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ORIGINAL RESEARCH

The Relationship Between MRI Findings of Posterior Ligamentous Complex and Lumbar Instability in Degenerative Spondylolisthesis

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Background: To determine the factors in posterior ligamentous complex indicating lumbar instability in patients diagnosed with degenerative spondylolisthesis on conventional magnetic resonance imaging (MRI).

Methods: We retrospectively analyzed patients who underwent PLIF surgery for degenerative spondylolisthesis at our institution between 2018 and 2020 and who had complete eligible preoperative imaging data for review and study, including lumbar MRI and anteroposterior and flexion-extension radiographs.

Results: Fifty-three patients were confirmed to have lumbar instability (Unstable Group, 44%), while sixty-seven patients (Stable Group, 56%) did not have instability on radiographs. The patients in the stable group had more advanced status of the degeneration of intervertebral disc than in the unstable group ($p<0.05$). The degeneration of supraspinous ligament (SSL) was more severe in the unstable group ($p<0.05$). Compared with the patients with rotatory instability, advanced degeneration of interspinous ligament (ISL) and SSL was observed in patients with translatory instability ($p<0.05$). However, there was no significant difference with regard to the height of the spinous process and the interspinous distance in patients with or without instability.

Conclusion: This MRI analysis showed that abnormal segmental motion is closely associated with the pathological characteristics of supraspinal ligament. Advanced degeneration of SSL in patients with degenerative spondylolisthesis should raise the suspicion for lumbar instability and additional evaluations. The status of ISL and ligamentum flavum (LF) may not be helpful for the diagnosis of lumbar instability. Functional radiographs combined with MRI may provide valuable information when diagnosing lumbar instability in patients with mechanical back pain.

Keywords: interspinous distance, lumbar instability, MRI, posterior ligament complex, spinal process

Background

Lumbar spondylolisthesis is commonly observed in patients with lumbar degeneration, resulting in low back pain. Although some patients can have symptom relief through conservative treatment, surgery is the final approach for patients who fail conservative management strategies. However, there still exists controversy regarding the optimal strategy for patients with spondylolisthesis. Fusion or not should be considered according to the stability of the spine.[1–3] Despite the debate on the definition of lumbar instability, it is mostly accepted as an abnormal response to applied loads characterized kinematically by abnormal movement in the motion segment beyond normal constraints, which may be explained by damaged or lax restraining structures.[4] This excessive movement may suggest abnormalities in spinal mechanics and may be involved in the cause of certain types of LBP.

Previous studies have demonstrated that the posterior column plays a significant role in maintaining the stability of the spine. The posterior ligamentous complex (PLC), which protects the spine from excessive translation, rotation, flexion, and distraction, is composed of the facet joint capsules (FC), interspinous ligament (ISL), supraspinous ligament

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(SSL), and ligamentum flavum (LF).[5] Ligament structure has been reported to degenerate as early as the late second decade and rupture in more than 20% of the subjects older than 20 years, particularly at L4–L5 and L5–S1.[6] The impotence of ligamentous structures has been well studied in literature when defining spinal stability in traumatic cases. However, the pathologic appearance of each PLC component has not been described in detail in lumbar degenerative diseases. There have been reports that the height of the spinous process and the interspinous distance correlated with age.[7,8] It was suggested that enlarged spinous process and narrowed interspinous distance occurred secondary to the disc degeneration, resulting in the prevention of the hyperextension of the spine and the increase of spinal stiffness and stability. As the two parameters are usually used in the assessment of spinal injury or postoperative graft collapse and pseudoarthrosis, we hope to extend their application to the diagnosis of lumbar instability.

Spinal ligaments do not show up well on plain X-rays or computed tomography (CT) scans. It has been demonstrated in numerous studies that magnetic resonance imaging (MRI) has the ability to depict soft tissues directly, including the spinal ligaments. The purpose of the present study was to investigate the factors in posterior ligamentous complex seen on conventional MR images that are indicative of lumbar segmental instability.

