

Early Trabecular Bone Remodeling and Paraspinal Muscle Preservation After Unilateral Biportal Endoscopic Versus Minimally Invasive Transforaminal Lumbar Interbody Fusion for Mild Degenerative Lumbar Spondylolisthesis: A Retrospective Comparative Study

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Abstract

Objective

To compare the clinical and radiological outcomes of unilateral biportal endoscopic transforaminal lumbar interbody fusion (UBE-TLIF) and minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF) in the treatment of single-level mild degenerative lumbar spondylolisthesis.

Methods

A retrospective analysis was conducted on 80 patients with single-level mild degenerative lumbar spondylolisthesis, including 40 patients treated with UBE-TLIF and 40 patients treated with MIS-TLIF. Perioperative parameters, visual analog scale (VAS) scores, Oswestry Disability Index (ODI), modified MacNab scores, fusion rates, trabecular bone remodeling (TBR) at 3 months postoperatively, and multifidus atrophy and fat infiltration rates at 12 months postoperatively were compared between the two groups.

Results

The UBE-TLIF group had significantly less intraoperative blood loss and shorter hospital stays, but longer operative times compared with the MIS-TLIF group (all $P < 0.001$). At 3 days postoperatively, the VAS score for low back pain was significantly lower in the UBE-TLIF group than in the MIS-TLIF group (2.98 ± 1.12 vs. 3.62 ± 1.27 , $P = 0.018$), whereas no significant differences were observed between groups in VAS scores at the remaining time points or in ODI scores (all $P > 0.05$). The UBE-TLIF group showed significantly higher TBR positivity at 3 months and a higher fusion rate at 6 months postoperatively compared with the MIS-TLIF group ($P < 0.05$), while no significant difference in fusion rate was observed at 12 months. At 12 months postoperatively, the multifidus atrophy rate ($29.50 \pm 7.72\%$ vs. $34.04 \pm 10.55\%$, $P = 0.031$) and fat infiltration rate ($34.85 \pm 7.69\%$ vs. $38.19 \pm 6.02\%$, $P = 0.033$) were both significantly lower in the UBE-TLIF group than in the MIS-TLIF group.

Conclusion

Both UBE-TLIF and MIS-TLIF provide satisfactory clinical outcomes in the treatment of single-level mild degenerative lumbar spondylolisthesis. Compared with MIS-TLIF, UBE-TLIF demonstrates certain advantages in early postoperative pain relief, preservation of paraspinal muscles, and early osteointegration during the fusion process.

Introduction

With the acceleration of population aging, the prevalence of degenerative lumbar spondylolisthesis (DLS) has increased rapidly. Among individuals aged 66–70 years, DLS affects up to 15% of men and more than 50% of women^[1]. DLS is characterized by anterior displacement of the superior vertebral body relative to the inferior vertebra, a pathological change that may lead to spinal instability and subsequent neural compression^[2]. Clinically, DLS commonly presents with chronic low back pain with or without radicular lower extremity pain, significantly impairing patients' quality of life. When conservative treatment fails, surgical intervention is commonly adopted in clinical practice. Lumbar fusion surgery can effectively alleviate symptoms and help maintain spinopelvic sagittal balance^[3]. Since Harms and Jerszenszky first provided a detailed description of transforaminal lumbar interbody fusion (TLIF) in 1998^[4, 5], this technique has become a widely adopted surgical approach in clinical practice due to its high safety in intervertebral disc space preparation and cage implantation, as well as its low incidence of postoperative radiculitis. Conventional open TLIF provides reliable clinical outcomes and adequate decompression; however, it is associated with substantial soft tissue injury, leading to increased postoperative muscle atrophy and higher infection rates. With the advancement of minimally invasive techniques, an increasing number of surgeons have adopted small-incision, endoscopy-assisted approaches for lumbar interbody fusion^[6]. In 2004, Foley^[7] introduced a minimally invasive TLIF technique by combining tubular retractors with microscopic assistance, known as minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF). Compared with open surgery, MIS-TLIF markedly reduces iatrogenic injury caused by extensive muscle retraction that obstructs the surgical field. However, because of the depth of the surgical corridor, complete separation of all soft tissues cannot be achieved, and visualization may still be limited. In addition, prolonged retraction of the paraspinal soft tissues by the tubular system can result in ischemic injury to the paraspinal muscles, thereby adversely affecting postoperative recovery. With the advancement of spinal endoscopic techniques and the introduction of a fluid medium, unilateral biportal endoscopic transforaminal lumbar interbody fusion (UBE-TLIF) has gained increasing attention because of its clear surgical field and greater flexibility in instrument selection^[8, 9].

Based on this background, the present study adopted a single-center retrospective design to comparatively analyze the clinical and radiological outcomes of patients with single-level mild degenerative lumbar spondylolisthesis treated with UBE-TLIF or MIS-TLIF. The primary focus was to evaluate differences between the two surgical techniques in terms of clinical efficacy, perioperative parameters, early trabecular bone remodeling during fusion, and changes in paraspinal muscle morphology. Through a comprehensive assessment integrating multidimensional imaging and functional outcomes, this study aims to provide new clinical evidence to inform the optimal selection of minimally invasive lumbar fusion techniques and to enhance the understanding of fusion-related biological mechanisms.

Methods

Inclusion criteria: (1) Single-level grade I degenerative lumbar spondylolisthesis (Meyerding classification) with radiological findings consistent with clinical symptoms; (2) a definitive preoperative diagnosis confirmed by lumbar hyperextension and flexion radiographs, lumbar computed tomography (CT), and magnetic resonance imaging (MRI); (3) failure to achieve significant symptom relief after more than three months of conservative treatment; and (4) completion of at least one year of postoperative follow-up.

Exclusion criteria: (1) A history of previous lumbar spine surgery; (2) the presence of spinal tumors, spinal fractures, spinal tuberculosis, severe scoliosis, or severe osteoporosis; (3) coagulation disorders, severe cardiopulmonary dysfunction, or other conditions rendering the patient unable to tolerate surgery; and (4) incomplete clinical data.

A retrospective analysis was performed on 80 patients with single-level mild degenerative lumbar spondylolisthesis who met the inclusion criteria and were treated at Wuxi People's Hospital affiliated with Nanjing Medical University between March 2020 and January 2025. Among them, 40 patients in the study group underwent UBE-TLIF, while 40 patients in the control group received MIS-TLIF. There were no significant differences between the two groups in baseline characteristics, including sex, age, body mass index (BMI), surgical level, preoperative visual analog scale (VAS) scores for low back and leg pain, or Oswestry Disability Index (ODI) scores (all $P>0.05$), indicating good comparability. All patients provided written informed consent, and this study was approved by the Ethics Committee of Wuxi People's Hospital(2025010).

