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Interspinous Process Fixation versus Posterior Lumbar Interbody Fusion Following Decompression for Single-Level Grade I Degenerative Spondylolisthesis: A Retrospective Propensity Score-Matched Study

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Abstract

Objective: To compare clinical outcomes and radiographic parameters between interspinous process fixation (ISPF) and posterior lumbar interbody fusion (PLIF) in patients with single-level degenerative lumbar spinal stenosis (LSS) associated with Meyerding Grade I spondylolisthesis.

Methods: We retrospectively analyzed 107 patients who underwent ISPF (n = 55) or PLIF (n = 52) between January 2019 and January 2023. Propensity score matching (PSM) was performed using covariates including age, sex, BMI, symptom duration, smoking history, diabetes mellitus, hypertension, and affected spinal level, resulting in 36 matched pairs. Clinical efficacy was evaluated using the Visual Analog Scale (VAS), Oswestry Disability Index (ODI), Japanese Orthopaedic Association (JOA) score, and Macnab criteria. Radiographic assessments included lumbar lordosis (LL), pelvic incidence (PI), pelvic tilt (PT), segmental angle (SA), and disc height (DH). All patients completed more than 24 months of follow-up.

Results: Post-matching analysis demonstrated good baseline balance (SMD < 0.20, P > 0.05). ISPF showed superior short-term outcomes, with significantly greater improvement in VAS scores both immediately postoperatively (2.52 ± 1.39

vs. 3.21 ± 1.23, P=0.0078) and at the 3-month follow-up (1.83 ± 1.31 vs. 2.54 ± 1.20, P=0.0042). Similarly, ODI favored ISPF at the immediate postoperative evaluation (38.64 ± 8.86 vs. 42.17 ± 6.77, P=0.0221) and at 3 months (25.61 ± 8.84 vs. 30.15 ± 6.75, P=0.0035), whereas no significant between-group differences were observed at 1 year and at the final follow-up (both P > 0.05). Radiographically, ISPF achieved superior LL (45.13° ± 4.97 vs. 40.37° ± 7.37, P=0.0002) and lower PT (12.49° ± 7.62 vs. 15.80° ± 8.26, P=0.0334), whereas PLIF demonstrated greater correction of the slip angle (SA: 10.99° ± 2.53 vs. 12.52° ± 1.48, P=0.0004). Long-term clinical outcomes and patient satisfaction rates were comparable (Macnab excellent-to-good: 86.11% ISPF vs. 83.33% PLIF, P=0.9420).

Conclusions: ISPF provided better short-term clinical recovery and maintenance of sagittal alignment, whereas PLIF offered greater slip correction. Both procedures yielded comparable long-term clinical outcomes, supporting individualized surgical decision-making in patients with degenerative LSS and Grade I spondylolisthesis.

Keywords: Lumbar spinal stenosis; Degenerative lumbar spondylolisthesis; Interspinous process fixation; Posterior lumbar interbody fusion; Propensity score matching

Introduction

Degenerative lumbar spondylolisthesis (DLS) has emerged as a prevalent spinal degenerative disorder whose incidence increases markedly with global population aging[1]. Epidemiological studies have revealed that in the 66-70-year age group, DLS affects approximately 15% of men and over 50% of women[2]. This condition is characterized by anterior slippage of a superior vertebral body relative to the adjacent inferior segment, often leading to spinal instability and neural compression. Clinically, patients most commonly present with chronic low back pain and radicular leg symptoms[3]. DLS often coexists with lumbar spinal stenosis (LSS), exacerbating symptom severity and substantially impairing quality of life[3,4]. Consequently, DLS places a significant burden on both patients and healthcare systems worldwide.

Currently, surgical decompression combined with internal fixation or fusion remains the mainstay treatment for DLS and LSS, aiming to alleviate symptoms and improve functional outcomes. However, with global population aging, the incidence of postoperative complications following spinal fusion procedures may increase, which warrants increased clinical attention[5]. Conventional posterior lumbar interbody fusion (PLIF) employs a pedicle screw-rod construct to achieve segmental arthrodesis and restore spinal biomechanical stability. PLIF is widely adopted in clinical practice and is associated with well-documented outcome profiles[6]. However, long-term complications, particularly adjacent segment degeneration (ASD) have raised increasing concerns[7]. With advances in minimally invasive spine surgery, interspinous dynamic stabilization systems, such

as interspinous process fixation (ISPF) have gained clinical traction[8]. These semi-rigid implants provide segmental support by bridging the spinous processes while preserving partial physiological motion. Theoretically, dynamic stabilization may mitigate ASD risk and has therefore attracted increasing interest[9].

Whereas PLIF offers robust segmental stability through interbody fusion, ISPF aims to achieve symptom relief with less soft-tissue disruption. Both PLIF and ISPF represent established surgical options for Meyerding Grade I lumbar spondylolisthesis with concomitant LSS. Comparative mid- to long-term outcomes between the two remain poorly characterized. ISPF may offer potential advantages over PLIF, including reduced intraoperative blood loss, shorter hospitalization, and lower perioperative complication rates[10]. However, direct comparative studies assessing the clinical efficacy and safety of these techniques are scarce. The current literature largely consists of small-scale prospective trials or short-term follow-up studies, yielding a low level of evidence. Consequently, mid- to long-term differences in clinical outcomes between PLIF and ISPF remain inadequately characterized[11].

This retrospective comparative study systematically evaluated the mid-to-long-term clinical outcomes and safety profiles of conventional PLIF versus ISPF in patients with single-level degenerative LSS and Meyerding Grade I spondylolisthesis over a 2-year follow-up. The objective of this study is to generate robust evidence to refine surgical strategy selection and optimize treatment strategies for DLS.

Materials and methods

Study design and patients

We retrospectively reviewed the medical records of patients with single-level degenerative LSS and Meyerding Grade I spondylolisthesis who underwent either ISPF or PLIF at our institution between January 2019 and January 2023. This study was approved by the Ethics Review Committee of the Sixth Medical Center of the General Hospital of the Chinese People's Liberation Army (Approval No. HZKY-PJ-2025-29).

The inclusion criteria were as follows: (1) presence of low back pain and/or radicular leg pain, with or without neurogenic claudication; (2) radiographic evidence (X-ray or CT) of single-level Grade I spondylolisthesis with concurrent LSS at the same level, confirmed by MRI or CT showing absolute stenosis (cross-sectional area [CSA] < 75 mm^2) or relative stenosis (CSA < 100 mm^2); (3) failure of conservative treatment ≥ 3 months; (4) age > 18 years; (5) a follow-up duration of ≥24 months with complete clinical records. The exclusion criteria were as follows: (1) presence of spinal tuberculosis, tumor, infection, or trauma; (2) diagnosed osteoporosis with a T-score < −2.5; (3) history of previous lumbar spine surgery; (4) presence of spinal scoliosis with a Cobb angle > 25°; (5) multi-level pathology involving more than two spinal segments; (6) inability to tolerate surgical intervention.

Based on the inclusion criteria, 107 patients were included in the study cohort: 55

in the ISPF group and 52 in the PLIF group. All procedures were performed by a single senior spine surgeon to minimize variability in surgical technique.

Propensity score matching (PSM) was performed to minimize baseline imbalances between groups[12]. Propensity scores were estimated via a logistic regression model including the following baseline covariates: age, sex, body mass index (BMI), symptom duration, hypertension, diabetes mellitus, smoking history, and affected spinal level (L3–L4, L4–L5, or L5–S1). Follow-up duration was descriptively compared descriptively between groups after matching to confirm comparable follow-up periods but was not included in the matching model to avoid post-treatment bias. A 1:1 nearest-neighbor matching algorithm with a caliper width of 0.02 and no replacement was applied. Group balance was evaluated using standardized mean differences (SMDs), with an SMD < 0.2 indicating adequate balance[13] (Table 1).

Surgical procedures

PLIF approach

Posterior lumbar interbody fusion (PLIF) was performed through a midline posterior incision of approximately 3–6 cm, with subperiosteal elevation of the erector spinae muscles from the laminae bilaterally to expose the spinous processes, laminae, facet joints, and when necessary, the transverse processes at one or two adjacent levels (e.g., for an L4–L5 PLIF: the L4 spinous process and lamina, the L3–L4 and L4–L5 facets joints, and the L4–L5 transverse processes). The spinous process at the index level was removed, followed by a laminectomy to

decompress the thecal sac in the midline and to visualize the exiting nerve roots on both sides; the facet joints were undercut (medial facetectomy) as required to enlarge the lateral recess and neural foramina. The nerve roots were then gently retracted medially to access the posterior annulus fibrosus, bilateral annulotomies were performed, the disc material was removed, and the endplates were prepared to create an optimal fusion bed while preserving the subchondral bone integrity; the same steps were repeated contralaterally to facilitate bilateral interbody work. Two interbody spacers (one per side), each packed with a bone graft, were inserted into the disc space to restore disc height and neural foraminal dimensions, and final segmental stabilization was achieved with bilateral pedicle screws placed in the vertebrae above and below the fused level and connected by rods to support fusion across the vertebral bodies. The implant position and alignment were confirmed under fluoroscopy, hemostasis was secured, and layered closure was performed [14].

