Predicting spondylolisthesis correction with prone traction radiographs

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Abstract

Aims: To determine the utility of prone traction radiographs in predicting postoperative slip distance, slip angle, disc height changes, and lumbar lordosis after surgery for lumbar degenerative spondylolisthesis.

Patients and Methods: Consecutive patients with degenerative spondylolisthesis with preoperative prone traction radiographs obtained since 2010 were studied. Measurements of slip distance, slip angle, disc height, segmental lordosis and global lordosis (L1-S1) were performed on preoperative lateral standing radiographs, flexion-extension lateral radiographs, prone traction lateral radiograph and postoperative lateral standing radiographs. Patients were divided into two groups: posterolateral fusion or posterolateral fusion with interbody fusion.

Results: A total of 63 patients was studied. The average change in segmental lordosis and global lordosis was 7.1±6.7° and 2.9±9.9° respectively for the interbody fusion group, and 0.8±5.1° and -0.4±10.1° respectively for the posterolateral fusion only group. Segmental lordosis ($\rho=0.794$, $p<0.001$) corrected with interbody fusion was best correlated with prone traction radiographs. Global lumbar lordosis ($\rho=0.788$, $p<0.001$) was best correlated with the interbody fusion group and preoperative lateral standing radiographs. The least difference in slip distance (-0.3±1.7mm, $p<0.001$), slip angle (0.9±5.2°, $p<0.001$) and disc height (0.02±2.4mm, $p<0.001$) was observed between prone traction and postoperative radiographs. Regression analyses suggested that prone traction parameters best predicted slip distance correction (AICc=37.336) and disc height correction (AICc=58.096), while slip angle correction (AICc=26.453) was best predicted by extension radiographs. ROC cut-off showed that a prone traction disc height of 8.5mm warranted an interbody fusion with 68.3% sensitivity and 64.5% specificity to achieve 3.0° increase in segmental lordotic angle.

Conclusion: Prone traction radiographs provide the best prediction of slip distance and disc height corrections that are achieved with interbody fusion for lumbar degenerative spondylolisthesis. To achieve this maximum correction, interbody fusion should be performed if a disc height of more than 8.5mm is achieved on preoperative prone traction radiographs.

Clinical relevance:

- Prone traction radiographs provide best prediction of slip distance and disc height correction in lumbar degenerative spondylolisthesis.
- Interbody fusion achieves greater segmental lordosis gains.
- Disc height of 8.5mm achieved on prone traction radiographs warrants an interbody fusion

Level of Evidence: Level II Prognostic Study

Key Words: spondylolisthesis; prone traction; TLIF; interbody fusion

Introduction

Preoperative radiological assessment of degenerative spondylolisthesis entails a static standing radiograph for the severity of the slip as well as dynamic radiographs to identify any radiological instability. Flexion-extension radiographs are routinely obtained to determine segmental instability and whether fusion is necessary. Through these dynamic radiographs, any excessive mobility of a spinal segment is identified. Instability can be quantified by the change in slip distance, slip angle and disc height. There are various definitions in the literature for instability as proposed by Boden[1], Sonntag and Marciano[2], White and Panjabi[3], Posner[4], and Hanley[5]. These variabilities limit the significance of these radiological changes and have limited predictive capability for when fusion is required.[6-9]

When managing spondylolisthesis, the issue of whether an interbody fusion is necessary is always debatable. In segmental fusion of these inherently unstable conditions, the need for an anterior column support to enhance fusion rates should be considered. The literature supports the role of interbody fusions to improve fusion rates but they are associated with increased operative time and perioperative risks.[10] When considering transforaminal lumbar interbody fusions (TLIFs), a recent randomized controlled trial showed no benefit in improving sagittal alignment.[11] Hence, it should only be performed when necessary.

Most consider significant changes in dynamic radiographs to suggest disc degeneration and loss of anterior column support for the functional spinal unit.[12-16] In such situations, restoring the anterior column with an interbody fusion is prudent for construct stability. Without anterior column support, the spondylolisthesis has increased risk of slipping forward under loading. Based on this principle, restoration of the disc height can result in tensioning of the spinal ligaments and contribute to reduction of the slip. Restoring the lost disc height provides the necessary anterior column stability. This vertical instability is not obvious with flexion-extension radiographs but is better represented by prone traction radiographs.[17] Traction radiographs are able to reverse the failure mechanism where extension radiographs are unable to demonstrate segmental spinal translations.[18]

With severe disc degeneration, the disc space may also become contracted.[19] At this stage, traction radiographs may not be able to restore disc height to demonstrate any vertical instability. These anterior columns are more stable and thus preclude the need for interbody fusions. The role of these prone traction radiographs to predict postoperative radiological parameters after surgery for degenerative spondylolisthesis is uncertain. Hence, we aim to study the predictive capabilities of prone traction radiographs on changes in slip distance, slip angle, disc height gains, and lumbar lordosis correction for lumbar degenerative spondylolisthesis surgery.

Methods

Study design

This was a retrospective study of 112 consecutive patients with degenerative spondylolisthesis undergoing primary spinal surgery since 2010. All patients who underwent preoperative prone traction radiographs obtained since 2010 were studied. Only patients who subsequently had one- or two-level lumbar fusions were included. Patients without fusion surgery or long-segment deformity corrections were excluded. A total of 63 patients (46 females; 71.9%) remained for analysis after exclusion (n=49 with decompression-only surgery). Ethics was approved by the local institutional review board.

Management process

All patients underwent at least 3 months of conservative treatment (physiotherapy training and analgesic treatment) prior to decision for surgery. All patients were assessed by a multidisciplinary team of surgeons, physiotherapists and occupational therapists. Patients who had predominantly lower limb symptoms contributing to spinal stenosis such as paresthesia and claudication were treated with decompression-only via fenestrations and medial facetectomies to avoid iatrogenic instability.

Radiological instability was defined by evidence of increased degree of slip, change in slip angle and disc height on flexion-extension and prone traction radiographs.[17] Those who were considered for lumbar fusion surgery must have mechanical back pain as well as lumbar instability on flexion-extension radiographs identified as change of 4 mm in translation and slip angle change of >5°.[20] Lumbar fusion was performed via posterolateral fusion (PLF) by segmental pedicle screws, exposure of the posterolateral gutter and decortication of the intervening transverse processes and lateral facet, and with autogenous bone grafting (from the laminectomy) laid in the gutter. Compression across the screws was performed before final locking.

Interbody fusions were considered for patients with vacuum sign and increased disc height on prone traction radiographs.[20] For this study, all patients had TLIFs performed in addition to PLF. The standardized TLIF procedure was performed with removal of a unilateral facet joint to expose the posterior annulus. This approach provides adequate exposure of the disc space for grafting with minimal neural retraction, and spares the contralateral facet and pars interarticularis as fusion beds. An annulotomy with discectomy and removal of the cartilaginous endplates were performed. The disc spaces were sized to a cage that provided a snug-fit spacer. Compression across the instrumentation was made at the end of the procedure to load the interbody cage and attempt at creating more segmental lordosis.