Methods

Patient Population

We retrospectively analyzed patients who were diagnosed with lumbar spondylolisthesis and underwent PLIF surgery, with or without fusion, at our institution from January 2018 to December 2020. Our exclusion criteria include: 1. Multi-segmental lesions 2. Combined with other spinal diseases (infection, tumor, tuberculosis, trauma, etc.), patients with previous lumbar surgery history are also excluded 3. Imaging data with poor image quality (Not all spinous processes can be fully displayed on the sagittal plane in MR). All the patients were informed of their inclusion in the study, which followed the Declaration of Helsinki principles.

Functional Lateral Radiographs and Magnetic Resonance Imaging

The simple standing plain radiographs were analyzed, including anteroposterior and functional lateral radiographs. Two segmental motions (translation and angulation) were measured at each lumbar level. On the lateral flexion and extension standing radiographs, translation greater than 3 mm was considered to show translatory instability, and changes in angulation greater than 9° was considered as rotatory instability (Figure 1). Using these criteria, patients were divided into stable and unstable groups. The MR images were acquired on a 3.0-tesla system using turbo spin-echo pulsed sequences, boosted with T1-weighted and T2-weighted fat suppression on sagittal and axial planes. Patients were placed in the supine position during the process.

Disc degeneration was divided into 5 grades according to Pfirrmann's criteria.[9] Grade I corresponded to normal discs and Grade V indicated advanced disc degeneration. The components of the posterior ligament complex were classified into a 4-grade category according to the modified Fujiwara's criteria described by Kong.[10] Type 1 (low intensity on both T1- and T2-weighted images without hypertrophy of the spinous process); Type 2 (low intensity on T1-weighted and high intensity on T2-weighted images); Type 3 (high intensity on T1- and intermediate to high intensity on T2-weighted images); and Type 4 (low intensity on both T1- and T2-weighted images with hypertrophy of the spinous process, mixed-signal or same signal pattern) (Figure 2). To quantify the degree of disc and ligament degeneration, we performed points according to grade and type. To measure the height of the spinous process, a line parallel to the posterior wall of the vertebral body was drawn first and the maximum length among all the slice lengths was obtained[7] (Figure 1). The interspinous distance was defined as the distance between midpoints of the spinous processes[8] (Figure 1).

Data Analysis

Two well-trained orthopedic surgeons, who were blinded to clinical information, each measured the various parameters twice, with the second measurement performed 2 weeks after the first measurement. Statistical analysis was performed using IBM SPSS Statistics 27.0 (IBM Corp.,Armonk,NY,USA). The *t*-test was used for a comparison of means, while the $\chi 2$ test was used for analyzing categorical variable data. Statistical significance was set at probability values <0.05.

