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Original Article

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Different Degeneration Patterns of Paraspinal Muscles Between Double-Level and Single-Level Lumbar Spondylolisthesis: An Magnetic Resonance Imaging Analysis of 140 Patients

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Objective: To evaluate the degeneration patterns of paraspinal muscles in double-level degenerative lumbar spondylolisthesis (dl-DLS) versus single-level degenerative lumbar spondylolisthesis (sl-DLS).
Methods: A total of 67 dl-DLS and 73 sl-DLS patients were included. Multifidus (MF), erector spinae (ES), and psoas major (PM)'s fatty infiltration (FI) and relative cross-sectional area (rCSA) were measured. Sagittal parameters such as lumbar lordosis (LL), sagittal vertical axis (SVA), pelvic incidence (PI), pelvic tilt (PT), sacral slope (SS) were also assessed. Comparisons and correlation analysis were performed between the 2 groups.
Results: MF atrophy is worse in dl-DLS patients from L3–4 to L5–S1, with higher FI from L1–2 to L5–S1 compared to sl-DLS patients. ES atrophy and FI are more pronounced in dl-DLS patients from L1–2 to L5–S1. PM atrophy is more significant in dl-DLS patients at L2–3 to L5–S1, with heavier FI from L1–2 to L3–4, though no difference in FI from L4–5 to L5–S1. The rCSA and FI of MF and ES show significant differences between adjacent segments in both groups, except for MF rCSA between L3–4 and L4–5 in dl-DLS. In dl-DLS, PM rCSA negatively correlates with PT from L4–5 to L2–3, while FI of MF and ES in L5–S1 positively correlates with LL. In sl-DLS, PM FI in L4–5 and L5–S1 negatively correlates with LL.
Conclusion: Degeneration of MF, ES, and PM is more severe in dl-DLS patients, particularly at the spondylolisthesis level. Severe paraspinal muscle degeneration can lead to spinal force imbalance and progression from sl-DLS to dl-DLS. The degradation of PM and ES correlates negatively with PT and SVA, indicating a link to pelvic decompensation and SVA abnormalities, potentially causing disproportionate degenerative changes in dl-DLS patients.

Keywords: Paraspinal muscle, Double-level degenerative lumbar spondylolisthesis, Relative cross-sectional area, Fatty infiltration

INTRODUCTION

Degenerative lumbar spondylolisthesis (DLS) refers to the acquired anterior displacement of one vertebra relative to the vertebra below it, typically accompanied by degenerative changes, yet without any disruption or defect in the vertebral ring.[1] This condition, frequently debilitating, is a spinal disorder that ranks among the most prevalent indications for lumbar spine surgery in older adults.[2] The prevalence of DLS is 25.0% in women and 19.1% in men.[3] Spondylolisthesis can affect one or more

vertebras. Double-level DLS (dl-DLS) is a rare condition that occurs with a prevalence ranging from 5% to 11% in all DLS patients.[4] Compared to individuals with single-level DLS (sl-DLS), those affected by dl-DLS are prone to experiencing more severe lumbar spinal stenosis, stooping posture, and lower back pain.[5] In recent years, many researchers have studied the features of dl-DLS from sagittal plane, and the results showed that compared with sl-DLS, patients with dl-DLS usually have greater pelvic incidence (PI), lumbar lordosis (LL), and sagittal vertical axis (SVA), and patients will improve the forward inclination of the trunk through pelvic retroversion and compensatory flexion of the hip and knee joints.[6] Despite the imbalance of the sagittal parameters, paraspinal muscle also play an important role in DLS. A series of studies indicate that as the important parts of paraspinal muscles, erector spinae (ES), multifidus muscle (MF), and psoas major (PM) are essential for lumbar spine motion and stabilization.[7,8] MF, ES, and PM are not consistent in innervation, anatomic characteristics and biomechanical effects. Although the anatomical location of the MF and the ES are close, and even the boundary between the two is difficult to distinguish on imaging, these 2 muscles are with different fascicles and innervation patterns.[9] The cross-sectional area (CSA) and fatty infiltration (FI) are commonly used degenerative change indexes in paraspinal muscles. The degenerative change of paraspinal muscles has been proven to be associated with DLS.[10] However, different degrees of degeneration in MF, ES, and PM can often be observed in different patient populations. The CSA of PM and MF in asymptomatic population increases caudalward gradually, while the CSA of ES gradually decreases.[11] Whether the degenerative changes of the paraspinal muscles are related to the severity of DLS and sagittal imbalance remains controversial. It needs to be clear whether the different paraspinal muscles play the same or different role in DLS and exhibit consistent pattern of degeneration. To the best of our knowledge, rare study has studied paraspinal muscle degenerative changes comparatively between dl-DLS and sl-DLS and their relation with sagittal parameters, whereas analyzing features of paraspinal muscle in these 2 types of DLS, both as symptoms and as therapeutic target, provides new evidence and targets for disease assessment, the development of personalized treatment plans and enriches our overall understanding of DLS. Therefore, the present study focused on comparing the degenerative characters of MF, ES, and PM in patients with dl-DLS and sl-DLS, and to observe their correlation with sagittal parameters. We hypothesize that (1) patients with dl-DLS and those with sl-DLS will differ in the extent and segmental distribution of degenerative changes in MF, ES, and PM; (2) the degree of paraspinal muscles degeneration in the 2 groups may have different correlation effect with the severity of the sagittal malalignment.