Study parameters

Measurements of slip distance, slip angle, disc height, global lumbar lordosis (L1-S1) and segmental lordotic angle were performed on preoperative lateral standing radiographs, flexion-extension lateral recumbent radiographs, prone traction lateral radiograph and postoperative lateral standing radiographs. Maximum flexion-extension was performed for the recumbent radiographs. For prone traction films, patients were placed prone on a traction table and in-line traction force half of the body weight was applied through a set of chest and pelvic straps before cross-table lateral radiographs were taken centered at the site of the spondylolisthesis. In prone traction films, immediate change in disc height was evidence of a deficient anterior column. The global lumbar lordosis from L1-S1 and the segmental lordotic angle of the level operated on were measured. An L4-5 angle for example was measured from the upper endplate of L4 to the lower endplate of L5. The change in lumbar lordosis was calculated from the difference between postoperative and preoperative lateral standing radiographs.

For measurement of the degree of slip (Figure 1), a line was dropped from the posterior border of the cranial vertebrae to the caudal vertebrae. The distance from this point to the posterior border of the caudal vertebrae was divided by the total vertebral body width of the caudal vertebrae. Slip angle (Figure 1) was measured by the superior endplate of caudal vertebrae and inferior endplate of cranial vertebrae. For measurement of the disc height (Figure 1), a line was dropped from the midline inferior endplate of the cranial vertebrae to the upper endplate of the caudal vertebrae. A ratio between this distance and the midline vertebral height of the cranial vertebrae was compared on dynamic views.

All measurements were performed by two independent observers (JPYC and HKF) who were blinded to the patient details. The images were archived by another investigator (PWHC) for the two readers to measure. All datapoints within 1° or 1 mm were averaged. Any datapoints beyond this threshold was discussed between the readers for a final score for analysis.

Statistical analysis

Overall preoperative and postoperative data was presented as mean ± standard deviation (SD). The data was tested for its normality using Shapiro-Wilk test. Medians, range and interquartile range (IQR) were presented. Spearman's correlation was performed for testing the correlations between preoperative and postoperative parameters, and between postoperative and preoperative, flexion, extension and prone traction parameters. The differences between preoperative and postoperative parameters were compared between different types of radiographs (lateral, flexion, extension, prone traction) by the Kruskal-Wallis H test, with post-hoc pairwise comparison using the Bonferroni correction. For global and segmental lordosis, preoperative and postoperative values, as well as postoperative and prone traction values were compared using Wilcoxon signed-rank test. The role of various preoperative predictors of postoperative slip distance, slip angle and disc height were studied with non-linear regression with curve estimation for optimal fit. Scatter plots were used to analyze the relationships between parameters and linearity tests were run. The fit of the regression models generated was assessed using the Corrected Akaike's Information Criterion (AIC_C), which is recommended as it is more accurate than the AIC, with correction based on the number of data-points and number of parameters in the regression.[21] The value of AIC can be evaluated for both linear and non-linear regression models, as compared to R^2.[22] AIC decreases as residual variance decreases, therefore smallest AIC value represents best fit of data and allows selection of most appropriate model. Furthermore, patients were then divided into two groups: PLF or TLIF and PLF (PTLIF). Receiver operating characteristic was used to determine the cut-off value of traction disc height and segmental lordotic angle that was indicated for interbody fusion. Relevant area under the curve (AUC) was reported along with the 95% confidence interval (CI). P-value <0.05 was considered statistically significant. Statistical analyses were performed using SPSS Windows 26.0 (IBM SPSS Inc., Chicago, Illinois, USA)

Results

The mean age of patients was 60.9 ± 10.9 years. Two levels were fused in 9 patients giving rise to 72 lumbar levels for analysis. Of these, 46 levels (63.0%) had PTLIF, and 26 (37.5%) had PLF. L4-5 was the most common level (72.6%), followed by L3-4 (16.4%) and L5-S1 (11.0%). PTLIF was performed in 41 patients and PLF was performed in 22 patients.

The mean segmental lordosis and global lordosis was 9.1 ± 9.2° and 37.5 ± 17.2° respectively for standing lateral radiographs, was 15.4 ± 9.2° and 43.7 ± 12.0° respectively for prone traction radiographs, and was 14.0 ± 8.0° and 39.3 ± 14.8° respectively for postoperative standing lateral radiographs. When comparing PLF and PTLIF groups, the prone traction measurements matched better for the PTLIF group (Table 1). The average change in segmental lordosis and global lordosis was 7.1 ± 6.7° and 2.9 ± 9.9° respectively for the PTLIF group, and

0.8 ± 5.1° and -0.4 ± 10.1° respectively for the PLF group. The least difference in slip distance (-0.5mm, IQR 2.4), slip angle (0.8°, IQR 5.0) and disc height (0.0mm, IQR 2.9) was observed between prone traction and postoperative radiographs (Table 2).

Significant correlations were observed for all preoperative dynamic parameters with the postoperative images except for disc height for flexion radiographs and global lordosis for prone traction radiographs (Table 3). The strongest corrections were found for slip distance. Segmental lordosis ($\rho=0.794$, $p<0.001$) corrected with PTLIF was best correlated with prone traction radiographs. Global lumbar lordosis ($\rho=0.788$, $p<0.001$) was best correlated with the PTLIF group using preoperative lateral standing radiographs.

Regression analyses suggested that prone traction parameters best predicted slip distance correction (AICc=37.336) and disc height correction (AICc=58.096), while slip angle correction (AICc=103.872) was best predicted by extension radiographs (Table 4). Scatter plots supported the close relationship of prone traction parameters with postoperative slip distance (Figure 2), postoperative slip angle (Figure 3), and postoperative disc height (Figure 4). However, no relationships were observed for postoperative segmental or global lordotic angles. ROC (Figure 5) showed that 8.5 mm disc height on prone traction radiographs warranted an interbody fusion with 68.3% sensitivity and 64.5% specificity (AUC 0.649; p=0.031; 95% CI: 0.521-0.778) to achieve 3.0° increase in segmental lordosis.

Discussion

Spondylolisthesis is often associated with axial mechanical back pain, radicular leg pain and claudication. In addition to neural decompression, fusion is often required in the presence of radiological instability with significant mechanical back pain. Radiological instability is based on dynamic radiographs which help illustrate increased segmental mobility within a functional spinal unit. Flexion-extension radiographs are most commonly adopted but there are variabilities in its interpretation and method of imaging. Prone traction radiographs are useful to assess the vertical instability contributed by disc degeneration and associated disc height loss. In this study, we compared the prone traction radiograph to recumbent flexion-extension radiographs to predict postoperative parameters. The prone traction is superior to flexion-extension radiographs by matching the postoperative slip distance, slip angle and disc height better. There was a greater increase in segmental lordosis with PTLIF as compared to PLF but the change in lordosis is not well-predicted by the prone traction parameters.