Surgical Technique All procedures were performed by the same surgeon with more than five years of experience in minimally invasive spinal surgery.

Observation group (UBE-TLIF):After satisfactory induction of general anesthesia, the patient was placed in the prone position, and the operating table was adjusted to achieve a horizontal lumbar alignment. The surgical level was confirmed using C-arm fluoroscopy. Surface landmarks corresponding to the target intervertebral space, the spinous processes of the adjacent vertebrae, and the bilateral pedicle projections were marked. After routine skin preparation and draping, a puncture needle was inserted along the surface projection of the pedicle under fluoroscopic guidance. Once the needle entered the vertebral body, a guidewire was placed for localization. On the symptomatic side, two oblique transverse skin incisions of approximately 1 cm were made at the surface projections of the upper and lower pedicles. Taking the left side as an example, the cranial incision was used as the viewing portal and the caudal incision as the working portal, with the configuration reversed on the right side. Tubular dilators were used to establish the portals, and fluoroscopy was repeated to confirm accurate access to the target level. Continuous saline irrigation was applied to maintain a clear endoscopic field. Through the working portal, a radiofrequency probe was introduced to remove soft tissues surrounding the lamina, fully exposing the inferior lamina of the cranial vertebra, the medial border of the inferior articular process of the cranial vertebra, and the superior lamina of the caudal vertebra on the operative side. An osteotome and Kerrison rongeur were used to resect the inferior lamina of the cranial vertebra, the

superior lamina of the caudal vertebra, and the superior and inferior articular processes. The resected bone was preserved for grafting. The attachment points of the ligamentum flavum were fully exposed, and the ligamentum flavum and epidural adipose tissue were removed. A nerve root retractor was inserted to gently retract the nerve root and dural sac contralaterally, thereby exposing the intervertebral disc. The nucleus pulposus was removed using pituitary forceps, and the cartilaginous endplates were carefully curetted under direct endoscopic visualization until punctate bleeding was observed, indicating adequate endplate preparation. After cage trial, an appropriately sized interbody cage was selected and packed with autologous bone and artificial bone before insertion. Following confirmation of adequate decompression and relaxation of the nerve root and dural sac, the endoscope was withdrawn. Percutaneous pedicle screw-rod fixation was then performed along the guidewires. After fluoroscopic confirmation of correct cage and instrumentation positioning, the surgical field was irrigated with saline, a drainage tube was placed, and the incision was closed and covered with sterile dressings.

Control group (MIS-TLIF): After satisfactory induction of general anesthesia, the patient was placed in the prone position, and the operating table was adjusted to achieve a horizontal lumbar alignment. The target surgical level was confirmed using C-arm fluoroscopy, and surface landmarks corresponding to the involved intervertebral space, the spinous processes of the adjacent vertebrae, and the bilateral pedicle projections were marked. After routine skin preparation and draping, a skin incision of approximately 2 cm was made about 3 cm lateral to the midline along the line connecting the spinous processes. The dorsal fascia was incised, and blunt dissection was performed through the intermuscular plane between the multifidus and longissimus muscles until the bony surface was reached. Sequential tubular dilators were then inserted and fixed in place, and the soft tissues overlying the facet joints were thoroughly cleared. After adequate exposure, the superior and inferior articular processes at the affected level and a portion of the lamina were resected and preserved for bone grafting. The dural sac and nerve root were fully exposed, and a nerve root retractor was used to gently retract the nerve root and dural sac contralaterally, thereby exposing the intervertebral disc. The nucleus pulposus was removed using pituitary forceps, and the cartilaginous endplates were curetted. Bone grafting was performed, followed by insertion of an appropriately sized interbody cage. Pedicle access was achieved by inserting a puncture needle along the surface projection of the pedicle under fluoroscopic guidance. After confirmation of needle entry into the vertebral body, a guidewire was placed, and cannulated pedicle screws of appropriate length were inserted. Following fluoroscopic confirmation of correct cage and instrumentation positioning, the surgical field was irrigated with saline, a drainage tube was placed, and the incision was closed and covered with sterile dressings.

Postoperative Management

All patients received prophylactic antibiotics 30 minutes before surgery and for 48 hours postoperatively to prevent infection. Short-term nonsteroidal anti-inflammatory drugs were administered for postoperative analgesia. Patients in both groups were maintained on strict bed rest immediately after surgery, and systemic corticosteroids were administered at 24 hours postoperatively for anti-inflammatory purposes. The drainage tube was removed 48 hours after surgery. Ambulation was

encouraged 2 days postoperatively under the protection of a brace, which was worn for at least 2 months. Bending, heavy lifting, and other load-bearing activities were prohibited for 3 months after surgery.

Follow-up assessments were scheduled according to the predefined outcome variables. Clinical assessments included VAS scores for low back and leg pain preoperatively and at 3 days, 3 months, and 12 months postoperatively; ODI preoperatively and at 3 and 12 months postoperatively; and modified MacNab scores at 12 months postoperatively. Radiographic evaluations included lumbar radiographs and CT according to the fusion assessment schedule, with TBR evaluated on 3-month postoperative CT and interbody fusion assessed on 6- and 12-month postoperative CT. Lumbar MRI was obtained preoperatively and at 12 months postoperatively for quantitative multifidus assessment.

Outcome Assessment:

Clinical efficacy outcomes: Low back and leg pain were assessed using VAS scores preoperatively and at 3 days, 3 months, and 12 months postoperatively. Functional disability was evaluated using ODI preoperatively and at 3 and 12 months postoperatively. Clinical satisfaction was assessed using the modified MacNab criteria at 12 months postoperatively^[10].

Perioperative parameters: Surgery time, intraoperative blood loss, and length of hospital stay were compared between the two groups.

Trabecular bone remodeling (TBR): Trabecular bone morphology on CT images at 3 months postoperatively was compared between patients. TBR was defined on coronal CT images as a radiological manifestation observed in adjacent vertebrae and was distinguished by comparison with the morphology and density of normal vertebral trabeculae. TBR represents newly formed bone structures that appear after surgery and are not observed on preoperative or immediate postoperative CT images. TBR may extend vertically or obliquely from the contact area between the interbody cage and the vertebral endplate toward the pedicle screws. In addition, because TBR exhibits higher density (higher Hounsfield unit values), similar to cortical bone, it can be clearly differentiated from the background trabecular bone^[11,12], (Figure 1).