MATERIALS AND METHODS

1. Patients

The patients' demographic information was encoded by hospitalization number. This retrospective study was approved by the Institutional Review Board (IRB) of The Third Affiliated Hospital of Hebei Medical University (No. K2022-064-1) and all the participants were fully aware of confidentiality the Helsinki Declaration ethical standards. Retrospective cross-sectional analysis involved the review of existing data, and as such, the requirement for obtaining written informed consent from all participants was waived by the IRB. This decision was based on the minimal risk involved in the study and the fact that the data were analyzed anonymously, ensuring the confidentiality and privacy of the participants. Our study included 140 patients with DLS diagnosed. Positive DLS refers to a displacement exceeding 5 mm at the anterior vertebral body margin, which occurs concomitantly with degenerative alterations. This condition does not involve any disruption or defect in the vertebral ring, as evident from standing nonfunctional x-ray examinations, as illustrated in Figs. 1 and 2 and treated at our hospital

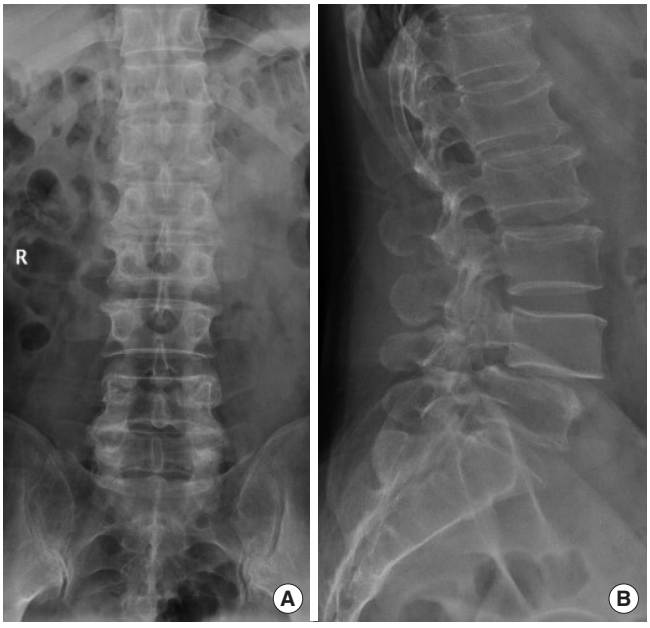

Fig. 1. Standing nonfunctional anterior-posterior (A) and lateral x-ray images (B) of single-level degenerative lumbar spondylolisthesis.

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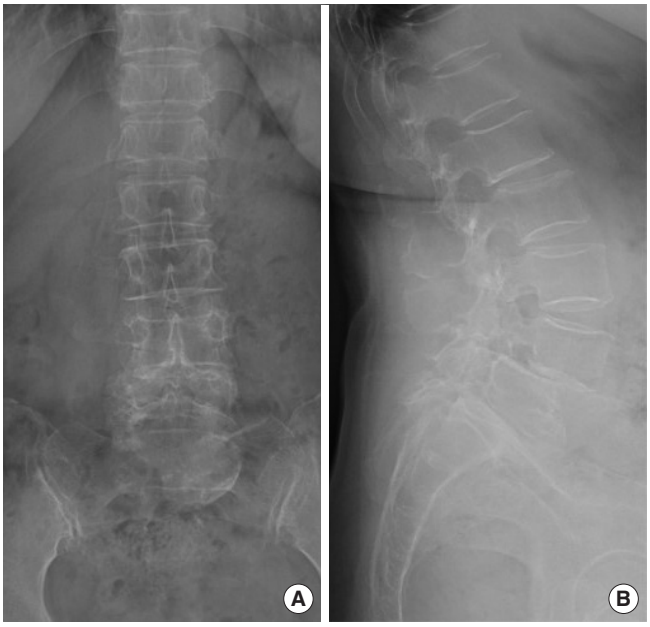

Fig. 2. Standing nonfunctional anterior-posterior (A) and lateral x-ray images (B) of double-level degenerative lumbar spondylolisthesis.

between January 2020 and June 2023. These patients were enrolled during their preoperative hospital stay. The average duration of symptoms (pain, neurogenic claudication etc.) in patients was 12 months (6–32 months). Patients under 18 and over 90 years of age were excluded from the study. A total of 67 patients diagnosed with dl-DLS and 73 patients with sl-DLS were selected as subjects. For the dl-DLS group, the spondylolisthesis vertebrae were L4 and L5, whereas L4 was the spondylolisthesis vertebra in the sl-DLS group. Exclusion criteria included lumbar spinal tumor, neuromuscular disease, spinal infections, ankylosing spondylitis, scoliosis, and patients with previous lumbar trauma or surgery. DLS patients were diagnosed by 3 spinal surgeons based on subjective symptoms, clinical examinations and radiological data including x-ray and magnetic resonance imaging (MRI).[12]

2. Imaging Technique

For all patients, standing radiographs of the whole spine in the anterior-posterior and lateral plane (GE DR system, General Electric, Boston, MA, USA) had been required as one part of their earlier clinical investigation. For the lateral films, the patients stood with their knees fully extended, the feet shoulder width apart, looking straight ahead, with their elbows bent and knuckles in the supraclavicular fossa bilaterally. The MRI data were acquired on the Siemens Trio Tim 3.0 T MR imager (Siemens, Munich, Germany). The patients were placed in the supine position, with their legs straight and the lumbar spine in a neutral posture. Measurements were performed from the L1 superior endplate to the S1 superior endplate. Slices were obtained parallel to the superior endplate of the lower vertebra at each level.