The degree of instability is variable depending on the type of spondylolisthesis. Spondylolytic spondylolisthesis as compared to degenerative spondylolisthesis has more significant deficiency of the posterior constraints and thus restoring the posterior tension band is important for stability. Degenerative spondylolisthesis may not necessarily result in segmental instability[23] and may benefit from decompression surgery alone, similar to those excluded in our analyses. However, static radiographs do not adequately determine the dynamic instability in degenerative spondylolisthesis and a spectrum of hypermobility is observed.[24] Dynamic radiographs are often adopted for guiding treatment as only those with spinal instability should undergo stabilization and fusion.[11,25-27] In degenerative spondylolisthesis, there is an intact posterior bony-ligamental complex which contributes to stability. However, the integrity of the intervertebral disc is an important component to consider. If the disc is collapsed and no disc height is restored, posterior compressive instrumentation is adequate to provide the stability required for fusion as the ligamentous structures are not placed in tension. With disc height restoration that is often necessary for slip reduction and correction of segmental lordosis, the ligamentous structures become under tension. Posterior instrumentation alone is not advised and the construct rigidity will benefit from anterior column reconstruction.

Achieving reduction of spondylolisthesis is useful for restoration of alignment and providing a stable base for fusion. Determining when to perform interbody fusions is hence a challenge. The use of lumbar flexion-extension radiographs is the most common tool for detecting segmental instability and whether fusion is needed. However, the variabilities in definition limit its usefulness for predicting the amount of possible surgical correction.[6-9] Despite strong correlations, we observed that the changes on recumbent extension radiographs do not match the postoperative correction except for slip angle. With extension, the cranial vertebrae may pivot onto the caudal vertebrae instead of translating into reduction. This may contribute to a better slip angle than what is achieved with surgery. However, because it is not a true reduction of the slip, the slip distance and disc height are substandard as compared to the postoperative findings. The use of standing or recumbent flexion-extension radiographs is also debatable. The slip distance is greater in the standing position than the recumbent supine position due to axial compression forces.[28] However, there is also a huge dependence on patient effort and cooperation as pain leads to reduced intervertebral motion. In symptomatic patients, like in our study, recumbent flexion-extension radiographs are therefore better suited to identify pathological segmental motion. One study even suggested that the difference between standing lateral and flexion images are adequate to show the extent of translational shift as extension rarely achieves adequate extension due to heightened muscle tone restricting intervertebral motion.[29] In this study, we wanted to compare the potential correctability of surgery predicted by various preoperative dynamic radiographs. Hence, it was necessary to measure the maximum intervertebral mobility in a symptomatic patient to compare with the traction films. We utilized recumbent flexion-extension radiographs and the extension radiographs provided the best prediction for slip angle.

Maximum reduction of the spondylolisthesis with correction of the slip, kyphotic angle and restoration of disc area can be demonstrated by the prone traction radiograph.[17] We found that the prone traction radiograph best predicted slip distance correction and disc height correction. This was consistent for both PLF (Figure 6) and PTLIF (Figure 7) cases. As compared to extension radiographs, the correction of slip angle and disc height on traction radiographs is especially accurate to what is achieved postoperatively. In degenerative spondylolisthesis, disc degeneration with loss of intervertebral disc height leads to increased anterior shearing forces and slippage of the facet joints. Reversing this pathomechanism by restoration of disc height aids in reduction of the spondylolisthesis. This is contrasted by extension radiographs which only demonstrate segmental spinal translations.[18] Traction radiographs are able to demonstrate segmental spinal translation even in the absence of flexion-extension movement.[18] Furthermore, vertical instability is only appropriately measured by prone traction films.

Depending on the degree of vertical instability, a degenerative spondylolisthesis may be treated by restoring the anterior column support with an interbody fusion or completely collapsing the disc to allow settling of the upper and lower vertebra.[30,31] A deficient anterior column with significant vertical instability indicates laxity of the surrounding ligamental structures. The posterior ligamentous structures as a result are placed under tension and if only posterior instrumentation is used, forceful posterior reduction of the superior vertebrae back over the inferior vertebrae is required to reduce the slip. All of the load will transfer to the posterior instrumentation which is undesirable from a mechanical standpoint, leading to potential nonunion or instrumentation failure. An anterior graft or cage to support the anterior column will transform the posterior instrumentation from a cantilever device to a compressive device which greatly increases the construct stability.[17] On the contrary, if traction is unable to elicit vertical instability, the disc space and surrounding ligaments must be contracted. These anterior columns are likely more stable and do not require interbody fusions for construct stability.

PLF has traditionally been used as the mainstay treatment for spondylolisthesis. Despite relatively good results from PLF, there is increased popularity towards utilizing interbody fusions.[32] Interbody fusion techniques especially TLIF have shown better odds of achieving solid fusion and associated relief of back pain, but with drawbacks of longer operative times and more perioperative complications.[10] There is also an increased risk for additional surgery without improvement in patient-reported outcomes.[33] The benefits of interbody fusions in reduction of the spondylolisthesis and restoring the lumbar lordosis appear more pronounced. Colman *et al*[34] showed that interbody fusions may result in better segmental lordosis increases by average of 4° and disc height increases by average of 1.5 mm. Challier *et al*[11] also studied the differences in lordotic change between PLF and TLIF using a randomized controlled trial study design but found no differences between the two surgeries. However, it is important to note that they studied the global lumbar lordosis (L1-S1) which may be influenced by a myriad of factors instead of the pure effect of surgery on segmental lordosis. Our findings suggest that PTLIF creates significantly more lordosis with average 7.2 degrees as compared to only 0.8 degrees with PLF. The disc height similarly was significantly more impressive with on average 3 mm increases with PTLIF as compared to 1.4 mm with PLF. We also did not observe significant differences in global lumbar lordosis. In our analyses, a disc height of 8.5 mm is likely to result in 3° of segmental lordosis change with a PTLIF procedure. Hence, the traction radiograph is also a predictability tool for generating segmental lordosis.

There are several limitations to note for this study. Due to its study design, we were unable standardize the surgical team or the decision to utilize either PLF or PTLIF. However, it is important to note this study was conducted in a university unit with a standardized surgical strategy. In addition, we do not expect much variations in the prediction analyses as we were directly comparing the differences observed between flexion-extension and prone traction radiographs with the postoperative findings. It may be interesting to compare these findings in other centers with different surgical techniques. The degree of soft tissue release may impact the amount of disc height restoration and lordotic gains. It is nevertheless important to note that the results are based only on radiological parameters. There is only modest correlation between slip reduction and clinical outcomes.[35] Future clinical study comparing the clinical outcomes of the two surgical methods is needed to better understand its clinical implications.

Conclusions

Achieving reduction of the slip and restoration of disc height leads to good results from degenerative spondylolisthesis surgery. We have identified benefits of using prone traction radiographs in addition to flexion-extension radiographs for better examination of the degree of segmental instability especially in the vertical plane. The prone traction radiographs are also a predictive tool for the corrections achievable with PLF and PTLIF. The slip distance, slip angle and disc height changes match the postoperative changes well. Disc height of 8.5 mm or more warrants an interbody fusion to restore the anterior column deficiency where a gain of 3° in segmental lordosis is expected.