Fusion status: Fusion was evaluated on postoperative CT scans at 6 months and 1 year by two independent and experienced radiologists using the Bridwell interbody fusion grading system. According to this system, Grade I was defined as a reconstructed fusion mass with trabecular bone remodeling; Grade II as an intact graft with incomplete remodeling; Grade III as an intact graft with radiolucent areas at the cranial or caudal interface; and Grade IV as nonunion with graft collapse or resorption. Bridwell Grades I and II were considered indicative of successful fusion.

Impact of surgery on paraspinal muscles: Image J software was used to measure the cross-sectional area (CSA) of the multifidus muscle on the surgical approach side at the mid-disc level of the fused segment on preoperative and 12-month postoperative images. Fat tissue within the region of interest

was identified by threshold-based segmentation, and the fat area was quantified. The multifidus atrophy rate was calculated as (preoperative CSA – postoperative CSA) / preoperative CSA×100%. The multifidus fat infiltration rate (FI ratio) was defined as the ratio of fat area to total muscle CSA. All measurements were performed three times, and the mean values were included in the analysis to minimize measurement error.(Figure2)

Statistical Analysis

Statistical analyses were performed using SPSS version 27.0. Continuous variables were tested for normality and are presented as mean ± standard deviation. Between-group comparisons of continuous variables were conducted using the independent-samples t test. Categorical variables, including sex, surgical level, fusion status, and TBR positivity, were compared using the chi-square (χ^2) test, with Fisher's exact test applied when the expected cell count was less than 5. A two-sided P value < 0.05 was considered statistically significant. The intraobserver and interobserver ICC values for all radiological measurements were greater than 0.80, indicating good measurement reliability.

Results

Demographic Characteristics

A total of 80 patients were included in this study, with 40 patients in the UBE-TLIF group and 40 patients in the MIS-TLIF group. There were no statistically significant differences between the two groups in baseline characteristics, including sex, age (64.28 ± 9.39 vs. 61.77 ± 8.79 years, $P = 0.223$), body mass index (BMI; 23.02 ± 2.56 vs. 22.98 ± 2.43 kg/m², $P = 0.942$), or surgical level (all $P > 0.05$), indicating good comparability between groups (Table 1).

Operation parameters

Operative time was significantly longer in the UBE-TLIF group than in the MIS-TLIF group (143.50 ± 37.14 vs. 114.70 ± 19.00 min, $P < 0.001$). In contrast, intraoperative blood loss was significantly lower in the UBE-TLIF group (163.95 ± 60.64 mL) compared with the MIS-TLIF group (234.20 ± 85.92 mL, $P < 0.001$). Additionally, the length of hospital stay was significantly shorter in the UBE-TLIF group than in the MIS-TLIF group (8.05 ± 1.52 vs. 9.38 ± 1.76 days, $P < 0.001$) (Table 1, Fig. 3).

Table 1
Demographic and Clinical Characteristics of Patients Undergoing UBE-TLIF and MIS-TLIF

Demographic	UBE-TLIF Group	MIS-TLIF Group	P
Gender			
Male	13	18	0.251
Female	27	22	
Age(years)	64.28 ± 9.39	61.77 ± 8.79	0.223
BMI(kg/m ²)	23.02 ± 2.56	22.98 ± 2.43	0.942
Surgery level			
L4-5	26	23	0.491
L5-S1	14	17	
Length of Surgery Time (mins)	143.50 ± 37.14	114.70 ± 19.00	< 0.001
Estimated Blood Loss (mL)	163.95 ± 60.64	234.20 ± 85.92	< 0.001
Length of Hospital Stay (days)	8.05 ± 1.52	9.38 ± 1.76	< 0.001

Clinical outcomes

VAS score: There were no significant differences between the two groups in preoperative VAS scores for low back pain (6.45 ± 1.22 vs. 6.30 ± 1.20 , $P = 0.581$) or leg pain (6.22 ± 1.31 vs. 6.35 ± 1.53 , $P = 0.696$). At postoperative day 3, the UBE-TLIF group demonstrated a significantly lower VAS score for low back pain than the MIS-TLIF group (2.98 ± 1.12 vs. 3.62 ± 1.27 , $P = 0.018$). No significant differences in VAS scores were observed between the two groups at the remaining postoperative time points, including low back pain at 3 months (1.62 ± 0.77 vs. 1.60 ± 0.87 , $P = 0.892$) and 12 months (0.65 ± 0.53 vs. 0.78 ± 0.58 , $P = 0.317$), as well as leg pain at postoperative day 3 (1.57 ± 0.68 vs. 1.82 ± 0.78 , $P = 0.130$), 3 months (1.32 ± 0.69 vs. 1.52 ± 0.64 , $P = 0.184$), and 12 months (0.75 ± 0.49 vs. 0.78 ± 0.42 , $P = 0.808$). ODI and MacNab scores: No significant differences were identified between the two groups in ODI scores preoperatively (58.70 ± 9.02 vs. 59.15 ± 9.50 , $P = 0.829$), at 3 months postoperatively (24.05 ± 5.26 vs. 26.12 ± 6.22 , $P = 0.111$), or at 12 months postoperatively (12.22 ± 3.77 vs. 13.62 ± 3.85 , $P = 0.105$), nor in the modified MacNab scores at 12 months postoperatively ($P > 0.05$). (Fig. 4)

Fusion status: At 6 months postoperatively, the fusion rate in the UBE-TLIF group (85.0%) was significantly higher than that in the MIS-TLIF group (65.0%) ($P < 0.05$). However, no significant difference in fusion rates was observed between the two groups at 12 months postoperatively ($P > 0.05$).

TBR: At 3 months postoperatively, the positive rate of TBR was significantly higher in the UBE-TLIF group (57.5%) than in the MIS-TLIF group (30%) ($P < 0.05$) (Table 2.).

Table 2
Comparative Analysis of Patient-Reported Outcome Measures Following UBE-TLIF and MIS-TLIF

Subjects	UBE-TLIF Group	MIS-TLIF Group	P
VAS of back pain			
Preoperative	6.45 ± 1.22	6.30 ± 1.20	0.581
D3 postoperative	2.98 ± 1.12	3.62 ± 1.27	0.018
3M postoperative	1.62 ± 0.77	1.60 ± 0.87	0.892
12M postoperative	0.65 ± 0.53	0.78 ± 0.58	0.317
VAS of leg pain			
Preoperative	6.22 ± 1.31	6.35 ± 1.53	0.696
D3 postoperative	1.57 ± 0.68	1.82 ± 0.78	0.130
3M postoperative	1.32 ± 0.69	1.52 ± 0.64	0.184
12M postoperative	0.75 ± 0.49	0.78 ± 0.42	0.808
ODI			
Preoperative	58.70 ± 9.02	59.15 ± 9.50	0.829
3M postoperative	24.05 ± 5.26	26.12 ± 6.22	0.111
12M postoperative	12.22 ± 3.77	13.62 ± 3.85	0.105
12M Macnab satisfaction			
Excellent	21	20	0.924
Good	16	18	
Fair	1	1	
Poor	2	1	
Bridwell			
6M postoperative	34,6	26,14	< 0.05
12M postoperative	39,1	37,3	0.615
TBR			
TBR(+)	23	12	< 0.05
TBR(-)	17	28	

Imaging outcomes

The intra-observer and inter-observer ICC values for all radiological measurements were greater than 0.80, indicating good reliability.