3. Radiological Parameters

PACS (picture archiving and communication system) were applied for the collection and measurement of all patients' radiological data. Measurement parameters include relative paraspinal muscle CSA (rCSA), paraspinal muscle FI, LL, SVA, PI, pelvic tilt (PT), sacral slope (SS), PI minus LL (PI–LL), C7 plumb line minus the center of sacral vertical line (C7PL–CSVL). The muscle parameters (rCSA and FI) were obtained on the middle layer of the MRI at each segment. Paraspinal muscle CSA was measured using the grayscale discrimination method through which dividing the region of interest (ROI) according to the boundaries of each paraspinal muscle in each layer.[13] Relative paraspinal muscle CSA was adopted to eliminate the individual differences in muscle volume that may interfere the results.[14] The acquisition of rCSA was calculated by the ratio of paraspinal CSA to vertebral body CSA at the same segment. The sum value of both sides was measured and adopted for analysis. Image J Threshold method (https://imagej.net/ij, National Institutes of Health, Bethesda, MD, USA) was applied to measure the degree of paraspinal muscles' FI, namely the percentage of the number of fat pixels in the total number of pixels in each paraspinal muscle ROI.[15] Currently, there is no unified standard for selecting the threshold grayscale value for measuring fat infiltration in spinal paravertebral muscles. The common value ranges vary, but in many studies, certain specific values such as 120 are widely used to distinguish the pixels of intramuscular fatty tissue.[16-18] Figs. 3–5 show the measurement method.

The LL, PI, PT, SS, C7PL, SVA, and CSVL were measured on anterior-posterior and lateral radiographs. LL is defined as the angle between the L1 vertebral superior endplate and the S1 vertebral superior endplate. PI is defined as the angle between the line perpendicular to the sacral endplate at the upper sacrum and the line connecting the center of the femoral head to the center of the upper sacral endplate. PT is defined by the angle between the vertical and the line through the midpoint of the sacral plate to femoral head axis. SS is defined by angle between the upper sacral endplate and the horizontal line. C7PL is a vertical line drawn downward from the center of the C7 vertebral body. SVA was measured as the perpendicular distance

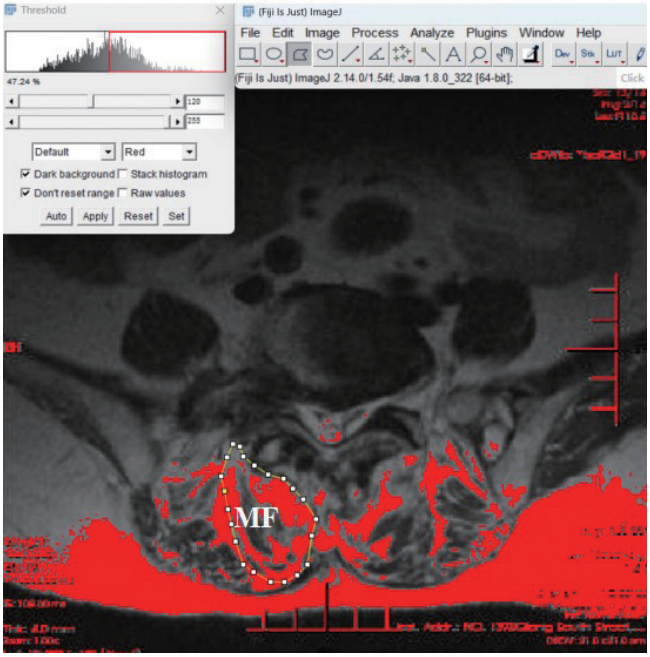

Fig. 3. Measurement method of the MF FI. The Image J Threshold method on the middle layer of magnetic resonance image in each segment. Red pixels represent fat tissues. MF, multifidus muscle; FI, fatty infiltration.

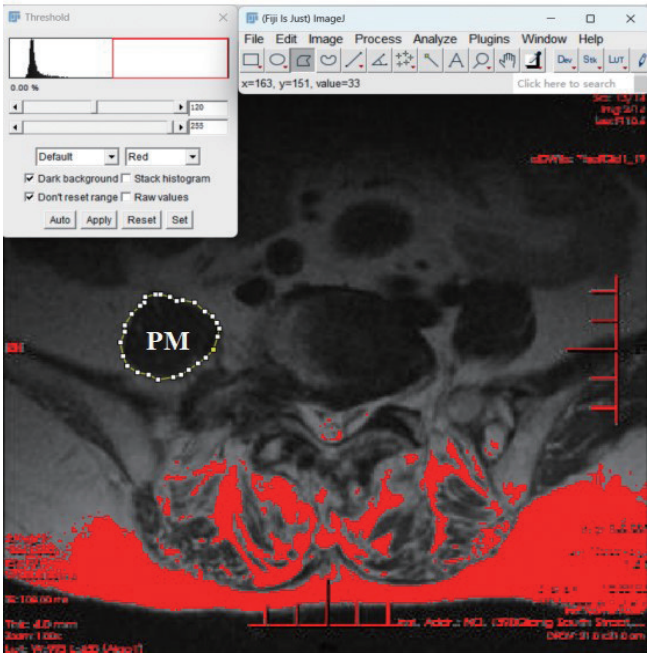

Fig. 5. Measurement method of the PM FI. The Image J Threshold method on the middle layer of magnetic resonance image in each segment. Red pixels represent fat tissues. PM, psoas major; FI, fatty infiltration.