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Table 1: Radiographic measurements

Parameters	Preoperative standing lateral			Flexion			Extension			Prone traction			Postoperative standing lateral		
	Overall	PTLIF	PLF	Overall	PTLIF	PLF	Overall	PTLIF	PLF	Overall	PTLIF	PLF	Overall	PTLIF	PLF
Slip Distance (mm)	8.0 (4.4)	8.0 (4.7)	7.9 (3.8)	9.4 (4.4)	9.2 (4.6)	9.7 (4.2)	7.5 (4.6)	7.4 (4.6)	7.7 (4.5)	5.3 (3.2)	4.9 (2.8)	6.0 (3.8)	5.0 (3.1)	4.5 (2.5)	6.0 (4.0)
Slip Angle (degrees)	1.4 (8.1)	2.5 (8.9)	-0.7 (6.0)	5.5 (7.2)	6.9 (7.3)	2.7 (6.4)	-1.5 (7.2)	-1.0 (6.9)	-2.5 (7.9)	-3.9 (6.4)	-4.1 (7.3)	-3.5 (4.4)	-3.0 (5.4)	-4.0 (5.0)	-1.3 (5.7)
Disc Height (mm)	6.1 (2.7)	6.4 (2.7)	5.5 (2.6)	5.5 (2.6)	5.9 (2.6)	4.8 (2.5)	6.4 (2.7)	6.6 (2.5)	5.9 (2.9)	8.5 (2.7)	9.1 (2.4)	7.5 (3.0)	8.5 (2.6)	9.4 (2.0)	6.9 (2.9)
Global lordosis (degrees)	37.5 (17.2)	36.0 (17.2)	41.0 (17.1)							43.7 (12.0)	41.9 (12.5)	46.9 (10.8)	39.3 (14.8)	38.8 (15.7)	40.7 (13.3)
Segmental lordosis (degrees)	9.1 (9.2)	8.3 (9.3)	11.1 (8.4)							15.4 (9.2)	15.7 (10.6)	15.4 (6.2)	14.0 (8.0)	15.5 (8.5)	11.9 (6.3)

Measurements in mean (standard deviation)

mm: millimetres; PTLIF: posterolateral fusion and transforaminal interbody fusion; PLF: posterolateral fusion only

Table 2: (a) Difference between postoperative and preoperative slip distance, slip angle and disc height and their comparison across different types of radiographs and (b) comparison between postoperative and baseline, and between postoperative and prone traction global and segmental lordosis

	Lateral			Flexion			Extension			Prone traction		
	Median	Range	IQR	Median	Range	IQR	Median	Range	IQR	Median	Range	IQR
Difference between postoperative and baseline Slip Distance (mm)	-2.6	16.3	3.1	-4.3	14.2	3.4	-2.0	16.1	3.6	-0.5	8.4	2.4
Difference between postoperative and baseline Slip Angle (degrees)	-4.6	53.3	7.3	-8.0	37.3	7.9	-1.6	28.7	6.1	0.8	41.8	5.0
Difference between postoperative and baseline Disc Height (mm)	2.4	16.4	4.4	3.3	13.8	3.9	1.9	14.2	3.8	0.0	15.5	2.9
Global lordosis (degrees) - Preoperative - Postoperative	34.8 39.7	87.0 73.3	25.8 19.8									
Segmental lordosis (degrees) - Preoperative - Postoperative	8.6 12.1	49.1 34.3	10.2 8.8									
Global lordosis (degrees) - Prone traction - Postoperative										46.0 39.7	56.6 73.3	13.4 19.8
Segmental lordosis (degrees) - Prone traction - Postoperative										14.9 12.1	40.5 34.3	9.7 8.8

Comparison

Parameters	p-value^	Post-hoc analysis	p-value with Bonferroni correction
Difference between postoperative and baseline Slip Distance	<0.001*	Flexion vs lateral Flexion vs extension Flexion vs prone traction Lateral vs extension Lateral vs prone traction Extension vs prone traction	0.022* 0.001* <0.001* 1.000 <0.001* <0.001*
Difference between postoperative and baseline Slip Angle	<0.001*	Flexion vs lateral Flexion vs extension Flexion vs prone traction Lateral vs extension Lateral vs prone traction Extension vs prone traction	0.002* <0.001* <0.001* 0.105 <0.001* 0.021*
Difference between postoperative and baseline Disc Height	<0.001*	Flexion vs lateral	1.000

		Flexion vs extension Flexion vs prone traction Lateral vs extension Lateral vs prone traction Extension vs prone traction	0.500 <0.001* 1.000 <0.001* <0.001*
Postoperative vs baseline Global lordosis #	0.265	-	
Postoperative vs baseline Segmental lordosis #	<0.001*	-	
Postoperative vs prone traction Global lordosis #	0.002*	-	
Postoperative vs prone traction Segmental lordosis #	0.056	-	

^ Kruskal-Wallis H test, * statistical significance at $p < 0.05$, # Wilcoxon signed-rank test, - not applicable

SD: standard deviation, mm: millimetres, IQR: interquartile range

Table 3: Correlations of preoperative radiographic parameters with postoperative findings

Parameters	Preoperative lateral		Flexion		Extension		Prone traction	
	PTLIF	PLF	PTLIF	PLF	PTLIF	PLF	PTLIF	PLF
Slip Distance	0.791**	0.864**^	0.746**	0.855**^	0.706**	0.891**^	0.748**	0.905**
Slip Angle	0.598**	0.566*	0.479*	0.518*	0.657**	0.538*	0.602**	0.755**
Disc Height	0.349*	0.430*	0.218	0.497*	0.379*	0.726**	0.474*	0.688**
	Preoperative lateral						Prone traction	
	PTLIF	PLF					PTLIF	PLF
Global lordosis	0.788**	0.697**					0.662**	0.333
Segmental lordosis	0.662**	0.667**					0.794**	0.475*

Spearman's correlation tests with Rho coefficient; * $p<0.05$; ** $p<0.001$

PTLIF: posterolateral fusion and transforaminal interbody fusion; PLF: posterolateral fusion only

Table 4: Assessing predictors for surgical outcomes using regression models – non-linear regressions with best fit

