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Impact of Flatback Deformity and Stiff Spinopelvic Mobility on 3-Dimensional Pelvic and Hip Kinematics After Total Hip Arthroplasty

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Background: Spinopelvic abnormalities have been reported to be a risk factor for dislocation after total hip arthroplasty (THA). This study aimed to compare the kinematics of the pelvis and hip joints in patients with and without spinopelvic abnormalities after THA and to elucidate dynamic forward-leaning movement during chair-rising, which are not detectable through static radiographs.

Methods: This case series included 108 hips that underwent dynamic anteroposterior radiographic imaging of the sit-to-stand motion after THA. The average age at surgery was 68 ± 10 years, with 95 hips (88%) in women (average body mass index, 23.5 ± 3.2 kg/m^2). Kinematic analysis was performed to measure the anterior pelvic plane angle (APPa) and hip flexion/extension angles from seated to standing positions using model-image registration techniques. Pelvic incidence (PI) and lumbar lordosis (LL) were measured to calculate PI-LL.

Results: Flatback deformity was present in 45 hips (42%) and stiff spinopelvic mobility (SPM) in 35 hips (32%), with both deformities present in 21 hips (19%). The pelvis was consistently significantly posteriorly tilted in the flatback deformity group throughout the movement compared with the normal group, with the greatest difference observed in the standing position. The hip flexion angles in the flatback deformity group showed significant extension in the standing position (7° greater than that in the normal group). For stiff SPM, a significant posterior tilt in the standing position was observed. Accordingly, the range between the maximum hip flexion and extension was 13° greater. There was no significant difference between the maximal flexion and extension centers.

Conclusions: Patients with flatback deformities consistently exhibited posterior APPa, especially when standing. In stiff SPM, a large range of hip flexion and extension while chair-rising increased the risk of impingement, indicating the necessity for a wider range of motion without changing the target orientation. These findings highlight the importance of considering spinopelvic alignment when planning cup positioning in THA to minimize the risk of dislocation.

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

Each author certifies that they have no commercial associations that may pose a conflict of interest in connection with the submitted article.

This study was approved by our Institutional Review Board (23,113-00). This study was conducted in accordance with the principles of the Declaration of Helsinki.

This study was supported by a grant from the Ogata Memorial Foundation, Inc. (No. 135) and the Foundation for The Advancement of Clinical Medicine, Fukuoka, Japan.

Disclosure: The **Disclosure of Potential Conflicts of Interest** forms are provided with the online version of the article (http://links.lww.com/JBJSOA/A748).

Introduction

Total hip arthroplasty (THA) is highly effective for pain relief and functional improvement, and the number of surgeries continues to increase[1-3]. However, postoperative dislocation is an important complication that may require reoperation[4,5].

Recently, abnormalities in spinopelvic alignment have garnered attention as risk factors for dislocation[6,7]. Flatback deformity, an imbalance between pelvic incidence (PI) and lumbar lordosis (LL), is reportedly associated with a high risk of dislocation[6]. Stiff spinopelvic mobility (stiff SPM), characterized by a minimal (<10°) change in the anterior pelvic plane angle (APPa)[8] between sitting and standing, is considered a high-risk factor for posterior dislocation[7]. A study reported that using the hip–spine classification, which combines the presence of flatback deformity and stiff SPM to set target cup orientations for each classification, reduces the risk of dislocation[9]. These targets were determined on the basis of pathology rather than dynamic kinematics. It is important to analyze the dynamics of standing up from a chair because this movement is frequently performed in daily life and a previous study reported that sitting and standing are the most common movements in which dislocations occur[10]. Although there have been 2-dimensional studies examining APPa and hip flexion angles in relation to spinopelvic alignment abnormalities using static radiographs in sitting and standing positions[11,12], little research has focused on the dynamic forward-leaning movement from sitting to standing. The model-image registration technique is useful for this evaluation, providing a highly accurate and detailed 3-dimensional assessment[13,14].

Therefore, this study aimed to compare pelvis and hip joint kinematics after THA between patients with flatback deformity or stiff SPM and those without, using model-image registration techniques. On the basis of these comparisons, this study also aimed to elucidate the kinematics during the transition from sitting to standing, specifically the forward-leaning movement just before rising from a chair, which is not detectable through static radiographs.

Materials and Methods

This study was conducted in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology statement[15] and was approved by our facility's Institutional Review Board (IRB number 23113-00). This retrospective case series study included patients who underwent primary THA for

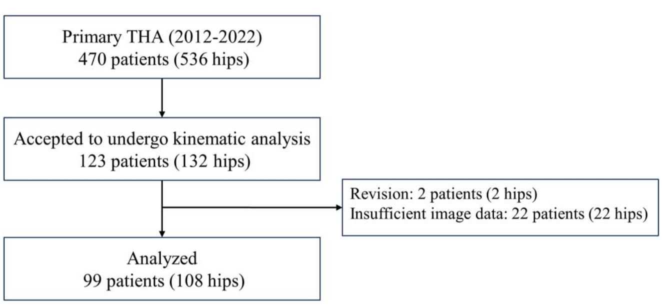

Fig. 1
Flow diagram of patient selection. THA = total hip arthroplasty.