ISPF approach

An interspinous process fusion plate (BacFuse Spinous Process Fusion Plate; Spire™ Stabilization System) was used for distraction and posterior column fusion. The implant consists of a central hollow body spanning the midportions of adjacent spinous processes and bilateral flanges with multiple spikes; once seated, the spikes are secured into the cranial and caudal spinous processes, and the lumen is packed with a bone graft to promote fusion. The available sizes range from 8 to 16 mm to achieve the desired distraction. The instrument set includes a

compressor, inserter, driver, protective sleeve, rasp, and sequential dilators. Patients underwent spinal or combined spinal-epidural anesthesia and were positioned prone. Through a midline posterior approach, the spinous processes were exposed; the interspinous ligament was divided while the supraspinous ligament was preserved. The interspinous interval was sequentially dilated and measured intraoperatively to select the appropriate implant size. When indicated for stenosis, fenestration with partial laminectomy provided neural decompression. Cem-Ostetic® bone graft (Berkeley Advanced Biomaterials, Berkeley, CA), a two-component system comprising liquid and solid components (hydroxyapatite, β-tricalcium phosphate, and calcium sulfate), was prepared and packed into the device lumen. The plate was introduced from one side over a sleeve, and compressed into final position, and the titanium spikes were locked to the adjacent spinous processes. Fluoroscopic imaging verified the position, distraction, and fixation prior to closure [15].

Data collection and measurements

Demographic and perioperative data for matched patients were collected. The perioperative data included the operative time, fluoroscopy time, intraoperative blood loss, length of hospital stay, and total length of incision. All patients were followed up regularly for more than two years, including clinical functional scores, imaging data, and complications. Complications were systematically recorded and classified as early (<90 days after the index surgery) or late (≥90 days). Early events included postoperative low back pain and lower-limb pain requiring

additional intervention, surgical-site infection, dural tear, disc-space infection, and new/worsened neurologic deficit; late events included implant failure and reoperation.

Clinical evaluation

Pain and functional outcomes were assessed using the Visual Analog Scale (VAS), Oswestry Disability Index (ODI), and Japanese Orthopaedic Association (JOA) score at five time points: preoperatively, immediately postoperatively, and at 3 months, 1 year, and final follow-up. Overall recovery and patient satisfaction at the last follow-up were further evaluated according to the modified Macnab criteria [16–19].

Imaging measurements

All patients underwent standardized X-ray, CT, and MRI preoperatively, immediately postoperatively, at 3 months, at 1 year, and at the final follow-up. The following parameters were obtained on lateral radiographs or reconstructed CT images: lumbar lordosis (LL), pelvic incidence (PI), pelvic tilt (PT), segmental angle (SA), disc height (DH) [20–25]**.** All radiographic measurements were performed independently by two blinded observers, and the average of the two readings was used for analysis. Figure 1 illustrates a schematic diagram of the imaging measurements.

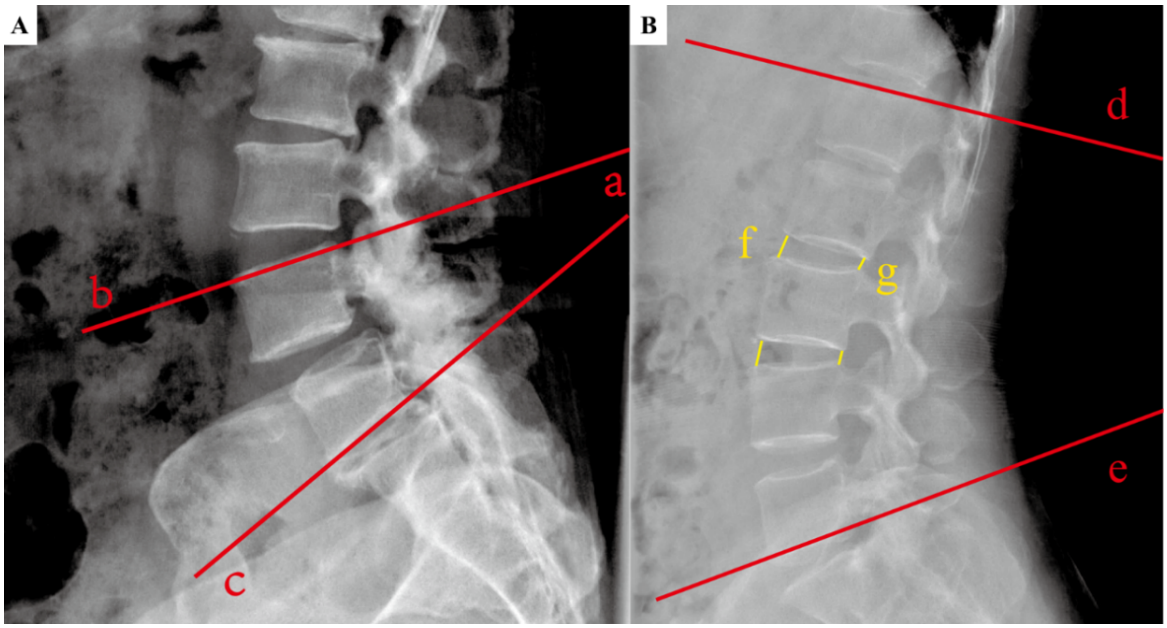


Figure 1. Schematic illustration of SA, DH, and LL measurements. (A) Measurement of segmental angle (SA): a, upper endplate line of the slipped vertebra; b, lower endplate line of the inferior vertebra; c, angle formed between lines a and b, defined as SA. (B) Measurement of lumbar lordosis (LL) and disc height (DH): d, upper endplate of L1; e, sacral endplate of S1; the angle between d and e is defined as LL. f, anterior disc height; g, posterior disc height; the average of f and g is defined as DH.

Statistical analysis

Statistical analyses were conducted using SPSS version 27.0 (IBM Corp., Armonk, NY, USA). Continuous variables were reported as means ± standard deviations (SDs) and compared using independent-sample t tests. Categorical variables were compared using χ^2 tests. In addition, PSM was performed in R (MatchIt and cobalt packages; R Foundation for Statistical Computing, Vienna, Austria). A two-tailed

P value < 0.05 was considered statistically significant.

Results

Baseline characteristics before and after propensity score matching

The baseline demographic characteristics of the two groups before matching are shown in Table 1. Before matching, 107 patients with single-level LSS were enrolled, including 55 in the ISPF group and 52 in the PLIF group. SMD ≤ 0.20 and P > 0.05 were considered to indicate adequate covariate balance. Two

Variable	PLIF Group	ISPF Group	P-value	SMD
Age	61.13 ± 6.71	58.43 ± 6.49	0.0366*	0.4092*
BMI	25.09 ± 2.62	24.04 ± 2.36	0.0313*	0.4216*
Disease Duration	28.16 ± 5.54	30.30 ± 5.25	0.0425*	0.3969*
Follow-Up Time	45.14 ± 2.05	45.90 ± 2.31	0.0762	0.3470*
Sex	22 (42.31%)	26 (47.27%)	0.7477	0.0998
Hypertension	27 (51.92%)	28 (50.91%)	1.0000	0.0203
Diabetes	17 (32.69%)	24 (43.64%)	0.3346	0.2253*
Smoking	42 (80.77%)	38 (69.09%)	0.2431	0.2694*
L3-L4	9 (17.31%)	10 (18.18%)	1.0000	0.0229
L4-L5	37 (71.15%)	37 (67.27%)	0.8219	0.0841
L5-S1	6 (11.54%)	8 (14.55%)	0.8617	0.0893
□	□	□	□	□

variables remained imbalanced prior to matching: symptom duration (SMD = 0.370, $P = 0.048$) and age (SMD = 0.206, $P = 0.291$). BMI, smoking history, and diabetes mellitus demonstrated SMDs near the threshold (0.15–0.19). Consequently, these variables were incorporated into the propensity score model to improve baseline comparability.

Table 1 Baseline characteristics before PSM

Using 1:1 nearest-neighbor propensity score matching with a caliper width of 0.02 and no replacement, 36 matched pairs (n = 72) were obtained. After matching, nearly all covariates had SMDs ≤ 0.20 and P > 0.05, except for diabetes (SMD = 0.211), indicating adequate balance between the ISPF and PLIF groups for age, BMI, symptom duration, smoking history, and affected spinal level distribution (Table 2). Mean follow-up duration was also comparable between groups (P > 0.05), confirming similar observation periods. The Love plot (Figure 2) demonstrated a marked leftward shift in the SMD distributions after matching, further confirming the effectiveness of the matching procedure.