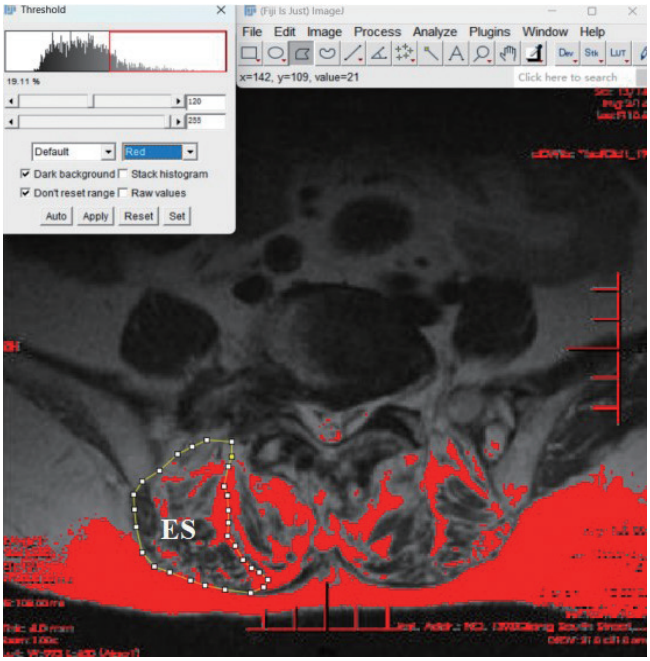

Fig. 4. Measurement method of the ES FI. The Image J Threshold method on the middle layer of magnetic resonance image in each segment. Red pixels represent fat tissues. ES, erector spinae; FI, fatty infiltration.

between the C7 plumb line and the superior posterior corner of the S1 vertebra. CSVL is defined as the vertical line that is drawn perpendicular to an imaginary tangential line drawn across the top of the iliac crests which bisects the sacrum.

All parameters were measured by 2 experienced spinal surgeons. Mean value of the 2 measurements was adopted for analysis.

4. Statistical Analysis

Statistical analysis was conducted with IBM SPSS Statistics ver. 26.0 (IBM Co., Armonk, NY, USA). Data distribution was tested visually and with the Shapiro-Wilk test for normality. Student t-test was conducted for comparison of FI, rCSA, and sagittal spinal-pelvic radiological parameters between the 2 groups. The comparison of paraspinal muscle parameters between segments used mixed analysis of variance with segmental level as the within-subject factor and the patient group as the between-subject factor. *Post hoc* comparisons were performed using a pairwise comparison with Bonferroni correction to examine the subgroup differences. The statistical analysis was 2-tailed test, as we were interested in determining whether the dl-DLS group was significantly different from the sl-DLS group. The correlation between paraspinal muscle parameters and sagittal

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spinal-pelvic radiological parameters was analyzed by Pearson correlation test. Intraobserver reliability and the interobserver reliability for rCSA of PM, ES, and MF were evaluated using the intraclass correlation coefficient (ICC).[19] The data are presented as mean values ± standard deviation. A p-value of < 0.05 was considered to be statistically significant.

RESULTS

1. Patient Demographics and Radiological Parameters

The dl-DLS group included 57 females and 10 males, with 61.49 ± 8.62 (50–89) years of age; the average body mass index (BMI) was 25.98 ± 3.88 kg/m^2. The sl-DLS group included 51 females and 22 males, with 60.45 ± 10.26 (49–70) years of age; the average BMI was 25.83 ± 3.30 kg/m^2. Patients in the dl-DLS group were older, but with no statistically significance (p = 0.519). There exist noteworthy disparities in sex distribution in the 2 groups, with a higher proportion of women experiencing lumbar spondylolisthesis compared to men (p < 0.05). BMI did not differ significantly between the 2 groups (p = 0.810). The PI, PT, SS, PI–LL, and SVA in dl-DLS group were significantly larger in dl-DLS group than that in the sl-DLS group (p < 0.001, p = 0.001, p < 0.001, p = 0.019, p = 0.002). The LL and C7PL–CSVL in dl-DLS group was larger, but with no statistical difference comparing to sl-DLS group (p = 0.195, p = 0.543). Patient demographics and spinal-pelvic radiological parameters are summarized in Table 1.

Table 1. Demographics and sagittal radiological parameters of patients in dl-DLS and sl-DLS patients

Variable	dl-DLS	sl-DLS	p-value
Sex, men:women	10:57	22:51	0.032
Age (yr)	61.49 ± 8.62	60.45 ± 10.26	0.519
BMI (kg/m^2)	25.98 ± 3.88	25.83 ± 3.30	0.810
LL	49.55 ± 15.38	46.61 ± 11.15	0.195
SVA	5.56 ± 2.44	4.51 ± 1.31	0.002*
PI	59.20 ± 11.56	49.85 ± 9.15	0.000*
PT	30.58 ± 9.36	25.41 ± 7.99	0.001*
SS	28.63 ± 7.79	24.45 ± 4.78	0.000*
PI–LL	9.69 ± 18.02	3.26 ± 13.95	0.019*
C7PL–CSVL	1.67 ± 0.23	1.45 ± 0.33	0.543

Values are presented as mean ± standard deviation.
dl-DLS, double-level degenerative lumbar spondylolisthesis; sl-DLS, single-level degenerative lumbar spondylolisthesis; BMI, body mass index; LL, lumbar lordosis; SVA, sagittal vertical axis; PI, pelvic incidence; PT, pelvic tilt; SS, sacral slope; PI–LL, pelvic incidence minus lumbar lordosis; C7PL–CSVL, C7 plumb line minus the center of sacral vertical line.
*p < 0.05, statistically significant differences.