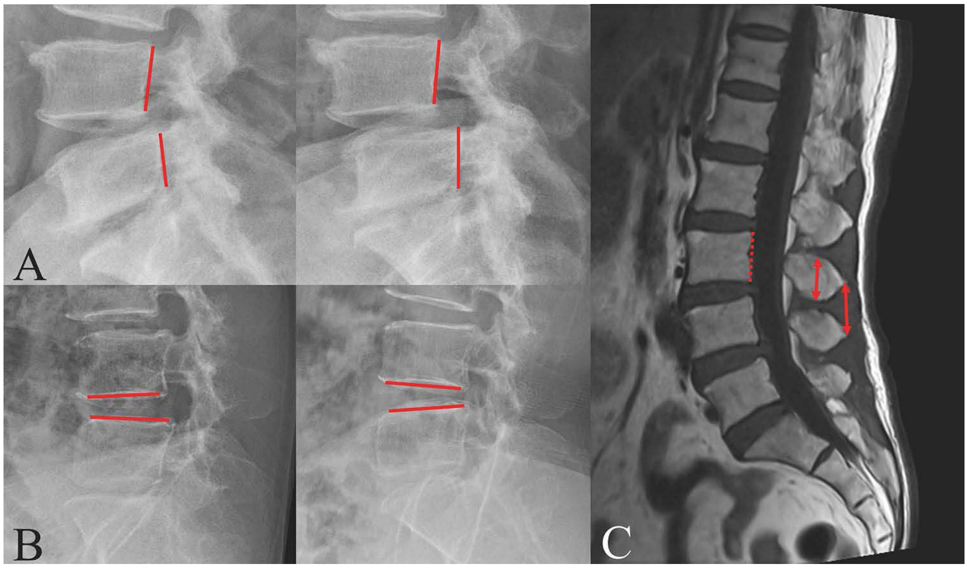

Figure 1 Functional lateral radiographs and magnetic resonance imaging. (**A** and **B**). Translation greater than 3 mm or changes in angulation greater than 9° subtended between solid lines on the lateral flexion and extension standing radiographs were considered to show segmental instability. C. To measure the height of the spinous process (anterior arrow), a line parallel to the posterior wall of the vertebral body (dotted line) was drawn first and the maximum length among all the slice lengths was obtained. Inter-spinous process distance (posterior arrow) was defined as the distance between midpoints of the spinous processes.

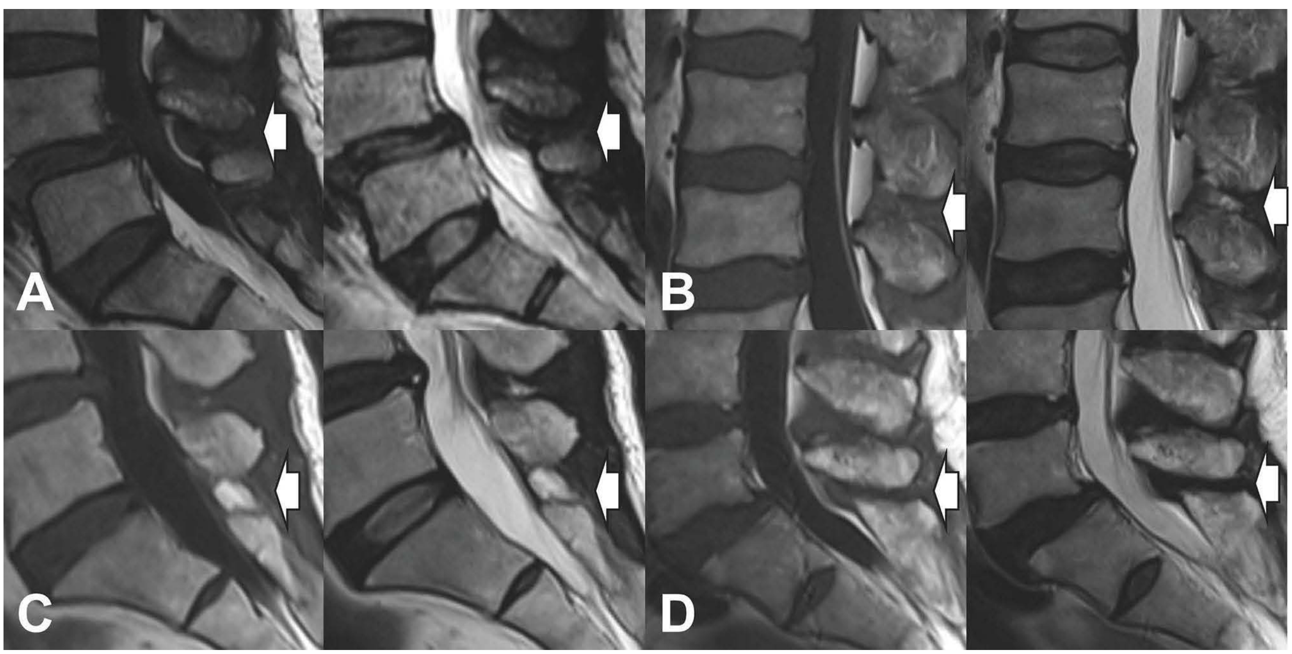

Figure 2 The components of the posterior ligament complex (white arrow) were classified into a 4-grade category according to the modified Fujiwara's criteria described by Kong. (**A**). Type 1 (low intensity on both T1- and T2-weighted images without hypertrophy of the spinous process); (**B**). Type 2 (low intensity on T1-weighted and high intensity on T2-weighted images); (**C**). Type 3 (high intensity on T1- and intermediate to high intensity on T2-weighted images); (**D**). Type 4 (low intensity on both T1- and T2-weighted images with hypertrophy of the spinous process, mixed signal or same signal pattern).