Table 2 Baseline characteristics after PSM

Variable	PLIF Group	ISPF Group	P-value	SMD
Age	59.23 ± 6.91	59.60 ± 6.06	0.8261	0.0579
BMI	24.43 ± 2.16	24.18 ± 2.27	0.6695	0.1127
Disease Duration	30.74 ± 4.69	30.29 ± 5.68	0.7461	0.0854
Follow-Up Time	45.44 ± 2.06	45.57 ± 2.08	0.8122	0.0627
Sex	15 (41.67%)	15 (41.67%)	1.0000	0.0000
Hypertension	17 (47.22%)	19 (52.78%)	0.6374	0.1113
Diabetes	16 (44.44%)	12 (33.33%)	0.3336	0.2294
Smoking	26 (72.22%)	25 (69.44%)	0.7954	0.0611
L3-L4	8 (22.22%)	6 (16.67%)	0.5515	0.1407
L4-L5	25 (69.44%)	25 (69.44%)	1.0000	0.0000
L5-S1	3 (10.34%)	5 (13.89%)	0.4533	0.1775
□	□	□	□	□

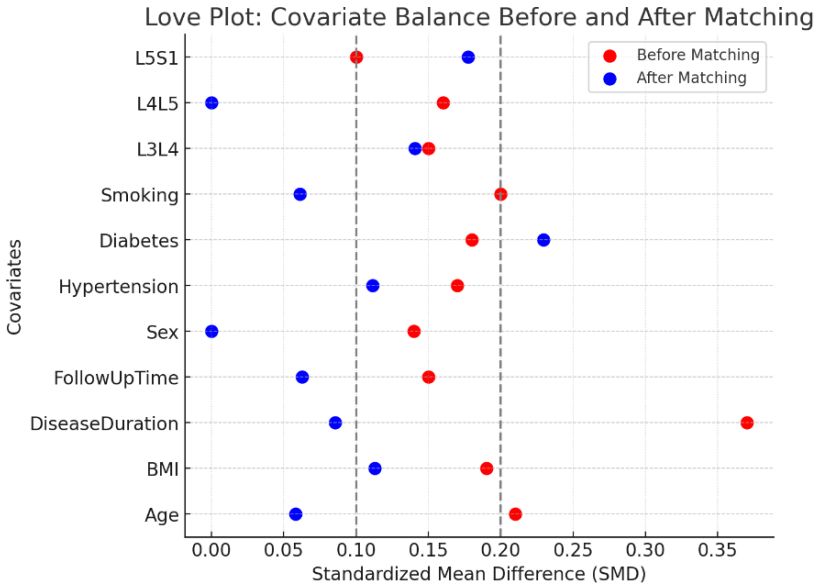
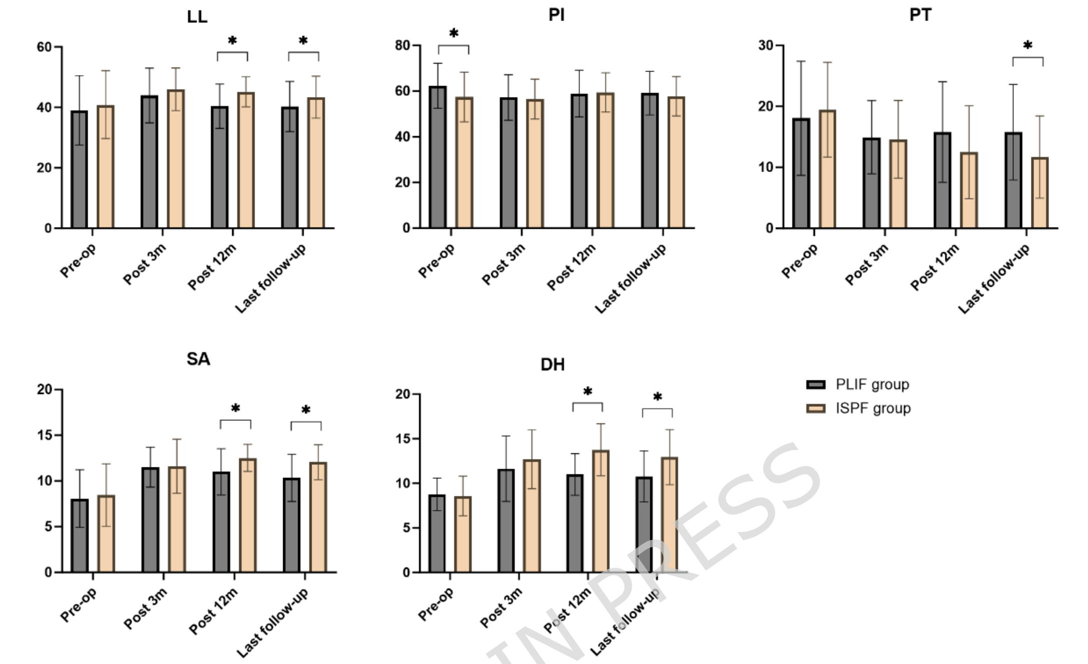


Figure 2. Covariate balance before (red) and after (blue) propensity score matching, as assessed by the standardized mean difference (SMD).

Image measurements

The comparison of the imaging data between the groups is shown in Table 3 and Figure 3. Preoperatively, the ISPF and PLIF groups did not differ significantly in LL, PT, SA, or DH (all $P > 0.05$).

Table 3 Comparison of radiographic parameters of DLS-LSS patients between 2 groups



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LL(°) ,			
Pr[illegible]			
3 postop[illegible]			
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PI(°) ,			
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3 postop[illegible]			
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At[illegible]			
PT(°) , x̄ ± s			
Preoperatively	18.05 ± 9.36	19.46 ± 7.77	0.3968
3 months postoperatively	14.94 ± 6.01	14.59 ± 6.38	0.7738
1 year follow-up	15.80 ± 8.26	12.49 ± 7.62	0.0334
At final follow-up	15.77 ± 7.84*	11.69 ± 6.75*	0.0047
SA(°) , x̄ ± s			
Preoperatively	8.07 ± 3.15	8.46 ± 3.42	0.5435
3 months postoperatively	11.51 ± 2.18	11.61 ± 2.96	0.8350
1 year follow-up	10.99 ± 2.53*	12.52 ± 1.48*	0.0004
At final follow-up	10.34 ± 2.59*	12.05 ± 1.91*	0.0003
DH(mm) , x̄ ± s			
Preoperatively	8.77 ± 1.82	8.58 ± 2.23	0.6259
3 months postoperatively	11.64 ± 3.66	12.69 ± 3.30	0.1220
1 year follow-up	10.99 ± 2.34*	13.76 ± 2.92*	0.0001
At final follow-up	10.77 ± 2.87*	12.93 ± 3.09*	0.0003

Figure 3. Comparison of radiographic parameters between the ISPF and PLIF

groups at different time points. Lumbar lordosis (LL), pelvic incidence (PI), pelvic tilt (PT), segmental angle (SA), and disc height (DH) were measured preoperatively, postoperatively, at 3 months, 12 months, and at the last follow-up. *P < 0.05 indicates statistical significance at the corresponding time point.

However, the PI was greater in the PLIF group than in the ISPF group ($P = 0.0159$). At 3 months postoperatively, both cohorts exhibited significant improvements compared with baseline in LL, PT, SA, and DH (all $P < 0.05$), with no intergroup differences observed at this time point (all $P > 0.05$).

At the 1-year follow-up, the ISPF group demonstrated greater lumbar lordosis (LL: 45.13° ± 4.97 vs. 40.37° ± 7.37; $P = 0.0002$) and lower pelvic tilt (PT: 12.49° ± 7.62 vs. 15.80° ± 8.26; $P = 0.0334$) compared with the PLIF group, indicating superior sagittal balance restoration. The PLIF cohort achieved a smaller segmental angle (SA: 10.99° ± 2.53 vs. 12.52° ± 1.48; P=0.0004), reflecting more effective segmental angle correction. Additionally, disc height restoration was greater in the ISPF group (13.76 ± 2.92 mm vs. 10.99 ± 2.34 mm; $P = 0.0001$). These differences persisted through the final follow-up.

Clinical outcomes

Tables 4 and 5 and Figures 4, 5, and 6 present the clinical outcomes for the two groups. The preoperative VAS score did not differ between the ISPF and PLIF groups ($P = 0.9409$). The ISPF cohort, however, experienced greater pain relief

284 immediately postoperatively and at the 3-month follow-up. At the 1-year and final

285 follow-up, the VAS scores were comparable between the groups (both $P > 0.05$).

Index	ISPF group (n=36)	PLIF group (n=36)	P value
VAS score, $\bar{x} \pm s$	□	□	□
Preoperatively	7.05 ± 1.30	7.07 ± 1.18	0.9409
Postoperatively	2.52 ± 1.39*	3.21 ± 1.23*	0.0078
3 months postoperatively	1.83 ± 1.31*	2.54 ± 1.20*	0.0042
1 year follow-up	0.78 ± 1.37	1.07 ± 1.22	0.2435
At final follow-up	0.62 ± 1.33	0.92 ± 1.22	0.2284
JOA score, $\bar{x} \pm s$			
Preoperatively	19.77 ± 2.32	20.16 ± 2.47	0.3999
Postoperatively	23.33 ± 2.26	22.86 ± 2.42	0.3119
3 months postoperatively	25.17 ± 2.34	24.62 ± 2.66	0.2666
1 year follow-up	27.15 ± 2.37	27.15 ± 2.50	0.9799
At final follow-up	27.79 ± 2.32	27.70 ± 2.53	0.8347
ODI score, $\bar{x} \pm s$			
Preoperatively	55.63 ± 8.80	56.22 ± 6.75	0.6982
Postoperatively	38.64 ± 8.86*	42.17 ± 6.77*	0.0221
3 months postoperatively	25.61 ± 8.84*	30.15 ± 6.75*	0.0035
1 year follow-up	10.61 ± 8.79	12.29 ± 6.70	0.2648
At final follow-up	7.62 ± 8.81	7.21 ± 6.80	0.7833
Macnab Grading of Clinical Outcome			
Excellent	18	17	-
Good	13	13	-
Fair	5	6	-
Poor	0	0	-

Excellent-Good Rate(%)	86.11	83.33	χ^2 = 0.12, P = 0.9420

	PLIF Group (N=36)	ISPF Group (N=36)	P value
Operative time (min)	265.23 ± 6.85	168.31 ± 7.36	<0.001
Fluoroscopy times	18.61 ± 1.63	8.68 ± 1.09	<0.001
Intraoperative blood loss (mL)	122.45 ± 5.22	86.58 ± 4.68	0.002
Length of hospital stay (days)	14.21 ± 0.96	10.98 ± 0.75	< 0.001
Total length of incision (cm)	8.61 ± 0.79	5.12 ± 0.88	<0.001

Table 4 Comparison of clinical scores between the ISPF and PLIF groups

Table 5 Comparison of perioperative data between the two groups

JOA scores improved significantly from baseline at all postoperative time points in both cohorts (all $P < 0.05$), with no significant intergroup differences observed (all $P > 0.05$). According to the Macnab criteria, the excellent-to-good rates were 86.11% in the ISPF group and 83.33% in the PLIF group ($\chi^2 = 0.12$; $P = 0.9420$) (Figures 4, 5, and 6).