TABLE I Participants' Demographic Data*

n	99 Patients and 108 Hips
Age at surgery (yrs)	68 ± 10
Sex (women/men)	95 hips/13 hips
Height (cm)	153 ± 6.5
Weight (kg)	55.3 ± 8.8
Body mass index (kg/m^2)	23.5 ± 3.2
Disease (OA/ONFH)	98 hips/10 hips
Postoperative period of kinematic radiographs (mo)	13.7 ± 12.8
Spinal pathology; patients (hips) Degenerative lumbar spondylolisthesis/ vertebral fracture/lumbar spinal stenosis/ lumbar disc herniation/spinal fusion	73 (80)/20 (25)/ 13 (15)/2 (3)/2 (3)

*Data are presented as mean ± SD. OA = osteoarthritis, and ONFH = osteonecrosis of the femoral head.

osteoarthritis or femoral head necrosis performed by 2 senior surgeons (S.H. and Y.N.) between April 2012 and March 2022. Patients younger than 18 years or older than 90 years, as well as those with dementia or neuromuscular disorders, were excluded from the study. Among those, patients who underwent both dynamic radiographs and postoperative computed tomography (CT) scans were included in the analysis. All the participants provided informed consent to participate in the study and were informed of the risk of radiation exposure. Ninety-nine patients and 108 hips met the eligibility criteria (Fig. 1). The patient demographics are presented in Table I. Of the 98 hips with osteoarthritis, 80 hips (82%) were secondary to developmental dysplasia of the hip. Degenerative lumbar spondylosis was observed in 80 hips, vertebral fractures in 25 hips, lumbar spinal stenosis in 15 hips, and lumbar disc herniation in 3 hips. Three hips had a history of spinal fusion. All THA procedures were conducted using a similar standardized technique with a posterolateral approach, including posterior soft-tissue repair. Information on the implants used is provided in Appendix Table 1.

Image Acquisition

All patients underwent postoperative standing lateral spinopelvic radiography and CT scans (Aquilion; Canon Medical Systems) with a 512 × 512 matrix, 0.35- × 0.35-pixel size, and 1-mm slice thickness from the pelvis to below the knee joint.

Dynamic anteroposterior radiographic images of the chair-rising motion were captured using a flat panel x-ray detector (Ultimax-I; Canon Medical Systems Corporation; Fig. 2). This detector features an image area of 420 mm (H) × 420 mm (V) and a resolution of 0.274 mm × 0.274 mm per pixel. The frame rate was set at 3.5 fps to obtain high-resolution images. During chair-rising, participants stood from sitting on a chair with 46.5-cm height to match radiography conditions[16,17]. Anteroposterior radiographic images were used because, in lateral views, the