2. Paraspinal Muscles Parameters

The results reveal that the MF rCSA in the dl-DLS cohort was reduced compared to the sl-DLS cohort at the L3–4 to L5–S1 segments. Conversely, the MF FI in the dl-DLS group exceeded that of the sl-DLS group across all segments, ranging from L1–2 to L5–S1. In the dl-DLS group, the ES rCSA was observed to be smaller compared to the sl-DLS group across all levels from L1–2 to L5–S1. Conversely, the ES FI in the dl-DLS group exhibited a larger value at all segments ranging from L1–2 to L5–S1. Additionally, the PM rCSA in the dl-DLS group was smaller compared to the sl-DLS group at L2–3 to L5–S1, while the PM FI was larger in the dl-DLS group from L1–2 to L3–4. There was no significant difference in PM rCSA at L1–2 and FI at L4–5 to L5–S1 between the 2 groups. The paraspinal muscle rCSA and FI of dl-DLS and sl-DLS group are summarized in Table 2.

In order to study the muscle degeneration segmentally, we compared the paraspinal muscles of each segment in both dl-DLS and sl-DLS groups. The rCSA and FI data for all muscles showed significant segmental differences, and for MF and ES, there were significant differences between patient groups. In addition, the FI of MF and ES has significant interaction effects between patient groups and lumbar segments (Table 3). It shows that the lumbar segments have different effects on the FI of MF and ES in the 2 groups.

Post hoc comparisons demonstrated significant differences in MF rCSA and FI among adjacent segments in both the dl-DLS and sl-DLS groups (p < 0.001). Notably, the difference in MF rCSA between L4–5 and L3–4 segments in the dl-DLS group was not statistically significant (p = 0.05). The rCSA and FI of ES and PM were not significantly different between L5–S1 to L4–5 in dl-DLS group, while all the other adjacent segments' differences in both groups were significant (Tables 4 and 5). Intraobserver ICC was excellent for rCSA for MF, ES, and PM (ICC = 0.996, 95% confidence interval [CI], 0.982–0.997; ICC = 0.998, 95% CI, 0.996–0.999; ICC = 0.962, 95% CI, 0.936–0.988). The mean interobserver reliability was also good to excellent in measurement of the rCSA of MF, ES, and PM in MRI (ICC = 0.972, 95% CI, 0.966–0.986; ICC = 0.982, 95% CI, 0.964–0.992; ICC = 0.964, 95% CI, 0.942–0.987).

3. Correlation Analysis

To evaluate the influence of paraspinal muscle parameters on sagittal spinal-pelvic parameters, a comprehensive correlation

Table 2. Muscle degeneration of multifdus muscle (MS), erector spinae (ES), and psoas major (PM) in dl-DLS and sl-DLS groups

Variable	rCSA			FI		
	dl-DLS	sl-DLS	p-value	dl-DLS	sl-DLS	p-value
MF						
L1–2	66.37 ± 23.07	54.56 ± 15.19	< 0.001*	9.93 ± 5.09	5.10 ± 4.27	< 0.001*
L2–L3	91.19 ± 29.78	81.83 ± 21.49	0.034*	18.81 ± 9.24	7.93 ± 5.57	< 0.001*
L3–4	70.18 ± 27.49	93.16 ± 23.87	< 0.001*	26.32 ± 13.00	15.52 ± 7.80	< 0.001*
L4–5	66.74 ± 25.75	90.34 ± 24.40	< 0.001*	42.45 ± 16.74	18.58 ± 8.48	< 0.001*
L5–S1	85.24 ± 23.46	110.88 ± 33.89	< 0.001*	34.56 ± 20.05	11.15 ± 5.85	< 0.001*
ES						
L1–2	72.55 ± 19.75	80.32 ± 23.09	0.035*	3.25 ± 2.73	1.86 ± 1.99	0.001*
L2–L3	95.91 ± 27.19	116.81 ± 36.34	< 0.001*	9.07 ± 8.52	3.61 ± 3.49	< 0.001*
L3–4	112.77 ± 27.44	151.08 ± 48.74	< 0.001*	12.48 ± 9.09	6.63 ± 5.11	< 0.001*
L4–5	105.43 ± 24.92	169.31 ± 54.07	< 0.001*	16.57 ± 10.39	11.47 ± 6.06	< 0.001*
L5–S1	104.06 ± 25.52	178.15 ± 58.78	< 0.001*	18.11 ± 14.04	4.31 ± 3.68	< 0.001*
PM						
L1–2	29.27 ± 13.12	31.26 ± 8.79	0.291	0.32 ± 0.48	0.01 ± 0.02	< 0.001*
L2–L3	46.84 ± 19.41	61.94 ± 19.05	< 0.001*	1.01 ± 1.06	0.03 ± 0.08	< 0.001*
L3–4	62.53 ± 22.68	87.11 ± 32.03	< 0.001*	0.63 ± 1.55	0.09 ± 0.19	0.003*
L4–5	66.92 ± 24.33	100.21 ± 35.71	< 0.001*	0.43 ± 0.67	0.44 ± 0.79	0.893
L5–S1	71.27 ± 22.54	127.09 ± 44.02	< 0.001*	0.50 ± 0.83	0.66 ± 0.84	0.274