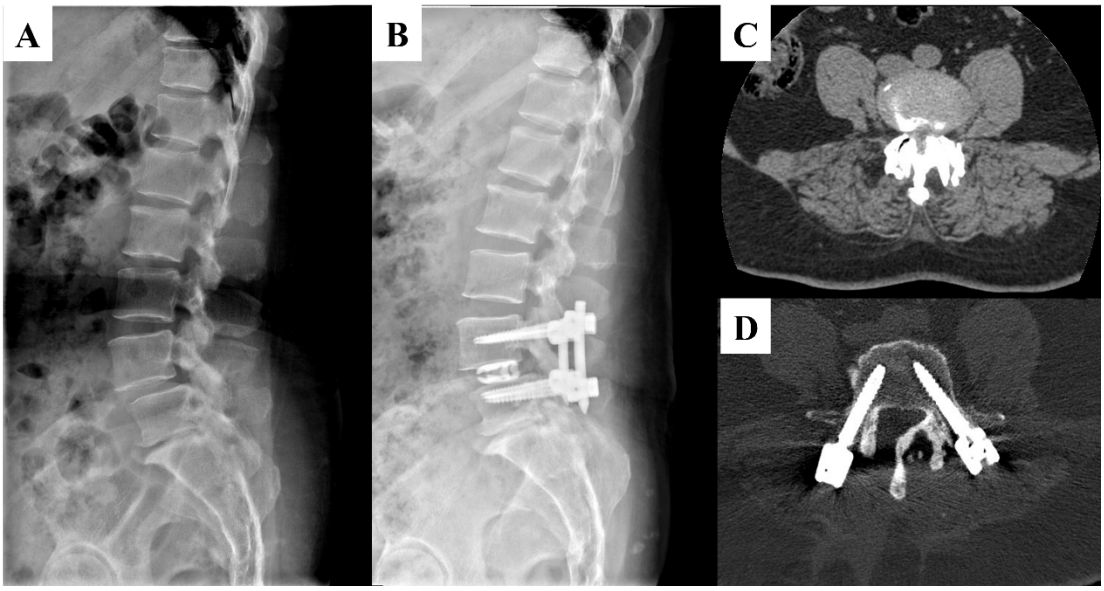

Figure 4. Preoperative and postoperative imaging of a patient who underwent posterior lumbar interbody fusion (PLIF). (A, C) Images before the operation showing L4-L5 spondylolisthesis and lumbar spinal stenosis. (B, D) Images after PLIF demonstrating satisfactory pedicle screw fixation and interbody fusion with adequate reduction and decompression

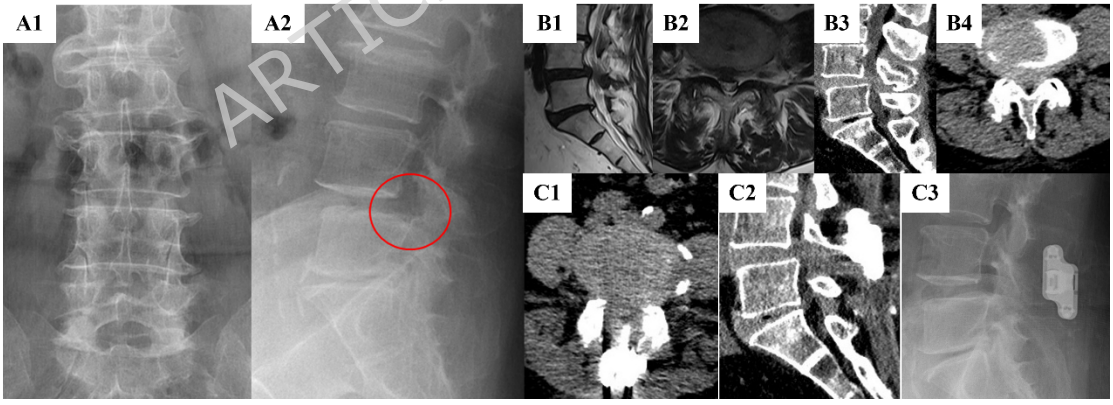

Figure 5. Preoperative and postoperative images of ISPF. (A1, A2; B1-B4) Preoperative images demonstrating lumbar spinal stenosis and segmental instability at L4-L5. (C1-C3) Postoperative images showing satisfactory interspinous device implantation and decompression effects

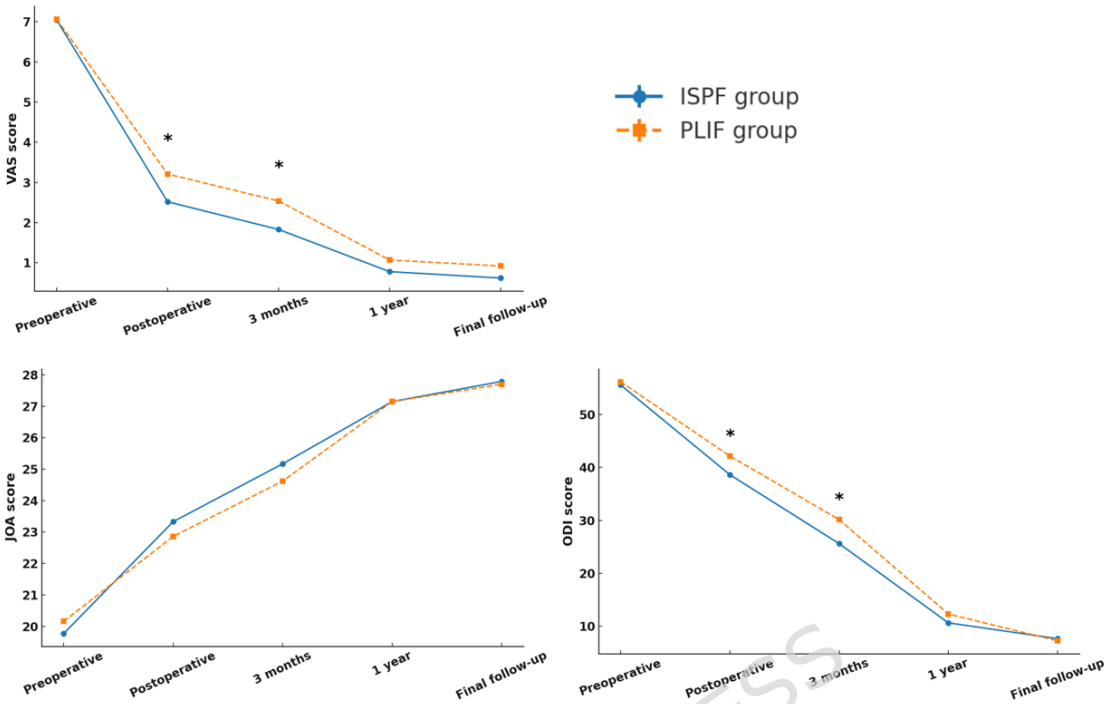

Figure 6. Comparison of clinical outcomes between the ISPF and PLIF groups. (A) Visual analog scale (VAS) scores, (B) Japanese Orthopaedic Association (JOA) scores, and (C) Oswestry Disability Index (ODI) scores were recorded preoperatively, postoperatively, at 3 months, 1 year, and at the last follow-up. *P < 0.05 indicates a significant difference between groups at the corresponding time point

Overall, the ISPF procedure conferred superior early outcomes in terms of pain relief, functional recovery, and selected radiographic parameters, whereas PLIF achieved greater correction of vertebral slippage. Importantly, both techniques achieved comparable long-term clinical outcomes and patient-reported satisfaction, suggesting that either approach represents a viable surgical option for managing single-level DLS with concurrent LSS.

Complications

Over a follow-up period exceeding 24 months, at least one complication occurred in 16/36 (44.4%) patients in the PLIF group and 5/36 (13.9%) in the ISPF group (P = 0.0086; Table 6). Early complications (<90 days) were significantly lower in the ISPF group than in the PLIF group (2/36 [5.6%] vs 12/36 [33.3%], P = 0.0059). Early events included postoperative low back pain and lower-limb pain requiring intervention, surgical-site infection, dural tear, disc-space infection, and new or worsened neurologic deficit. Notably, no surgical-site infection or dural tear occurred in the ISPF group. Late complications (≥90 days) were comparable between groups (ISPF 3/36 [8.3%] vs PLIF 4/36 [11.1%], P = 1.0000). The reoperation rates were identical (2/36 [2.8%] vs 2/36 [2.8%], P = 1.0000).

