Liu and Zhou *BMC Surgery* (2025) 25:125
https://doi.org/10.1186/s12893-025-02856-2

BMC Surgery

RESEARCH **Open Access**

Comparative efficacy and safety of three surgical procedures for the treatment of lumbar disc herniation: a Bayesian-based network analysis

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Abstract

Purpose Existing studies have suggested that the efficacy and safety of tubular microdiscectomy (TMD) and percutaneous transforaminal endoscopic discectomy (TED) for lumbar disc herniation (LDH) are similar to those of open microdiscectomy (OMD). However, there are no head-to-head randomized controlled trials (RCTs) making indirect or integrated comparisons of the efficacy and safety of TMD and TED for LDH. A network meta-analysis (NMA) of RCTs was used to compare the clinical efficacy and safety of OMD, TMD and TED for LDH in this research.

Methods We systematically searched the Cochrane Library, PubMed, and Embase databases from their inceptions through March 2023 for eligible literature. The following search terms were used: "transforaminal endoscopic discectomy," "microdiscectomy," "endoscopic," "minimally invasive," "tubular microdiscectomy," "spinal disease," and "randomized clinical trial". The primary outcomes were the Oswestry disability index (ODI) score and the visual analog scale (VAS) score for leg pain, complications, and reoperation. Direct comparison meta-analyses and NMA were carried out.

Results Eight RCTs (1391 patients) met the inclusion criteria. Pairwise meta-analysis showed that compared to OMD, TED has advantages in terms of VAS score (SMD=-1.10 95% CI −1.85 to -0.34, $P=0.005$) and ODI score (SMD=-5.17 95% CI −8.04 to -2.31, $P=0.004$). In contrast, the comparative analysis revealed no statistically significant differences between TMD and OMD across all outcome measures. By comparing TED to OMD and TMD to OMD, it was found that there was no significant difference in the complication and reoperation rates. NMA indicated that there was no significant difference in any of the outcomes between TED and TMD. Trend analyses of rank probabilities showed the cumulative probabilities of the most effective treatments, as measured by primary outcomes (VAS score, ODI score, reoperation and complication rates), were TED (95%, 77%, 23%, 58%), TMD (4%, 22%, 54%, 36%), and OMD (1%, 1%, 23%, 6%).

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Conclusion For LDH, TED outperformed OMD in clinical efficacy, while TMD matched OMD outcomes. All modalities showed similar complication/reoperation rates. Probabilistic analyses revealed TED as preferable for younger patients (enhanced pain control, shorter stays), whereas TMD better suited elderly comorbid patients for reoperation risk mitigation.

Keywords Network meta-analysis, Tubular microdiscectomy, Percutaneous transforaminal endoscopic discectomy, Lumbar disc herniation, Randomized controlled trial

Introduction

Sciatica secondary to lumbar disc herniation (LDH) is one of the primary etiologies of chronic low back and leg pain, with a globally increasing prevalence trend [1]. A Medicare cohort study in the United States revealed substantial impacts of this condition on healthcare resource utilization, mental health, and economic burdens including medical expenditures and productivity losses [2]. International clinical guidelines recommend surgical evaluation for LDH patients unresponsive to 12 weeks of standardized conservative treatment [3]. Randomized controlled trial (RCT) data indicate that over 40% of conservatively refractory LDH patients undergo surgical intervention within two years [4, 5].The surgical management system for LDH has evolved over nearly a century. The initial discectomy reported by Mixter and Barr in 1934 [6] was followed by the landmark introduction of open microdiscectomy (OMD) by Caspar and Yasargil in 1977, representing a critical breakthrough in minimally invasive LDH treatment [7, 8]. Recognized for its favorable clinical outcomes, OMD has been established as the "gold standard" for symptomatic LDH [9, 10]. However, this procedure necessitates paraspinal muscle stripping and partial laminectomy, carrying risks of postoperative spinal biomechanical instability, epidural fibrosis, and cerebrospinal fluid leakage [11, 12]. Recent advancements in minimally invasive technologies aim to minimize tissue damage, primarily including microendoscopic discectomy (MED), percutaneous transforaminal endoscopic discectomy (TED), and tubular microdiscectomy (TMD). MED, integrating tubular retractor systems with endoscopic visualization [13], significantly reduces soft tissue trauma compared to conventional open surgery. A prospective controlled study by Apaydin et al. demonstrated MED's superiority over OMD in pain relief, functional recovery, and quality of life [14]. Nevertheless, its requirement for laminar bone resection may predispose patients to chronic low back pain and segmental instability [15], driving research focus toward more tissue-preserving TED and TMD techniques. Since Kambin's description of the "safe triangular zone" in the late 1970s [16], transforaminal endoscopic technology has progressively matured. Leveraging high-definition endoscopic imaging and refined instrumentation, TED has gained prominence in LDH management through its natural anatomical corridor approach that maximizes preservation of spinal osseous structures [17–19]. Multiple studies confirm TED's advantages over OMD in reduced hospitalization, lower complication rates, and superior anatomical preservation [20–22]. The 2002 introduction of TMD by Greiner-Perth's team [23] addressed endoscopic visualization limitations through an intermuscular approach replacing subperiosteal dissection, combined with tubular retractors and microsurgical techniques. Emerging evidence highlights TMD's advantages over OMD in operative duration, intraoperative bleeding, and postoperative recovery [24].

