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ORIGINAL ARTICLE

Is pelvic incidence a constant, as everyone knows? Changes of pelvic incidence in surgically corrected adult sagittal deformity

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Abstract

Purpose Previous investigations have recognized the critical role of pelvic parameters in the setting of a fixed sagittal deformity. Pelvic incidence (PI) is a constant, as everyone knows. However, PI might change reciprocally because of increased shear force on the sacroiliac joint, following surgical correction of fixed lumbar lordosis (LL). The disparity in PI after surgery according to the surgical method, and its impact on final follow-up, has not been reported. This study was undertaken to analyze the disparity of PI before and after surgery, and to evaluate its impact on final sagittal alignment in surgically corrected lordosis when there is immediate postoperative normal alignment following correction of adult sagittal deformity.

Methods A prospective study of 29 subjects with adult spinal deformity (average age: 67.9 years) was conducted. At final evaluation after a minimum 2-year follow-up, normal sagittal alignment was achieved following consecutive sagittal correction. Surgical changes were measured by serial, pelvic standing, lateral, and whole spine radiographs, spinopelvic parameters measured included PI, sacral slope (SS), pelvic tilt (PT), LL, thoracic kyphosis (TK), and sagittal alignment.

Results The mean LL was 0.2° before surgery; −59.3° after surgery with pedicle subtraction osteotomy (PSO) ($n = 20$), anterior lumbar interbody fusion (ALIF) ($n = 20$, 33 segments), and posterior lumbar interbody fusion (PLIF) ($n = 21$, 36 segments); and −57.5° at last follow-up. The sagittal vertical axis was +14.8 cm before surgery, −0.7 cm after surgery, and 2.2 cm at last follow-up. The mean PI was 49.4° before surgery, and increased to 55.2° after surgery, 57.5° at 1-year follow-up, and 58.8° at last follow-up ($P = 0.02$). The mean disparity in PI preoperatively and at last follow-up was 11.4° without sacropelvic fixation ($n = 18$), and 5.9° with sacropelvic fixation ($n = 11$) ($P = 0.002$). Analysis revealed the disparity of PI to be significantly greater in non-sacropelvic fixation, and correlated with the follow-up period ($R = 0.442$, $P = 0.016$), but not with age, bone mineral density (BMD), number of fused segments, correction methods, corrected LL, or sagittal alignment.

Conclusions PI increased in all patients with surgically corrected, adult sagittal deformity, following surgical correction of fixed LL. The disparity of PI after surgery was significantly higher in non-sacropelvic fixation, and showed a significant correlation with follow-up period without influence on sagittal alignment at last follow-up.

Keywords Adult spinal deformity · Sagittal alignment · Pelvic incidence · Lumbar lorodsis · Spinopelvic alignment

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Introduction

Appropriate surgical corrections of adult spinal deformity with sagittal malalignment may be a possible contributory factor for alternation of sagittal plane and adjacent segment disease of non-instrumented motion level above the fusions

[1]. Surgical correction of fixed lumbar lordosis (LL) is indispensable for prevention of sagittal decompensation [2]. In addition, maintaining coronal alignment and restoration of neutral or negative sagittal alignment are considered to be successful surgical treatments with satisfactory surgical outcomes [3, 4].

The relationship between lumbar lordosis and pelvic incidence (PI) is important for the sagittal profile of the spine [5]. Loss of LL is an important factor in the causation of various spinal diseases, and is closely correlated with sagittal malalignment [6–10]. In general, PI, an anatomic parameter, is a constant value, and is an important factor for sagittal alignment regulation [11]. There have been multiple reports on spinopelvic parameters in normal adults [12, 13] and various attempts to apply pelvic parameters in the surgical treatment of sagittal malalignment [2, 14–17].

PI could be changed by motion of the sacroiliac joint due to degeneration, trauma or iatrogenic injury. If long lumbar fusion is performed to correct spinal deformity, the patient capacity to compensate a possible malalignment through lordosis or kyphosis is reduced, and the pelvis could possibly be the site for such a compensation [18].

