kg/m^2; Table I). All subjects were hospital health-care workers. Subjects were excluded on the basis of 6 criteria: (1) the presence of abnormalities in either of the hip joints, including joint-space narrowing and the presence of osteophytes (Tönnis grade of ≥2), as seen on anteroposterior hip radiographs; (2) moderate-to-severe lumbar abnormalities, such as multiple disc degeneration (Kellgren-Lawrence grade of ≥3), spondylolisthesis (Meyerding grade of ≥2), or scoliosis (>30°), as seen on anterior and lateral lumbar radiographs; (3) hip symptoms, as indicated by an Oxford Hip Score of <45 points (range, 0 [worst] to 48 [best]); (4) low-back pain, as indicated by an Oswestry Disability Index of >20 (range, 0 [no disability] to 100 [maximum disability]); (5) a history of hip or spinal surgery; and (6) an age of <20 years. Subjects with mild lumbar abnormalities were included if the abnormalities were considered asymptomatic. Eight volunteers were excluded because of hip or lumbar degeneration, and 7 volunteers were excluded because of inadequate radiographs. The study was approved by the institutional review board of the Kyoto City Hospital (authorization 621) and was conducted per the 2008 Declaration of Helsinki.

Using the values for PI classifications described by Thelen et al.[16], we divided all subjects into 3 subgroups on the basis of their PI: $PI < 45°$ (low PI), $45° \leq PI \leq 60°$ (medium PI), and $PI > 60°$ (high PI)[16], as shown in Table I.

Data Collection and Radiographic Analysis

We made full-body lateral radiographs in free-standing, standing with extension, relaxed-seated, and flexed-seated positions (Fig. 1). For the extension radiograph, the study volunteers were asked to hold onto a horizontal bar slightly higher than shoulder level and to extend their pelvis and spine as much as possible[17]. The relaxed-seated position was defined as a 90° sitting position on a height-adjustable chair with the femora parallel to the floor[18]. In the flexed-seated position, the femora were parallel to the floor with the trunk leaning maximally forward[19].

We measured the sacral slope (SS), PT, PI, L1-S1 lumbar lordosis (LL), and PFA on all of the radiographs (Fig. 1)[2,20,21]. PT is defined as the angle between a vertical line and the P-line. The P-line is defined as the line connecting the center of the acetabulum to the center of the sacral end plate. According to Vialle et al.[15], the theoretical normal value of PT (tPT) depends on the PI of the subject and can be estimated with use of the equation $tPT = -7 + 0.37 \times PI$, as previously described[22,23].

A new line, the H-line, was defined from the center of the acetabulum at a positive-angle tPT from the P-line (Fig. 1).

TABLE I Demographic Characteristics of the Cohort*

		Subgroup			
	Whole Cohort	Low PI (PI < 45°)	Medium PI (45° ≤ PI ≤ 60°)	High PI (PI > 60°)	P Value
No. of subjects	136	37 (27%)	70 (52%)	29 (21%)	<0.001
Sex *(no. [%] of subjects)*					NS
Female	94 (69%)	23	47	24	
Male	42 (31%)	14	23	5	
Age† *(yr)*	38 ± 11 (23-64)	36	37	40	NS
BMI† *(kg/m^2)*	22 ± 3 (17-31)	21	22	22	NS

*NS = not significant. †Values are given as the mean ± SD, with the range in parentheses.

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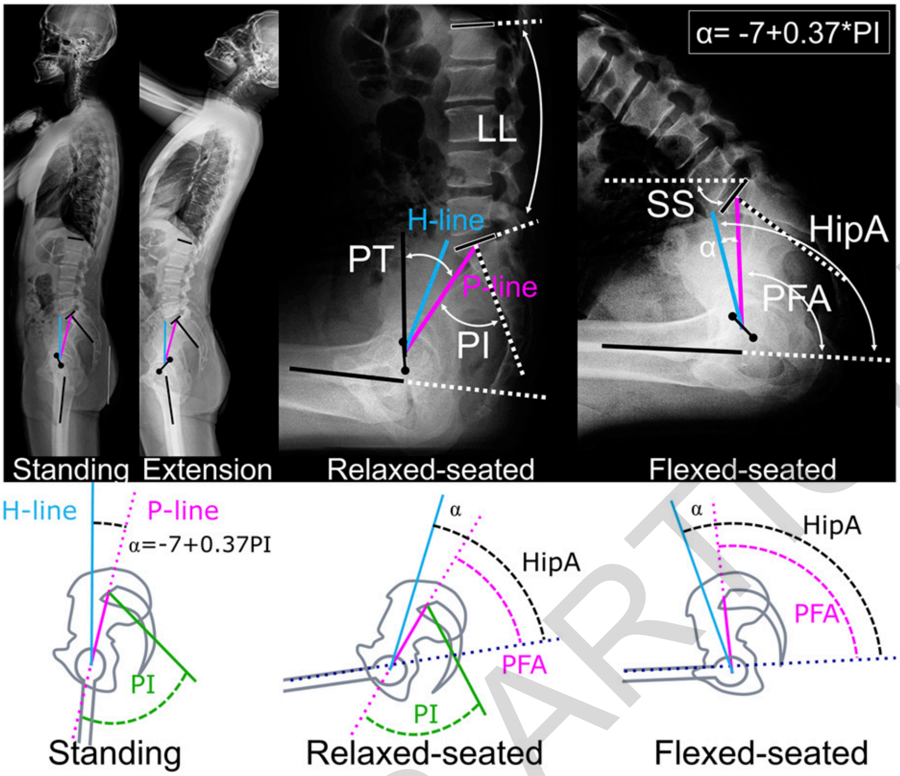