Results

Demographic results

The demographic data of patients are shown in Table 1. There were 67 patients (55.8%) in the stable groups and 53 patients (44.2%) in the unstable groups. The average age was 62.60±8.68 years in the stable group and 60.92±8.45 years

Table 1 Demographic Data of 2 Groups. BMI, Body Mass Index

Demographic Data	Total	Stable Group	Unstable Group	P value
Cases(n)	120(100%)	67(56%)	53(44%)	
Age(years)	61.86±8. 59	62.60±8.68	60.92±8.45	0.291
Gender(male/female)	51/69	29/38	22/31	0.845
Height(m)	1.63±0.08	1.63±0.86	1.63±0.78	0.935
Weight(kg)	64.40±9.78	64.67±9.99	64.06±9.60	0.735
BMI(kg/m²)	24.21±2.87	24.30±2.91	24.11±2.85	0.722

in the unstable group. The mean BMI was 24.21±2.87 and 24.30±2.91 kg/m^2, respectively. And there was no statistically difference in the gender composition between the two groups (P>0.05).

Comparative results of Functional Radiographs in Patients

There were 18 patients with translatory instability in the unstable group, with an average distance of 4.49 ± 1.35mm. And there were 34 patients with rotatory instability in the unstable group, with an average angulation of 11.35±2.57°. The most commonly involved level was L4/5 (75 cases, 62.5%), followed by L5/S1 (33 cases, 27.5%), L3/4 (10 cases, 8.3%), L2/3 (2 cases, 1.7%). Excessive translatory motion was most prevalent in patients between 60 and 69 years of age (18.5%). Excessive rotatory motion was most prevalent in the youngest age group (57.1%) and those 50–59 years of age (36.1%) compared to all other age groups (Table 2).

Comparative Results of Magnetic Resonance Imaging in Patients

The mean disc degeneration grade according to the Pfirrmann's grade system was 3.73±0.83 in the stable group and 3.43 ±0.75 in the unstable group (p<0.05). In the lesion segment, the mean degenerative degree of SSL increased significantly in the unstable group than in the stable group (p<0.05). In terms of ISL and FL, no significant difference was observed between the 2 groups (p>0.05) (Table 3). Patients with translatory motion were shown to have advanced degeneration of ISL and SSL compared with patients with rotatory motion (p<0.05). Although not statistically significant, degeneration of ligaments was also more severe in patients with translatory motion than in patients with rotatory motion (Table 4). The heights of the spinous process were increased in the unstable group. Similarly, the interspinous distance increased in the unstable group. However, there was no significant difference between the 2 groups (P > 0.05) (Table 5).

Discussion

Lumbar spondylolisthesis is a degenerative disease that affects the elderly frequently, which is becoming more common in the aging society. Intervertebral fusion is the classic surgical approach for spondylolisthesis, and performing lumbar fusion in patients without lumbar instability may expand the scope of indications for surgery. Therefore, a clear judgment of lumbar instability has important clinical significance for the selection of surgical methods.

