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RESEARCH

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Percutaneous endoscopic unilateral laminotomy and bilateral decompression improves gait quality and stance balance in patients with lumbar spinal stenosis: a retrospective cohort study

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Abstract

Background Percutaneous endoscopic unilateral laminotomy and bilateral decompression (Endo-ULBD) has been applied to patients with lumbar spinal canal stenosis (LSS). However, it remains unclear whether gait and postural balance in LSS patients fully recover to normal levels following ULBD surgery.

Methods This retrospective study included 60 symptomatic LSS patients (LSS group) and 60 healthy age-matched adults (control group). The LSS group was assessed at four time points: preoperatively, 3, 6, and 12 months postoperatively. Evaluations included the Visual Analog Scale (VAS) and Oswestry Disability Index (ODI) scores, as well as assessments of gait and balance. The control group underwent gait and balance evaluations on the day of recruitment.

Results The LSS group showed significant improvement in VAS and ODI at 3, 6, and 12 months after ULBD surgery ($p < 0.05$). Cadence improved at 3 months postoperatively, while walking speed, stride length, and double support duration improved at 6 months postoperatively. At 12 months postoperatively, there was no significant difference in gait spatiotemporal parameters between the LSS group and the healthy control group ($p > 0.05$). Preoperatively, the LSS group exhibited differences in COP path length and 90% COP postural sway area compared to the control group. Postoperatively, there was no significant improvement in COP path length at any time point. However, there were differences in 90% COP postural sway area at 12 months after surgery compared to the preoperative and control groups.

Conclusion LSS patients showed significant improvement in gait after ULBD surgery, with gait parameters comparable to those of healthy controls at 12 months. While balance stability improved at 12 months, it remained inferior to that of age-matched healthy controls, indicating that postoperative balance training is necessary for full recovery.

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Trial registration This study was a single-center retrospective cohort study, approved by the Ethics Committee of the First Affiliated Hospital of Anhui Medical University (Ethical Application Reference: PJ2023-07-13 Anhui, China) and was registered at the Chinese Clinical Trial Registry at 20/06/2023 (ChiCTR2300072649). The research was conducted in accordance with the Declaration of Helsinki and clinical practice guidelines.

Keywords Lumbar spinal stenosis, Endoscope, Gait, Center of pressure (COP), Balance control

Background

Lumbar spinal stenosis (LSS) is a common disease in the elderly, with prevalence estimates ranging from 1.7 to 13.1% [1]. The hallmark clinical features of LSS include neurogenic claudication, characterized by radiating pain in the buttocks and lower extremities. These symptoms are exacerbated by standing or walking and relieved by lumbar flexion, sitting, or lying down [2]. Surgical intervention is recommended for patients with long-standing, symptomatic LSS who have failed conservative treatment [3]. Currently, laminectomy with preservation of the facet joint is considered the gold standard surgical treatment [4] for LSS. However, traditional open surgery, which requires a larger incision, can result in damage to anatomical structures such as muscles and ligaments, leading to potential postoperative complications, including pain, muscle atrophy, iatrogenic spinal instability, adjacent segment degeneration, and blood loss [5].

In response to these challenges, there has been a growing focus on minimally invasive techniques. Over the past few decades, surgeons have increasingly adopted procedures that involve smaller incisions and reduced surgical trauma, such as endoscopic spinal surgery. In recent years, percutaneous endoscopic unilateral laminotomy and bilateral decompression (Endo-ULBD) has been increasingly applied to LSS patients. This technique decompresses only one side of the lamina while achieving bilateral decompression, preserving the spinous process, nerve roots, and contralateral lamina, thereby minimizing damage to the posterior spinal structures and reducing the risk of subsequent spinal instability [6].Studies have demonstrated that Endo-ULBD reduces intraoperative trauma, blood loss, and recovery time, without compromising the quality or extent of bone decompression [7, 8], yielding clinical outcomes comparable to open surgery [9]. As a result, minimally invasive surgery has gained popularity as a treatment for LSS.

The surgical outcomes of LSS are commonly evaluated through patient-reported outcomes [10], which can be influenced by factors such as the patient's educational level. Therefore, it is important to include objective measures in the assessment of postoperative results.Changes in sensory and proprioceptive function due to lumbar nerve root compression are associated with balance control disorders in LSS patients [11]. Additionally, spinal deformities, muscle weakness, and delayed activation of deep trunk muscles may impair balance [11].Gait analysis is widely used in orthopaedics and neurosurgery to assess both kinematic and spatiotemporal parameters [12, 13]. Traditionally, plantar pressure systems have been used to analyze gait, with center of pressure (COP) movement serving as a key indicator of static balance [14].Previous research has shown that LSS leads to abnormal gait characteristics and balance deficitst [14, 15], with LSS patients exhibiting slower gait velocity, shorter stride length, and increased COP displacement compared to healthy controls [16, 17].Further studies have demonstrated improvements in gait [13] and balance [18] following open decompression surgery.However, it remains unclear whether gait and postural balance in LSS patients fully return to normal after ULBD surgery. Therefore, the objective of this study was to evaluate the postoperative changes in gait and balance in LSS patients who underwent ULBD surgery, and to compare these changes with those in age-matched healthy controls. We hypothesized that while gait quality and balance during stance would improve after surgery, they would still differ from those of normal individuals.

Methods

This study was a single-center retrospective cohort study, approved by the Ethics Committee of the First Affiliated Hospital of Anhui Medical University (Ethical Application Reference: PJ2023-07-13 Anhui, China) and was registered at the Chinese Clinical Trial Registry at 20/06/2023 (ChiCTR2300072649). The research was conducted in accordance with the Declaration of Helsinki and clinical practice guidelines. All patients had signed informed consent for the procedure.