Fig. 1

Lateral radiographs and diagrams in the free-standing (i.e., standing), standing with extension (i.e., extension), relaxed-seated, and flexed-seated positions. The main radiographic parameters are depicted, including the sacral slope (SS), pelvic tilt (PT), pelvic incidence (PI), lumbar lordosis (LL), pelvic-femoral angle (PFA), and hip angle (HipA = PFA + α). α is the theoretical normal value of PT (tPT = −7 + 0.37 × PI). The P-line is defined as the line connecting the center of the acetabulum to the center of the sacral end plate. The H-line is defined as the line extending from the center of the acetabulum at a positive-angle tPT from the P-line.

When the PT of the patient coincides with the tPT, the H-line will be vertical while standing, regardless of the PI. The hip angle (HipA) was defined as the angle between the femur and the H-line. This can be calculated with use of the following equation: $\text{HipA} = \text{PFA} + \text{tPT} = \text{PFA} - 7 + 0.37 \times \text{PI}$. HipA is a femoral flexion angle relative to the anatomical reference of the pelvis that provides a quantitative assessment of the hip flexion angle, similar to a physical examination with the patient in a supine position. The H-line can be considered an anatomical reference of the pelvis as it does not depend on pelvic position.

Two experienced operators (1 hip surgeon [Y.K.] and 1 physiotherapist [H.T.]) performed the radiographic measurements. Measurements in 4 positions were repeated, in a blinded fashion, for 20% of all subjects, who were selected at random. Intraobserver repeatability and interobserver reproducibility were assessed via the intraclass correlation coefficient, which showed an excellent agreement of 0.850 to 0.978 for interobserver reproducibility (see Appendix Table I).

Spinopelvic and hip mobilities were calculated as the change between the standing (i.e., standing or extension) and sitting (i.e., relaxed-seated or flexed-seated) positions, indicated as $\Delta X_{\text{standing/sitting}} = X_{\text{sitting}} - X_{\text{standing}}$.

We divided the dynamic spine-pelvis-hip motion into pelvic, hip, and lumbar mobilities[1]. Pelvic mobility was defined as the difference in SS between the standing and sitting positions ($\Delta SS_{\text{standing/sitting}}$) and was classified as stiff ($\Delta SS_{\text{standing/relaxed-seated}} \geq -10°$), normal ($-10° > \Delta SS_{\text{standing/relaxed-seated}} > -30°$), or hypermobile ($\Delta SS_{\text{standing/relaxed-seated}} \leq -30°$)[24]. We defined hip mobility as the difference in PFA between the standing and sitting positions ($\Delta PFA_{\text{standing/sitting}}$). Lumbar mobility was defined as the difference in LL between the standing and sitting positions ($\Delta LL_{\text{standing/sitting}}$) and was classified as stiff ($\Delta LL_{\text{standing/flexed-seated}} > -20°$), flexible ($-20° \geq \Delta LL_{\text{standing/flexed-seated}} > -40°$), or hypermobile ($\Delta LL_{\text{standing/flexed-seated}} \leq -40°$)[1,25].