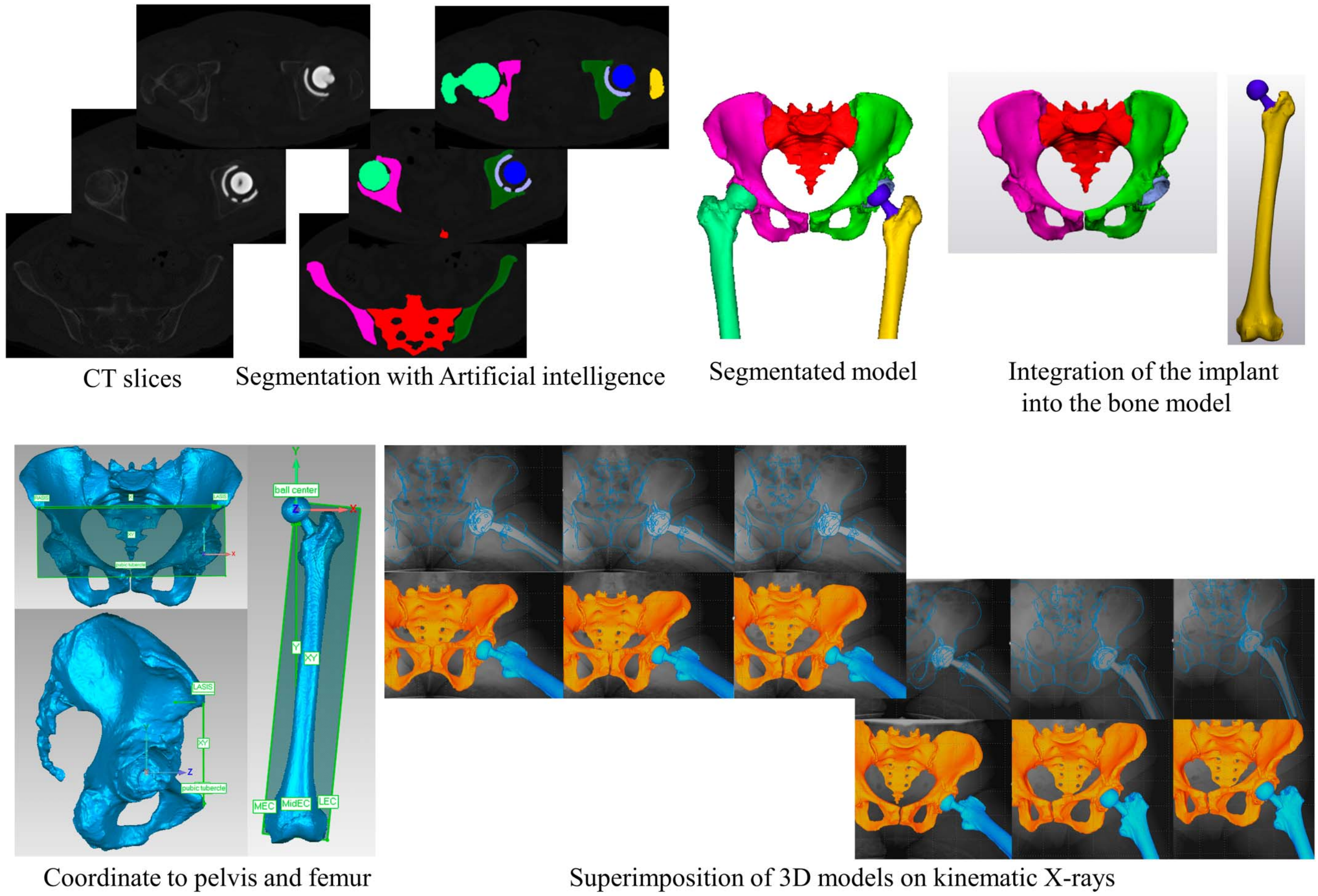

Fig. 2
Process of kinematic analysis using model-image registration techniques.

femoral head can overlap with the contralateral femoral head or parts of the pelvis, which can interfere with the analysis.

Measurement of Radiographs and CT

LL was measured using static lateral spinopelvic radiographs as the angle between the superior endplate of the L1 body and the sacral endplate[18]. PI was assessed using CT scans because radiographic measurements can be inaccurate owing to variations in patient positioning during imaging[19,20]. The PI was measured as the angle between the perpendicular line from the center of the sacral endplate and the line connecting the center of the sacrum to the center of the femoral head (Fig. 3)[18,19]. The posterior APPa in the supine position was also measured as the angle between the anterior pelvic plane (APP)[21] and the floor. Measurements based on the CT images were obtained using ZedHip (Lexi)[22].

Creation of the Bone Model and the Coordinate System

Three-dimensional reconstructions of the pelvic bone, acetabular cup, femur bone, and stem were performed using Mimics (version 26.0; Materialize, Leuven, Belgium) combined with postoperative CT scans. In Mimics, high-precision segmentation using artificial intelligence is achievable[23]. Using 3-matic (version 18.0; Materialize), the acetabular cup was combined with the pelvic bone, and the stem was combined with the femur bone. The anatomical coordinate systems of the pelvis and femur were embedded in these models using Geomagic Wrap 2021 (Raindrop Geomagic). The coordinate system of the femur was based on the recommendations of the International Society of Biomechanics, and the origin was determined as the center of the femoral head[16]. The coordinate system of the pelvis was based on the APP[24], and the origin was set at the origin of the femur (center of the femoral head) (Fig. 2).

Kinematic Analysis

Pelvis and hip joint kinematics were quantified using open-source software for 3D-to-2D model-image registration (JointTrack, www.sourceforge.net/projects/jointtrack)[25,26]. The bone model was projected onto dynamic radiographs, and its 3-dimensional pose was iteratively adjusted to match its silhouette with that of the radiographic image (Fig. 2). The accuracy of this method was 0.2 mm for in-plane translation, 0.5 mm for out-of-plane translation, and 1.6° for rotations[27].

The orientation of the pelvis and the orientation of the femur relative to the pelvis were calculated using custom

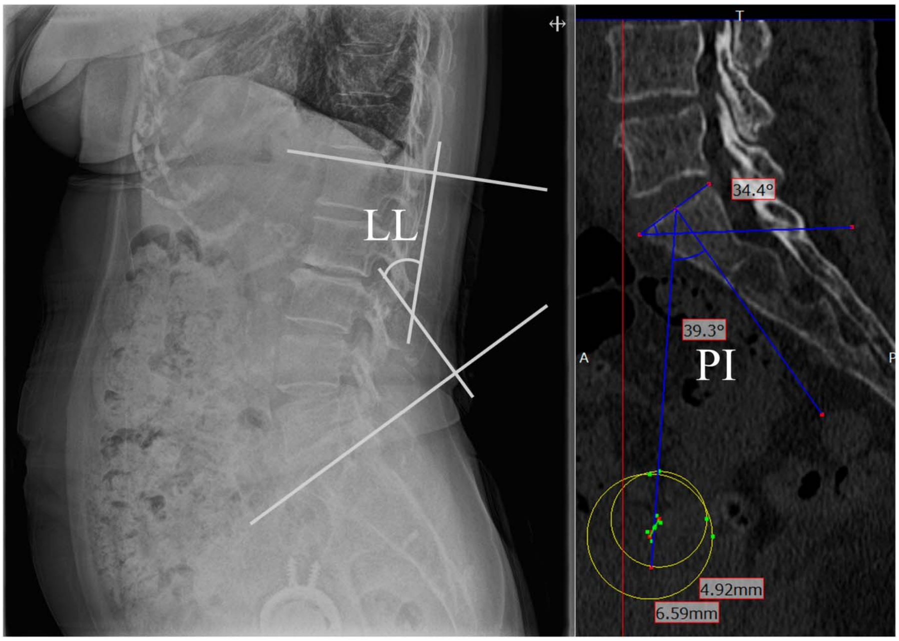

Fig. 3
Measurement of lumbar lordosis (LL) and pelvic incidence (PI). LL was measured with lateral spinopelvic radiographs and PI with computed tomography.