Table 2 Abnormal Segmental Motion Stratified by Patient Age

Age(yrs)	Num of Segments	Abnormal segmental motion	
		Translatory Motion	Rotatory Motion
<50	7	0	4(57.1%)
50–59	36	5(13.9%)	13(36.1%)
60–69	54	10(18.5%)	14(25.9%)
>70	23	4(17.4%)	4(17.4%)
Total	120	19(15.8%)	35(29.2%)

Table 3 Comparative Results of MRI Findings in Patients with or Without Lumbar Instability

	Stable Group	Unstable group	P value
Disc degeneration (1–5 point)	3.73±0.83	3.43±0.75	0.044*
Lesion segment(1–4 point)			
ISL	2.66±1.15	2.66±1.14	0.986
SSL	2.37±1.09	2.96±1.11	0.004*
FL	2.33±1.43	1.96±1.37	0.159
Superior segment(1–4 point)			
ISL	2.10±1.25	1.96±1.16	0.523
SSL	2.33±1.27	2.00±1.19	0.152
FL	1.57±1.09	1.40±0.97	0.372
Inferior segment(1–4 point)			
ISL	2.54±0.96	2.49±0.93	0.784
SSL	2.07±1.06	2.12±1.14	0.811
FL	1.96±1.13	1.80±1.10	0.530

Note: *Statistically significant difference (P < 0.05).

Table 4 Comparative Results of MRI Findings in Different Types of Motion

	Translatory motion	Rotatory motion	P value
Disc degeneration (1–5 point)	3.61±0.78	3.34±0.73	0.219
Lesion segment(1–4 point)			
ISL	3.17±1.04	2.4±1.12	0.019*
SSL	3.33±0.77	2.77±1.22	0.045*
FL	2.17±1.51	1.86±1.31	0.442
Superior segment(1–4 point)			
ISL	2.33±1.37	1.77±1.00	0.136
SSL	2.39±1.20	1.80±1.16	0.089
FL	1.78±1.31	1.20±0.68	0.093
Inferior segment(1–4 point)			
ISL	2.67±0.90	2.38±0.94	0.354
SSL	2.33±1.18	2.00±1.13	0.376
FL	2.13±1.13	1.62±1.06	0.149

Note: *Statistically significant difference (P < 0.05).

Although different scholars have put forward different definitions, what they have in common is the loss of the ability to control abnormal activities under physiological loads. This instability means that the spine cannot achieve the function of protecting the neural structure, which will lead to further damage, resulting in corresponding clinical manifestations. Lumbar instability usually presents with symptoms such as LBP, sciatica, and lumbar postoperative syndrome, which can be exacerbated by exercise and prolonged sitting. Weiler et al reported that lumbar instability could be diagnosed in approximately 20–30% of patients with low back pain.[11] However, low back pain is not suitable for the diagnosis because of its extremely low specificity, as several completely different lumbar lesions yield the same symptom, which makes imaging examination crucial.

Table 5 Height of Spinous Process and Interspinous Distance Between Two Groups

Height of Spinous Process and Interspinous Distance	Size Range (mm)	Mean Size (mm)		P value
		Stable Group	Unstable group	
Height of Spinous process				
Lesion segment	10.40–28.44	19.16±3.36	19.29±3.49	0.845
Superior segment	13.59–32.81	20.84±3.23	21.32±3.46	0.436
Inferior segment	5.25–27.71	16.33±3.96	16.76±3.87	0.617
Interspinous Distance				
Lesion segment	1.46–12.19	4.95±1.65	5.33±2.32	0.290
Superior segment	2.27–11.82	5.58±1.56	5.91±1.98	0.315
Inferior segment	2.23–17.48	6.30±2.85	6.78±2.93	0.437

Knuttson first proposed to diagnose lumbar instability by measuring the sagittal plane displacement and rotation of the corresponding segmental vertebral body on the functional flexion-extension lateral film in 1944.[12] Because of its simplicity, low expense and wide availability, the functional lateral radiograph is the most thoroughly studied and the most widely used method in disclosing abnormal vertebral motion before deciding on surgical fusion. However, more abnormal motions were observed with patients in the lateral decubitus position compared with the standing position. One possible explanation for this phenomenon could be the splinting effect from the paraspinal postural or abdominal musculature may reduce the spine's range of motion when the patient is standing. Pain may also inhibit muscle function in symptomatic patients, resulting in an underestimation of spinal mobility. Besides, it is difficult to determine the cutoff between normal and abnormal motion due to the great variation in normal and symptomatic patients. Dvorák et al once reported that sagittal rotation may be as high as 25° in healthy young volunteers.[13] The magnification effect of X-ray imaging, the quality of the radiograph, and the compound shift of multiple axes may affect the diagnostic accuracy of the lateral view to varying degrees. Therefore, some may consider functional radiographs as a rough and imprecise method in the diagnosis of lumbar instability.