Statistical Analysis

After describing the cohort in terms of baseline demographics and radiographic alignments, we conducted comparisons of the radiographic measurements between positions with use of the paired t test and chi-square test. We made demographic and radiographic-parameter comparisons across the PI subgroups (i.e., low, medium, and high PI) with use of either analysis of variance or the Kruskal-Wallis test, according to the normality of the data, which was checked with use of the Shapiro-Wilk

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test. We applied a Tukey-Kramer correction to multiple comparisons. The level of significance was set at $p < 0.05$. We utilized MATLAB 2020b (MathWorks) for the calculations. We performed a correlation analysis with use of Microsoft Excel (version 16.0) to determine the Pearson correlation coefficient (r) between the parameters. Correlation was defined as strong ($r \geq 0.7$), moderate ($0.4 < r < 0.7$), or weak ($r \leq 0.4$).

Results

Demographic data of the asymptomatic volunteers are presented in Table I. There were no significant differences in demographic data between the 3 subgroups. However, more subjects ($p < 0.001$) presented with a medium PI (52%) than a low PI (27%) or a high PI (21%), which was expected.

Spinopelvic and Hip Alignment

There were significant differences between some of the 3 subgroups (low, medium, and high PI) with respect to the LL, SS, PT, and PFA in each of the 4 positions (extension, standing, relaxed-seated, and flexed-seated; Table II). No significant differences were found between the subgroups with respect to the HipA, nor was any difference found in the mean HipA between women (3.1° ± 6.6°) and men (5.2° ± 4.7°; $p = 0.07$) in the standing position.

Lumbar, Pelvic, and Hip Mobilities

No significant differences in ΔLL, ΔSS, or ΔPFA were found between the 3 groups when moving from a standing to a relaxed-seated position or from an extension to a flexed-seated position (Table III). A stiff pelvis was demonstrated in 51% of the cohort, and a hypermobile pelvis was demonstrated in 1%, with a normal pelvis demonstrated in the remaining subjects (Table IV). All subjects demonstrated a hypermobile lumbar spine.

Relationship of PI with PFA and Lumbar, Pelvic, and Hip Mobilities

PI was moderately correlated with PFA$_{extension}$ ($R = -0.48$; $p < 0.0001$) and PFA$_{standing}$ ($R = -0.53$; $p < 0.0001$; Fig. 2). Similarly, PI was weakly correlated with PFA$_{relaxed\text{-}seated}$ ($R = -0.37$; $p < 0.0001$) and moderately correlated with PFA$_{flexed\text{-}seated}$ ($R = -0.47$; $p < 0.0001$; Fig. 2). However, there was no significant

TABLE II Spinopelvic and Hip Parameters in the Standing, Extension, Relaxed-Seated, and Flexed-Seated Positions*

Parameter	Position	Whole Cohort	Subgroup: Low PI	Subgroup: Medium PI	Subgroup: High PI	P Value: L Versus M	P Value: L Versus H	P Value: M Versus H
PI *(deg)*	Standing	52 ± 11	39 ± 4	52 ± 4	68 ± 5	<0.001	<0.001	<0.001
LL *(deg)*	Extension	62 ± 11	55 ± 10	63 ± 10	68 ± 10	<0.05	<0.001	NS
	Standing	53 ± 11	46 ± 10	54 ± 10	60 ± 8	<0.001	<0.001	<0.05
	Relaxed-seated	34 ± 14	27 ± 14	34 ± 14	40 ± 10	<0.05	<0.001	NS
	Flexed-seated	−9 ± 11	−16 ± 9	−8 ± 11	−2 ± 10	<0.001	<0.001	<0.05
PI-LL *(deg)*	Standing	−1 ± 10	−6 ± 9	−2 ± 8	7 ± 11	<0.05	<0.001	<0.001
SS *(deg)*	Extension	35 ± 9	30 ± 8	36 ± 8	42 ± 6	<0.001	<0.001	<0.001
	Standing	39 ± 8	32 ± 6	39 ± 6	46 ± 5	<0.001	<0.001	<0.001
	Relaxed-seated	28 ± 10	21 ± 9	29 ± 10	36 ± 8	<0.001	<0.001	<0.05
	Flexed-seated	62 ± 14	56 ± 11	62 ± 16	68 ± 10	<0.05	<0.001	NS
PT *(deg)*	Extension	16 ± 9	10 ± 8	15 ± 7	24 ± 8	<0.05	<0.001	<0.001
	Standing	13 ± 7	8 ± 5	13 ± 5	21 ± 6	<0.001	<0.001	<0.001
	Relaxed-seated	24 ± 11	20 ± 10	24 ± 10	31 ± 9	NS	<0.001	<0.05
	Flexed-seated	−9 ± 13	−15 ± 10	−10 ± 12	−1 ± 11	NS	<0.001	<0.001
PFA *(deg)*	Extension	−13 ± 9	−8 ± 8	−13 ± 8	−20 ± 9	<0.05	<0.001	<0.001
	Standing	−8 ± 7	−4 ± 7	−8 ± 6	−15 ± 6	<0.05	<0.001	<0.001
	Relaxed-seated	69 ± 12	74 ± 13	69 ± 11	63 ± 11	NS	<0.001	<0.05
	Flexed-seated	103 ± 12	109 ± 11	103 ± 10	94 ± 12	<0.05	<0.001	<0.05
HipA *(deg)*	Extension	−1 ± 8	−1 ± 8	−1 ± 8	−2 ± 8	NS	NS	NS
	Standing	4 ± 6	4 ± 7	4 ± 6	3 ± 5	NS	NS	NS
	Relaxed-seated	81 ± 11	81 ± 13	81 ± 11	81 ± 10	NS	NS	NS
	Flexed-seated	115 ± 10	117 ± 11	115 ± 10	112 ± 11	NS	NS	NS