MATLAB programs (MathWorks)[16]. Hip movements were determined using the Cardan-Euler angle system in the x-z-y order (flexion/extension, adduction/abduction, and internal/external rotation). This analysis provided the intermittent angles of anterior/posterior tilt of the pelvis relative to the vertical plane as well as the angles of hip flexion/extension, abduction/adduction, and external/internal rotation from a sitting to a standing position. Posterior APPa, hip flexion, hip abduction, and external hip rotation were defined as positive. The hip flexion and extension angles were converted to functional pelvic plane (FPP) criteria[28,29]. Specifically, the flexion and extension angles of the hip joint relative to the APP were adjusted by adding the APPa in the supine position to calculate the angles relative to the FPP. The difference between the maximum and minimum hip flexion angles during the transition from sitting to standing was defined as the range of hip flexion and extension during chair-rising, whereas the midpoint of this range was defined as the center of hip flexion during chair-rising (Fig. 4).

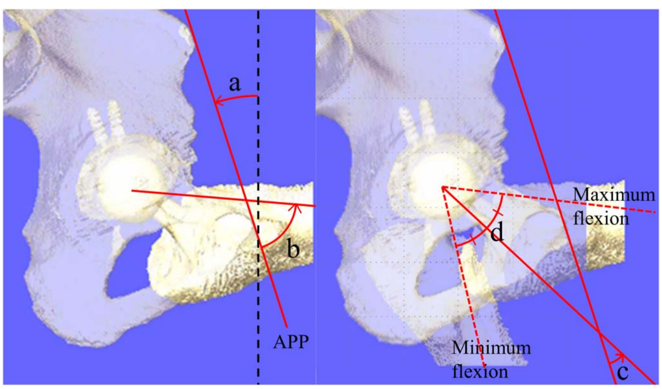

Fig. 4
Measurement angles of the pelvis and hip joints based on model-image registration techniques. a: Anterior pelvic plane angle (APPa), b: hip flexion angle relative to APP, c: center of hip flexion during chair-rising, and d: range of hip flexion and extension during chair-rising. Hip flexion angles of the hip joint relative to the APP were adjusted by adding the APPa in the supine position to calculate the angles relative to the supine FPP. FPP = functional pelvic plane.

TABLE II Participants' Spinopelvic Parameters*

n	99 Patients and 108 Hips
PI	47.9 ± 10.0
LL	37.6 ± 20.9
PI-LL	10.3 ± 20.7
APPa in the supine position	−3.8 ± 8.5
APPa in the seated position	21.8 ± 12.6
APPa in the standing position	6.0 ± 13.4
ΔAPPa (seated − standing)	15.8 ± 9.6
Flatback deformity	45 hips (42%)
Hyperlordosis	**11 hips (10%)**
Stiff spinopelvic mobility	35 hips (32%)
Hypermobility	**9 hips (8%)**

*Data are presented as mean ± SD. APPa = anterior pelvic plane angle (describing posterior tilt as positive), LL = lumbar lordosis, and PI = pelvic incidence. Flatback deformity; PI-LL >10°, Hyperlordosis; PI-LL <-10°, Stiff spinopelvic mobility; ΔAPPa (seated-standing) <10°, Hypermobility; ΔAPPa (seated-standing) >30°

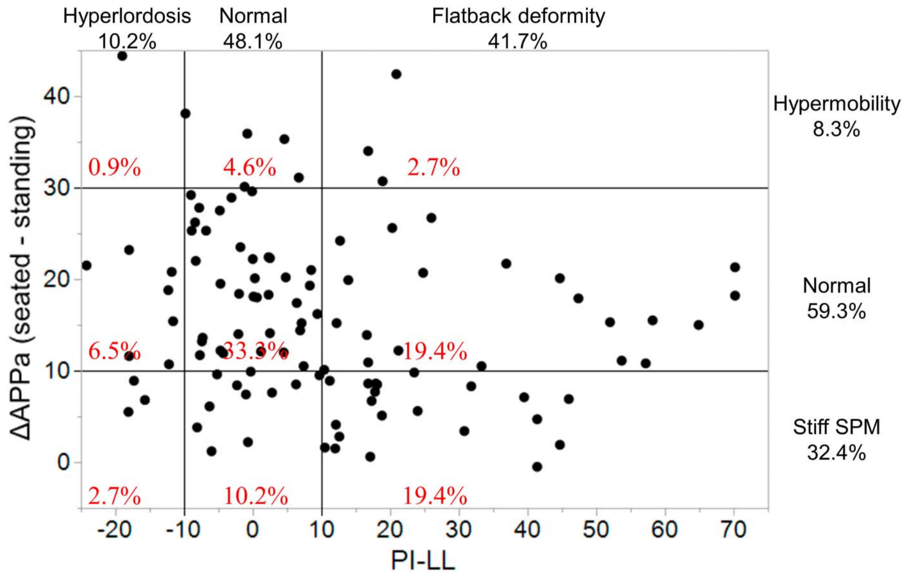

Fig. 5
Scatter plot based on spinopelvic alignment. PI = pelvic incidence, LL = lumbar lordosis, APPa = anterior pelvic plane angle.