Complication	PLIF (n=36)	ISPF (n=36)	P value
Overall complications	16 (44.4%)	5 (13.9%)	0.0086
Early (<90 days)	12 (33.3%)	2 (5.6%)	0.0059
Low back pain	4 (11.1%)	1 (2.8%)	0.3570
Lower limbs pain	3 (8.3%)	1 (2.8%)	0.6142
Surgical site infection	2 (5.6%)	0 (0.0%)	0.4930
Dural tear	2 (5.6%)	0 (0.0%)	0.4930
Disc space infection	0 (0.0%)	0 (0.0%)	1.0000
Neurologic deficit	1 (2.8%)	0 (0.0%)	1.0000
Late (≥90 days)	4 (11.1%)	3 (8.3%)	1.0000
Implant failure	2 (5.6%)	1 (2.8%)	1.0000

Reoperation	2 (5.6%)	2 (5.6%)	1.0000

Table 6 Complications within ≥24 Months after Surgery

Discussion

This study compared the clinical efficacy of ISPF and PLIF in the treatment of single-level degenerative LSS with Meyerding Grade I spondylolisthesis. These findings indicate distinct yet complementary therapeutic profiles for each technique. During the early postoperative phase (≤3 months), the ISPF technique resulted in superior improvement in clinical symptoms. However, at long-term follow-up (≥24 months), both groups achieved comparable clinical success rates. Radiographically, both techniques were associated with improvements in sagittal balance parameters. ISPF tended to maintain lumbar lordosis and disc height more effectively, whereas PLIF achieved greater correction of the slip angle.

The early clinical benefits of the ISPF procedure stem from its minimally invasive approach and dynamic stabilization mechanism. By achieving indirect decompression through distraction of the spinous processes, ISPF obviates extensive laminectomy and direct disc manipulation, thereby reducing soft-tissue trauma and subsequent inflammatory response. This approach facilitates accelerated functional recovery in properly indicated patients, particularly those with predominant neurogenic claudication symptoms[26]. Notably, even minimally invasive biportal or endoscopic interbody fusion remains technique-dependent and entails a substantial learning curve, with higher complication rates during the early phase of adoption[27]. In contrast, PLIF confers rigid stabilization through interbody fusion but necessitates more extensive surgical exposure and soft-tissue

dissection. The safety of transforaminal interbody fusion variants is highly technique-dependent because of the narrow working corridor (Kambin's triangle); a recent CT-based 3D modeling study quantified the L4–L5 Kambin's triangle to delineate a safer operating region and potentially reduce nerve injury during TPLIF[28]. Despite the greater extent of intraoperative trauma, PLIF achieves superior restoration of disc height and segmental angle correction, resulting in a radiographic advantage in postoperative assessments[14]. The biomechanical advantage of PLIF becomes increasingly evident as fusion matures, ultimately leading to comparable long-term clinical outcomes between the two techniques despite their differing stabilization mechanisms.

These findings align with the contemporary literature while contributing methodological and interpretative innovations. Jung et al. reported that ISPF patients achieved more rapid improvements in VAS and ODI scores, accompanied by significantly lower intraoperative blood loss and shorter operative times[26]. By applying propensity score matching (PSM) to control for confounders such as age, BMI, symptom duration, and smoking history, our study strengthens these observations with improved statistical validity. Long-term follow-up studies have also reported comparable clinical efficacy between ISPF and PLIF, including the 2-year evaluation by Chen et al. evaluation in elderly patients[29], the 4-year longitudinal analysis by Spallone[15], and the large retrospective cohort study by Sabatino et al.[30]. With a minimum of 24 months of follow-up, our data not only corroborate these conclusions but also refine patient selection criteria, suggesting

that ISPF may be preferable for cases requiring early functional recovery, whereas PLIF may be more appropriate for patients with significant spinal instability or advanced disc degeneration.

Our findings partially align with those of previous studies. While PLIF achieved greater slip correction, ISPF showed greater disc height preservation and comparable sagittal alignment. Fusion rate assessment was not included in our study; thus, no definitive conclusion can be drawn regarding fusion superiority. Notably, our study is among the first to systematically correlate radiographic parameters with long-term clinical outcomes. We found that PLIF's radiographic advantages did not translate into additional clinical benefits, thereby providing objective, evidence-based insight to guide clinical surgical decision-making in degenerative lumbar spine disease.

Current clinical evidence indicates safety advantages for the ISPF procedure. Skoblar et al. reported lower incidences of infection, adjacent segment degeneration, and device-related complications with ISPF compared with PLIF[31]. Chen et al. reported the efficacy of ISPF in moderate lateral recess stenosis, though benefits were limited in severe central canal stenosis[23]. In this rigorously matched cohort, the safety and perioperative advantages of ISPF were further confirmed, highlighting its suitability for elderly patients, those with multiple comorbidities or limited tolerance for surgery, and individuals desiring accelerated postoperative recovery.

The principal strength of this study lies in its robust propensity score–matching

design, which achieved balanced baseline characteristics and effectively mitigated potential confounders. The study's extended follow-up (≥24 months) and the novel correlation of radiographic parameters with long-term clinical outcomes provides valuable evidence to inform surgical decision-making. However, several limitations warrant consideration. First, as a single-center, retrospective analysis with a relatively modest sample size, the generalizability of our findings may be constrained. Second, this investigation did not assess the incidence of adjacent segment degeneration nor did it explore the underlying biomechanical mechanisms in depth. Future research should prioritize multicenter randomized controlled trials with standardized radiographic protocols, longer-term surveillance for ASD (≥5 years), and the incorporation of performance-based functional assessments to further elucidate the comparative effectiveness of these surgical approaches.

Conclusions

This propensity score-matched comparative study with a minimum follow-up of 24 months provides clinically relevant insights for surgical strategy selection in single-level degenerative lumbar spinal stenosis patients with Meyerding Grade I spondylolisthesis. The findings indicate that: (1) ISPF offers superior early recovery advantages with lower perioperative morbidity, making it particularly suitable for elderly patients and those with multiple comorbidities; (2) PLIF may be more appropriate for patients requiring greater vertebral slip correction or rigid fixation, whereas ISPF offers an effective and less invasive alternative for

patients prioritizing faster recovery. These evidence-based conclusions enable spine surgeons to optimize individualized treatment selection based on patient-specific factors including age, comorbidity profile, spinal stability requirements, and postoperative rehabilitation goals.

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Contributions

J.M.: Writing – original draft, Writing – review & editing, Visualization, Validation, Methodology, Formal analysis, Data curation. T.L.: Data curation, Formal analysis, Writing – review & editing. N.S.: Investigation, Data curation, Writing – review & editing. R.R.: Validation, Writing – review & editing. Y.D.: Corresponding author, Resources, Software, Funding acquisition, Writing – review & editing, Supervision. All authors have read, revised, and approved the final manuscript.

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Ethics declarations

Ethics approval and consent to participate:

All procedures performed were in accordance with the ethical standards of the institutional review board and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. The study was approved by the

Ethics Review Committee of the Sixth Medical Center of the General Hospital of the Chinese People's Liberation Army (No. HZKY-PJ-2025-29).

Consent for publication:

Not applicable.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The datasets used during the current study are available from the corresponding author on reasonable request.

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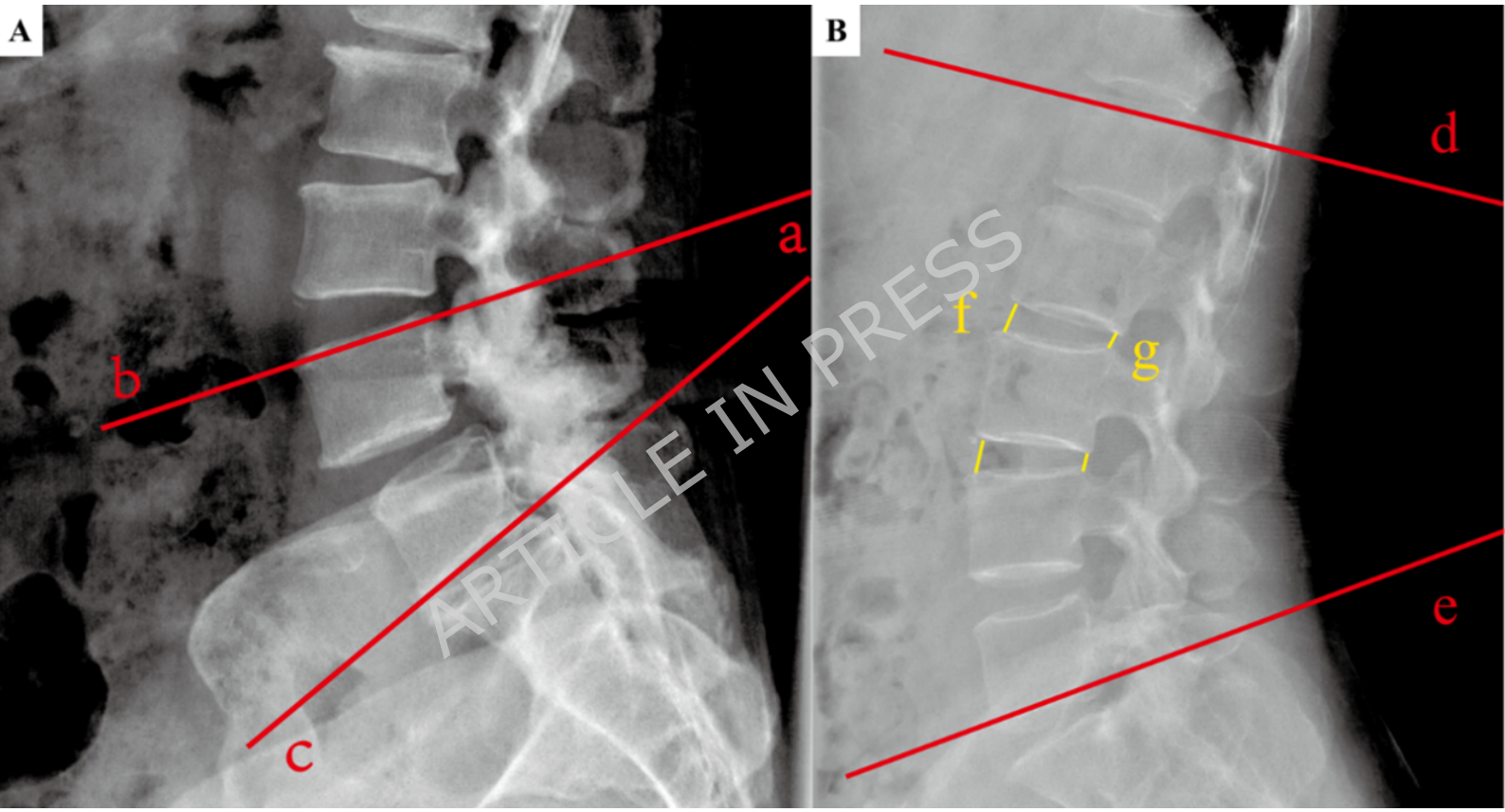