Magnetic resonance imaging can be a powerful tool in the assessment of disc and soft tissue degeneration. Fujiwara et al found that ISL could have different MR manifestations and corresponding histological manifestations in lumbar degenerative changes. Type 2 MRI findings can be found in 47% of lumbar instability, which could be histologically recognized with massive proliferation of blood vessels and cells.[14] Although it has been argued that MRI can only obtain static images in a horizontal non-weight-bearing position, making it impossible to see the cause of the problem, we still believe that the pathological changes seen on MRI can assist in the diagnosis of lumbar instability.

In our study, the grade of degeneration of SSL was significantly higher in the unstable group than in the stable group, which may be related to its anatomy and function. Interspinous–supraspinous ligament complex was determined to contribute approximately 19% of the passive spinal bending moment at full flexion and was the first to sprain beyond the limit of flexion.[15] The dorsal layer of the interspinous ligament, which weaves into the supraspinous ligament as it inserts into the spinous process, is the least elastic. Although they are farthest from the center of rotation, edema and injury tend to start at the posterosuperior corner of the interspinous-supraspinous ligament.[16] It has also been found that the resection of the SSL ligament leads to the most obvious increase in the ROM and IAR movement (the shift of the IAR) during the flexion process of the spine.[17] Our results showed that patients with translatory instability correlated with advanced degeneration of ISL and SSL, though not statistically significant. In patients with rotatory instability, the multifidus muscles at the lesion level as well as adjacent levels might play a significant role in assisting stabilizing the spine, when triggered in response to sensory inputs from mechanoreceptors in SSL.

We also found that the degree of disc degeneration was higher in the stable group than in the unstable group, which is consistent with previous studies.[18] Together with the increased height of the spinous process, it may be due to the collapse of the intervertebral space and the formation of enthesopathy spurs which reform a new stable state in the late stage of instability. Besides, we noticed an increase in the interspinous distance in the unstable group. As demonstrated in previous studies, large interspinous distance indicates segmental kyphosis unless anatomical variation exists.[8] However, we did not measure parameters of sagittal balance in this research, which should be performed in future studies. Although it was presumed that degenerative changes in the intervertebral discs and interspinous ligaments seemed to be concurrent and not consecutive in time,[4] the interspinous ligament and ligamentum flavum did not show significant differences between the two groups in our study. These findings suggest that the interspinous ligament makes very little contribution to the clinical stability of the lumbar spine in the adult.

The stability of the spine as a whole is maintained through the interaction of the components of the functional spine unit (FSU), which consists of two adjacent vertebrae, the intervertebral disc and all adjacent ligaments between them. In the range of physiological activities, the FSU is always in the "neutral zone" of the load–displacement curve.[19] Although the osteoligamentous stability mechanisms exert little or no influence for the smallest internal resistance in this zone, degeneration of intervertebral discs and ligaments can affect the stability of the lumbar spine. Instability may in turn lead to chronic inflammation and small vessel proliferation in the posterior ligament complex during chronic lumbar degeneration. PLC is usually used in the TLICS score to stratify the stability of spinal fractures, but we believe that PLC also has certain diagnostic significance in chronic lumbar instability.

Previous studies have also attempted to evaluate lumbar instability by grading facet joint degeneration.[18,20] The degeneration of the facet joints tends to lead to anterior subluxation on the view of lateral X-ray in physiological weight-bearing flexion. When performing MR examinations in the supine position, the spine is unloaded and has a tendency to reset backward, thus creating a gap in the degenerated facet joint. Rihn et al showed a linear relationship between facet joint effusion index and lumbar instability.[21] However, there are also studies suggesting that degeneration of facet joints may be delayed by 20 years compared with degeneration of intervertebral discs.[20] Therefore, we believe that an earlier and more reliable observation item may be needed to judge lumbar instability.