Evaluation of Spinopelvic Abnormality

Using the PI measured from postoperative CT scans and the LL measured from postoperative standing lateral radiographs, the PI-LL was calculated. PI-LL >10° was defined as a flatback deformity, whereas a PI-LL < −10° was defined as hyperlordosis[18]. With the APPa obtained from the kinematic analysis, the angle in the standing position was subtracted from the angle in the sitting position, and a difference of less than 10° was defined as stiff SPM, whereas a change of more than 30° was defined as hypermobility[30]. Individuals without flatback deformity, hyperlordosis, stiff SPM, or hypermobility were included in the normal group.

Statistical Analysis

All data are expressed as mean ± SD. The Wilcoxon rank-sum test was used to analyze continuous variables, whereas the Fisher exact test was used for categorical variables. We compared the APPa and hip flexion angles in the sitting, standing,

TABLE III Comparison of Demographic Data and Pelvic and Hip Kinematics Between the Flatback Deformity and Normal Groups*

	Flatback Deformity	Normal	p	Post Hoc Power
Age at surgery (yrs)	71 ± 9.0	66 ± 8.7	**0.0015**	0.81
Sex (women/men)	39 hips/6 hips	30 hips/6 hips	0.76	NA
Height (cm)	152 ± 6.2	153.9 ± 7.2	0.46	0.24
Weight (kg)	55.4 ± 8.0	56.9 ± 9.1	0.36	0.13
APPa in the supine position	1.9 ± 7.6	−7.0 ± 6.6	**<0.0001**	1.0
APPa in the seated position (maximum)	28.7 ± 13.3	18.7 ± 8.4	**0.0004**	0.97
APPa in the standing position	15.9 ± 12.7	−0.5 ± 9.0	**<0.0001**	1.0
ΔAPPa (seated − standing)	12.8 ± 9.4	19.3 ± 5.7	**<0.0001**	0.95
Minimum APPa	3.6 ± 16.5	−10.1 ± 10.6	**0.0002**	0.99
Hip flexion in the seated position	42.9 ± 12.5	45.3 ± 10.1	0.35	0.16
Hip flexion in the standing position (minimum)	−9.7 ± 9.4	−2.4 ± 8.6	**0.0019**	0.95
Maximum hip flexion	55.6 ± 15.1	59.9 ± 12.1	0.23	0.27
Center of hip flexion during chair-rising	23.0 ± 9.5	28.7 ± 8.6	**0.0087**	0.80
Range of hip flexion and extension during chair-rising	65.3 ± 16.5	62.3 ± 12.1	0.28	0.15

*Data are presented as mean ± SD. APPa = anterior pelvic plane angle (describing posterior tilt as positive); flatback deformity, pelvic incidence-lumbar lordosis >10°; normal, patients without flatback deformity, hyperlordosis, stiff spinopelvic mobility, or hypermobility. Significant differences are displayed in bold.

TABLE IV Comparison of Demographic Data and Pelvic and Hip Kinematics Between the Stiff Spinopelvic Mobility and Normal Groups*

	Stiff Spinopelvic Mobility	Normal	p	Post Hoc Power
Age at surgery (yrs)	70 ± 9.4	66 ± 8.7	**0.017**	0.54
Sex (women/men)	29 hips/6 hips	30 hips/6 hips	1.0	NA
Height (cm)	153.7 ± 6.5	153.9 ± 7.2	0.57	0.052
Weight (kg)	56.3 ± 9.7	56.9 ± 9.1	0.63	0.059
APPa in the supine position	−2.0 ± 7.9	−7.0 ± 6.6	**0.008**	0.82
APPa in the seated position (maximum)	16.4 ± 11.7	18.7 ± 8.4	0.33	0.16
APPa in the standing position	10.4 ± 12.5	−0.5 ± 9.0	**0.0008**	0.99
ΔAPPa (seated − standing)	5.9 ± 3.0	19.3 ± 5.7	**<0.0001**	1.0
Minimum APPa	−5.0 ± 14.5	−10.1 ± 9.6	0.32	0.37
Hip flexion in the seated position	52.0 ± 7.8	45.3 ± 10.1	**0.011**	0.87
Hip flexion in the standing position (minimum)	−9.5 ± 8.1	−2.4 ± 8.6	**0.0038**	0.94
Maximum hip flexion	63.5 ± 10.2	59.9 ± 12.1	0.28	0.29
Center of hip flexion during chair-rising	27.0 ± 6.8	28.7 ± 8.6	0.35	0.15
Range of hip flexion and extension during chair-rising	73.0 ± 12.4	62.3 ± 12.9	**0.0008**	0.95

*Data are presented as mean ± SD. APPa, anterior pelvic plane angle (describing posterior tilt as positive); stiff spinopelvic mobility, Δanterior pelvic plane angle (seated − standing) <10°; normal, patients without flatback deformity or stiff spinopelvic mobility. Significant differences are displayed in bold.

and supine positions, as well as the minimum and maximum angles, between patients with abnormal spinopelvic alignment and individuals in the normal group. In addition, the range and midpoint angles of hip flexion and extension were assessed. $p < 0.05$ were considered statistically significant. Statistical analyses were performed using JMP Software (version 16; SAS Institute). Power analysis indicated that a sample size of 100 hips would provide 80% statistical power, detecting a 5.7° difference between the 2 groups. This assumes a probability value of less than 0.05 and an SD of 10°.