Study design and population

Patients who underwent ULBD between 2019 and 2022 at the First Affiliated Hospital of Anhui Medical University were recruited into LSS group. The inclusion criteria were: (1) age > 40 years; (2) single level LSS; (3) clinical symptoms of LSS, including intermittent neurological claudication, confirmed by imaging; (4) failure of conservative treatment for at least 3 months. Exclusion criteria were: (1) reluctant to participate in the study; (2) other musculoskeletal disorders, such as lumbar disc herniation, degenerative spondylolisthesis, bone metastasis, or paresis of the knee extensors and hip flexors; (3) mental or psychological disorders, including schizophrenia and depression; (4) inability to complete the ODI or walk ≥ 10 m independently.

Age-matched healthy individuals were recruited as the control group from the community. Inclusion criteria were: (1) age > 40 years; (2) pain-free status; (3) no functional limitations.Exclusion criteria were: (1)neurological or motor system disorders that affect gait and balance. (2) history of cerebrovascular disease, vestibular disorders, or visual impairments that affect walking; (3) lower limb conditions, such as knee arthritis or previous injuries; (4) history of lumbar or abdominal surgery; (5) co-existing muscular or neurogenic disorders.

Surgical procedure

The patient was placed in the prone position, and an 8-mm longitudinal incision was made 2–3 cm from the posterior midline. A guide rod was inserted vertically to the target vertebral space, followed by the placement of the working channel and endoscope. The inner edges of the facet joints were identified. A visual trepan was then used to excise part of the inner edge of the lower articular process. The excision was extended from the attachment point of the ligamentum flavum towards the cephalad ring. The working sleeve was then repositioned at the junction of the vertebral lamina and the spinous process root for further removal. The procedure continued, removing tissue towards the opposite lower articular process and extending to the ligamentum flavum attachment point. The opposite upper articular process was excised to the attachment point of the caudal ligamentum flavum. The same approach was repeated on the initial side, removing the inner portion of the upper articular process, from the upper edge and root of the lower vertebral lamina to the ligamentum flavum attachment point. At this stage, the ligamentum flavum became loose and was detached. The free ligamentum flavum was removed using nucleus pulposus forceps, and the intervertebral disc was carefully examined. If intervertebral disc herniation was present, it was thoroughly excised using nucleus pulposus forceps [6] (Fig. 1).

Postoperative pain relief, anti-inflammatory treatment, and promotion of wound healing were administered. The patient wore a waist support and was encouraged to get out of bed 24 h after surgery. Verbal instructions were given to walk moderately and avoid strenuous exercise in the short term. No specialized rehabilitation exercises were prescribed by a rehabilitation physician.

Study measures

Data collection

Patients in the LSS group underwent baseline measurements upon admission to the clinic before surgery. These assessments included VAS scores, ODI scores, gait, and static balance evaluations, which were performed 1 day preoperatively, and at 3, 6, and 12 months postoperatively in the outpatient clinic. For the control group, assessments were performed once, at the time of enrollment.

ODI assessment

The Oswestry Disability Index (ODI) is a questionnaire used to assess a patient's subjective dysfunction. It consists of ten questions covering pain intensity, ability to perform daily personal care, lifting, walking, sitting, standing, sleeping, sexual activity, social life, and traveling. The evaluation is based on the patient's level of pain and subjective scoring. A lower score indicates better lumbar function [19].

Surgical efficacy assessment

Surgical efficacy was evaluated using the modified MacNab criteria at 3, 6, and 12 months post-surgery. These criteria were divided into four categories: excellent, good, fair, and poor.

- Excellent: Complete symptom resolution, with return to original work and life activities.
- Good: Mild symptoms with slight activity restrictions, but no impact on work or daily life.
- Fair: Alleviated symptoms with activity restrictions, affecting normal work and life.

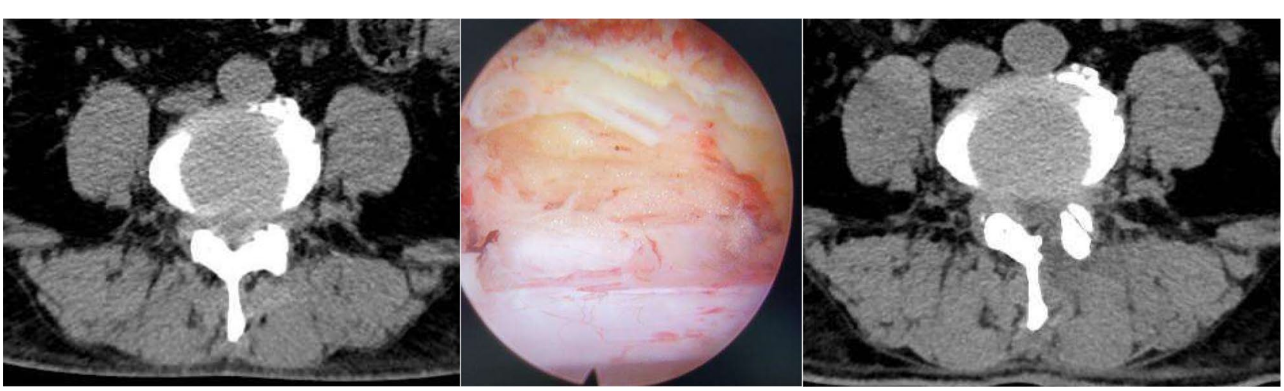

Fig. 1 Preoperative CT, intraoperative endoscopic imaging, and postoperative CT of ULBD patients

- Poor: No improvement, or worsening of symptoms compared to pre-treatment [20].

Gait function assessment

In a quiet indoor environment, subjects walked at a self-selected pace [21], starting 2 m in front of a walkway composed of pressure plates, walking along the centerline of the trail, and continuing for 2 m beyond the walkway to ensure consistent speed. One experimenter monitored the passage, without any physical contact or verbal prompts, except for providing psychological comfort. On the day of the test, two pretests were conducted to familiarize the subjects with the procedure and precautions. Each subject then completed three tests, with a 5-minute rest between each to prevent fatigue. The average of the three tests was used for statistical analysis (Fig. 2).