With the deepening of the understanding of the relationship between lumbar instability and degenerative spondylolisthesis, Kirkaldy-Willis and Farfan proposed three clinical and biomechanical stages in a functional sense: temporary dysfunction, unstable phase, and stabilization.[22] In the third or stable phase, osteophytes and marked intervertebral space narrowing lead to the reduction in the range of motion and stabilization of the motion segment, sometimes after the occurrence of spondylolisthesis. Degenerative spondylolisthesis seen radiographically at this time does not necessarily present lumbar instability, as new stabilization has been established. However, most surgeons still seem to believe in their usefulness and use them to judge whether there is instability. The requirement of stability is essential to the spinal column to prevent premature mechanical and biological deterioration of its components. It is also fundamental to protect the spinal cord and nerve roots and to minimize energy expenditure.

This study had its limitations. Firstly, it was a retrospective comparative study. Secondly, the sample size was relatively insufficient. Thirdly, the research did not study other relevant variables and factors. Therefore, a prospective randomized controlled study and a long-term follow-up with a large sample size are badly needed to analyze different parameters of lumbar instability in patients with degenerative spondylolisthesis.

Conclusions

Advanced degeneration of SSL in patients with degenerative spondylolisthesis should raise suspicion for lumbar instability and additional evaluations such as functional radiographs. The status of ISL and LF may not be helpful for the diagnosis of lumbar instability.

List of Abbreviations

MRI, magnetic resonance imaging; PLC, posterior ligamentous complex; ISL, interspinous ligament; SSL, supraspinous ligament; LF, ligamentum flavum.

Data Sharing Statement

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

Ethics Approval and Consent to Participate

This study was approved by the Medical Research Ethics Committee of the First Affiliated Hospital of Soochow University. This research was conducted in full compliance with the codes of ethical conduct from the Declaration of Helsinki. Written informed consent was obtained from the patients before they were enrolled in the study.

Author Contributions

Yixue huang, Wenhao Wang and Zihao Zhan wrote the main manuscript text. Yun Teng and Zihao Zhan collected the data. Peng Yang and Huilin Yang came up with the conception and designed the study. Peng Yang revised the manuscript. All authors reviewed the manuscript. All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

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Disclosure

The authors declare that they have no competing interests in this work.