Results

In the entire cohort, PI was 47.9° ± 10.0°, LL was 37.6° ± 20.9°, and PI-LL was 10.3° ± 20.7°. The APPa values in the seated and standing positions were 21.8° ± 12.6° and 6.0° ± 13.4°, respectively. The APPa values in the sitting, maximum anterior tilt, and standing positions were compared using analysis of variance, revealing significant differences between each position ($p < 0.0001$). Similarly, significant differences were found between each position in hip flexion angles during sitting, maximum flexion, and standing ($p < 0.0001$). The

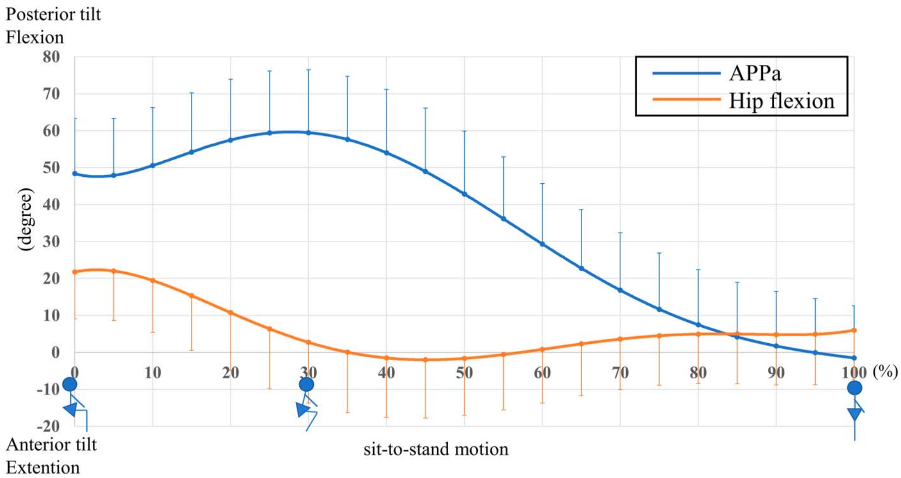

Fig. 6

Kinematics of the pelvis and hip joint in the chair-rising movement in the entire cohort. The *x* axis represents the time axis, with 0% corresponding to the sitting position and 100% to the standing position. The *y* axis indicates the anterior/posterior APPa (posterior tilt as positive) and the hip flexion/extension angle (flexion as positive). APPa = anterior pelvic plane angle.

amount of change in the APPa from sitting to standing was 15.8° ± 9.6°. Flatback deformity was observed in 45 hips (42%), stiff SPM in 35 hips (32%), and both in 21 hips (19%). The normal group consisted of 36 hips (33%) (Table II, Fig. 5). There were no significant differences in the demographic data, including height, between the flatback deformity and normal groups, or between the stiff SPM and normal groups, except for age (Tables III and IV).

Figure 6 illustrates the APPa and hip flexion angles during chair-rising in the entire cohort. The pelvis showed maximum posterior tilt in the seated position, transitioning to the maximum anterior tilt midway to the standing position. The hip flexion angle peaked midway to standing with maximum flexion and then transitioned to maximum extension in the standing position (Table II).

In the flatback deformity group, the pelvis was significantly posteriorly tilted when compared with the normal group across all positions—sitting, maximum anterior tilt, and standing—with the greatest difference observed in the standing position (Fig. 7-A). There was no significant difference in the hip flexion angle between the groups in the sitting position or at maximum flexion. However, in the standing position, the flatback deformity group exhibited significantly more extension (Fig. 7-B, Table III).

The stiff SPM group exhibited significant anterior tilt in the supine position and significant posterior tilt in the standing position compared with the normal group. No significant difference was observed in the minimum APPa. The difference in the APPa between the sitting and standing positions was significantly smaller in the stiff SPM group (Fig. 8-A). Regarding the hip flexion angle, the stiff SPM group showed significantly more flexion in sitting and maximum flexion and significantly more extension in standing. Accordingly, the ranges of hip flexion and extension were also significantly greater by >10°. There was