Taking PI into consideration, the authors performed surgical correction of LL with long lumbar fusion in patients with adult spinal deformity and sagittal malalignment. If a normal sagittal alignment could be achieved, increased sacral slope (SS) and pelvic anteversion, resulting in elevated shear force on the sacroiliac joint, which in turn could increase postoperative PI. To our knowledge, there have been no reports for analyzing this hypothesis. The purpose of this study is to evaluate the changes in PI before and after surgery, along with the impact of the changed postoperative PI on sagittal alignment in patients undergoing deformity correction due to sagittal deformity.

Patients and methods

Study patients

Surgical correction of LL exceeding the predictive value of the Lee formula ($SS = 0.80193 + 0.74213 \times PI$, maximal $LL = 17.416 + 0.962\ SS$) [12] was performed on patients with degenerative lumbar kyphosis accompanying sagittal malalignment. This study was conducted after approval was obtained from the Institutional Review Board of our hospital. This is a prospective study of 29 subjects with adult spinal deformity patients who were thought to have obtained normal sagittal alignment, based on more than 2 years of follow-up. The mean age was 67.9 years, and all were female. Four cases were classified as preoperative Takemitsu type 1, and 25 were type 2 [19]. Preoperative degenerative lumbar scoliosis accompanied 14 cases, and the mean Cobb angle was 21°.

Radiographic analysis

Measurements were obtained on 36-inch-long cassette anteroposterior and lateral radiographs of the spine, with the patient standing. Lateral radiographs of all subjects standing in a neutral, unsupported position, with arms in the clavicle position, were obtained [20].

The spinopelvic parameters examined in this study were thoracic kyphosis (TK), LL, PI, SS, pelvic tilt (PT), and sagittal vertical axis (SVA). TK was measured using the Cobb method between T5 and T12, and LL was measured between T12 and S1. SVA was defined as the horizontal distance between the posterior corner of the sacrum and the C7 plumb line and was designated positive (+) when the C7 plumb line was anterior from the posterosuperior corner of the sacrum and negative (−) when the C7 plumb line was posterior from the posterosuperior corner of the sacrum.

We had measured the standing pelvis lateral radiographs to be centered sacral endplate for accurate measurement of pelvic incidence instead of whole spine radiographs to minimize the measurement errors. On the standing pelvis lateral radiographs, pelvic parameters were measured on preoperative, early postoperative (between 6 and 8 weeks), 1-year postoperative, and last follow-up radiographs with a minimum of 2-year follow-up [11].

All digital radiographs were evaluated using a picture archiving communication system (Infinitt, Seoul, Korea), which is software designed to allow accurate calculation of parameters by magnification of anatomic landmarks of the spine and pelvis on a lateral radiograph. All radiological parameters were measured by two spine surgeons who did not participate in the operation and the mean measurements were used for analysis.

Surgical decisions and methods

As outlined in Table 1, a single posterior approach and a combined anterior and posterior approach were performed in 9 and 20 cases, respectively. A mean of 6.3 segments were fused (range 3–8). The uppermost instrumented vertebra (UIV) was T10 in 16 cases, T12 in 3, L1 in 2, L2 in 3, and L3 in 5. For the lowest instrumented vertebra (LIV), fusion was performed to the sacrum in all cases and sacropelvic fixation was performed using iliac screws in 11 cases. The UIV was T12, L1, L2, or L3 in thoracolumbar compensated patients with a small PI [9]. Otherwise, fusion was performed to T10. Surgical correction for all patients included anterior lumbar interbody fusion (ALIF) ($n = 20$, 33 segments), posterior lumbar interbody fusion (PLIF)

Table 1 Surgical procedures

	Patients (n = 29)
Surgical approach	
Anterior and Posterior	20
Posterior only	9
UIV	
T10	16
T12	3
L1	2
L2	3
L3	5
LIV	
Sacrum	29
Sacropelvic fixation with iliac screw	
Yes	11
No	18
PSO	
Yes	20
No	9

UIV uppermost instrumented vertebra, *LIV* lowest instrumented vertebra, *PSO* pedicle subtraction osteotomy

Table 2 Level of interbody fusion

	Patients/segments
Number of patients	
ALIF	20
L2–S1	1
L3–S1	2
L4–S1	6
L5–S1	11
PLIF	21
L3–L4	4
L3–L5	6
L3–S1	3
L4–L5	5
L5–S1	3
Number of segments	
ALIF	33
L2–L3	1
L3–L4	3
L4–L5	9
L5–S1	20
PLIF	36
L3–L4	13
L4–L5	17
L5–S1	6

ALIF anterior lumbar interbody fusion, *PLIF* posterior lumbar interbody fusion

(n = 21, 36 segments) (Table 2), and pedicle subtraction osteotomy (PSO) (n = 20). Subjects with pseudarthrosis and proximal junctional kyphosis were excluded from the study.