The P-WALK system (BTS, Milan, Italy) was used to analyze gait and record the center of pressure (COP). The system consists of four force-measuring plates with pressure sensors (dimensions: 700 mm × 10 mm × 500 mm) arranged in a row, forming a 2 m long and 0.5 m wide walkway. It operates based on distributed array pressure sensors, converting force signals into digital data, which are transmitted to a computer. The system, through the G-STUDIO software (Version 2.0), automatically analyzes spatiotemporal and pressure parameters, processes the data, and generates a comprehensive evaluation report.

Static balance assessment

To eliminate the influence of vision on balance ability, all subjects performed the static balance test with their eyes closed. Subjects adopted the Romberg posture [22](feet together) while standing barefoot on the pressure plate, with arms naturally resting at their sides (Fig. 3). Stability parameters were recorded once the subjects achieved a consciously stable posture. Each subject performed three 30-second trials. The positions of the feet were marked to ensure consistency across tests. To avoid COP signal drift, the force platform was calibrated before each trial by resetting the unloaded platform. During the trials, none of the participants took painkillers or sedatives.

COP path length refers to the length of COP swing path in 30s (Fig. 4), and 90% COP postural sway area refers to the sway area of the 90% confidence ellipse. Increased COP path length and 90%COP sway area represent decreased balance stability.

Statistical analysis

Statistical analyses were conducted using SPSS 25.0 software. Measurement data were expressed as mean ± standard deviation($x \pm SD$). Shapiro-Wilk test was used to assess data normality. A one-way repeated-measures ANOVA was performed to compare outcomes at different time points, with Tukey's method used to correct for multiple comparisons. The rank-sum test was applied for ranked data, while an independent-samples t-test was used for comparisons between the LSS and control groups. The χ^2 test was employed for categorical data. A p-value of < 0.05 was considered statistically significant.

Results

A total of 167 participants were initially enrolled in the study, with 47 excluded. Among these, 12 participants did not meet the inclusion criteria. Although they reported no history of neurological or lower limb disorders affecting gait, significant abnormalities were observed during gait testing. Participants who were found to have knee