Multifidus muscle atrophy rate

The multifidus muscle atrophy rate was significantly lower in the UBE-TLIF group ($29.50 \pm 7.72\%$) than in the MIS-TLIF group ($34.04 \pm 10.55\%$) at 12 months postoperatively ($P = 0.031$).

Fat infiltration rate

No significant difference in fat infiltration rate was observed between the two groups preoperatively ($23.21 \pm 8.43\%$ vs. $21.31 \pm 6.93\%$, $P = 0.275$). At 12 months postoperatively, the fat infiltration rate in the UBE-TLIF group ($34.85 \pm 7.69\%$) was significantly lower than that in the MIS-TLIF group ($38.19 \pm 6.02\%$, $P = 0.033$) (Table 3, Fig. 5).

Table 3
Comparative Analysis of Muscle Characteristics Changes in the Multifidus (MF)

Subjects	UBE-TLIF Group	MIS-TLIF Group	P
MF atrophy rate(%)	29.50 ± 7.72	34.04 ± 10.55	0.031
Fat infiltration rate of MF(%)			
Preoperative	23.21 ± 8.43	21.31 ± 6.93	0.275
12M postoperative	34.85 ± 7.69	38.19 ± 6.02	0.033

Discussion

DLS is a common and frequently encountered condition in the elderly population. It typically presents with low back pain, with or without radicular lower extremity pain, and some patients may also develop symptoms of intermittent claudication. This condition can substantially impair patients' quality of life^[13, 14]. With the acceleration of global population aging, the incidence of this condition has continued to rise steadily, making it one of the most common degenerative disorders of the spine encountered in clinical practice^[15]. When conservative treatment fails to provide adequate symptom relief, lumbar fusion surgery is often indicated^[16]. Conventional open lumbar fusion surgery is associated with substantial soft tissue trauma. With continuous advances in spinal endoscopic techniques, minimally invasive lumbar fusion procedures have progressively replaced traditional open surgery and have become the predominant surgical approach in clinical practice^[17, 18]. Accordingly, whether different minimally invasive fusion techniques differ in terms of perioperative surgical trauma, early bone integration during fusion, and preservation of paraspinal musculature—while maintaining comparable clinical efficacy—remains to be further elucidated.

In this single-center retrospective study, we compared the clinical outcomes and radiological characteristics of UBE-TLIF and MIS-TLIF for the treatment of single-level mild DLS. The results indicated that both surgical techniques achieved satisfactory clinical outcomes; however, differences were observed with respect to early postoperative pain relief, perioperative parameters, early TBR during fusion, and preservation of paraspinal muscle structure. These findings suggest that different minimally invasive fusion techniques may offer distinct advantages in terms of soft tissue injury and the early biological processes involved in spinal fusion.

Comparable overall clinical efficacy of minimally invasive fusion techniques

In the present study, both groups showed improvements in VAS scores for low back pain and leg pain, as well as ODI scores, at all postoperative follow-up time points compared with preoperative values. Except for the low back pain VAS score at postoperative day 3, no statistically significant differences were observed between the two groups in the remaining VAS or ODI comparisons. These findings indicate that UBE-TLIF and MIS-TLIF provide comparable mid-term efficacy in terms of neural decompression and functional improvement. This result is consistent with previous studies comparing MIS-TLIF and UBE-TLIF in the treatment of lumbar spondylolisthesis and degenerative lumbar spine disorders [19–21].

In addition, no significant difference in the modified MacNab scores was observed between the two groups, indicating that both surgical techniques achieved satisfactory clinical outcomes from the perspectives of patient-reported satisfaction and recovery of daily function. These findings further suggest that, when adequate decompression and spinal stability are ensured, the two minimally invasive approaches yield comparable mid-term functional outcomes.

Differences in early postoperative low back pain and potential soft tissue injury mechanisms

Although comparable mid-term outcomes were achieved, the results of this study demonstrated that the low back pain VAS score at postoperative day 3 was significantly lower in the UBE-TLIF group than in the MIS-TLIF group, suggesting a distinct advantage of UBE-TLIF in early postoperative pain relief. Previous studies have indicated that early postoperative low back pain is closely associated with the extent of paraspinal muscle injury, the pressure exerted by retractors, and local inflammatory responses [19,22,23].

A possible explanation for this finding is that, although MIS-TLIF utilizes the Wiltse intermuscular approach, it relies on tubular retractors to maintain the surgical field. Prolonged radial retraction may result in ischemia of the multifidus muscle and impairment of local microcirculation, which can subsequently activate oxidative stress–related pathways and lead to muscle injury, thereby contributing to early postoperative pain [23, 24]. In contrast, the initial working space in UBE-TLIF is established within the multifidus triangle, a potential anatomical interval between the multifidus muscle and the posterior

lamina–spinous process complex. The use of a biportal endoscopic system allows for the creation of a dynamic operative corridor without the need for fixed retractors, thereby substantially reducing compression-related ischemic injury to the paraspinal musculature^[25–27].

In addition, continuous saline irrigation under endoscopic visualization not only facilitates a clear operative field but may also attenuate postoperative inflammatory responses by reducing local tissue temperature, diluting inflammatory mediators, and minimizing compression of microvascular structures^[19, 26, 28]. Collectively, these mechanisms may account for the observed advantage of UBE-TLIF in early postoperative low back pain control.

Explanations for differences in perioperative parameters

In the present study, the UBE-TLIF group exhibited significantly lower intraoperative blood loss and a shorter length of hospital stay compared with the MIS-TLIF group. These findings are highly consistent with the results reported by Huang et al. [29] and several other studies. The magnified endoscopic view enables more precise identification of the epidural venous plexus and active bleeding sites, allowing for more efficient hemostasis using radiofrequency coagulation and thereby reducing both overt and occult blood loss [20,30]. Moreover, the UBE technique achieves accurate endoscopic decompression through a biportal approach, which may result in less iatrogenic injury to the paraspinal muscles and facet joints [31].