Surgical outcomes	Predictors	Regression models with curve estimation					
		Type of curve	F	Standard error of the estimate of model	Error variance	AICc	p-value of the model
Slip Distance	Preoperative Extension - Flexion	Linear	1.676	2.836	8.041	67.570	0.200
		Quadratic	4.497	2.715	7.373	64.392	0.015*
		Cubic	4.934	2.633	6.934	62.004	0.004*
	Preoperative Extension - Lateral	Linear	4.865	2.773	7.689	-65.771	0.031*
		Quadratic	3.183	2.763	7.637	-65.984	0.048*
		Cubic	2.540	2.759	7.610	-66.094	0.064
	Preoperative Prone traction - Lateral	Linear	2.420	2.791	7.789	-65.367	0.124
		Quadratic	57.770	1.748	3.057	37.780	<0.001*
		Cubic	38.821	1.749	3.058	37.336	<0.001*
Slip Angle	Preoperative Extension - Flexion	Linear	5.675	6.960	48.435	123.718	0.020*
		Quadratic	3.948	6.903	47.646	122.741	0.024*
		Cubic	3.768	6.794	46.161	121.281	0.015*
	Preoperative Extension - Lateral	Linear	54.894	5.389	29.037	107.719	<0.001*
		Quadratic	34.733	5.114	26.149	103.980	<0.001*
		Cubic	22.966	5.143	26.453	103.872	<0.001*
	Preoperative Prone traction - Lateral	Linear	8.304	6.912	47.769	124.192	0.005*
		Quadratic	16.611	6.049	36.592	115.407	<0.001*
		Cubic	16.469	5.644	31.860	110.620	<0.001*
Disc Height	Preoperative Extension - Flexion	Linear	3.672	2.913	8.483	69.242	0.060
		Quadratic	2.078	2.923	8.544	69.005	0.133
		Cubic	1.729	2.922	8.541	68.520	0.170
	Preoperative Extension - Lateral	Linear	23.416	2.579	6.651	61.633	<0.001*
		Quadratic	11.762	2.592	6.716	61.477	<0.001*
		Cubic	8.020	2.598	6.751	61.167	<0.001*
	Preoperative Prone traction - Lateral	Linear	0.003	2.951	8.710	70.976	0.955
		Quadratic	16.894	2.436	5.932	58.514	<0.001*
		Cubic	11.555	2.437	5.939	58.096	<0.001*

* statistical significance at $p < 0.05$

F: overall F test, AIC: Akaike's Information Criterion, AICc: Corrected Akaike's Information Criterion

Figure legends

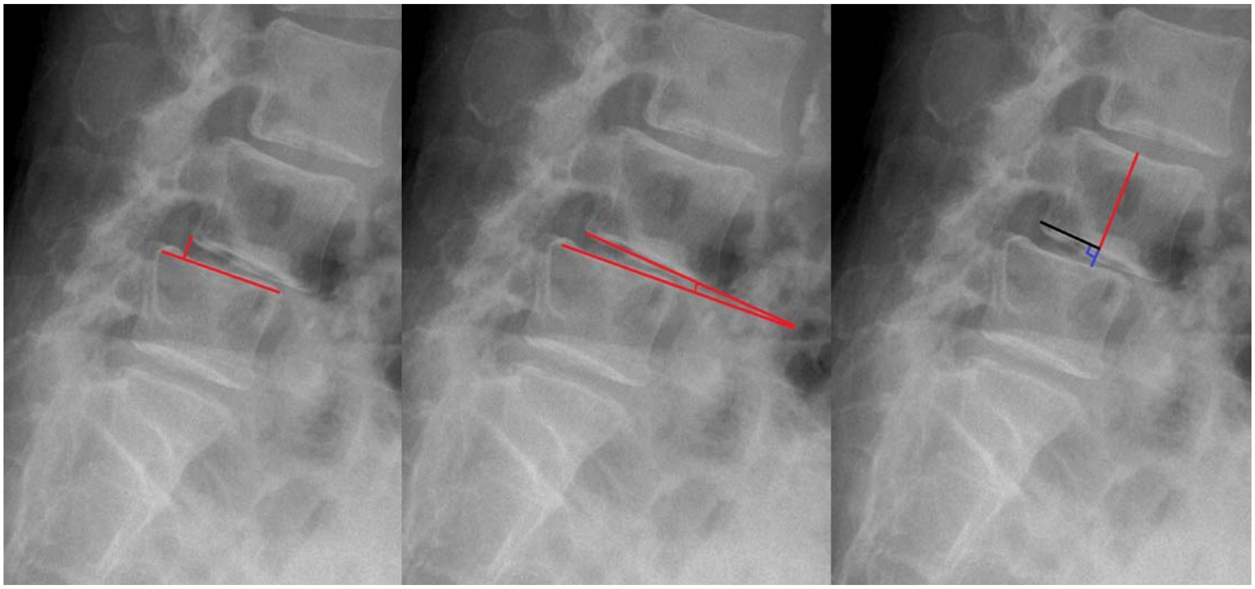

Figure 1: Illustrative diagram demonstrating the measurement of degree of slip (left), slip angle (middle) and disc height (right). For degree of slip, a line is dropped from the posterior border of the cranial vertebrae to the caudal vertebrae. The distance from this point to the posterior border of the caudal vertebrae was divided by the total vertebral body width of the caudal vertebrae. Slip angle is measured by the superior endplate of caudal vertebrae and inferior endplate of cranial vertebrae. Disc height is measured by a line dropped from the midline inferior endplate of the cranial vertebrae to the upper endplate of the caudal vertebrae.