Statistical analysis

Statistical analysis was performed using SPSS software (version 20.0 SPSS Inc., Chicago, IL, USA). A repeated-measures analysis of variance (ANOVA) test was performed for comparison between each dependent variable. Student's t test and Pearson's correlation coefficient were used for analysis of each radiological parameter; a P value <0.05 for all analyses was considered statistically significant. Inter-observer reliability was calculated by Fleiss' kappa statistics, or intra-class correlation coefficient (ICC) as appropriate for each radiologic measurement. ICC values for all radiographic parameters exceeded 0.90.

Results

Spinal parameters

The mean SVA was +14.8 cm before surgery, −0.7 cm after surgery, and 2.2 cm at last follow-up. The mean TK was +1.8° before surgery, +20.5° after surgery, and +25.1° at last follow-up. The mean LL was +0.2° before surgery, −59.3° after surgery, and −57.5° at last follow-up.

The mean preoperative PI was 49.4° ± 9.8, and the mean predictive LL according to the Lee formula [12] was −53.5° ± 7.0. The mean surgical correction of LL was 59.5° ± 19.3, which was corrected by −59.3° ± 10.9 on average after surgery; this resulted in overcorrection of the predictive LL, as calculated using the Lee formula [12] in all cases.

Changes in pelvic incidence

The mean preoperative PI was 49.4°, which increased to 55.2° after surgery, 57.5° at 1-year postoperative follow-up, and 58.8° at last follow-up. The mean preoperative SS was 17.5°, which increased to 39.2° after surgery, and 38.9° at last follow-up. The preoperative PT was 31.9°, which decreased to 13.9° after surgery, but increased to 19.8° at last follow-up. There was an increase compared to the immediate postoperative value (Table 3).

PI of patients with (n = 11) and without (n = 18) sacropelvic fixation values with iliac screws was 50.8° vs. 48.6° before surgery, 55.7° vs. 54.8° after surgery, 56.5° vs. 58.1° at 1-year postoperative follow-up, and 56.7° vs. 60.0° at last follow-up. The disparity between preoperative and last follow-up PI was 5.9° vs. 11.4° for the groups with

Table 3 Spinopelvic parameters

Radiographic parameter	Preoperative	Postoperative (*)	Last follow-up (**)
SVA	14.8 ± 7.3	−0.7 ± 2.4 (0.00)	2.2 ± 2.7 (0.00)
TK	1.8 ± 14.4	20.5 ± 13.1 (0.00)	25.1 ± 15.8 (0.00)
TL	2.0 ± 16.0	−11.4 ± 23.3 (0.015)	−6.3 ± 25.1 (0.00)
LL	0.2 ± 19.4	−59.3 ± 10.9 (0.00)	−57.5 ± 11.4 (0.007)
LS	−3.6 ± 16.0	−29.7 ± 12.1 (0.00)	−29.4 ± 12.2 (0.750)
PI	49.4 ± 9.8	55.2 ± 11.8 (0.00)	58.8 ± 11.6 (0.00)
SS	17.5 ± 11.8	39.2 ± 8.7 (0.00)	38.9 ± 11.0 (0.862)
PT	31.9 ± 13.9	13.9 ± 7.3 (0.00)	19.8 ± 11.6 (0.05)

SVA sagittal vertical axis, *TK* thoracic kyphosis, *TL* thoracolumbar junction, *LS* lumbosacral junction, *PI* pelvic incidence, *SS* sacral slope, *PT* pelvic tilt