However, the operative time was significantly longer in the UBE-TLIF group. Under endoscopic conditions, extensive identification of anatomical landmarks, thorough decompression, meticulous endplate preparation, and percutaneous pedicle screw fixation are all time-consuming procedures. In addition, effective control of intraoperative bleeding and maintenance of a clear surgical field are critical factors that further influence operative duration [30]. Previous studies have suggested that this phenomenon is largely attributable to a pronounced learning curve associated with the UBE technique. Statistical analyses indicate that operative efficiency improves substantially after approximately 34 cases, particularly during endoscopic endplate preparation and intervertebral disc manipulation [32]. With increasing surgical experience, operative time can be progressively reduced; therefore, the longer operative time observed in the present study may not necessarily reflect a long-term disadvantage of UBE-TLIF.

Significance of trabecular bone remodeling (TBR) as a novel indicator of early osseointegration during spinal fusion

Conventional assessment of spinal fusion primarily relies on fusion grading systems or the presence of continuous bony bridging; however, these methods are limited in their ability to capture the dynamic biological processes occurring in the early phase of fusion. Vertebral endplate cysts (VECs) have traditionally been regarded as predictive indicators of nonunion or delayed union after fusion surgery. When micromotion occurs at the instrumented segment, stress-related microfractures or bone resorption may be induced, leading to the formation of VECs. Nevertheless, owing to their potential

reversibility, VECs cannot directly predict successful fusion and instead require serial CT examinations to monitor changes in cyst size over time ^[33, 34] .

Segi et al. ^[35] were the first to propose TBR as a novel radiological indicator of early osseointegration following lumbar interbody fusion. TBR was defined as a high-density (high Hounsfield unit) trabecular pattern extending vertically or obliquely from the interface between the interbody cage and the vertebral endplate toward the pedicle screw. This radiological feature can be observed as early as 3 months after fusion surgery and is considered to reflect effective early osteoconduction between the cage and adjacent vertebral bodies. Their study demonstrated that patients with positive early TBR findings had a significantly lower incidence of vertebral endplate cysts at 1 year postoperatively ($P = 0.003$), while severe complications such as pedicle screw loosening requiring revision surgery and pseudarthrosis were observed exclusively in the TBR-negative group. Collectively, these findings suggest that TBR may serve as a positive imaging marker of initial postoperative stability and the early activation of osseointegration^[35].

In the present study, the UBE-TLIF group exhibited a significantly higher positive rate of TBR at 3 months postoperatively compared with the MIS-TLIF group, indicating that a microenvironment conducive to osseointegration may be established at an earlier stage. A plausible explanation is that, relative to MIS-TLIF, UBE-TLIF enables more thorough removal of the cartilaginous endplate under direct endoscopic visualization while maximally preserving the integrity of the bony endplate, with punctate endplate bleeding serving as an intuitive indicator of adequate endplate preparation ^[8]. This approach may facilitate the formation of an optimal graft–endplate interface and improve mechanical load transfer between the interbody cage and the adjacent bony surfaces.

Although the follow-up period in this study is limited, the higher early TBR positivity rate in the UBE-TLIF group, which aligns with its trend toward a higher fusion rate at 6 months, suggests that TBR may serve as a promising imaging biomarker for predicting the fusion progression.

Imaging Evidence of Paraspinal Muscle Structural Changes and Their Clinical Significance

The paraspinal muscles, particularly the multifidus, play a crucial role in maintaining lumbar segmental stability, facilitating sagittal rotation, and controlling fine movements^[36, 37]. Sihvonen et al. ^[38] indicated that postoperative paraspinal muscle atrophy is closely associated with iatrogenic denervation of these muscles during lumbar surgery. Previous studies have confirmed that atrophy and fat infiltration of the multifidus muscle are significantly correlated with chronic low back pain, functional impairment, and unfavorable postoperative outcomes^[39–41] .

Magnetic resonance imaging (MRI) serves as an excellent modality for soft tissue differentiation. In contrast to CT, it does not expose patients to ionizing radiation, offering a safer method for the quantitative and qualitative assessment of muscles. MRI is superior to CT in discriminating fat

infiltration among muscle fibers, particularly in the context of atrophic changes^[42]. Axial MRI scans are a reliable tool for evaluating multifidus morphology, utilizing established grading methods such as fat infiltration rate or total CSA to assess muscle quality^[43].

In the present study, quantitative MRI analysis demonstrated that at 12 months postoperatively, the UBE-TLIF group had significantly lower rates of multifidus CSA atrophy and fat infiltration compared with the MIS-TLIF group. These findings suggest a potential long-term advantage of UBE-TLIF in preserving paraspinal muscle integrity. The underlying mechanisms may include avoidance of prolonged retractor-induced muscle ischemia, reduced soft-tissue dissection, and better preservation of local neurovascular supply—factors that are inherently less optimized in the MIS-TLIF approach [20,22]. Furthermore, the lower rates of multifidus atrophy and fat infiltration observed in the UBE-TLIF group may, at least in part, account for its more favorable early clinical presentation characterized by reduced pain at postoperative day 3 and a quicker recovery trajectory.

Limitations

This study has several inherent limitations. First, as a single-center retrospective analysis, it is inevitably subject to selection bias and potential confounding factors, despite the comparability of baseline characteristics between the two groups. Second, the operative time and some perioperative parameters for UBE-TLIF may have been influenced by the learning curve associated with the technique, which could introduce a degree of interference in the comparative results. Third, the follow-up period was primarily focused on the early to mid-term postoperative phase, which is insufficient to comprehensively evaluate long-term fusion stability, adjacent segment degeneration, and sustained functional outcomes.

From an imaging perspective, TBR, as a newly proposed indicator of early osseointegration, currently lacks a unified quantitative standard for its interpretation. Furthermore, this study did not correlate the observed TBR findings with vertebral endplate cysts (VECs) to discuss their combined impact on the fusion process.

Future research should involve multicenter, prospective studies with longer follow-up durations and standardized imaging evaluation protocols to further validate the conclusions drawn from this study.

Conclusions

This study compared the clinical and radiological efficacy of UBE-TLIF and MIS-TLIF for the treatment of single-level mild degenerative lumbar spondylolisthesis. The results demonstrate that both techniques achieved comparable and satisfactory pain relief and functional improvement at mid-term follow-up. Compared with MIS-TLIF, UBE-TLIF demonstrated advantages in terms of early postoperative pain relief, reduced intraoperative blood loss, shorter hospital stay, superior preservation of paraspinal muscle structure, and more favorable early trabecular bone remodeling. These findings suggest that UBE-TLIF may be more conducive to minimizing soft tissue injury and promoting the early biological processes of spinal fusion. Although UBE-TLIF was associated with a longer operative time, this difference is likely

attributable to its associated learning curve. Both techniques are effective for mild degenerative lumbar spondylolisthesis, with UBE-TLIF showing potential benefits in facilitating early recovery and optimizing the fusion environment, thereby providing valuable evidence to inform clinical decision-making regarding minimally invasive fusion techniques.