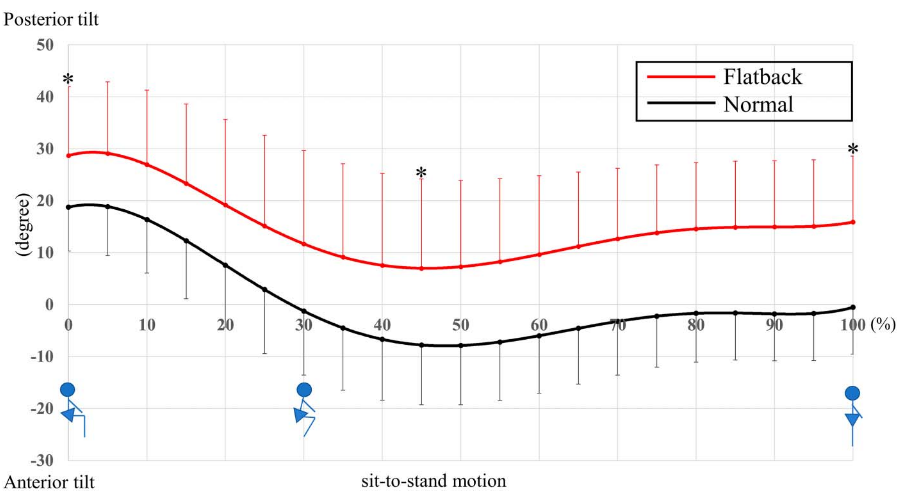

Fig. 7-A

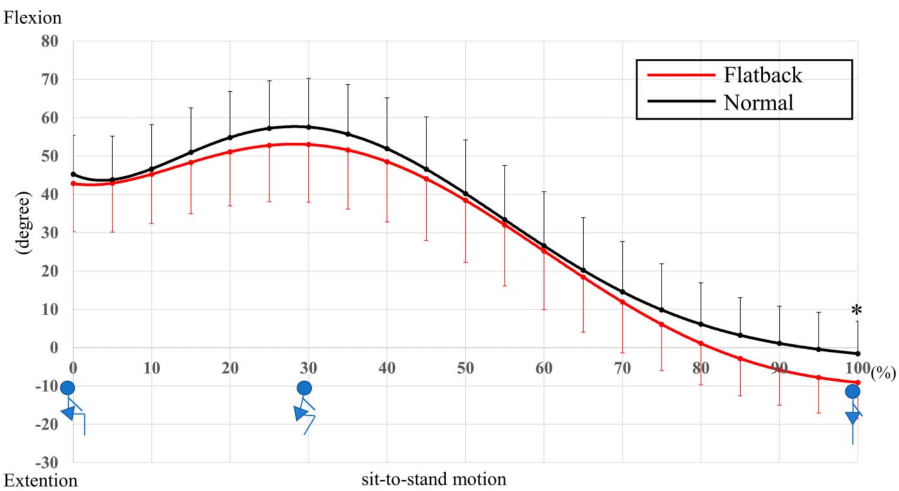

Fig. 7-B

Fig. 7 Kinematics of the (**Fig. 7-A**) pelvis and (**Fig. 7-B**) hip joint in the chair-rising movement in the flatback deformity and normal groups. The *x* axis represents the time axis, with 0% corresponding to the sitting position and 100% to the standing position. The *y* axis indicates the anterior/posterior APPa (posterior tilt as positive) and the hip flexion/extension angle (flexion as positive). APPa = anterior pelvic plane angle.

no significant difference in the center of maximal flexion and extension during chair-rising (Fig. 8-B, Table IV).

Discussion

This study is the first to compare the relationship between spinopelvic alignment abnormalities and kinematics of the pelvis and hip joint in patients after THA. The 2 important findings of this study were as follows: First, the pelvis was always more posteriorly tilted in patients with flatback deformity, with the difference being greatest in the standing position (18°); second, the range of hip flexion-extension was significantly greater than 10° in patients with stiff SPM. Notably, forward-leaning movement during chair-rising, which has not been extensively explored in previous research, emerges as a critical point of interest. This position represents a moment of increased risk in the context of daily activities, emphasizing the importance of this study's novelty.

In cases of flatback deformity, the pelvis was consistently more posteriorly tilted with the difference being the greatest in the standing position, which was 7° greater than that in the supine position. Therefore, placing the cup according to the same target orientation based on the supine FPP may result in an excessively large anteversion in the standing position. In addition, patients with flatback deformity exhibited 7° more extension in the standing position. A study reports that in cases of flatback deformity, posterior impingement between the cup and stem is more likely to occur[12], which supports the findings of this study. For additional validation, we conducted an analysis excluding cases with overlapping stiff SPM or hypermobility with flatback deformity. However, similar findings of posterior pelvic tilt and hip hyperextension in the standing position were observed (see Appendix Table 2), suggesting that these overlaps did not have a significant impact on the overall results.