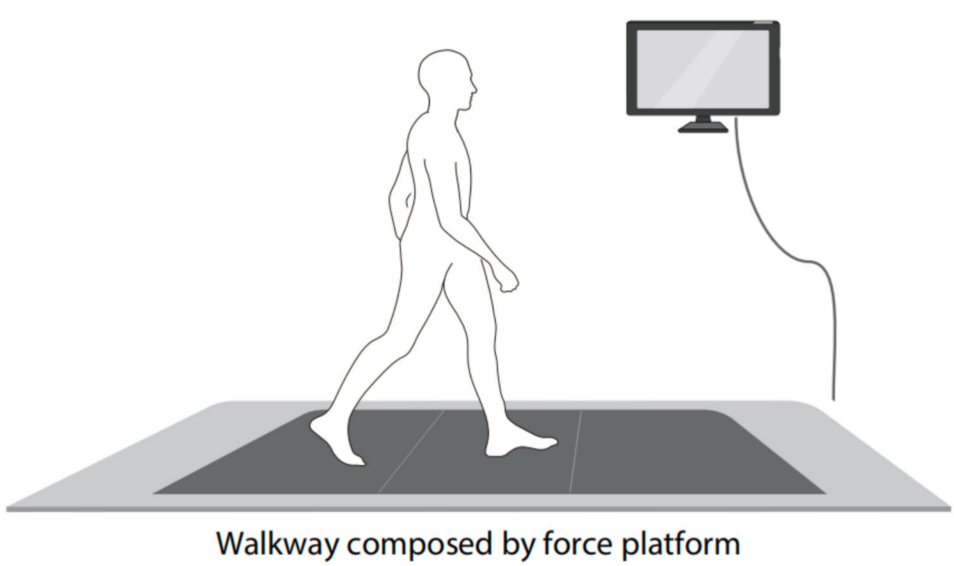

Fig. 2 Gait test

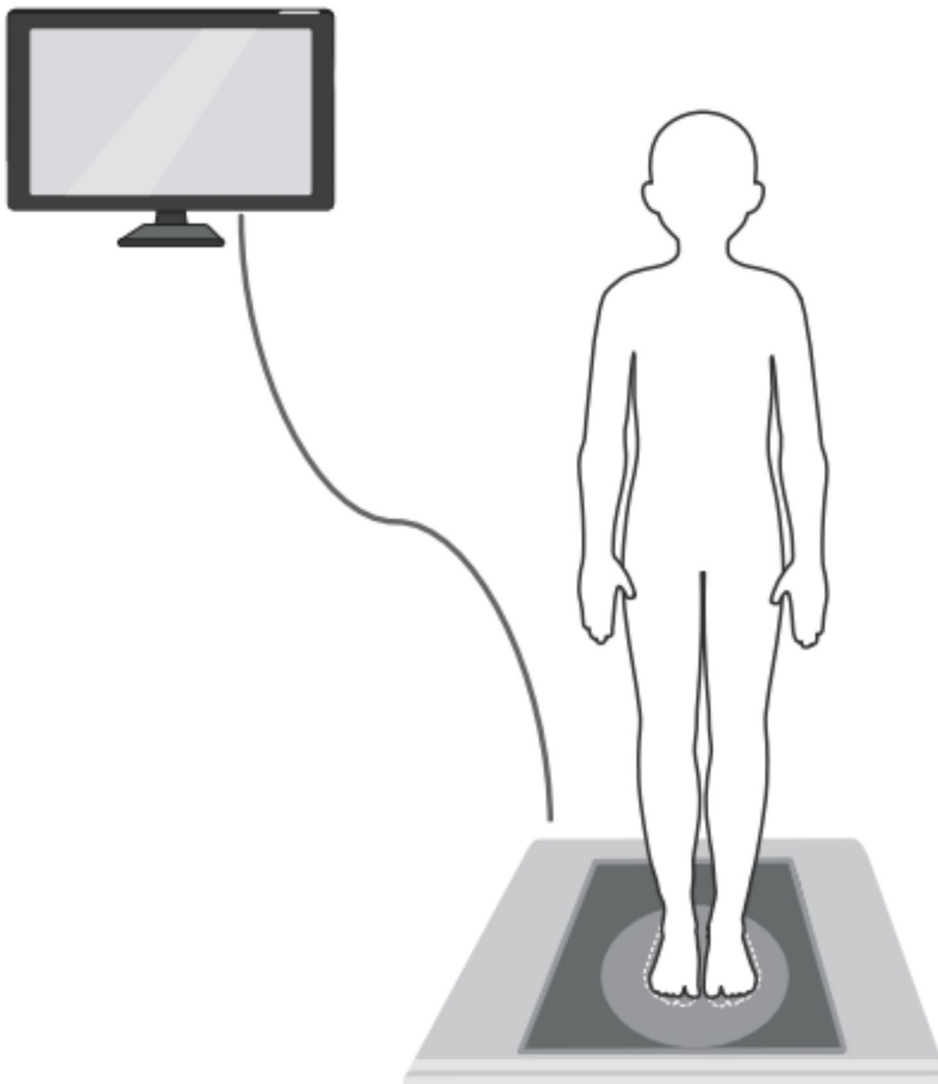

Fig. 3 Postural balance test

arthritis, spinal disorders, or other conditions during the physical examination were excluded. Additionally, 23 participants declined to participate in the study. Another 12 participants were excluded for various reasons, including loss to follow-up ($n = 10$), one healthy participant erroneously completing a static balance test with eyes open due to a technical error, and one participant's data being unavailable due to a malfunction of the force-measuring plates. Ultimately, 120 participants were included in the final analysis, with 60 in the LSS group and 60 in the control group (Fig. 5). Furthermore, no difference was observed in any of the measured baseline variables in both groups, including age, gender ratio, BMI, and other demographic characteristics(Table 1).

Pain and functional assessment

Figure 6 shows the changes in pain and functional assessment at all time points for the LSS group. The average VAS score of the LSS group before surgery was 62.14, which decreased to below 27.18 at 3 months after ULBD surgery, indicating a significant improvement in pain relief. Additionally, compared to baseline, the LSS patients experienced a 49.5% decrease in ODI score at 3 months postoperatively, demonstrating a notable improvement in functional outcomes after ULBD surgery.Compared to baseline, there were significant improvements in VAS and ODI at 3 months, 6 months, and 12 months postoperatively ($P < 0.05$). Furthermore, compared to 3 months after surgery, both ODI and VAS scores showed significant improvement at 6 months and

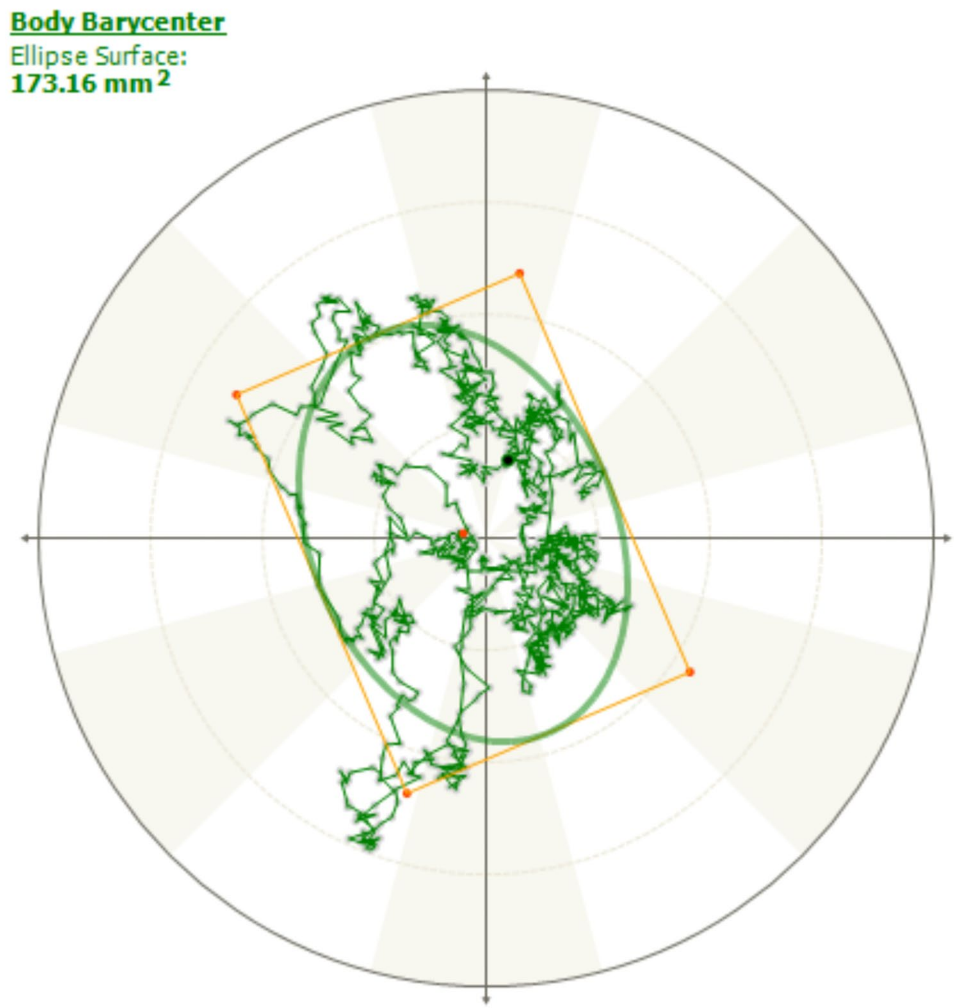

Fig. 4 90% COP postural sway area.This figure shows the movement trajectory of the patient's center of pressure within 30 s of standing with their eyes closed, and the ellipse includes 90% of the center of pressure trajectory

12 months for the LSS group ($P<0.05$). There were also significant changes observed between 6 months and 12 months postoperatively ($P<0.05$).

The excellent and good rate of the modified MacNab criteria at 12 months after surgery was 85% (Table 2).