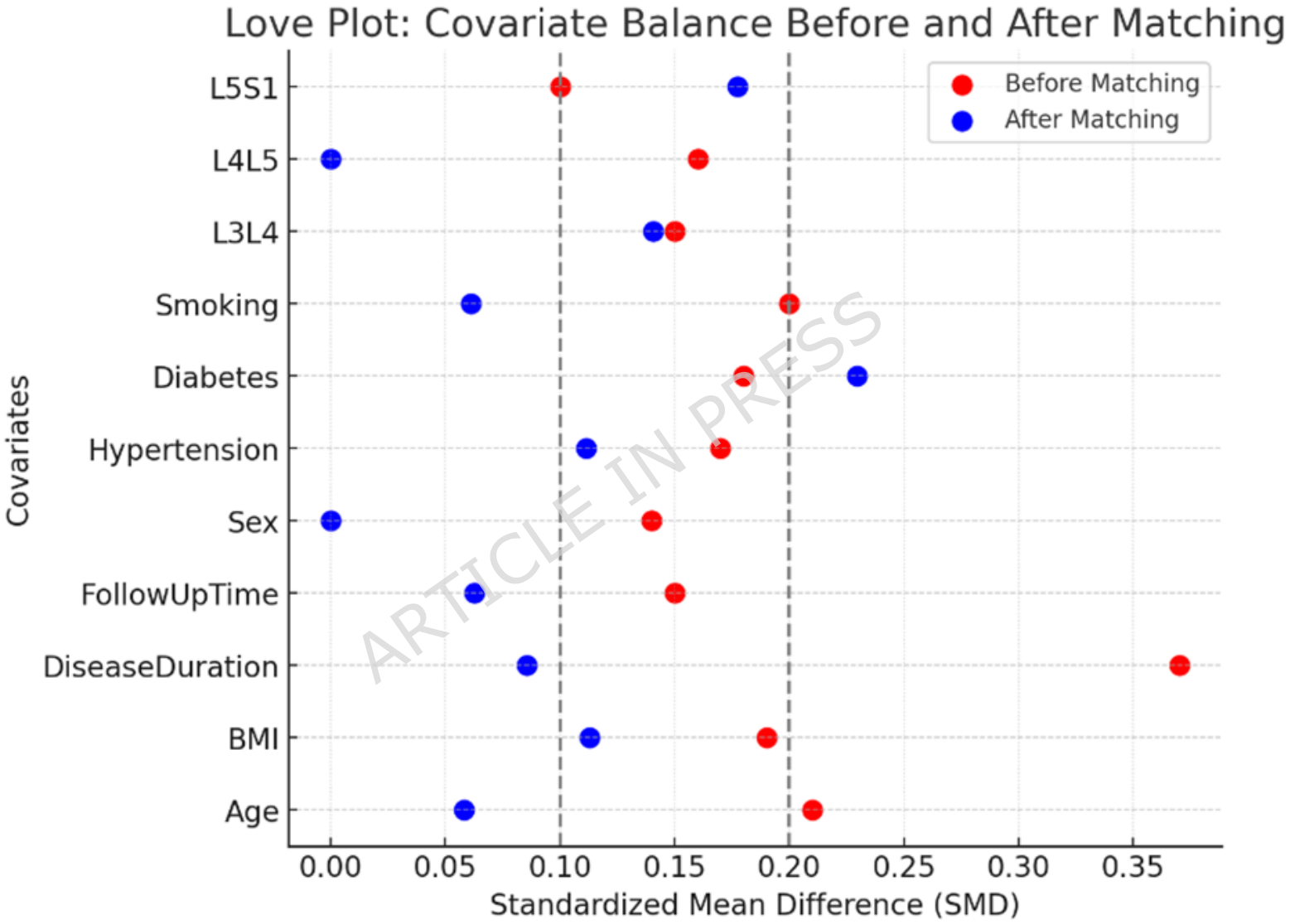

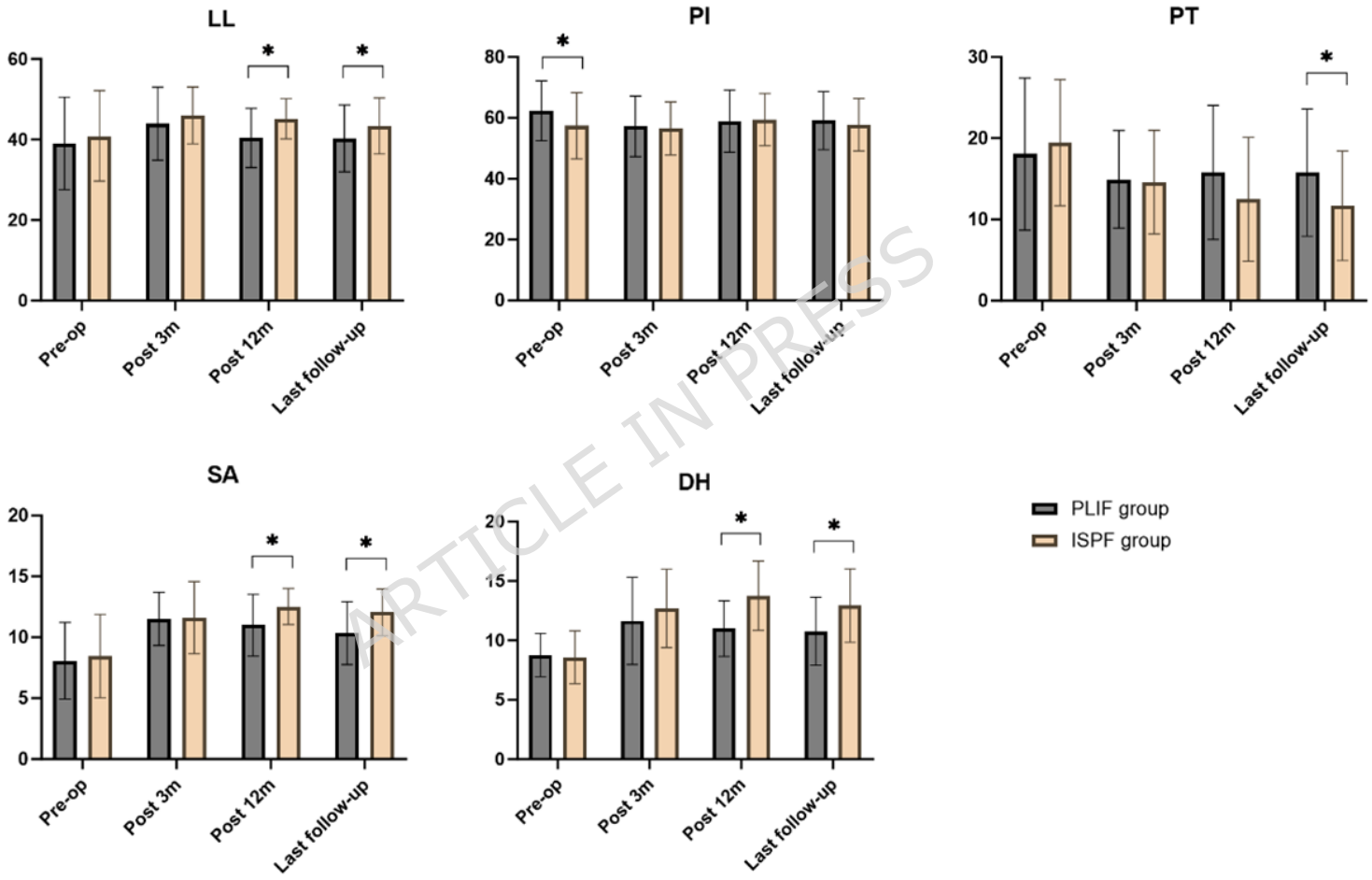

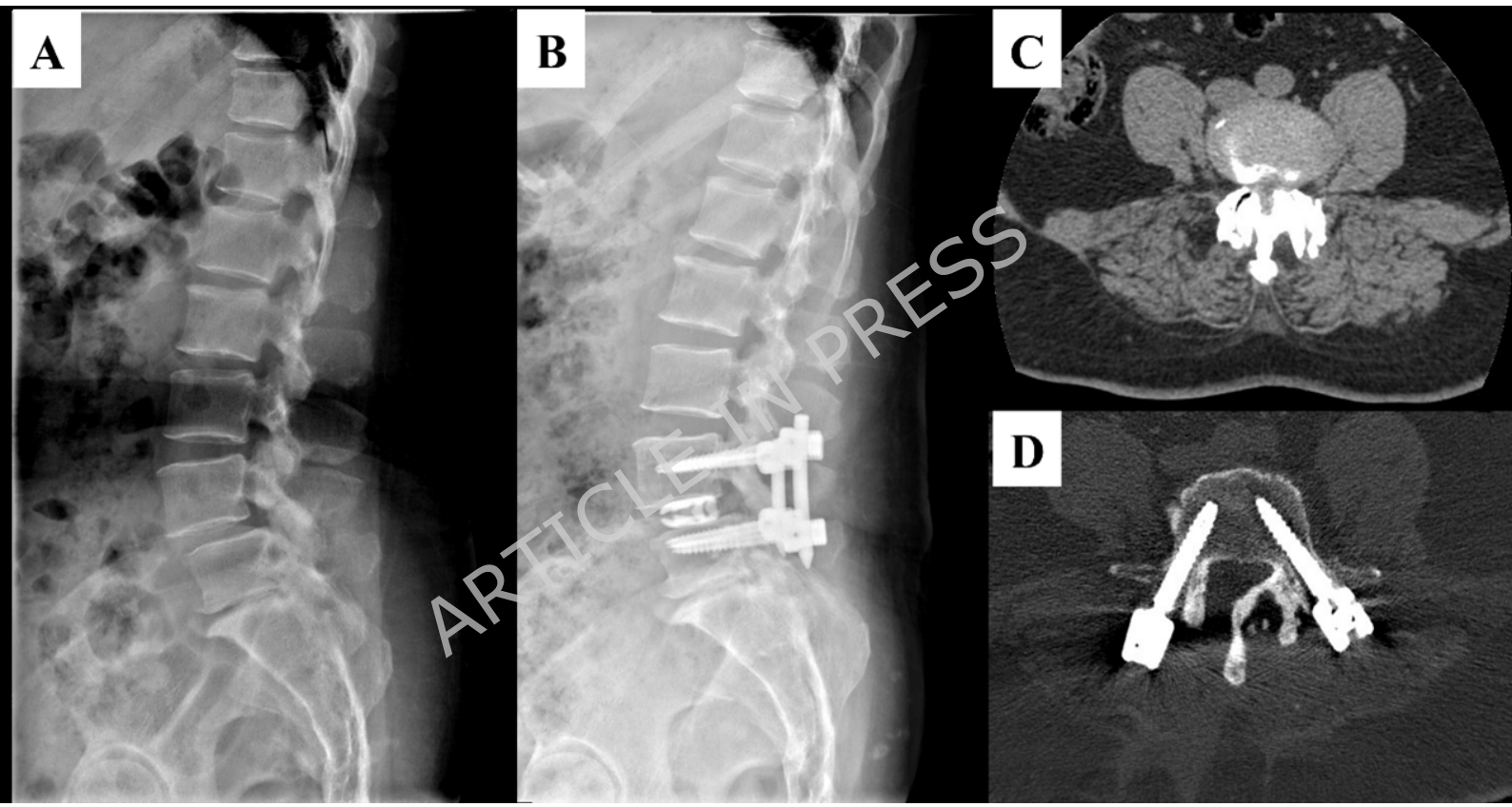

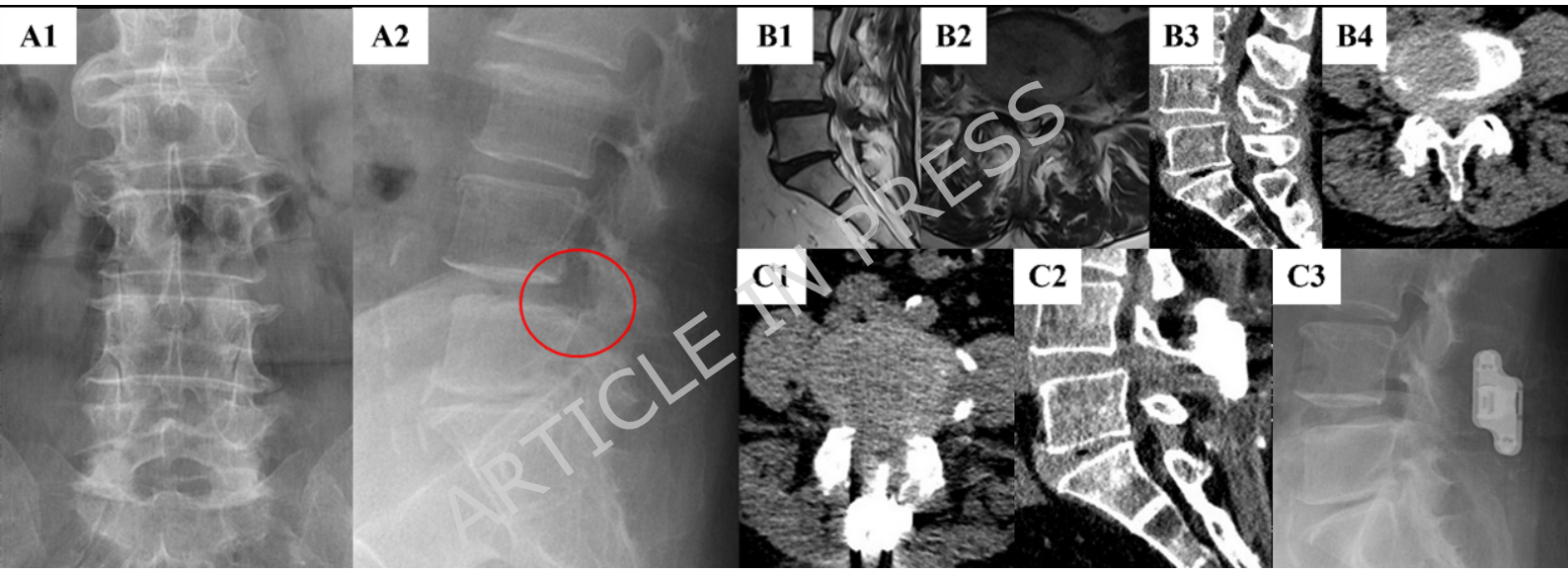

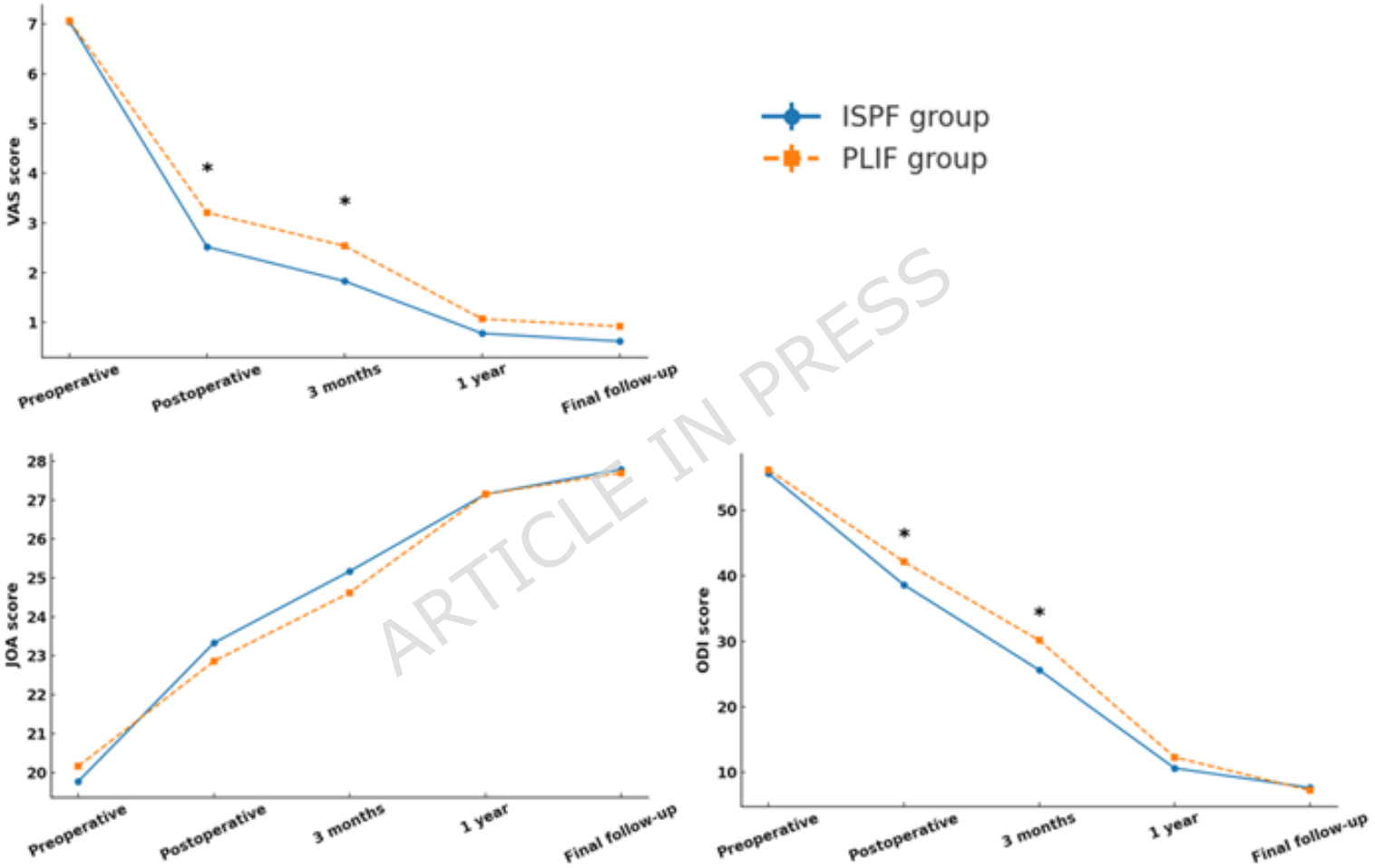

Table 1 Baseline characteristics before PSM

Variable	PLIF Group	ISPF Group	P-value	SMD
Age	61.13 ± 6.71	58.43 ± 6.49	0.0366*	0.4092*
BMI	25.09 ± 2.62	24.04 ± 2.36	0.0313*	0.4216*
Disease Duration	28.16 ± 5.54	30.30 ± 5.25	0.0425*	0.3969*
Follow-Up Time	45.14 ± 2.05	45.90 ± 2.31	0.0762	0.3470*
Sex	22 (42.31%)	26 (47.27%)	0.7477	0.0998
Hypertension	27 (51.92%)	28 (50.91%)	1.0000	0.0203
Diabetes	17 (32.69%)	24 (43.64%)	0.3346	0.2253*
Smoking	42 (80.77%)	38 (69.09%)	0.2431	0.2694*
L3-L4	9 (17.31%)	10 (18.18%)	1.0000	0.0229
L4-L5	37 (71.15%)	37 (67.27%)	0.8219	0.0841
L5-S1	6 (11.54%)	8 (14.55%)	0.8617	0.0893
□	□	□	□	□

Table 2 Baseline characteristics after PSM

Variable	PLIF Group	ISPF Group	P-value	SMD
Age	59.23 ± 6.91	59.60 ± 6.06	0.8261	0.0579
BMI	24.43 ± 2.16	24.18 ± 2.27	0.6695	0.1127
Disease Duration	30.74 ± 4.69	30.29 ± 5.68	0.7461	0.0854
Follow-Up Time	45.44 ± 2.06	45.57 ± 2.08	0.8122	0.0627
Sex	15 (41.67%)	15 (41.67%)	1.0000	0.0000
Hypertension	17 (47.22%)	19 (52.78%)	0.6374	0.1113
Diabetes	16 (44.44%)	12 (33.33%)	0.3336	0.2294
Smoking	26 (72.22%)	25 (69.44%)	0.7954	0.0611
L3-L4	8 (22.22%)	6 (16.67%)	0.5515	0.1407
L4-L5	25 (69.44%)	25 (69.44%)	1.0000	0.0000
L5-S1	3 (10.34%)	5 (13.89%)	0.4533	0.1775
□	□	□	□	□

Table 3 Comparison of radiographic parameters of DLS-LSS patients between 2 groups

Parameter	PLIF group (N=36)	ISPF group (N=36)	P value
LL(°) , $\bar{x} \pm s$			
Preoperatively	39.06 ± 11.48	40.90 ± 11.21	0.4043