References

1. Bridwell KH, Sedgewick TA, O'Brien MF, Lenke LG, Baldus C. The role of fusion and instrumentation in the treatment of degenerative spondylolisthesis with spinal stenosis. *J Spinal Disord*. 1993;6(6):461–472. doi:10.1097/00002517-199306060-00001
2. Herkowitz HN. Spine update. Degenerative lumbar spondylolisthesis. *Spine*. 1995;20(9):1084–1090. doi:10.1097/00007632-199505000-00018
3. Vibert BT, Sliva CD, Herkowitz HN. Treatment of instability and spondylolisthesis: surgical versus nonsurgical treatment. *Clin Orthop Relat Res*. 2006;443:222–227. doi:10.1097/01.blo.0000200233.99436.ea
4. Leone A, Guglielmi G, Cassar-Pullicino VN, Bonomo L. Lumbar intervertebral instability: a review. *Radiology*. 2007;245(1):62–77. doi:10.1148/radiol.2451051359
5. Chen JX, Goswami A, Xu DL, et al. The radiologic assessment of posterior ligamentous complex injury in patients with thoracolumbar fracture. *Eur Spine J*. 2017;26(5):1454–1462. doi:10.1007/s00586-016-4687-x
6. Newman PH. Sprung back. *J Bone Joint Surg Br*. 1952;34-B(1):30–37. doi:10.1302/0301-620X.34B1.30
7. Paholpak P, Wang Z, Sakakibara T, Kasai Y. An increase in height of spinous process is associated with decreased heights of intervertebral disc and vertebral body in the degenerative process of lumbar spine. *Eur Spine J*. 2013;22(9):2030–2034. doi:10.1007/s00586-013-2764-y
8. Shimizu T, Pongmanee S, Riew KD. Inter-spinous process distance: a novel parameter predicting segmental lordosis during posterior cervical spine deformity surgery. *Eur Spine J*. 2019;28(5):1192–1199. doi:10.1007/s00586-019-05922-5
9. Pfirrmann CW, Metzdorf A, Zanetti M, Hodler J, Boos N. Magnetic resonance classification of lumbar intervertebral disc degeneration. *Spine*. 2001;26(17):1873–1878. doi:10.1097/00007632-200109010-00011
10. Kong MH, Hymanson HJ, Song KY, et al. Kinetic magnetic resonance imaging analysis of abnormal segmental motion of the functional spine unit. *J Neurosurg Spine*. 2009;10(4):357–365. doi:10.3171/2008.12.SPINE08321
11. Weiler PJ, King GJ, Gertzbein SD. Analysis of sagittal plane instability of the lumbar spine in vivo. *Spine*. 1990;15(12):1300–1306. doi:10.1097/00007632-199012000-00012
12. Knutsson F. The instability associated with disk degeneration in the lumbar spine. *Acta Radiol*. 1944;25(5–6):593–609. doi:10.3109/00016924409136488
13. Dvorak J, Panjabi MM, Chang DG, Theiler R, Grob D. Functional radiographic diagnosis of the lumbar spine. Flexion-extension and lateral bending. *Spine*. 1991;16(5):562–571. doi:10.1097/00007632-199105000-00014
14. Fujiwara A, Tamai K, An HS, Shimizu K, Yoshida H, Saotome K. The interspinous ligament of the lumbar spine. Magnetic resonance images and their clinical significance. *Spine*. 2000;25(3):358–363. doi:10.1097/00007632-200002010-00017
15. Adams MA, Hutton WC, Stott JR. The resistance to flexion of the lumbar intervertebral joint. *Spine*. 1980;5(3):245–253. doi:10.1097/00007632-198005000-00007
16. Pizones J, Izquierdo E, Sanchez-Mariscal F, Zuniga L, Alvarez P, Gomez-Rice A. Sequential damage assessment of the different components of the posterior ligamentous complex after magnetic resonance imaging interpretation: prospective study 74 traumatic fractures. *Spine*. 2012;37(11):E662–7. doi:10.1097/BRS.0b013e3182422b2b
17. Wu CC, Jin HM, Yan YZ, et al. Biomechanical Role of the Thoracolumbar Ligaments of the Posterior Ligamentous Complex: a Finite Element Study. *World Neurosurg*. 2018;112:e125–e33. doi:10.1016/j.wneu.2017.12.171
18. Cho IY, Park SY, Park JH, Suh SW, Lee SH. MRI findings of lumbar spine instability in degenerative spondylolisthesis. *J Orthop Surg*. 2017;25(2):2309499017718907. doi:10.1177/2309499017718907
19. Panjabi MM. The stabilizing system of the spine. part II. neutral zone and instability hypothesis. *J Spinal Disord*. 1992;5(4):390–6 discussion 7. doi:10.1097/00002517-199212000-00002

20. Fujiwara A, Tamai K, Yamato M, et al. The relationship between facet joint osteoarthritis and disc degeneration of the lumbar spine: an MRI study. *Eur Spine J*. 1999;8(5):396–401. doi:10.1007/s005860050193
21. Rihn JA, Lee JY, Khan M, et al. Does lumbar facet fluid detected on magnetic resonance imaging correlate with radiographic instability in patients with degenerative lumbar disease? *Spine*. 2007;32(14):1555–1560. doi:10.1097/BRS.0b013e318067dc55
22. Kirkaldy-Willis WH, Farfan HF. Instability of the lumbar spine. *Clin Orthop Relat Res*. 1982;165:110–123. PMID: 6210480.