* *P* value of difference between preoperative and postoperative

** *P* value of difference between postoperative and final follow-up

Table 4 Pelvic incidence with or without sacropelvic fixation with iliac screws

	Total patient ($n = 29$)	Pelvic incidence (mean ± SD)	
		Sacropelvic fixation ($n = 11$)	No sacropelvic fixation ($n = 18$)
Preoperative (°)	49.4° ± 9.8	50.8° ± 7.7	48.6° ± 11.0
Postoperative (°) (*)	55.2° ± 11.8	55.7° ± 10.4 (0.003)	54.8° ± 12.9 (0.000)
1-year postoperative (°) (**)	57.5° ± 11.6	56.5° ± 9.8 (0.219)	58.1° ± 12.8 (0.001)
Last follow-up (°) (***)	58.8° ± 11.6	56.7° ± 9.8 (0.414)	60.0° ± 12.8 (0.009)

* *P* value of difference between preoperative and postoperative parameters

** *P* value of difference between postoperative and follow-up at 1-year parameters

*** *P* value of difference between follow-up at 1 year and last follow-up parameters

or without postoperative sacropelvic fixation, respectively. This showed a significant increase in the group without postoperative sacropelvic fixation (Table 4; Fig. 1).

When correlations with various factors, including follow-up period, age, bone mineral density (BMD), UIV, number of fused segments, changes in SS and LL after surgery, and correction of LL, were analyzed, only the longer follow-up period showed significant differences for last follow-up, preoperative, and postoperative PI values (Table 5).

Effects of PI changes on lumbar lordosis and sagittal alignment

The mean preoperative PI was 49.4° and the mean predictive LL according to the Lee formula [12] was −53.5°. In contrast, PI increased by 9.4° on average at the last follow-up, compared to the preoperative PI, resulting in a mean of 58.8°; the mean predictive LL calculated by the Lee formula [12] for PI also increased to −60.1° at last follow-up. Therefore, although 15 LL cases at last follow-up were classified as under-correction, in comparison with the predictive LL calculated by the last follow-up PI (−57.5°), there was no sagittal decompensation (Figs. 2, 3).

Inter-observer and intra-observer variability

Inter-observer agreement (Fleiss' kappa statistics) showed a desirable level of variance (kappa 0.91); the two observers also showed highly desirable levels of variance in ICC (0.92 and 0.90), which were significant ($P < 0.05$).

Discussion

Failure of compensatory mechanisms for spinal alignment in degenerative lumbar deformity may require a surgical treatment. There has been an emphasis on achieving spinal alignment in the sagittal and the coronal planes in deformity correction. However, these sagittal parameters may be altered by the position, aging, and deformity of the spinal column, which can cause altered sagittal plane alignment. On the other hand, the PI is a unique anatomical parameter

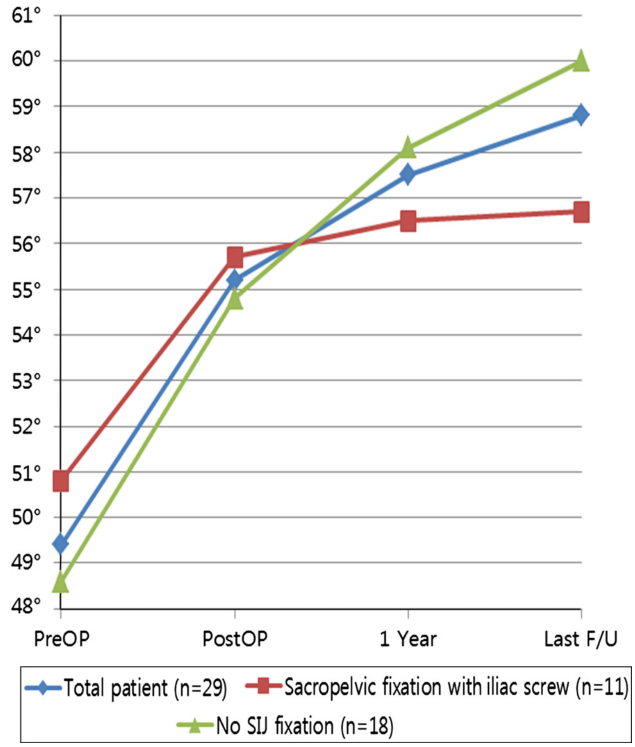

Fig. 1 Changes of pelvic incidence

in individuals, and is constant, regardless of the pelvic position and age. Therefore, most studies suggested the PI as the key parameter to estimate the ideal lumbar lordosis to be restored in lumbar fusion surgery in degenerative lumbar diseases [12, 21, 22].