3 months postoperatively	43.93 ± 9.05	45.98 ± 7.07	0.1922
1 year follow-up	40.37 ± 7.37*	45.13 ± 4.97*	0.0002
At final follow-up	40.28 ± 8.30*	43.37 ± 6.94*	0.0388
PI(°) , $\bar{x} \pm s$			
Preoperatively	62.32 ± 9.83*	57.39 ± 10.91*	0.0159
3 months postoperatively	57.18 ± 9.97	56.47 ± 8.73	0.6946
1 year follow-up	58.92 ± 10.22	59.43 ± 8.60	0.7829
At final follow-up	59.10 ± 9.51	57.73 ± 8.61	0.4334
PT(°) , $\bar{x} \pm s$			
Preoperatively	18.05 ± 9.36	19.46 ± 7.77	0.3968
3 months postoperatively	14.94 ± 6.01	14.59 ± 6.38	0.7738
1 year follow-up	15.80 ± 8.26	12.49 ± 7.62	0.0334
At final follow-up	15.77 ± 7.84*	11.69 ± 6.75*	0.0047
SA(°) , $\bar{x} \pm s$			
Preoperatively	8.07 ± 3.15	8.46 ± 3.42	0.5435
3 months postoperatively	11.51 ± 2.18	11.61 ± 2.96	0.8350
1 year follow-up	10.99 ± 2.53*	12.52 ± 1.48*	0.0004
At final follow-up	10.34 ± 2.59*	12.05 ± 1.91*	0.0003
DH(mm) , $\bar{x} \pm s$			
Preoperatively	8.77 ± 1.82	8.58 ± 2.23	0.6259
3 months postoperatively	11.64 ± 3.66	12.69 ± 3.30	0.1220
1 year follow-up	10.99 ± 2.34*	13.76 ± 2.92*	0.0001
At final follow-up	10.77 ± 2.87*	12.93 ± 3.09*	0.0003

Table 4 Comparison of clinical scores between the ISPF and PLIF groups

Index	ISPF group (n=36)	PLIF group (n=36)	P value
VAS score, $\bar{x} \pm s$	□	□	□
Preoperatively	7.05 ± 1.30	7.07 ± 1.18	0.9409
Postoperatively	2.52 ± 1.39*	3.21 ± 1.23*	0.0078
3 months postoperatively	1.83 ± 1.31*	2.54 ± 1.20*	0.0042
1 year follow-up	0.78 ± 1.37	1.07 ± 1.22	0.2435
At final follow-up	0.62 ± 1.33	0.92 ± 1.22	0.2284
JOA score, $\bar{x} \pm s$			
Preoperatively	19.77 ± 2.32	20.16 ± 2.47	0.3999