Gait Spatiotemporal parameters

Figure 7 demonstrates significant differences in walking speed, stride length, cadence, and double support duration between the LSS group before surgery and the healthy control group ($P<0.05$). Postoperatively, there was no significant improvement in walking speed, stride length, and double support duration within three months, but a significant improvement was observed after 6 months ($P<0.05$).Cadence showed a significant improvement at three months postoperatively. At twelve months postoperatively, there were no significant differences in walking speed, cadence, and double support duration between the LSS group and the healthy control group (Tables 3 & 4).

Standing balance assessment

There were significant differences between the LSS group and the healthy control group in COP path length. The COP path length of preoperative LSS group is 853.42 ± 152.71 mm, while the COP path length of control group is 449.28 ± 101.37 mm (Fig. 8). However, there was no significant improvement in COP path length at twelve months postoperatively compared to preoperative group, with a value of 789.24 ± 128.36 mm. In the LSS group, 90% COP postural sway area was 216.33 ± 112.31mm^2, while the control group was 129.73 ± 90.85mm^2. There were obvious differences between the two groups. In the LSS group, 90% COP postural sway area was 166.59 ± 93.63mm2 at twelve months after surgery, which

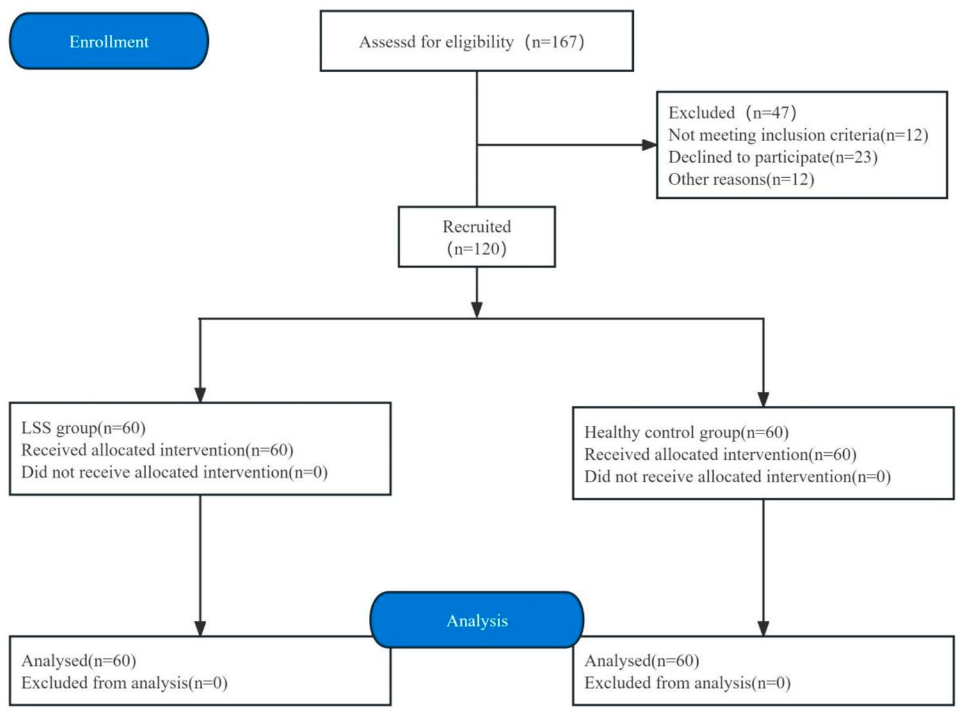

Fig. 5 Flowchart of participant recruitment

Table 1 Demographics characteristics of participants

Characteristic	LSS group (*n* = 60)	Control group (*n* = 60)	*p* value
Sex (male/female)	26/34	28/32	0.71
Age (years)	69.58 ± 10.9	70.58 ± 11.23	0.62
Height (cm)	160.4 ± 8.9	161.8 ± 9.2	0.40
BMI[a] (kg/m2)	25.7 ± 3.1	24.8 ± 2.8	0.10
Diseased segment			
L3/4	5	NA[b]	
L4/5	32	NA	
L5/S1	23	NA	
Narrow type			
Central tube	30	NA	
Intervertebral foramina	14	NA	
Lateral crypt	16	NA	
Stenosis grade			
Grade 1	33	NA	
Grade 2	21	NA	
Grade 3	6	NA	
Dural sac cross-sectional area(cm^2)	0.58 ± 0.13	NA	

Values are mean ± SD or number

LSS = Lumbar spinal stenosis

[a]Body mass index

[b]Not available

was different compared with the preoperative group and nearly returned to the level of the control group ($P < 0.05$).

Discussion

The primary goal of this study was to investigate the changes in gait, posture balance, pain, and functional activities in patients with lumbar LSS after ULBD surgery. We compared these changes with those in age-matched healthy adults. Our results support the hypothesis that postoperative gait, static balance, pain, and functional outcomes (measured by the Oswestry Disability Index, ODI) improved in LSS patients. However, compared to healthy controls, postoperative gait and balance control in LSS patients remained less stable.

Pain and function improved after ULBD surgery

Pain and functional activity in LSS patients significantly improved after ULBD surgery, consistent with findings from other studies. Lee et al. [23]reported a significant decrease in lower limb and lower back pain, with VAS scores improving after ULBD, and a 93.8% excellent-to-good outcome rate according to the modified MacNab criteria at a 2-year follow-up. They concluded that Endo-ULBD is a safe, feasible, and effective surgical option for treating lumbar spinal or lateral recess stenosis. Zhao et al. [6] observed significant improvements in VAS, ODI, and EQ-5D scores at 1 day, 3 months, 6 months, and the last follow-up, with no significant differences in the modified MacNab criteria between ULBD and posterior