Abbreviations

UBE	Unilateral Biportal Endoscopy
UBE-TLIF	Unilateral Biportal Endoscopic Transforaminal Lumbar Interbody Fusion
MIS-TLIF	Minimally Invasive Transforaminal Lumbar Interbody Fusion
TLIF	Transforaminal Lumbar Interbody Fusion
DLS	Degenerative Lumbar Spondylolisthesis
VAS	Visual Analog Scale
ODI	Oswestry Disability Index
TBR	Trabecular Bone Remodeling
VECs	Vertebral Endplate Cysts
CSA	Cross-Sectional Area
FI	Fat Infiltration
MF	Multifidus
MRI	Magnetic Resonance Imaging
CT	Computed Tomography
BMI	Body Mass Index

Declarations

Ethics approval and consent to participate

This study protocol was approved by the Ethics Committee of Wuxi People’s Hospital(2025010) before data collection and analysis. The research adhered to the principles of the Declaration of Helsinki, and informed consent was obtained from all patients for MIS-TLIF or UBE-TLIF surgery. As this investigation is not a prospective clinical study assessing health outcomes, a clinical trial number is not applicable.

Consent for publication

Not applicable

Availability of data and materials

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

Competing interests

The authors declare no competing interests.

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Authors' contributions

Wen and Yang completed the data analysis and wrote the manuscript text. Gao checked the results and revised the manuscript. Wen prepared the figures and the tables. Zhao designed this project. All authors reviewed the manuscript.

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Figures

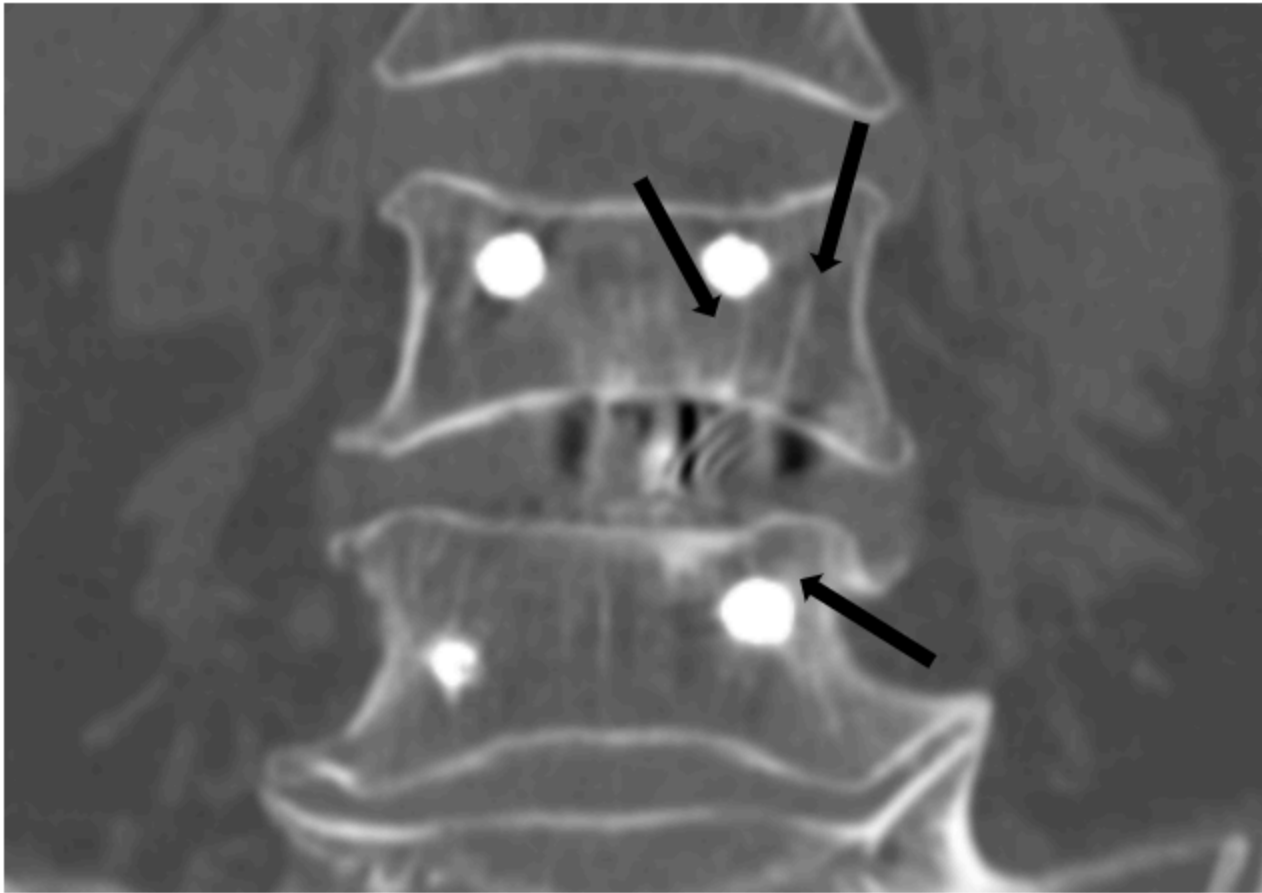


Figure 1

TBR: vertically or obliquely oriented high-density trabecular bone extending from the contact area between the interbody cage and the vertebral endplate toward the pedicle screws)