Postoperatively	23.33 ± 2.26	22.86 ± 2.42	0.3119
3 months postoperatively	25.17 ± 2.34	24.62 ± 2.66	0.2666
1 year follow-up	27.15 ± 2.37	27.15 ± 2.50	0.9799
At final follow-up	27.79 ± 2.32	27.70 ± 2.53	0.8347
ODI score, $\bar{x} \pm s$			
Preoperatively	55.63 ± 8.80	56.22 ± 6.75	0.6982
Postoperatively	38.64 ± 8.86*	42.17 ± 6.77*	0.0221
3 months postoperatively	25.61 ± 8.84*	30.15 ± 6.75*	0.0035
1 year follow-up	10.61 ± 8.79	12.29 ± 6.70	0.2648
At final follow-up	7.62 ± 8.81	7.21 ± 6.80	0.7833
Macnab Grading of Clinical Outcome			
Excellent	18	17	-
Good	13	13	-
Fair	5	6	-
Poor	0	0	-
Excellent-Good Rate(%)	86.11	83.33	χ^2 = 0.12, P = 0.9420
□	□ □		□

Table 5 Comparison of perioperative data between two groups

□	**PLIF Group (N=36)**	**ISPF Group (N=36)**	**P value**
Operative time (min)	265.23 ± 6.85	168.31 ± 7.36	<0.001
Fluoroscopy times	18.61 ± 1.63	8.68 ± 1.09	<0.001
Intraoperative blood loss (mL)	122.45 ± 5.22	86.58 ± 4.68	0.002
Length of hospital stay (days)	14.21 ± 0.96	10.98 ± 0.75	< 0.001
Total length of incision (cm)	8.61 ± 0.79	5.12 ± 0.88	<0.001
□	□	□	□

Table 6 Complications within >24 Months after surgery

Complication	PLIF (n=36)	ISPF (n=36)	P value
Overall complications	16 (44.4%)	5 (13.9%)	0.0086
Early (<90 days)	12 (33.3%)	2 (5.6%)	0.0059
Low back pain	4 (11.1%)	1 (2.8%)	0.3570
Lower limbs pain	3 (8.3%)	1 (2.8%)	0.6142
Surgical site infection	2 (5.6%)	0 (0.0%)	0.4930
Dural tear	2 (5.6%)	0 (0.0%)	0.4930
Disc space infection	0 (0.0%)	0 (0.0%)	1.0000
Neurologic deficit	1 (2.8%)	0 (0.0%)	1.0000
Late (≥90 days)	4 (11.1%)	3 (8.3%)	1.0000
Implant failure	2 (5.6%)	1 (2.8%)	1.0000
Reoperation	2 (5.6%)	2 (5.6%)	1.0000