*Values are given as the mean ± SD, and p values are reported for significant differences between the subgroups. L = low PI, M = medium PI, H = high PI, NS = not significant.

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TABLE III Changes in Spinopelvic and Hip Parameters from the Standing to Relaxed-Seated Position and the Extension to Flexed-Seated Position*

Parameter	Position	Whole Cohort	Subgroup			P Value
			Low PI	Medium PI	High PI	
ΔLL *(deg)*	Standing to relaxed-seated	−19 ± 13	−18 ± 14	−20 ± 14	−20 ± 11	NS
	Extension to flexed-seated	−71 ± 12	−72 ± 9	−70 ± 14	−70 ± 12	NS
ΔSS *(deg)*	Standing to relaxed-seated	−10 ± 9	−10 ± 9	−10 ± 9	−10 ± 8	NS
	Extension to flexed-seated	26 ± 13	27 ± 12	27 ± 15	26 ± 11	NS
ΔPFA *(deg)*	Standing to relaxed-seated	77 ± 10	78 ± 11	77 ± 10	78 ± 10	NS
	Extension to flexed-seated	116 ± 11	117 ± 12	116 ± 10	114 ± 11	NS

*Values are given as the mean ± SD. NS = not significant.

correlation between PI and $\Delta PFA_{standing/relaxed\text{-}seated}$ (R = −0.062; p = 0.48) or $\Delta PFA_{extension/flexed\text{-}seated}$ (R = −0.12; p = 0.18; Fig. 3). Similarly, there was no significant correlation between PI and ΔLL or ΔSS in either pair of positions.

Discussion

This study is among the first to describe the classification of spinopelvic and hip alignment and mobility based on the PI of asymptomatic volunteers in 4 positions (free-standing, extension, relaxed-seated, and flexed-seated). Spinopelvic and hip alignment (LL, SS, PT, and PFA) varied significantly according to the PI of the subject (low, medium, or high) in each position, with many of the differences between the subgroups being significant, whereas there were no significant differences in lumbar, pelvic, or hip mobility (ΔLL, ΔSS, and ΔPFA) between the low, medium, and high-PI subgroups. These results support our hypothesis that PI influences spinopelvic and hip parameters, including the PFA. The factors affecting spinopelvic and hip alignment and mobility in patients before and after THA are of increasing interest. It is important for surgeons to understand spinopelvic kinematics in order to identify patients who are at a high risk for dislocation and impingement before and after THA[3,26].

The role of PI is also an important consideration in the preoperative evaluation of a patient for spinal realignment surgery because PI directly influences spinopelvic alignment, including PT, SS, LL, and overall sagittal spinal balance[27]. Previous studies have shown that PI is strongly correlated with SS (r = 0.80) and LL (r = 0.60) in the standing position[6,15,28]. This finding is consistent with the results of the present study, which also examined different positions. Furthermore, we found that high PI was associated with a lower PFA (more extension of the femur relative to the P-line) and low PI was associated with a higher PFA (more flexion of the femur relative to the P-line) in the standing and sitting positions (Fig. 4). This relationship between PI and the PFA may lead to compensatory changes in spinopelvic alignment. Similarly, Ike et al. reported that, for patients with low-PI hips who were undergoing THA, more femoral flexion was required for sitting because the PFA in such patients was high[29] (note that the PFA measured by these authors was the complement of the definition utilized in the present study).