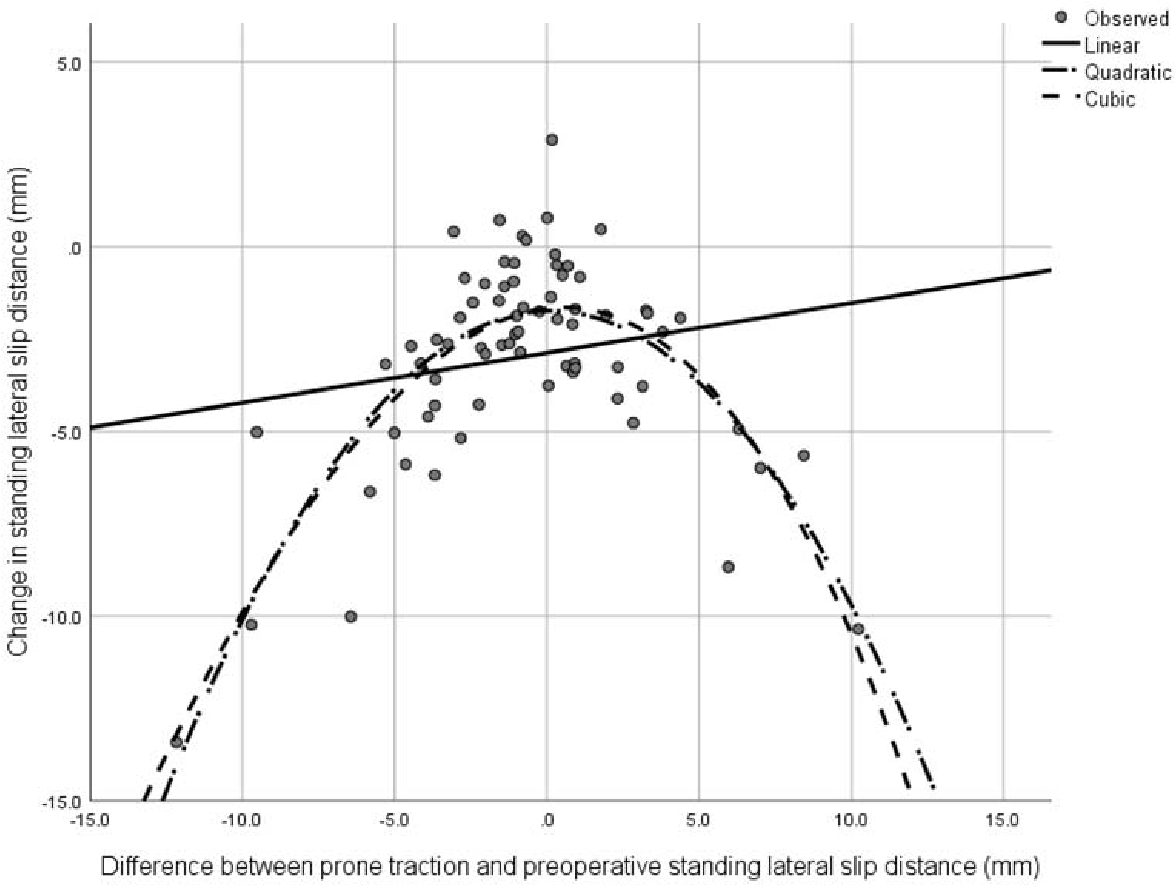

Figure 2: Non-linear regression identified a Cubic relationship between prone traction and postoperative standing lateral slip distance.

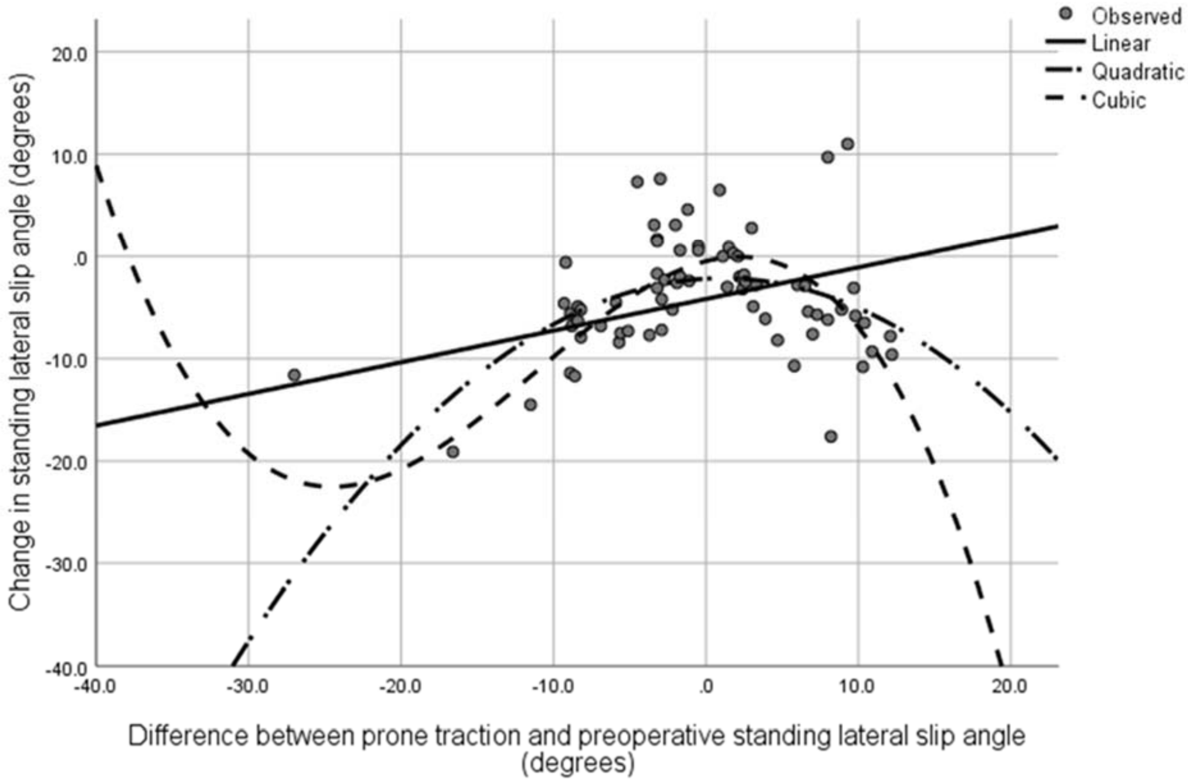

Figure 3: Non-linear regression identified a Cubic relationship between prone traction and postoperative standing lateral slip angle.

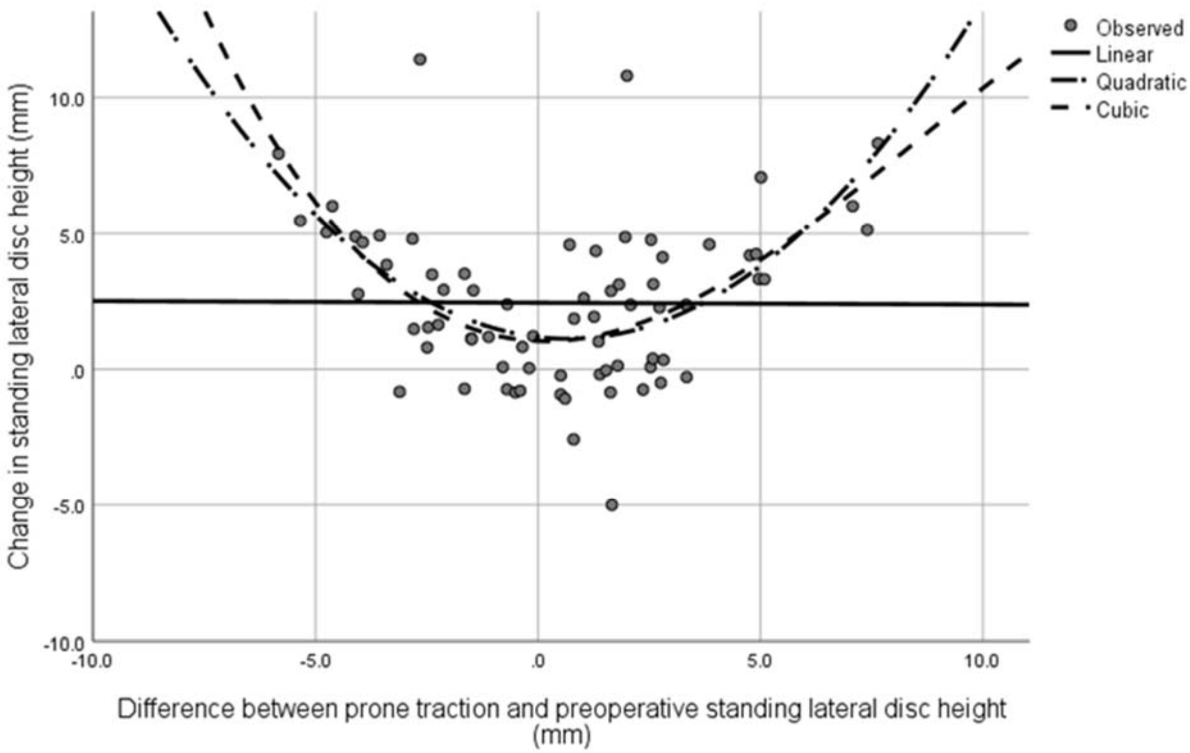

Figure 4: Non-linear regression identified a Cubic relationship between prone traction and postoperative standing lateral disc height.