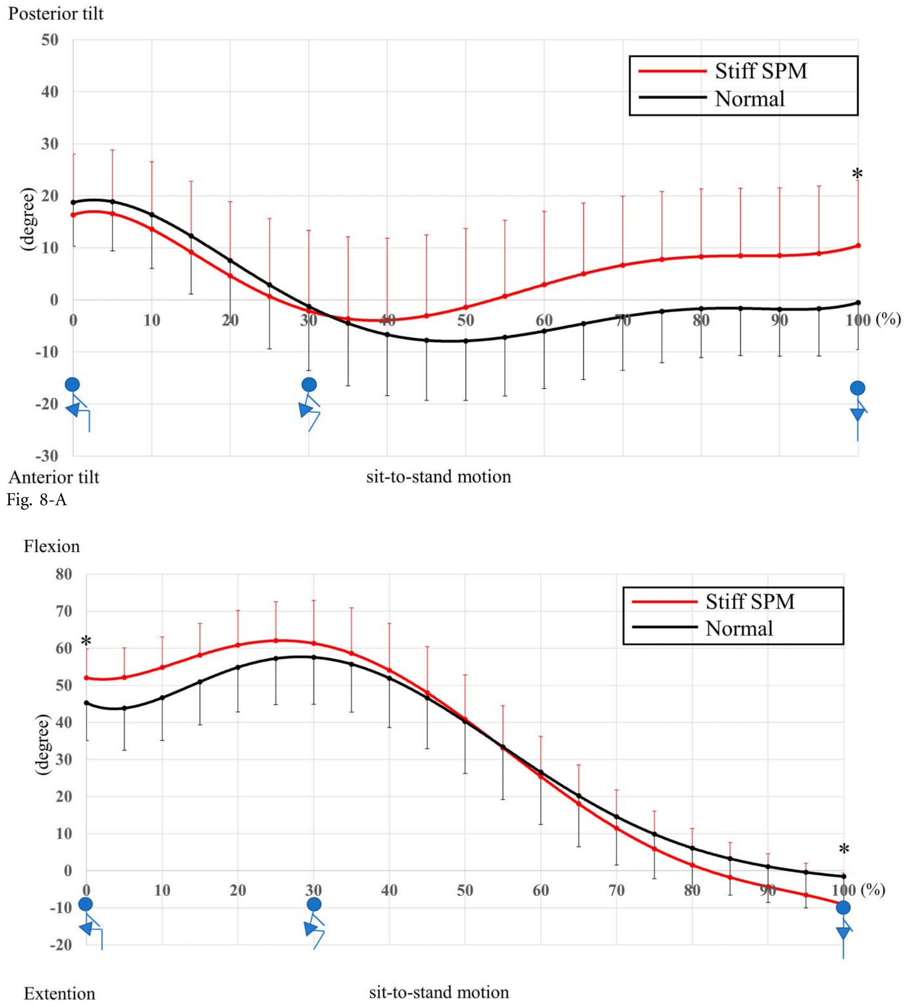

Fig. 8 Kinematics of the (**Fig. 8-A**) pelvis and (**Fig. 8-B**) hip joint in the chair-rising movement of the stiff spinopelvic mobility (stiff SPM) and normal groups. The *x* axis represents the time axis, with 0% corresponding to the sitting position and 100% to the standing position. The *y* axis indicates the anterior/posterior APPa (posterior tilt as positive) and the hip flexion/extension angle (flexion as positive). APPa = anterior pelvic plane angle.

The range between maximum hip flexion and extension during chair-rising was 13° greater in the stiff SPM group than in the normal group. This finding is consistent with those of previous reports indicating that a small physiological posterior tilt change in the pelvis may result in a larger range of motion of the hip joint, leading to an increased risk of impingement[31]. However, there was no significant difference in the center of the hip flexion and extension angles. It has been reported that cup positioning and the oscillation angle can influence the impingement-free range of motion[32,33]. Therefore, increasing the placement accuracy using computer-assisted surgery or enlarging the oscillation angle using large-diameter heads or dual-mobility liners may be useful in patients with stiff SPM. However, this study did not examine the impact of navigation, large-diameter heads, or dual mobility on kinematics, so further research is needed to assess their effects. For additional validation, we performed an analysis excluding cases with overlapping flatback or hyperlordosis. Similar findings of increased hip range of motion were observed, with no difference in the center of hip flexion and extension angles (see Appendix Table 3). Thus, we believe that this overlap did not have a significant impact on the overall results.

It is important to understand the limitations of this study. First, because of limited data, we could not compare postoperative patient-reported outcomes between the flatback deformity, stiff SPM, and normal groups. However, the primary aim of this study was to compare kinematics. Second, owing to the lack of data, preoperative spinopelvic alignment was not available. In patients with minor LL preoperatively, there is a tendency for the pelvis to tilt posteriorly postoperatively; however, there is not much change[34]. Further studies are needed to prospectively analyze preoperative and postoperative spinopelvic alignment and dynamics to determine the target cup orientation from the preoperative alignment. Third, stiff SPM was defined by changes in the APPa during sitting and standing, but spinal mobility itself was not assessed[35,36]. Verification focusing on mobility of the spine is also considered necessary in the future. Fourth, there was a difference in the proportion of women and flatback deformity in our study compared with that in Western studies[18,37]. In our study, 88% of participants were women, consistent with the 83% of THAs performed in women in Japan[38], likely because of the higher prevalence of developmental dysplasia of the hip[39]. In addition, 42% of patients had flatback deformity, aligning with that reported in a Japanese cohort study[40], reflecting potential population differences. Finally, all THA procedures in this study were performed using a posterolateral approach, and it remains unclear whether the findings can be generalized to cases in which other approaches were used. Despite these limitations, the strength of this study lies in its use of high-precision model-image registration techniques for more than 100 hips to analyze the kinematics of the pelvis and hip joint, identifying differences between those with and without spinopelvic alignment abnormalities.

In conclusion, the pelvis was always tilted posteriorly in patients with flatback deformity, and the difference was even greater in the standing position. In stiff SPM, the large range of hip flexion and extension during chair-rising increased the risk of impingement, suggesting the need to further expand the range of motion without changing the target orientation.

Appendix

eA Supporting material provided by the author is posted with the online version of this article as a data supplement at jbjs.org (http://links.lww.com/JBJSOA/A749, http://links.lww.com/JBJSOA/A750, http://links.lww.com/JBJSOA/A751). This content has not been copyedited or verified. ■

Note: The authors thank Editage (www.editage.com) for the English language editing.

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