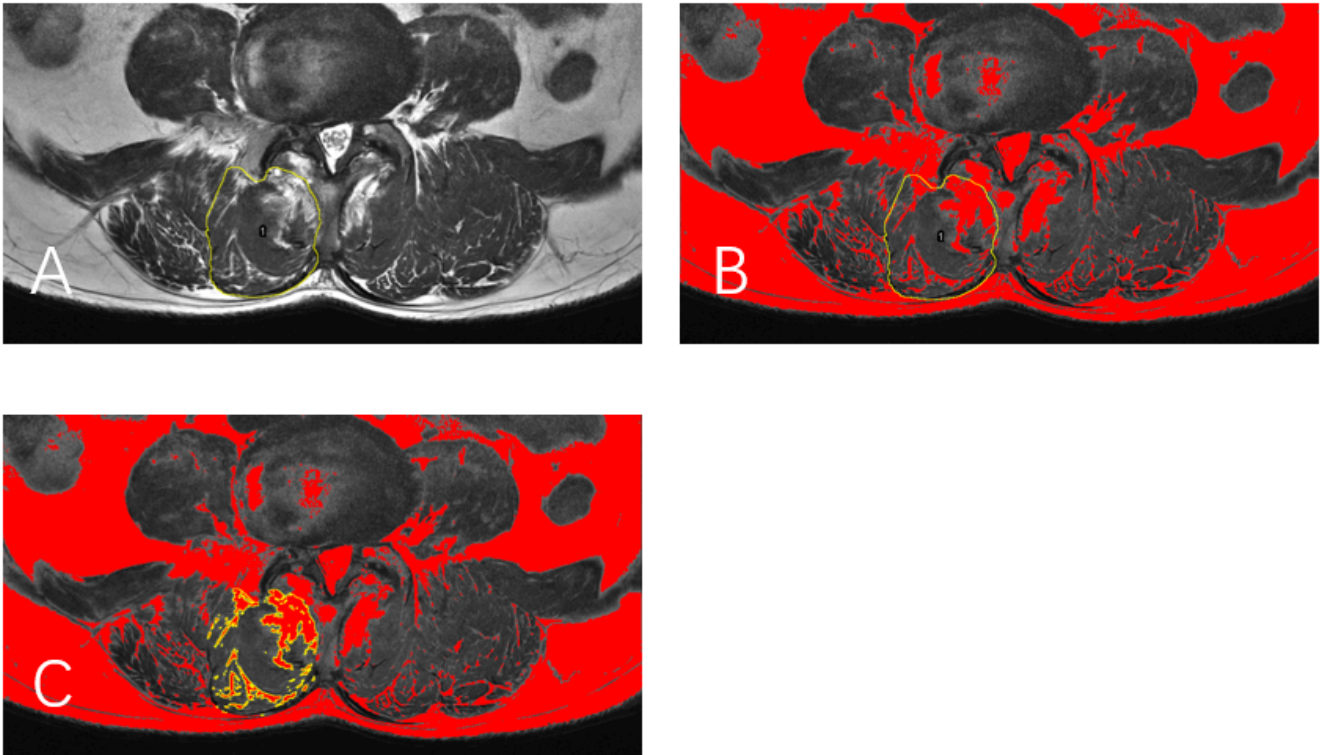


Figure 2

Quantitative assessment of paraspinal muscle CSA and FI on MRI using ImageJ. **A:** CSA of the multifidus muscle; **B:** threshold-based segmentation to identify adipose tissue; **C:** intramuscular fat within the multifidus muscle.

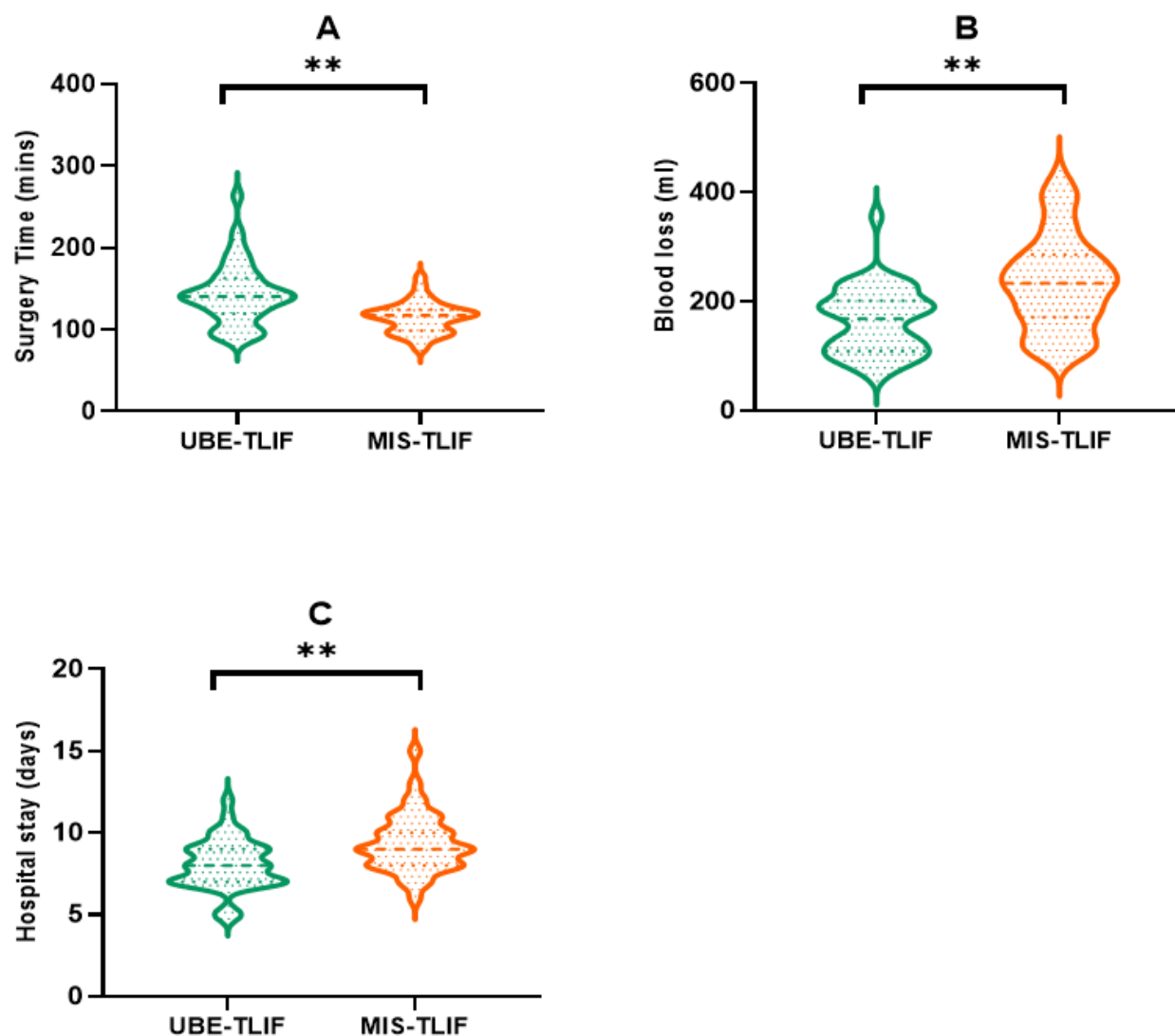


Figure 3

Comparison of perioperative conditions. **A:** Comparison of surgical time. **B:** Comparison of blood loss. **C:** Comparison of hospital stays. Note: **P < 0.01 compared with the control group.