Values are presented as mean ± standard deviation.
dl-DLS, double-level degenerative lumbar spondylolisthesis; sl-DLS, single-level degenerative lumbar spondylolisthesis; rCSA, relative paraspinal muscle cross-sectional area; FI, fatty infiltration.
*p < 0.05, statistically significant differences.

Table 3. Muscle parameters comparison between lumbar segments and patient groups

Variable	Patient group	Segments	Interaction effect
MF			
rCSA	< 0.001	< 0.001	0.235
FI	< 0.001	< 0.001	< 0.001
ES			
rCSA	< 0.001	< 0.001	0.156
FI	< 0.001	< 0.001	< 0.001
PM			
rCSA	0.238	< 0.001	0.239
FI	0.536	< 0.001	0.224

rCSA, relative paraspinal muscle cross-sectional area; FI, fatty infiltration; MF, multifdus muscle; ES, erector spinae; PM, psoas major.

Table 4. *Post hoc* comparisons of muscles degeneration between adjacent segments in dl-DLS group

Variable	L5–S1 to L4–5	L4–5 to L3–4	L3–4 to L2–3	L2–3 to L1–2
MF				
rCSA	< 0.001	0.050	< 0.001	< 0.001
FI	< 0.001	< 0.001	< 0.001	< 0.001
ES				
rCSA	0.624	< 0.001	< 0.001	< 0.001
FI	0.236	< 0.001	< 0.001	< 0.001
PM				
rCSA	0.068	0.001	< 0.001	< 0.001
FI	0.418	0.002	0.021	< 0.001

p-values of the *post hoc* comparisons are shown in the table.
dl-DLS, double-level degenerative lumbar spondylolisthesis; rCSA, relative paraspinal muscle cross-sectional area; FI, fatty infiltration; MF, multifdus muscle; ES, erector spinae; PM, psoas major.

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Table 5. *Post hoc* comparisons of muscles degeneration between adjacent segments in sl-DLS group

Variable	L5–S1 to L4–5	L4–5 to L3–4	L3–4 to L2–3	L2–3 to L1–2
MF				
rCSA	<0.001	0.005	<0.001	<0.001
FI	<0.001	<0.001	<0.001	<0.001
ES				
rCSA	0.010	<0.001	<0.001	<0.001
FI	<0.001	<0.001	<0.001	<0.001
PM				
rCSA	<0.001	<0.001	<0.001	<0.001
FI	0.004	<0.001	0.009	0.007

p-values of the *post hoc* comparisons are shown in the table.
sl-DLS, single-level degenerative lumbar spondylolisthesis; rCSA, relative paraspinal muscle cross-sectional area; FI, fatty infiltration; MF, multifdus muscle; ES, erector spinae; PM, psoas major.

analysis was conducted, comparing the rCSA and FI of MF, ES, and PM with LL, PI, PT, SS, PI–LL, SVA in both groups. In the dl-DLS group, the rCSA of PM was negatively correlated with PT in L4–5, L3–4, and L2–3 segments ($r = -0.320$, $r = -0.329$, $r = -0.263$; $p < 0.05$). There demonstrated no significant correlation in rCSA of all segments in dl-DLS group with LL, SS, PI, PI–LL, and SVA. In sl-DLS group, rCSA of all segments showed no significant correlation with LL, PI, PT, SS, SVA, and PI–LL.

In the dl-DLS group, The FI of MF and ES in L5–S1 segment were positively correlated with LL ($r = 0.253$, $r = 0.252$, $p < 0.05$). Other segments' FI showed no significant correlation with LL. FI of ES was positively correlated with PT ($r = 0.307$, $p < 0.05$) in L5–S1 segment and negatively correlated with SVA from L5–S1 to L1–2 segment ($r = -0.293$, $r = -0.248$, $r = -0.347$, $r = -0.329$, $r = -0.246$, $p < 0.05$), while FI of MF and PM showed no significant correlation with SVA. In the sl-DLS group, the FI of PM in L5–S1 and L4–5 segments were negatively correlated with LL ($r = -0.316$, $r = -0.285$, $p < 0.05$). Other segments' FI showed no significant correlation with LL, PI, PT, SS, SVA, and PI–LL in the sl-DLS group.

DISCUSSION

In the context of aging societies, the prevalence of obesity and sedentary lifestyles has led to a notable rise in degenerative lumbar diseases, necessitating a corresponding increase in surgical interventions. Devising strategies and non-surgical therapeutic options can mitigate the need for surgical intervention in DLS and it is imperative to develop a deeper and more nuanced understanding of the underlying pathophysiology. To achieve this objective, our research efforts were focused on elucidating the significance of paraspinal muscles across multilevels of DLS. In pursuit of this, we conducted a retrospective, cross-sectional study designed to analyze MRI-based disparities in the magnitude and segmental localization of degenerative alterations within the MF, ES, and PM, as well as their correlation with the severity of sagittal malalignment.