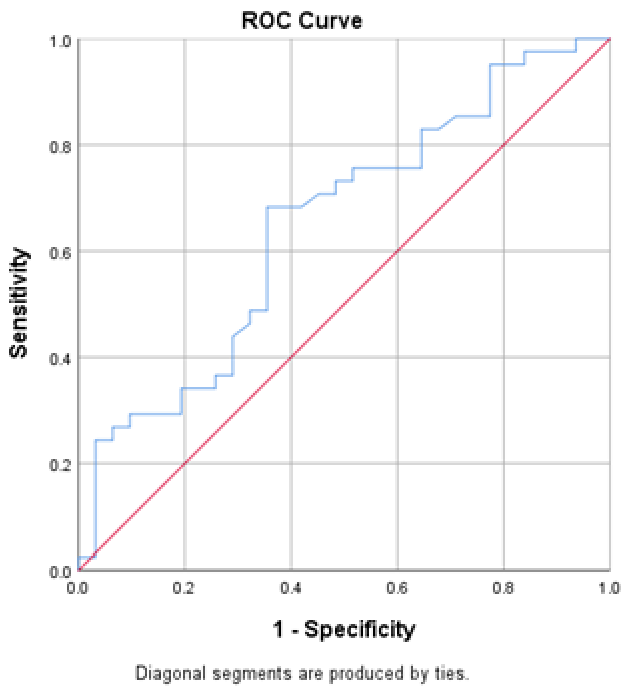

Figure 5: Receiver operating characteristic (ROC) curve illustrating the diagnostic ability of disc height on prone traction radiographs warranted an interbody fusion.

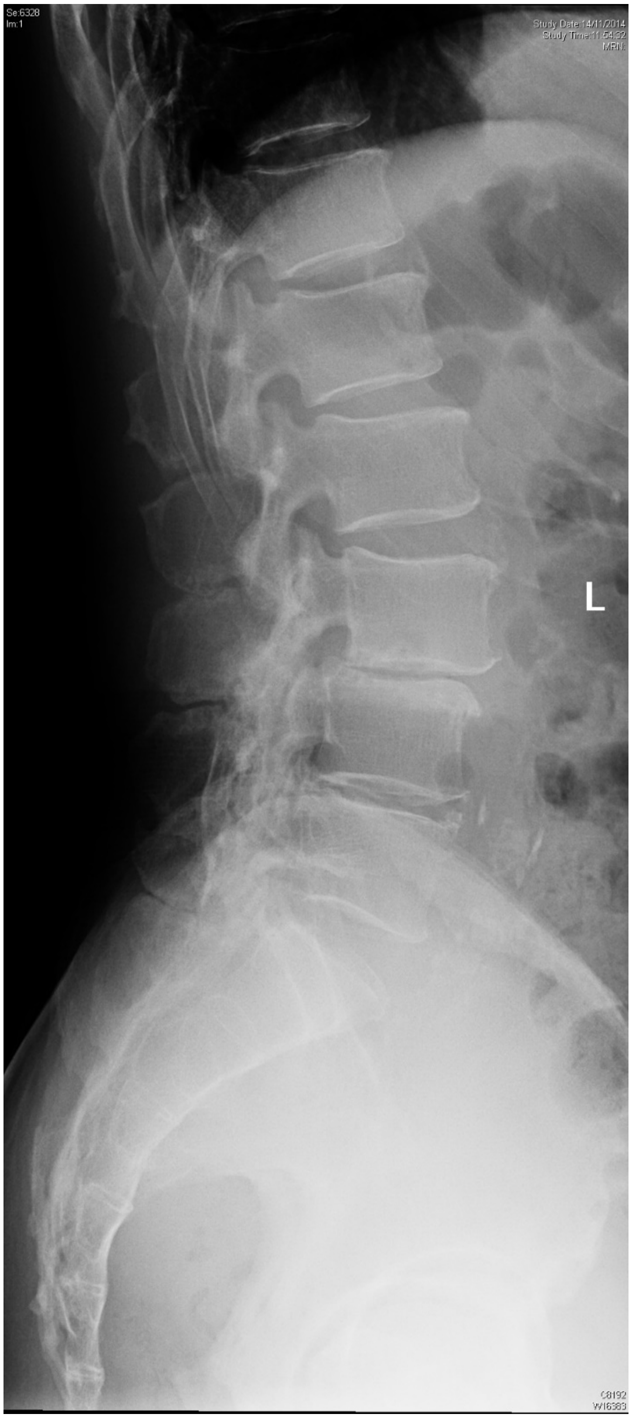

Fig 6a

Fig 6b

Figure 6: A 64-year-old female who underwent L3-4 posterolateral fusion only had a (A) preoperative lateral slip distance of 4.9 mm, slip angle of -2.1°, and disc height of 3.4 mm. The slip distance was 9.6 mm and 0.8 mm, slip angle was 5.8° and -10.1°, and disc height of 4.0 mm and 8.3 mm for flexion (B) and extension (C) radiographs respectively.

The prone traction (D) radiograph showed a slip distance of 1.3 mm, slip angle of -11.4° and disc height of 10.5 mm. Postoperatively (E), the slip distance was 2.4 mm, slip angle of -6.7° and disc height of 9.4 mm.