However, it is still controversial that postoperative PI changes occur over time in patients with long lumbar fusion. PI could be changed by motion of the sacroiliac joint if it is influenced by various causes. If long lumbar fusion is performed to correct spinal deformity, the patient capacity to compensate a possible malalignment through lordosis or kyphosis is reduced and compensatory motion decreases in lower vertebrae. Therefore, the pelvis could possibly be the site for such a compensation; this may cause pelvic motion, so there is a chance that PI may increase [18]. If PI increases after surgery, the predictive LL would concurrently increase; therefore, it is possible that postoperative surgically fixed LL would be classified as under-correction at last follow-up. However, there have been no reports for analyzing this hypothesis.

The sacroiliac joint is six times more resistant to lateral forces than the lumbar spine, and approximately one-half as resistant to axial direction and rotation forces [23]. Hence, stress on the sacroiliac joint could increase after spinal fusion to accelerate degenerative change, resulting in an increase in motion. These effects would occur more often after lumbosacral fusion [24–26]. However, Lafage et al. reported that the PI is a constant value, only if the orientation between the sacrum and the pelvis is maintained [15]. Kim et al. reported that PI increased about 3° on average at the postoperative last follow-up relative to preoperative PI in the suboptimal sagittal alignment group (C7 plumb to S1 >3 cm), compared to the optimal sagittal alignment group; however, this was not statistically significant [2]. Legaye reported the effect of the age and of a sagittal imbalance in the variability of the value of PI and concluded that combination of age and sagittal imbalance as the key factor for an individual increasing of the value of PI [27]. Skalli et al. reported that PI may change in some conditions, and also demonstrated that evolution of a patient's range of motion is directly related to pelvic adaptation [18]. Despite these differing reported results, spinopelvic parameters were measured on 36-inch-long cassette lateral radiographs of the spine in most studies. Nevertheless, since PI was defined as the angle between the perpendicular line from the sacral plate, and the line connecting the midpoint of the sacral plate to the

Table 5 Correlations of pelvic incidence with various factors at final follow-up

	Last F/U PI—preoperative PI		Last F/U PI—postoperative PI	
	R	*P*	*R*	*P*
Follow-up period	0.428	0.021	0.442	0.016
Age	−0.071	0.714	−0.148	0.444
BMD(*T* score)	−0.117	0.544	0.172	0.372
BMD(gm/cm^2)	−0.041	0.834	0.297	0.118
UIV	−0.012	0.952	−0.059	0.760
Fused segments	0.012	0.952	0.059	0.760
Postoperative SS	0.111	0.566	0.052	0.789
Postoperative LL	0.243	0.204	0.091	0.637
Correction of LL	−0.174	0.367	−0.277	0.277

F/U follow-up, *PI* pelvic incidence, *BMD* bone mineral density, *UIV* upper most instrumented vertebra, *SS* sacral slope, *LL* lumbar lordosis