Previous investigations have demonstrated a correlation between DLS and factors such as advanced age, female gender, obesity, the degradation of intervertebral discs and facet joints, as well as low back pain.[20,21] Our research further validates the association of female gender and older age among patients suffering from both dl-DLS and sl-DLS. Patients in the dl-DLS group were older and BMI were larger, but both with no statistically significance. Predominantly, it is hypothesized that these associations may stem from pregnancy, systemic joint laxity, hormonal influences, and the compactness of the lumbosacral ligaments.[22] As the 2 major features of muscle degeneration, atrophy and FI can weaken the ability of the paraspinal muscles to support and stabilize the lumbar spine, thereby increasing the risk of pain and instability. Over the past 2 decades, extensive research has demonstrated a profound linkage between the degeneration and functionality of paraspinal muscles and the progressive nature of lumbar degeneration. Furthermore, these findings have underscored the significant impact of paraspinal muscle degeneration on the long-term clinical prognosis of degenerative diseases affecting the lumbar spine.[23,24] Prior investigations have consistently revealed that, in patients suffering from DLS, there is a marked degeneration in the MF and ES, as compared to asymptomatic individuals with robust health.[25] Although anatomically adjacent and radiographically contiguous, MF and ES possess distinct biomechanical properties and innervation patterns. Consequently, these muscles fulfill diverse roles in lumbar spine motion and exhibit varying degenerative processes. Single-level DLS typically presents as segmental lumbar instability, local slippage, and increased lordosis of the lumbar spine. In contrast, patients with double-level DLS often exhibit distinct pelvic morphologies, along with greater sagittal malalignment.[26] These biomechanical disparities underlie the distinct patterns of paraspinal muscle degeneration observed in these 2 conditions.

The musculature, along with its neuromuscular control, is indispensable for preserving the stability and functionality of the spinal structure. Between the 2 groups, ES, MF, and PM ex-

hibited distinct patterns of degeneration. In patients with dl-DLS, the atrophy of MF was more pronounced in the regions ranging from L3–4 to L5–S1, whereas in the regions from L1–2 to L2–3, the atrophy was less severe. The atrophy of MF exhibited a segmental pattern, characterized by a notable decrease in the lower lumbar spine region, coupled with hypertrophic changes in the upper lumbar spine. Furthermore, the extent of MF FI was greater in dl-DLS patients compared to sl-DLS patients across all lumbar segments, displaying a segmental and gradually increasing trend in the lower lumbar spine. In terms of ES, a more significant degree of atrophy and a higher level of FI were observed in the dl-DLS groups compared to the sl-DLS group, extending from L1–2 to L5–S1. However, from the level L4–5 to L5–S1, no segmental differences in ES FI and atrophy were evident in dl-DLS patients, indicating a diffuse pattern of degeneration. Furthermore, the atrophy of the PM exhibits a more prominent manifestation in the dl-DLS group compared to the sl-DLS group, specifically from the L2–3 level to the L5–S1 level. Conversely, in terms of FI, the dl-DLS group demonstrates a more severe degree from the L1–2 level to the L3–4 level in comparison to the sl-DLS group. However, from L4–5 to L5–S1, there were no statistically significant differences observed between the 2 groups in terms of PM FI. During the correlation analysis, it was observed that the rCSA of PM was negatively correlated with PT from L4–5 to L2–3 segments in the dl-DLS group. FI of MF and ES in the L5–S1 segment positively coincided with the degree of LL in the dl-DLS group. However, in the sl-DLS group, a negative association was evident between the FI of PM in both the L5–S1 and L4–5 segments and LL. Moreover, the FI of ES extending from L5–S1 to L1–2 demonstrated negative correlation with SVA and negative correlation with PT in the L5–S1 segment from dl-DLS group. No correlation was discerned between MF and PM's FI and SVA in the dl-DLS group. In the research undertaken by Hiyama et al., they discovered a correlation between the decline in whole-body skeletal muscle mass and the reduction in PM CSA, which was intricately linked to PT.[7,27] Notably, PT emerged as the sagittal parameter that demonstrated the strongest association with skeletal muscle mass in patients suffering from degenerative spondylolisthesis and stenosis. The core findings of these prior studies, which predominantly centered on the relationship between paraspinal muscles and PT, align with our observations. Our study indicates a complex interaction among paraspinal muscles in the 2 distinct types of DLS. PM generates anterior shear forces, whereas ES exerts posterior pull forces on vertebral segments. The degeneration of these 2 muscles can cause potential muscular imbalance within these regions and may lead to kyphotic or lordotic tendencies in their respective distribution areas. It may ultimately result in anterior or posterior inclination of PT as a compensatory mechanism for an imbalanced spine. Furthermore, the reduced stabilizing capacity of the MF during rotational movements may lead to an unfavorable distribution of forces across the facet joints and intervertebral discs, subsequently accelerating degenerative changes, constraining the segmental range of motion. Central and foraminal stenosis have the potential to adversely impact the muscular innervation of both the MF and ES, specifically through their respective medial and lateral branches of the dorsal ramus, thereby intensifying the degenerative process. Consequently, this cascade of events may lead to further asymmetric muscular degeneration. In the present investigation, it was observed that there existed no significant disparity in the degree of PM fat infiltration between the 2 groups at the L4–5 and L5–S1 segments, which are known to be susceptible to slippage. However, a significant elevation in the fat infiltration of ES was evident in the dl-DLS group compared to the sl-DLS group, suggesting a more pronounced degenerative process. This could potentially lead to an imbalance between the anterior shear force and posterior tension force of the spine, thereby serving as a plausible mechanism for the progression from sl-DLS into dl-DLS. This research unveiled a significant inverse relationship between the rCSA of PM and PT, along with the FI of ES and SVA, among individuals experiencing double-level spondylolisthesis. It is hypothesized that these associations may be rooted in abnormality of SVA and decompensation of pelvis, which may trigger disproportionate degenerative alterations in the ES and PM.