However, the differences in PFA between individuals with low PI and those with high PI depend on the PI and not on the difference in femoral flexion angle. Nevertheless, the

TABLE IV Distribution of the Study Volunteers by Pelvic Mobility and Lumbar Mobility Types*

Mobility Type	Whole Cohort	Subgroup			P Value
		Low PI	Medium PI	High PI	
Pelvic mobility					
Stiff (ΔSS ≥ −10°)	51%	54%	51%	46%	NS
Normal (−10° > ΔSS > −30°)	48%	43%	48%	54%	NS
Hypermobile (ΔSS ≤ −30°)	1%	3%	1%	0%	NS
Lumbar mobility					
Stiff (ΔLL > −20°)	0%	0%	0%	0%	NS
Flexible (−20° ≥ ΔLL > −40°)	0%	0%	0%	0%	NS
Hypermobile (ΔLL ≤ −40°)	100%	100%	100%	100%	NS

*NS = not significant.

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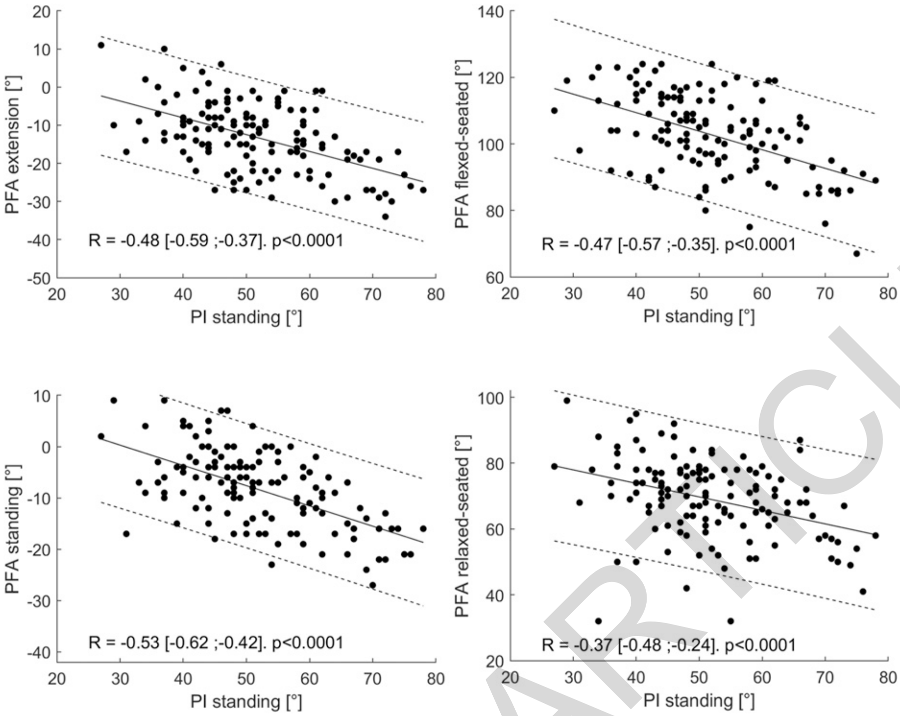

Fig. 2

Graphs showing the correlation between PI and PFA in each position. The solid line represents the linear regression between the parameters, and the dashed lines represent the bounds of the 95% prediction interval.