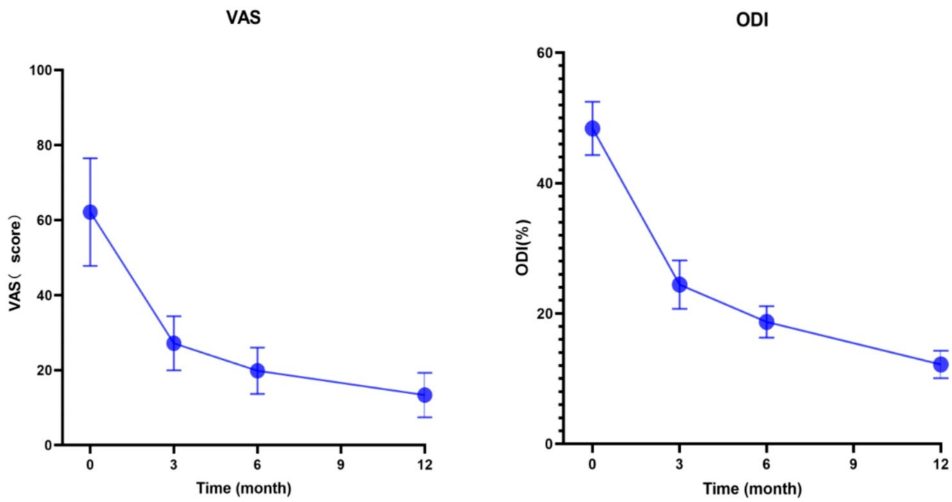

Fig. 6 Change trend of VAS and ODI of 60 patients over time

Table 2 Outcomes as measured by modified Mac Nab criteria

Mac Nab Criteria	3 M, No. (%)	6 M, No. (%)	12 M, No. (%)
Excellent	20 (33.3%)	23 (38.3%)	26 (43.3%)
Good	22 (36.7%)	24 (40%)	25(41.7%)
Fair	10(16.7%)	7(11.7%)	5(8.3%)
Poor	8(13.3%)	6(10%)	4 (6.7%)

lumbar interbody fusion. Markus [24]reported that 85.3% of patients had an excellent-to-fair operative result. McGrath et al. [25] found superior clinical outcomes at 1 year in patients undergoing full-endoscopic surgery compared to those treated with minimally invasive surgery using tubular retractors.Yang et al. found that full-endoscopic techniques, with their small incisions and rapid recovery, can be an alternative treatment for lumbar spinal stenosis, especially in elderly patients with comorbidities. Kim et al. [26] also reported significant reductions in VAS and ODI scores, with good-to-excellent MacNab outcomes in 96% of patients.

In this study, after one year of follow-up, the VAS score decreased from 62.14 ± 14.37 to 13.36 ± 5.92, and the ODI score decreased from 48.37 ± 4.11 to 12.18 ± 2.12. Most patients experienced significant pain relief, and the excellent-to-good operation rate was 85%.The reasons for this improvement may include: (1) ULBD preserves spinal stability by decompressing only the bone structures protruding into the spinal canal, while leaving the contralateral zygapophysial joint, ligaments, and muscles intact; (2) it is minimally invasive, preserving bilateral multifidus muscles and minimizing scar formation on the dura mater; and (3) it allows for high-precision visualization of the responsible nerve root with minimal risk of iatrogenic instability, muscle denervation, atrophy, or postoperative painn [27].

Spatiotemporal gait parameters improved after surgery

Before surgery, walking speed, cadence, and stride length in LSS patients were lower than in healthy individuals, which is consistent with previous studies by Li [15]and Loske [13]. Natarajan's literature review [16] also indicated that LSS patients exhibit slow walking speed, short stride length, and slightly reduced cadence. In our study, LSS patients had increased double support duration compared to normal individuals. This increase in double support duration is often associated with decreased stability, as patients may extend the double support phase to improve stability when walking difficulties arise. We suggest that this prolonged double support duration in LSS patients may reflect a decrease in balance ability.

After ULBD surgery, patients showed significant improvements in walking function, evidenced by increased walking speed, faster cadence, longer stride length, and a shorter double support phase. As nerve root compression was relieved, nerve function gradually recovered, leading to significant gait improvement.Loske et al. [13]also observed similar results, with improved 6-minute walk test performance and faster walking speed post-surgery. Suda et al. [28]reported similar gait improvements and significant increases in walking speed during their 7–8 month follow-up. Our findings suggest that ULBD yields gait improvements similar to those of open decompression surgery. Hiroto et al. [29] observed increased 6-minute walk distance, pain relief, and improved muscle strength following open decompression surgery. We speculate that improved gait is due to increased muscle strength and pain relief post-surgery. However, incomplete recovery of muscle strength and residual pain may explain why some patients' gaits still differ from those of healthy individuals.

In our study, walking speed, stride length, and double support duration showed no significant improvement