The posterior surgical approach involves dissection that significantly impacts the paraspinal muscles, thereby compromising postoperative recovery and maintenance of the normal spinal sequence. According to research, patients who experience postoperative low back pain exhibit MF degeneration, which manifests as muscular atrophy, accumulation of intramuscular adipose tissue, and denervation.[28] During the traditional posterior lumbar interbody fusion procedure, the anatomic characteristics of the region render the ES and MF particularly susceptible to injury. The primary sources of injury during this procedure typically stem from dissection, retraction, denervation, and immobilization.[29] Based on the presumption of a perpetual cycle between muscle degeneration and progressive segmental degeneration, leading to escalating slippage, interventions focused on enhancing the health of the paraspinal muscles may potentially prevent or decelerate the progression of early-

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stage DLS. Physiotherapeutic interventions have been explored to mitigate the presence of FI in paraspinal muscles, thereby enhancing muscular strength, proprioception, and alleviating low back pain.[30,31] It is also paramount to underscore the significance of muscle innervation in maintaining muscular functionality, thus, averting denervation, stemming from either degenerative nerve compression or iatrogenic damage, remains pertinent.[32] Regardless of the specific muscle-targeting therapy employed, initiating treatment early in the course of DLS may be beneficial. Spaceflight studies have demonstrated that certain muscular degenerative changes can be irreversible, even in physically fit astronauts.[33] Therefore, adopting an appropriate surgical approach and implementing effective exercise regimens can aid in protecting and strengthening the paraspinal muscles, potentially leading to positive clinical outcomes, particularly among elderly patients.[34]

However, it is imperative to acknowledge that this research possesses certain inherent many limitations. Firstly, the patient selection process and the study design exhibit certain constraints. The study's sample size, though adequate for the statistical analyses performed, may not fully represent the broader population. This limitation could potentially impact the generalizability of our findings. Being a retrospectively gathered, cross-sectional study, it is susceptible to biases that may skew the interpretation of our findings. Additionally, patients suffering from L5 spondylolisthesis exhibit significantly distinct biomechanical attributes and pathological manifestations in comparison to those unaffected by this condition. Furthermore, there is a latent risk of erroneously including cases of L5 spondylolisthesis within the study cohort. The analysis of spinopelvic parameters has unveiled substantial differences in the pathological presentations between L4 spondylolisthesis and those involving both L4 and L5, as evident in the PI, which is largely attributed to congenital factors. As the patients were not prospectively enrolled according to predefined criteria, but rather selected based on the accessibility of data, this approach may have resulted in a nonrepresentative sample that fails to comprehensively encapsulate the diversity of the patient population affected by the condition being studied. Secondly, the absence of longitudinal data constitutes a significant constraint. The lack of preoperative and postoperative comparisons hinders the ability to evaluate temporal alterations and the consequences of interventions or disease progression on paraspinal muscle degeneration. Theoretically, the progression of multi-level lumbar spondylolisthesis necessitates a clear elucidation of the involvement of paraspinal muscle atrophy. This understanding can be achieved through prospective follow-up studies, which would offer a more comprehensive grasp of the disease's natural history, particularly with regards to the development and progression of paraspinal muscle atrophy during the course of the degeneration. Thirdly, the cross-sectional design inherently restricts our capacity to definitively establish causality or discern the directional nature of the observed relationships. Consequently, further prospective research, encompassing preoperative versus postoperative comparisons, foundational research, and clinical validation, is imperative to unravel the precise mechanisms underlying the degenerative process. Furthermore, conducting on a multivariate analysis to determine the pivotal variables, including age, sex, BMI, radiographic indicators, and integrating additional disease groups (L4 solely, L3–4, or L4–5), would be a valuable endeavor in future research. In our subsequent researches, we aim to delve deeper into the intricate web of anatomical, physiological, neural, and other elements that contribute to muscle degeneration across diverse DLS patient cohorts.

CONCLUSION

The degeneration of MF, ES, and PM is more severe in dl-DLS patients than that in sl-DLS patients. Most MF, ES, and PM changes are segmental and the degeneration is more severe in spondylolisthesis level from both dl-DLS and sl-DLS patients. More severe paraspinal muscle degeneration has the potential to cause imbalance between the anterior shear force and posterior tension force of the spine, thereby serving as a plausible mechanism for the progression from sl-DLS into dl-DLS. The degradation of PM and ES exhibits a negative correlation with PT and SVA, leading to the hypothesis that this relationship may stem from decompensation of pelvis and abnormality in SVA. This abnormality may, in turn, precipitate disproportionate degenerative changes within the PM and ES among patients afflicted with dl-DLS.

NOTES

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