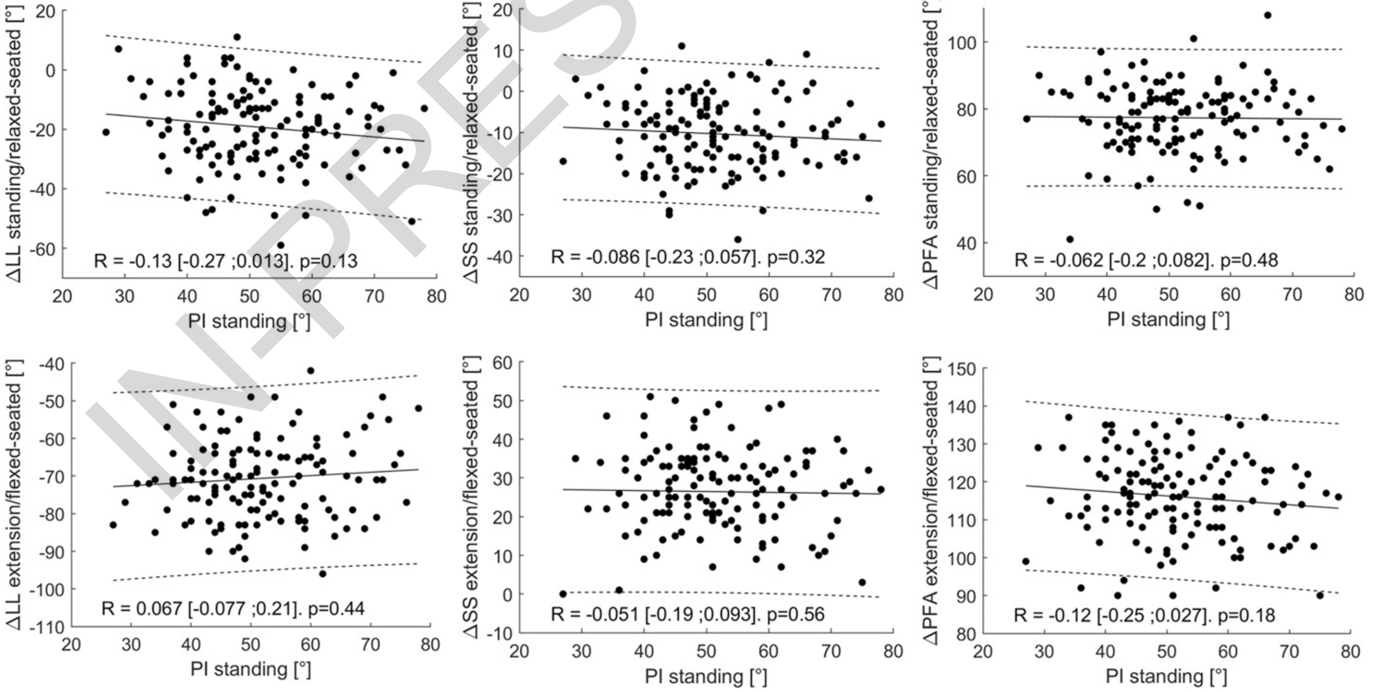

Fig. 3

Graphs showing the correlation of PI with ΔLL, ΔSS, and ΔPFA from the standing to relaxed-seated position and the extension to flexed-seated position. The solid line represents the linear regression between the parameters, and the dashed lines represent the bounds of the 95% prediction interval.

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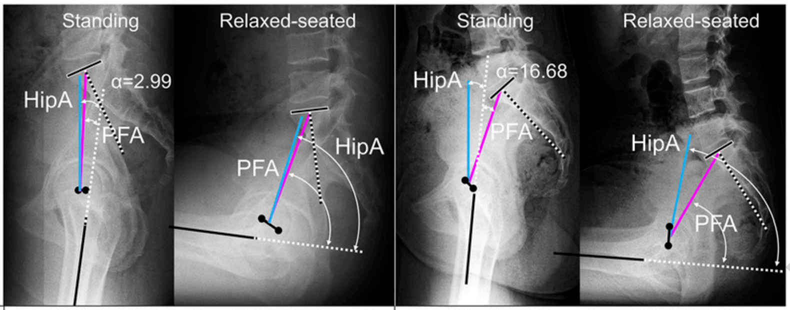


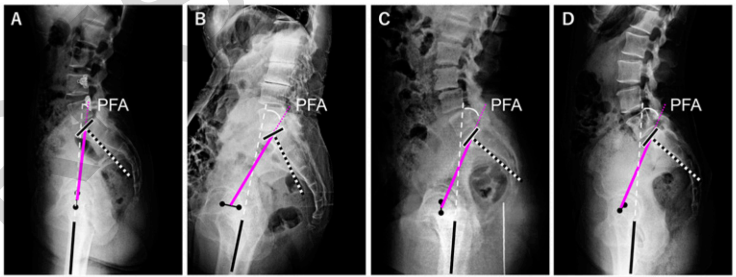
Parameter	Standing	Relaxed-seated	Standing	Relaxed-seated
PI (°)	27 (low PI)		64 (high PI)	
PT (°)	1		18	
PFA (°)	2	79	-9	65
HipA (°)	5	82	8	82

Fig. 4

Descriptions and diagrams of the spinopelvic and hip parameters in the standing and relaxed-seated positions in a subject with low PI and a subject with high PI. The solid blue line represents the H-line, the solid pink line denotes the P-line, and the striped white and black line represents the line orthogonal to the sacral plate. $\alpha = -7 + 0.37 \times \text{PI}$.

correlation between PFA and PI was only weak or moderate in all 4 positions (Fig. 2), suggesting that other variables influence this relationship. The posture of the subject in each of the 4 positions may affect the variability in the PFA that is not attributable to the PI. The differences in PFA should be considered during the preoperative and postoperative evaluation of patients undergoing THA (Figs. 5 and 6).