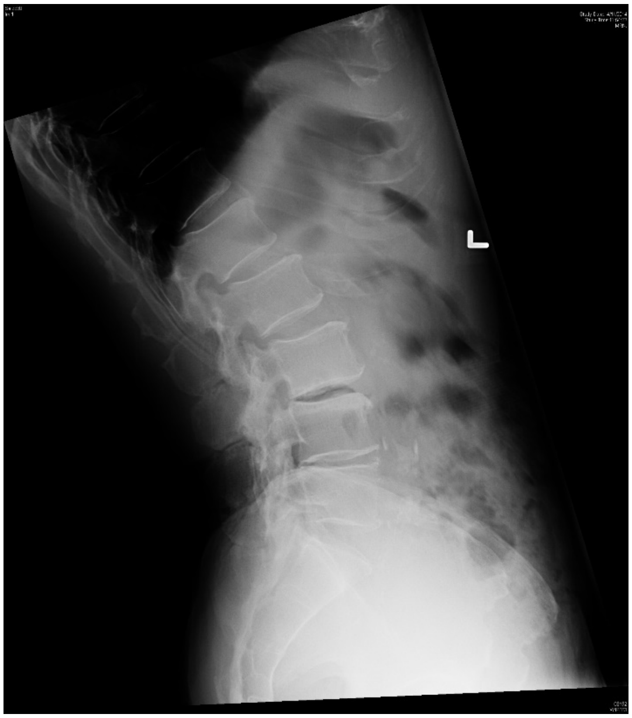

Fig 6c

Fig 6d

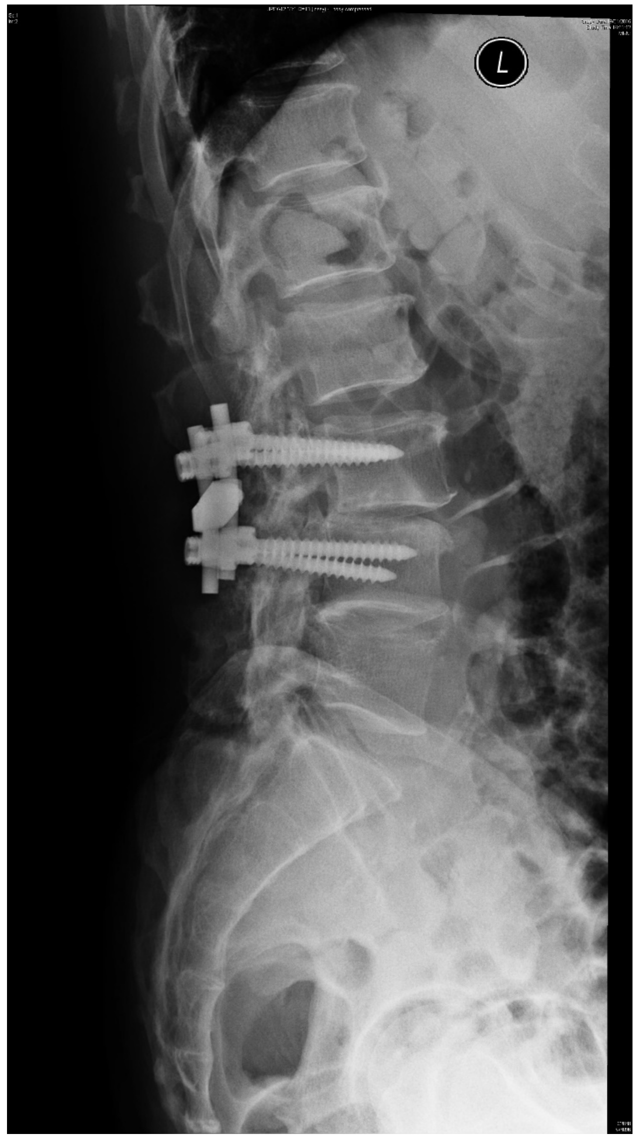

Fig 6e

Figure 7: A 75-year-old male who underwent L4-5 posterolateral fusion and transforaminal interbody fusion had a (A) preoperative lateral slip distance of 8.1 mm, slip angle of 3.7°, and disc height of 9.0 mm. The slip distance was 10.6 mm and 5.0 mm, slip angle was 1.1° and -6.6°, and disc height of 8.5 mm and 11.0 mm for flexion (B) and extension (C) radiographs respectively.

Fig 7a

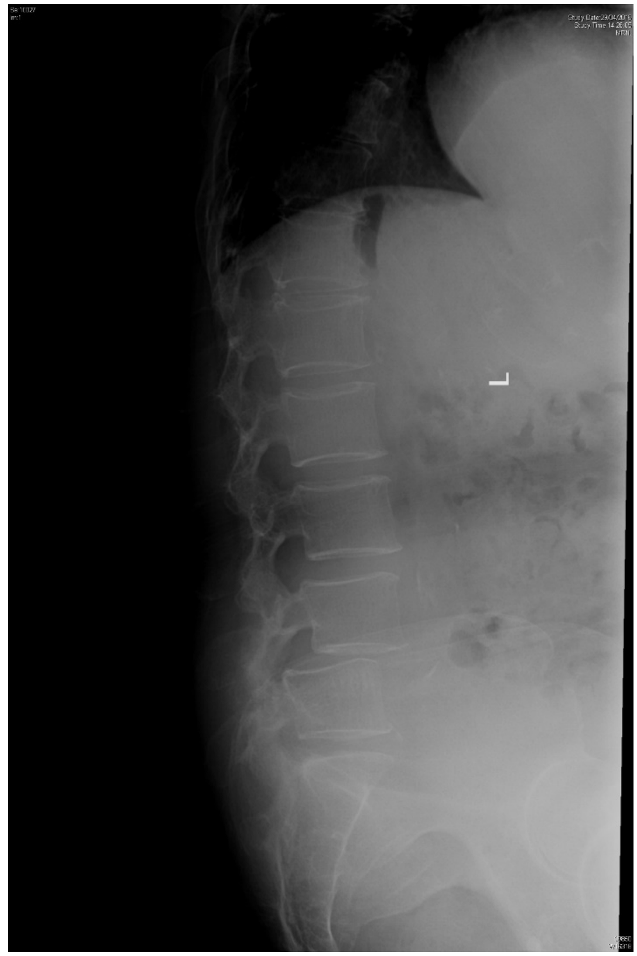

Fig 7b

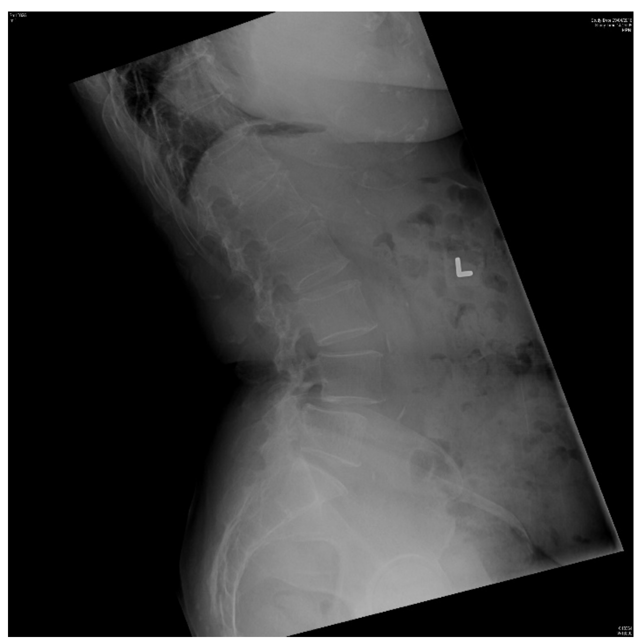

Fig 7c

Fig 7d

Fig 7e

The prone traction (D) radiograph showed a slip distance of 8.1 mm, slip angle of -7.2° and disc height of 9.8 mm. Postoperatively (E), the slip distance was 8.9 mm, slip angle of -5.6° and disc height of 9.1 mm.