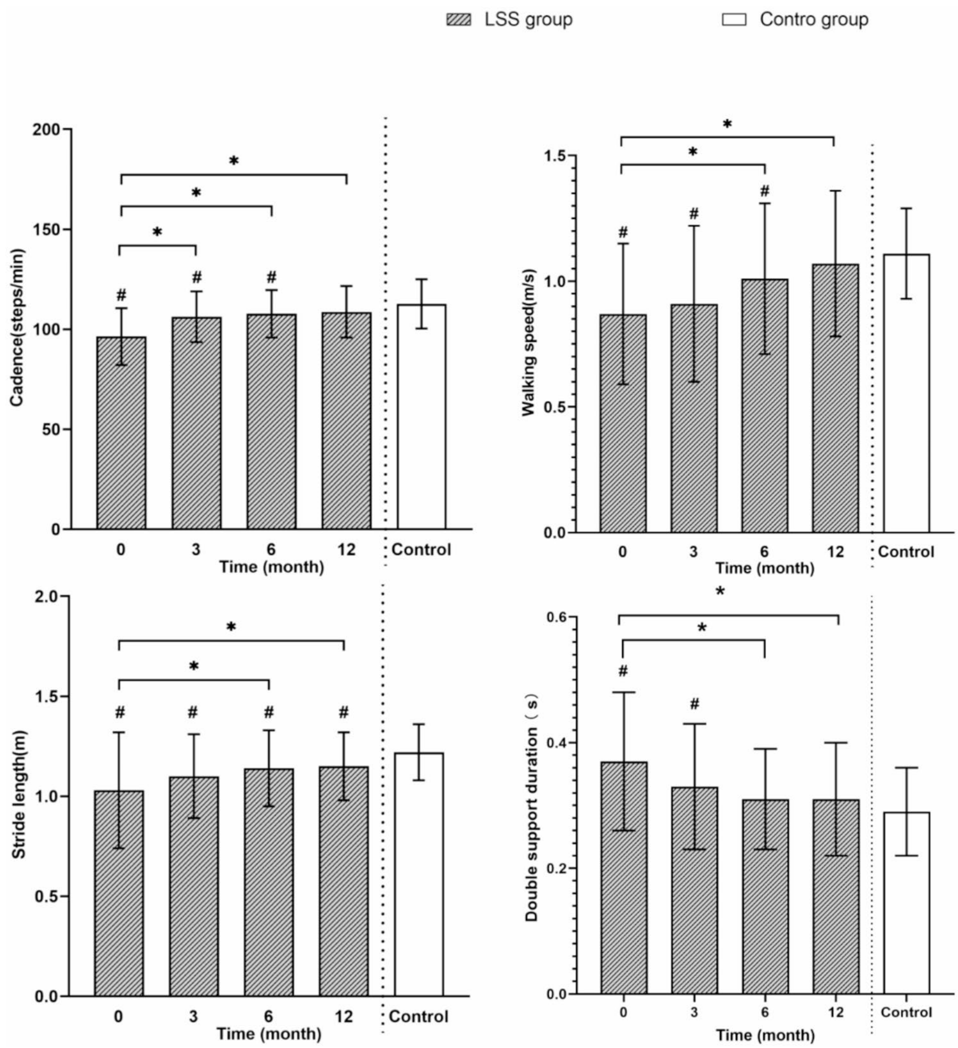

Fig. 7 Spatiotemporal gait parameters. Values are mean ± SD. * Lumbar spinal stenosis within-group comparisons ($P < 0.05$). # Between-group comparisons ($P < 0.05$)

Table 3 Parameters of pain, functional limitations, gait function, and balance ability at baseline, 3-month, 6-month, and 12-month follow-up

mean ± SD (min; max)	Patients with symptomatic LSS				Healthy control subjects (*N* = 60)
	Preoperative	3-month postoperative (*N* = 60)	6-month postoperative (*N* = 60)	12-month postoperative (*N* = 60)	
VAS[a]	62.14 ± 14.37	27.18 ± 7.21	19.82 ± 6.19	13.36 ± 5.92	NA[b]
ODI(%)[c]	48.37 ± 4.11	24.42 ± 3.71	18.72 ± 2.42	12.18 ± 2.12	NA
Walking speed(m/s)	0.87 ± 0.28	0.91 ± 0.31	1.01 ± 0.30	1.07 ± 0.29	1.11 ± 0.18
Cadence (steps/min)	96.33 ± 14.21	106.23 ± 12.73	107.71 ± 11.92	108.72 ± 12.89	112.72 ± 12.31
Stride length (m)	1.03 ± 0.29	1.10 ± 0.21	1.14 ± 0.19	1.15 ± 0.17	1.22 ± 0.14
Double support duration (s)	0.37 ± 0.11	0.33 ± 0.10	0.31 ± 0.08	0.31 ± 0.09	0.29 ± 0.07
COP path length (mm)	853.42 ± 152.71	817.28 ± 142.36	804.65 ± 139.64	794.34 ± 128.36	449.28 ± 101.37
90% COP postural sway area (mm^2)	216.33 ± 112.31	186.29 ± 106.39	172.64 ± 102.57	151.59 ± 97.63	129.73 ± 90.85

Values are mean ± SD

[a]Visual analogue scale

[b]Not available

[c]Oswestry Disability Index

Table 4 Differences in parameters of pain, functional limitations, gait function, and balance ability between assessment points for patients and between patients and control subjects at each assessment

P values	Within patients			Patients vs. control subjects			
	3-month postoperative vs. preoperative	6-month postoperative vs. preoperative	12-month postoperative vs. preoperative	Preoperative	3-month postoperative	6-month postoperative	12-month postoperative
VAS[a]	< 0.0001	< 0.0001	< 0.0001	NA[b]	NA	NA	NA
ODI(%)[c]	< 0.0001	< 0.0001	< 0.0001	NA	NA	NA	NA
Walking speed(m/s)	0.7994	0.0271	0.0008	< 0.0001	< 0.0001	0.0287	0.3659
Cadence (steps/min)	0.0001	< 0.0001	< 0.0001	< 0.0001	0.0053	0.0254	0.0848
Stride length (m)	0.1981	0.0182	0.0087	< 0.0001	0.0003	0.0098	0.0153
Double support duration (s)	0.0601	0.0020	0.0020	< 0.0001	0.0124	0.1477	0.1768
COP path length (mm)	0.3606	0.1469	0.0595	< 0.0001	< 0.0001	< 0.0001	< 0.0001
90% COP postural sway area (mm2)	0.2736	0.0613	0.0024	< 0.0001	0.0022	0.0168	0.2067