We hypothesized that the PFA is directly influenced by the PI, since the PFA is the angle of the femur relative to the pelvis[17,29]. HipA is a new angle that allows for the quantification of hip mobility while accounting for the PI. This was confirmed by the fact that the HipA did not vary with the PI, whereas the PFA did (Table II). Therefore, the HipA is independent of the PI and can be evaluated on its own, whereas the PFA should be considered according to the PI of the patient and may have a different interpretation in different patients. Surgeons should consider the newly developed radiographic femoral flexion angle (HipA) relative to the new calculated reference line (the



PI (°)	48 (Volunteer)	48 (Patient)	72 (Patient)	72 (Volunteer)
PI-LL (°)	6	33	7	10
SS (°)	36	16	48	46
PFA (°)	-6	-20	-20	-20
α (°)	11	11	20	20
HipA (°)	5	-9	0	0
Hip alignment	Normal	Hyperextended	Normal	Normal
Risk of anterior dislocation		>		

Fig. 5

Clinical application in the standing position. The lateral spinopelvic-hip radiographs of 2 study volunteers (**Figs. 5-A and 5-D**) and 2 patients with hip arthrosis (**Figs. 5-B and 5-C**) in the standing position illustrate the study measurements, with the solid pink line representing the P-line. The patient radiographs were made preoperatively. The patients had the same PFA (−20°) with different PIs (48° versus 72°). The calculated α angle ($-7 + 0.37 \times \text{PI}$) was 11° in **Fig. 5-B** but 9° higher, 20°, in **Fig. 5-C**. The calculated HipA ($\text{PFA} - 7 + 0.37 \times \text{PI}$) was −9° in **Fig. 5-B** but 0° in **Fig. 5-C**. The hip alignment in the standing position was normal in both the patient with high PI (**Fig. 5-C**) and the volunteer with the same PI (**Fig. 5-D**). However, the patient with low PI (**Fig. 5-B**) had hyperextended hip alignment due to compensation for lumbar kyphosis ($\text{PI} - \text{LL} = 33°$), whereas the volunteer with the same PI had normal hip alignment (**Fig. 5-A**). Although the 2 patients had the same preoperative PFA, the patient with low PI had a higher risk of anterior dislocation after THA as a result of the extension of the femur relative to the pelvis.

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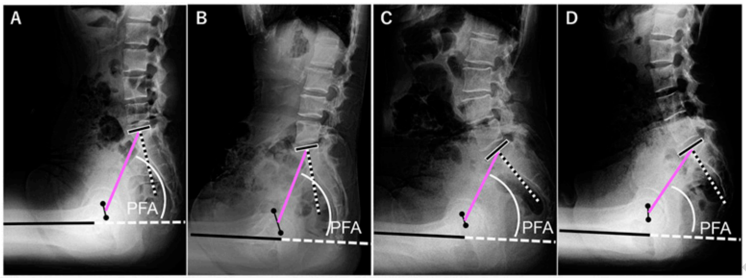

PI (º)	36 (Volunteer)	36 (Patient)	66 (Patient)	66 (Volunteer)
LL (º)	21	10	50	43
SS (º)	13	9	39	35
PFA (º)	72	72	72	57
α (º)	6	6	17	17
HipA (º)	78	78	89	74
Hip alignment	Normal	Normal	hyperflexed	Normal
Risk of posterior dislocation		<		

Fig. 6

Clinical application in the relaxed-seated position. The lateral spinopelvic-hip radiographs of 2 study volunteers (**Figs. 6-A and 6-D**) and 2 patients with hip arthrosis (**Figs. 6-B and 6-C**) in the relaxed-seated position illustrate the study measurements, with the solid pink line representing the P-line. The patient radiographs were made preoperatively. The patients had the same PFA (72°) with different PIs (36° versus 66°). The calculated α angle ($-7 + 0.37 \times \text{PI}$) was 6° in **Fig. 6-B** but 11° higher, 17°, in **Fig. 6-C**. The calculated HipA ($\text{PFA} - 7 + 0.37 \times \text{PI}$) was 78° in **Fig. 6-B** but 89° in **Fig. 6-C**. The hip alignment in the relaxed-seated position was normal in both the patient with low PI (**Fig. 6-B**) and the volunteer with the same PI (**Fig. 6-A**). However, the patient with high PI (**Fig. 6-C**) had hyperflexed hip alignment due to hip hypermobility, whereas the volunteer with the same PI had normal hip alignment (**Fig. 6-D**). Although the 2 patients had the same preoperative PFA, the patient with high PI had a higher risk of posterior dislocation after THA as a result of the flexion of the femur relative to the pelvis.