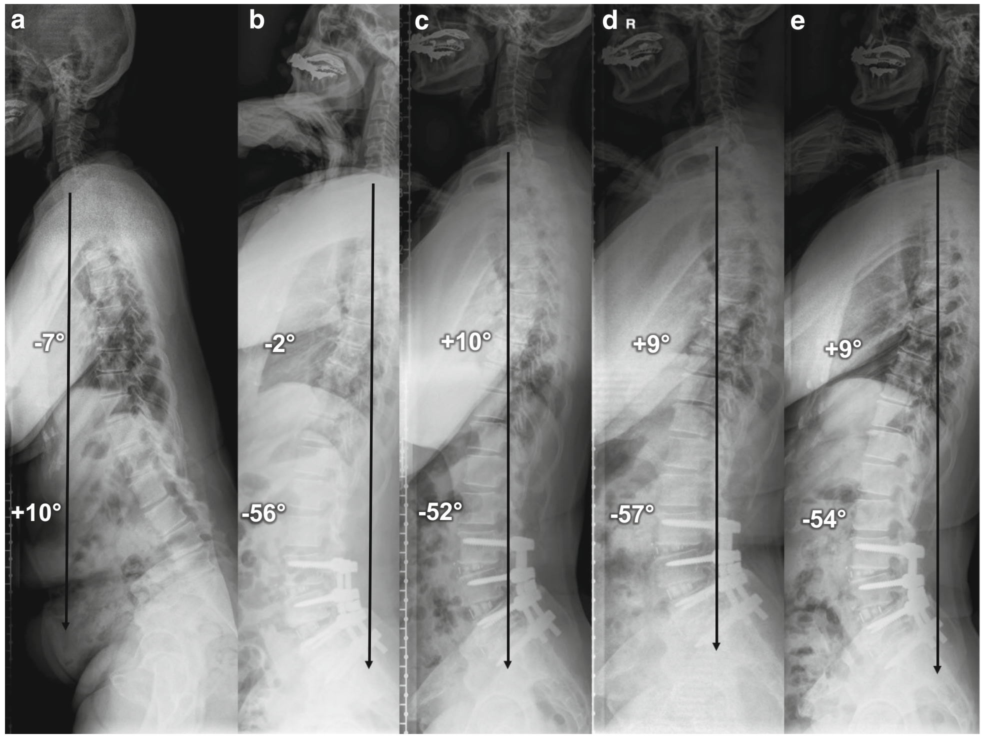

Fig. 2 Preoperative (**a**), postoperative (**b**), 1-year postoperative (**c**), 2-year postoperative (**d**), and 3-year postoperative (**e**), full-length sagittal radiographs; the patient has degenerative lumbar kyphosis, with normal sagittal alignment following anterior lumbar interbody fusion at L3–S1, and posterior fusion with instrumentation. *Vertical line* is the C7 plumb line

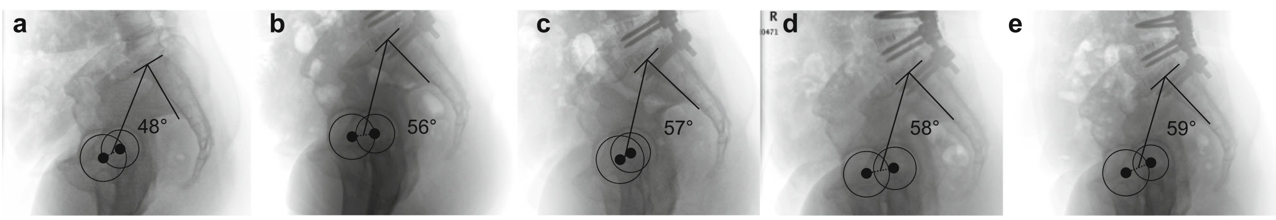

Fig. 3 Preoperative (**a**), postoperative (**b**), 1-year postoperative (**c**), 2-year postoperative (**d**), and 3-year postoperative (**e**), standing pelvis lateral radiographs. Note the substantial pelvic incidence (PI) increments. Preoperative PI was 48°. Predictive lumbar lordosis (LL) following this PI was 52°. Postoperative LL was corrected to −56°, resulting in overcorrection, and creating negative sagittal alignment. PI at 3-year postoperative follow-up increased to 59°, with predictive LL accordingly calculated as 60°. In addition, −54° of LL at 3-year postoperative follow-up can be classified as under-correction, while maintaining normal sagittal alignment. *Circles* represent femoral heads

bicoxofemoral axis, PI could be sensitively affected by the angle between the X-ray beam and the bicoxofemoral axis or sacral endplate [11].