[a]Visual analogue scale

[b]Not available

[c]Oswestry Disability Index

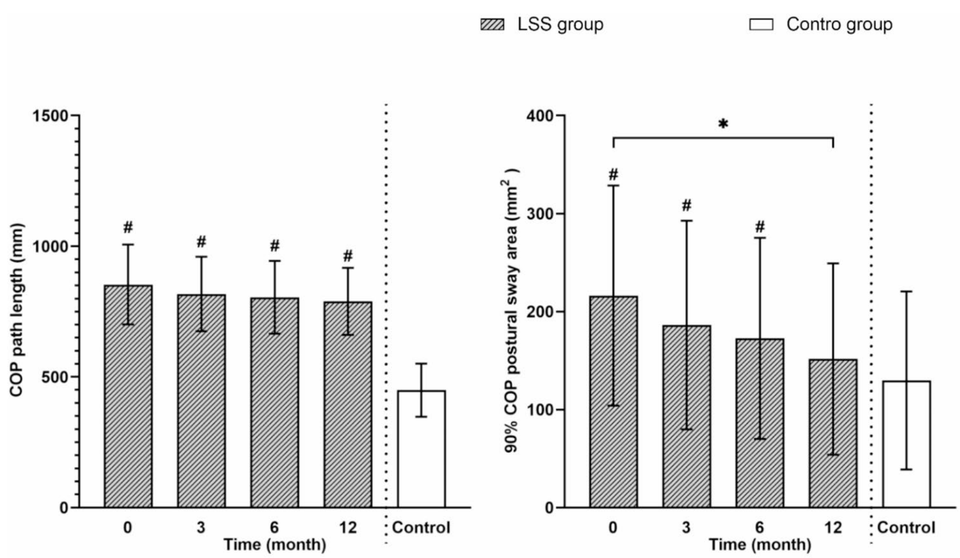

Fig. 8 Center of pressure. Values are mean ± SD.* Lumbar spinal stenosis within-group comparisons ($P < 0.05$). # Between-group comparisons ($P < 0.05$)

within the first three months after ULBD surgery. However, spatiotemporal gait parameters became statistically significant at six months postoperatively, suggesting that gait improvement may require more time than pain and functional recovery. During the three-month follow-up, VAS scores decreased by 56%, and ODI scores decreased by 50%. These results indicate that gait improvement may take longer. At 12 months postoperatively, walking speed, cadence, and double support duration showed no significant differences compared to the healthy control group, indicating that gait abnormalities can be corrected after surgery.

Balance control of individuals with LSS showed improvement after surgery

LSS patients had worse balance stability during closed-eyes standing than healthy individuals, consistent with previous studies [30]. Sasaki et al. [31]found that LSS patients with intermittent claudication exhibited decreased balance stability and a higher risk of falls, especially on the symptomatic side. Maintaining closed-eyes standing balance requires integration of vestibular and proprioceptive signals by the central nervous system, which then adjusts muscle activity to maintain stability [32]. Spinal canal stenosis compresses nerves, leading to sensory disturbances in the lower limbs and impaired proprioceptive feedback. Additionally, nerve compression causes muscle weakness [17], which prevents timely feedback on positional adjustment information from reaching the central nervous system. LSS affects both the feedback and execution processes of this closed-loop control system for maintaining body balance, leading to an increased risk of falls [33].

In our study, the balance ability of ULBD patients significantly improved one year after ULBD surgery, although it did not reach the level of normal individuals. Ujigo et al. [18]found that the severity of LSS negatively impacts balance ability, but that decompression surgery can improve static balance. We speculate that the improvement in static balance may be attributed to enhanced proprioceptive feedback, pain relief, and increased muscle strength following decompression. However, this study did not assess proprioceptive abilities in the participants, and further research is needed to investigate the relationship between balance improvement and proprioception.Yagci et al. [34]found that pain reduction and increased muscle strength after decompression surgery improved balance, Takenaka [29]found that muscle strength increases after decompression surgery in LSS patients, all of which can lead to improvements in balance function. However, Truszczyńska et al. [35]observed a downward trend in postoperative balance parameters but without statistical significance. This may be due to Truszczyńska measuring static balance with eyes open, which has a lower sensitivity to changes in balance ability due to visual information input. Sipko et al. [36]found greater improvements in balance stability with closed-eyes standing than with open-eyes standing in lumbar disc herniation patients.

In our study, the 90% COP postural sway area improved significantly after surgery, but no significant statistical improvement was observed in COP path length. This may be because COP path length is influenced by COP velocity, which did not significantly improve after surgery. Kneis et al. [17]similarly found no significant difference in COP velocity before and after decompression surgery in LSS patients.

These findings suggest that the evaluation of surgical outcomes should not rely solely on functional indicators. Although gait improved, balance ability remained suboptimal, highlighting the need for more specialized post-surgery balance training and interventions to promote comprehensive recovery. Additionally, further strategies to improve balance, such as new surgical techniques, rehabilitation programs, or assistive devices, should be explored.

Study limitations

This study has several limitations. First, it primarily focused on changes in gait and balance abilities in LSS patients following ULBD surgery, without exploring the underlying factors that may influence these changes. Future research should address this gap. Second, the control group consisted of age-matched healthy adults; future studies could include a nonsurgical patient group to more effectively assess the impact of surgery. Third, gait and balance outcomes were not correlated with disability scales or pain scores in this study. These correlations will be examined in future research.

Another notable limitation is the loss of data resulting from participant exclusion. A total of 47 participants were excluded from the initial cohort, with 12 excluded due to non-compliance with inclusion criteria, loss to follow-up ($n = 10$), and technical errors during data collection ($n = 2$). Although these exclusions were necessary to ensure the integrity of the dataset, they may have introduced selection bias, particularly if the excluded participants differed systematically from those included in the final analysis. Nevertheless, the final sample size of 120 participants (60 in each group) was considered adequate to preserve statistical power.

Conclusion

Patients with LSS experience improvements not only in pain and functional activities following ULBD surgery but also in gait and balance abilities. One year post-surgery, their gait becomes comparable to that of healthy individuals, although their balance abilities remain below the level of healthy controls. These findings provide valuable empirical evidence for the rehabilitation of LSS patients post-surgery, offering important insights to guide clinical practice and enhance patients' quality of life.

Abbreviations

COP	Center of pressure
Endo-ULBD	Percutaneous endoscopic unilateral laminotomy and bilateral decompression
LSS	Lumbar spinal stenosis
ODI	Oswestry Disability Index
VAS	Visual analogue scale

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Author contributions

PK, LW and YS designed this study. PK and LH wrote the manuscript and performed the experiments. WX and BZ assisted with data analysis. YS and LW revised the final manuscript. All authors read and approved the final manuscript.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
This study was a single-center retrospective cohort study, approved by the Ethics Committee of the First Affiliated Hospital of Anhui Medical University (Ethical Application Reference: PJ2023-07-13 Anhui, China) and was registered at the Chinese Clinical Trial Registry at 20/06/2023 (ChiCTR2300072649). The research was conducted in accordance with the Declaration of Helsinki and clinical practice guidelines.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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