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H-line), which is not affected by the PI of the individual before or after THA.

A recent study demonstrated that PI did not show any significant correlation with lumbar or pelvic mobility in patients undergoing THA[26]. However, that study preoperatively evaluated patients with osteoarthritis and hip contracture, which may affect lumbar and pelvic mobility[1], and did not evaluate hip mobility. The present study is the first, to our knowledge, to evaluate the spinopelvic and hip measurements of asymptomatic volunteers in order to clarify the role of PI in lumbar, pelvic, and hip mobilities. Our results confirmed that there were no significant differences in lumbar, pelvic, or hip mobility between the low, medium, and high-PI subgroups. This finding suggests that the functional hip's mobility cone for daily living activities and the risk of prosthetic impingement and edge loading are constant, regardless of the PI.

Interestingly, 51% of the volunteers in our study had a stiff pelvis. Patients with spinopelvic stiffness when moving from a standing to a sitting position are at a high risk for hip dislocation after THA[14,30]. Spinopelvic stiffness is a well-established parameter that can be measured with use of standing and sitting lateral radiographs[30]. However, a recent study found that a $\Delta SS_{\text{standing/relaxed-seated}}$ of $\geq -10°$ was not correlated with a stiff spine and overpredicted its presence[31]. Furthermore, we previously reported that improvements in hip mobility were associated with decreased postoperative lumbar and pelvic mobility[1]. The findings of these studies suggest that, in the present study, the presence of a stiff pelvis in half of a normal population without hip disease was the result of good hip flexion. Classifications of pelvic mobility warrant future studies.

Preoperative identification of abnormalities in spinopelvic and hip alignment and mobility can lead to patient-specific alterations in the position of the component to insure against impingement and mechanical instability following THA[3]. Furthermore, postoperative evaluation of these abnormalities in patients with impingement and late dislocation following THA can clarify the optimal surgical treatment[2,32]. Hip hypermobility is a risk factor for impingement and dislocation after THA[3,5,32], but previous studies, such as the one by Bodner et al.[3], have defined extension and flexion with use of the PFA. The results of the present study are supported by the findings of previous studies[3,33], including the findings reported by Ike et al.[29], who demonstrated that the combined sagittal index (CSI; i.e., the anteinclination of the cup + the PFA) was stratified by PI into 10°-stepped ranges for the standing and sitting positions. The present study showed that the difference in the PFA due to the PI should be considered when evaluating the spine-pelvis-hip alignment preoperatively.

The present study has several limitations. First, it included only volunteers and did not include any patient data, which was beyond the scope of this work. Future studies should include patients with spinal and hip disorders, especially because degenerative disease of the hip and lower back is a common comorbidity. Second, 69% of the volunteers were female, which might have resulted in a sex distribution bias. The impact of sex on spinopelvic and hip alignment and mobility requires future study. Third, the study volunteers had a low BMI relative to the general population, even if 77% of the volunteers were of a healthy weight between 18.5 and 24.9. Fourth, uncertainty regarding the angles of interest was evaluated by repeating the measurements on the same set of radiographs. Although the subjects were positioned correctly, repeated radiographs could have confirmed that. However, the reproducibility of the radiographs was not addressed because doing so would have increased the radiation exposure of the subjects. Fifth, although the subjects were placed orthogonal to the x-ray plane, the results showed some degree of oblique projection, which affected the measurements. Three-dimensional measurements of biplanar radiographs would address this issue and would allow for the assessment of uncertainty introduced by subject misalignment.

Conclusions

This study found that lumbar (ΔLL), pelvic (ΔSS), and hip (ΔPFA) mobilities were constant regardless of the PI in each functional position. However, spinopelvic and hip parameters, including the LL, SS, and PFA, were affected by PI and should be corrected according to the PI in a functional position. On the basis of these results, we suggest 3 specific recommendations for surgeons: (1) PI should be considered in preoperative planning and postoperative evaluation of spinopelvic and hip alignment in functional positions because of the difference in normal values between individuals with low and high PI; (2) the PFA should be considered key to determining the optimal cup orientation and CSI preoperatively[32]; and (3) the PFA should be corrected according to the PI of the patient, which determines the patient's specific functional safe zone. The optimal cup position relative to the PI of the individual should be addressed in future research.

Appendix

eA Supporting material provided by the authors is posted with the online version of this article as a data supplement at jbjs.org (http://links.lww.com/JBJS/I36). ■

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