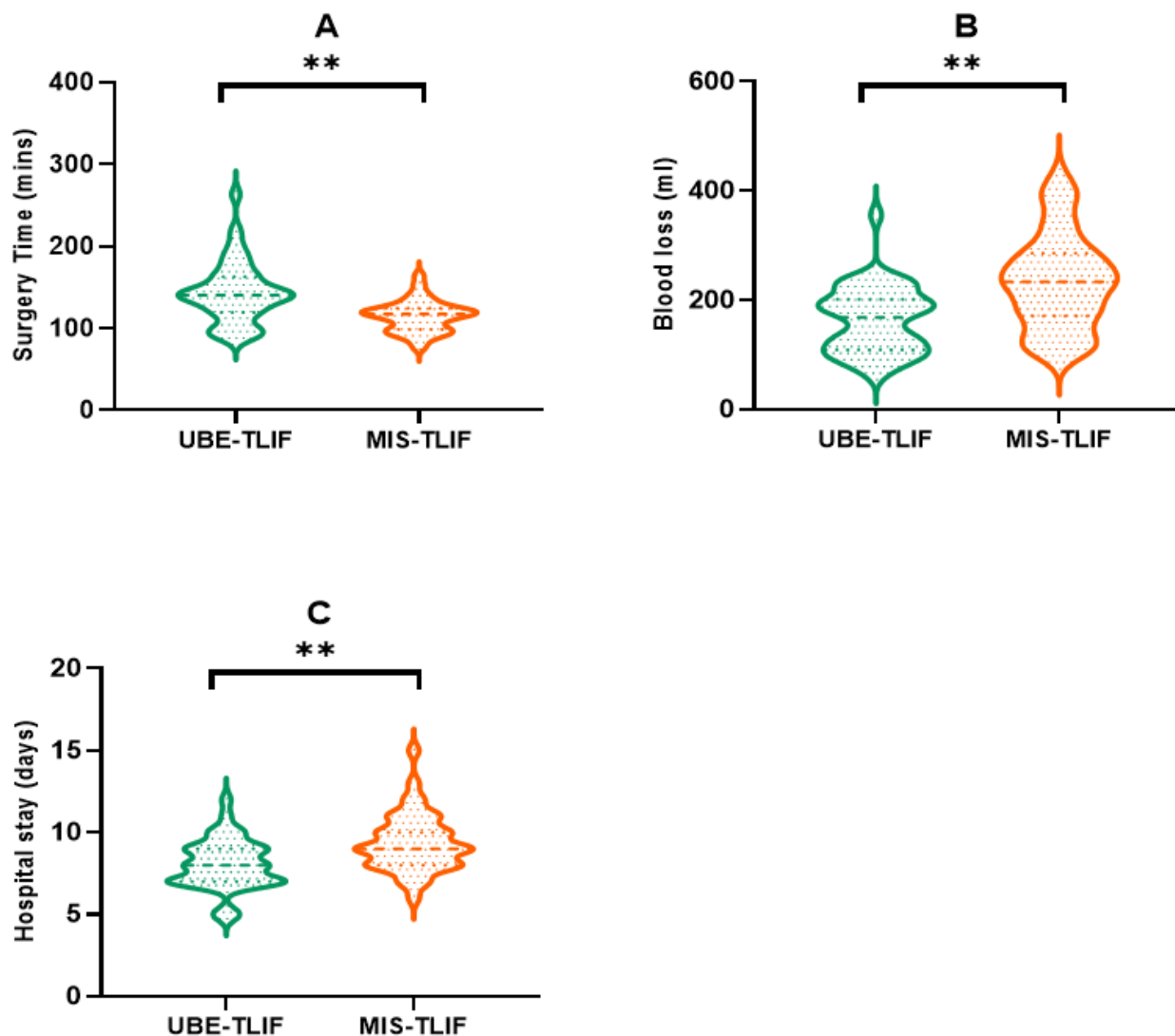


Figure 4

Comparison of Preoperative and Postoperative Scale Scores Between the Two Groups . A-B: VAS scores for back pain and leg pain, respectively, before surgery and at postoperative follow-up.C: ODI score before surgery and at follow-up.

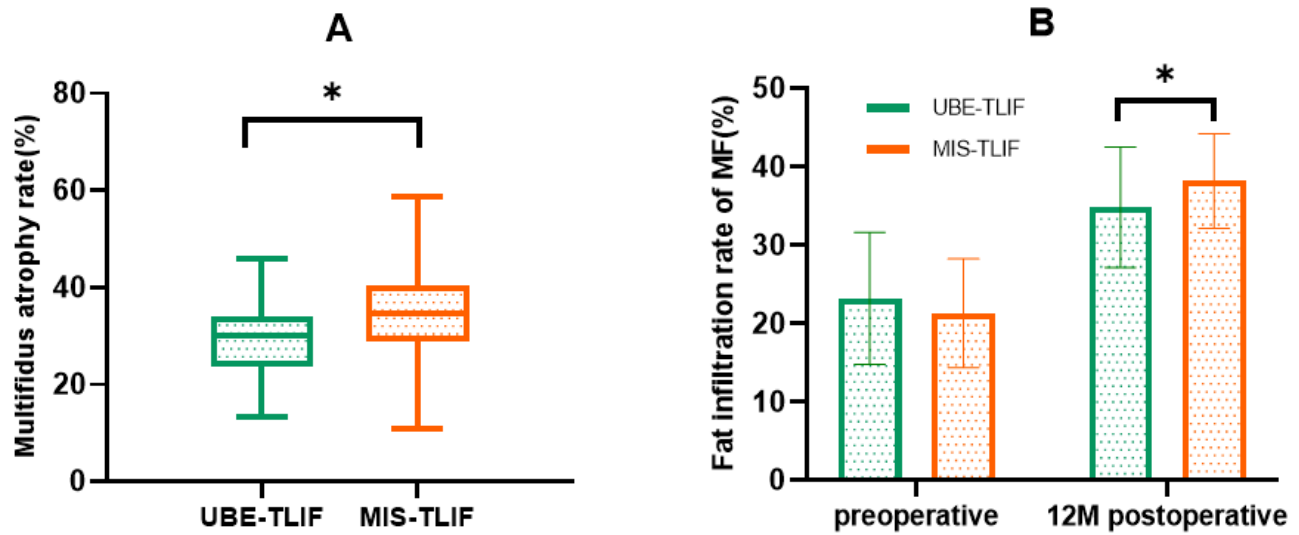


Figure 5

Comparative analysis of muscle characteristics changes in the MF.**A**: MF atrophy rate 12 months after surgery.**B** :The FI rate of MF before the operation and 12 months after the operation.