The difficulty of PI measurements is mainly due to difficulty in precisely identifying sacral endplate as well as the bicoxofemoral axis. The projection of whole spine radiographs is centered on the 12th vertebra whereas the standing pelvis lateral radiographs are centered on the S1 endplate. Yamada et al. analyzed the accuracy in measuring pelvic incidence and other spinopelvic parameters that tend to be inaccurate and contributing factors for the inaccuracy and reported that pelvic incidence tends to be a larger approximately 5° due to a large projection angle to sacral endplate in whole spine lateral standing radiographs compared with standing pelvis lateral radiographs [28]. Therefore, we had measured the standing pelvis lateral radiographs to be centered sacral endplate for accurate measurement of pelvic incidence instead of whole spine radiographs to minimize the measurement errors. As a result, the mean PI of all patients increased from 49.4° before surgery, to 55.2° after surgery, 57.5° at 1-year postoperative follow-up, and 58.8° at last follow-up.

Regarding the changes in postoperative PI values, the concept of sacroiliac joint motion remains controversial, and has been studied by various methods, including Roentgen stereophotogrammetric analysis. Sturesson et al. reported that the sacroiliac joint was mainly affected by shear forces, which resulted in 4° of rotation and about 1.6 mm of translation [29]. Jacob et al. reported 0.91°, 0.73°, and 0.44° of rotation at X, Y, and Z axes, and 0.45, 0.36, and 0.27 mm of translation, respectively [30]. In a cadaveric study, Smidt et al. reported a 3–17° range of motion of the sacroiliac joint, with 7° to the left and 8° to the right in the sagittal plane, using computed tomography (CT) [31]. Sturesson et al. reported 0.2° of rotation in the X, Y, and Z axes in standing hip flexion, with 0.3 mm of motion [32]. Frymoyer et al. reported long-term compensatory hypermobility of the sacroiliac joint following spinal fusion including the sacrum, which accelerated degenerative change [24]. Ha et al. reported that since the sacroiliac joint was also an adjacent segment of the lumbosacral junction, degenerative change could be induced by lumbar and lumbosacral fusion [25]. In the present study, the PI was compared between patients with ($n = 11$) and without ($n = 18$) sacropelvic fixation using iliac screws. The respective PI values of the groups with or without sacropelvic fixation were 50.8° vs. 48.6° before surgery, 55.7° vs. 54.8° after surgery, 56.5° vs. 58.1° 12.8 at 1-year postoperative follow-up, and 56.7° vs. 60.0° at last follow-up; PI disparities before surgery and the last follow-up were 6.0° vs. 11.4°, showing a significant increase in the group without postoperative sacropelvic fixation (Table 4; Fig. 1). The results suggested that there was motion in the SI joint, consistent with preceding studies. It is speculated that sacropelvic fixation with iliac screws affected later motion of the sacroiliac joint in long lumbar fusion patients, and that this motion also affected PI change. In addition, when changes of PT and SS were compared between the postoperative values and those at last follow-up, PT increased from 13.9° to 19.8°, whereas SS showed no change, at 39.2° and 38.9°. This suggests that increase of PI could be caused not by a change of SS, but by an increase in PT. Therefore, the motion mainly affecting the sacroiliac joint after long level fusion is caused by the sacrum, which nears the hip joint by vertical translation, not by rotation; a predicted cause affecting the sacroiliac joint would be shear force. On the other hand, an increase of PI leads to an increase of predictive LL, depending on PI. In our study, the mean preoperative PI was 49.4°, and the mean predictive LL according to the Lee formula [12] was −53.5°. PI at last follow-up increased by 9.4° on average, compared to the preoperative PI, resulting in a mean of 58.8°. The mean LL compared to the last follow-up PI also increased to −60.1°. Therefore, although 15 LL cases at last follow-up were classified as under-correction, in comparison with the predictive LL calculated with the last follow-up PI (−57.5°), there was no sagittal decompensation (Figs. 2, 3).

This study has some limitations. This is a retrospective study and does not contain clinical results. Further trials are needed to establish a correlation between correction and clinical outcome (Visual Analog Scale, Oswestry Disability Index, functional status, and patient satisfaction).

In conclusion, PI increased in all patients with surgically corrected adult sagittal deformity, following surgical correction of the fixed LL. PI might change reciprocally, because of increased shear force on a mobile sacroiliac joint, following long lumbar fusion with adult sagittal deformity. The disparity of PI after surgery was significantly higher in non-sacropelvic fixation, and showed a significant correlation with follow-up period without influence on sagittal malalignment at last follow-up.

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