Given that the indications for TMD and TED are similar to those for OMD surgery in patients with LDH [25, 26], surgeons are faced with a dilemma when deciding between these two minimally invasive techniques. A recent meta-review of research showed that the operative effects of TMD or TED and OMD for LDH are essentially equivalent [27]. Due to the lack of head-to-head comparisons between TMD and TED, most of the studies are pairwise meta-analyses of TMD and MD or TED and OMD [28, 29]. When comparing multiple treatment regimens, Bayesian network meta-analysis (NMA) demonstrates distinct advantages over conventional analytical methods. This methodology synthesizes both direct and indirect comparative evidence, and by generating posterior probability distributions, it enables precise discrimination of subtle differences among therapeutic interventions [28, 30]. A NMA on this topic has been performed previously, but the focus of this study was limited to evaluating the surgical complications and did not include an efficacy evaluation [31]. Thus, in the current study, we sought to provide some useful information about the comparison between TMD, TED and OMD through a Bayesian NMA, aiming to help surgeons and patients make the most suitable treatment choice.

Methods

This systematic review was preregistered (PROSPERO CRD42020156123) and conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Detailed compliance with PRISMA is provided in Supplemental Table 1.

Data sources and search strategy

We searched the Embase, Cochrane Central Register of Controlled Trials, and PubMed databases through March

2023 using the following keywords in various combinations: “transforaminal endoscopic discectomy,” “microdiscectomy,” “endoscopic,” “minimally invasive,” “tubular microdiscectomy,” “spinal disease,” and “randomized clinical trial”.

Study selection criteria

Studies were included if they:

1) Enrolled adults aged 18–80 years with LDH requiring surgery.
2) Compared TMD vs. OMD, TED vs. OMD, or TMD vs. TED.
3) Were randomized controlled trials (RCTs) with ≥ 12 months of follow-up.

Studies were excluded if they:

1) Focused on spinal fractures, deformities, infections, or tumors.
2) Were non-RCTs (e.g., observational studies or reviews).

Data extraction

Two investigators extracted data from the eligible studies to evaluate the following outcomes: (1) visual analog scale (VAS) score for leg pain [32]; (2) Oswestry disability index (ODI) score [33]; (3) complications; (4) reoperation rate; and (5) operative time, and length of hospital stay.

Risk of bias assessment and certainty of evidence

Two investigators assessed the risk of bias using twelve criteria recommended by the Cochrane Back Review Group [34]. The Grading of Recommendations Assessment, Development and Evaluation (GRADE) approach was used to evaluate both the strength of recommendations and the quality of evidence [35].

Data synthesis and analysis

In this study, we chose odds ratios (OR) and standardized mean difference (SMD) 95% confidence intervals (95% CIs) to represent the results of dichotomous outcomes and continuous outcomes. If the 95% CI included 0 for SMD or 1 for OR, there were no significant differences in the result [36].

The analytical protocol was conducted as follows: Initial pairwise meta-analyses comparing TMD/TED versus OMD were performed using RevMan software (Review Manager 5.3 version. Copenhagen: The Nordic Cochrane Centre, The Cochrane Collaboration, 2014.). Potential heterogeneity across studies was assessed through the inconsistency statistic I^2 index derived from forest plot analyses. A random-effects model was employed to pool effect sizes when significant heterogeneity was detected ($I^2 > 50\%$), with a fixed-effect model utilized under homogeneous conditions. In instances of substantial heterogeneity, univariate sensitivity analysis was implemented via sequential exclusion of individual studies to evaluate their influence on overall risk estimates.

To incorporate indirect comparisons, NMA was conducted using ADDIS software (Aggregate Data Drug Information System, version 1.16.5) to compare TED, TMD, and OMD, with calculation of ranking probabilities for indirect treatment effects. The software integrates direct and indirect evidence through common comparators to estimate relative effects in multi-intervention comparisons [37, 38]. ADDIS, a non-programmatic software, employs Markov chain Monte Carlo (MCMC) methods within a Bayesian framework for data evaluation and processing [39]. The parameter configuration in ADDIS was standardized as follows: number of chains = 4, tuning iterations = 20,000, simulation iterations = 50,000, thinning interval = 10, inference samples = 10,000, variance scaling factor = 2.5. Convergence of iterative simulations was evaluated using the potential scale reduction factor (PSRF) computed via the Brooks–Gelman–Rubin method, where PSRF values approaching 1 indicate optimal convergence, with PSRF < 1.2 deemed acceptable [40]. A Bayesian random-effects regression model was implemented in ADDIS 1.16 using MCMC methodology. Additionally, inconsistency standard deviation (ISD) analysis was performed to confirm statistical consistency. The consistency model was adopted if the 95% confidence interval of ISD encompassed 1; otherwise, the inconsistency model was applied [41]. The Bayesian framework enabled probabilistic ranking of treatments (best, second-best, etc.), with endpoint metrics ranked numerically where position 1 denotes least favorable and position N indicates optimal performance.

Results

Eligible studies

By searching the databases, 1130 studies were collected; 580 from EMBASE, 331 from PubMed, and 218 from the Cochrane Central Register of Controlled Trials. Only sixteen RCTs were included [25, 31, 42–55].Three of 16 studies included a follow-up of less than 1 year [43, 44, 50], and five were duplicate reports of the same set of patients [42, 51–54]. Eight RCTs with 1391 patients were included in the meta-analysis. There were 997, 248, and 558 patients allocated to the OMD, TMD, and TED groups, respectively (Fig. 1). The characteristics of the 8 studies are shown in Table 1 [31, 45–49, 55].

Risk of bias of individual studies

Figures 6 and 7 shows the risk of bias graph. In the included studies, 7 studies indicated “randomly allocating”. Only 3 trials described methods of randomization.

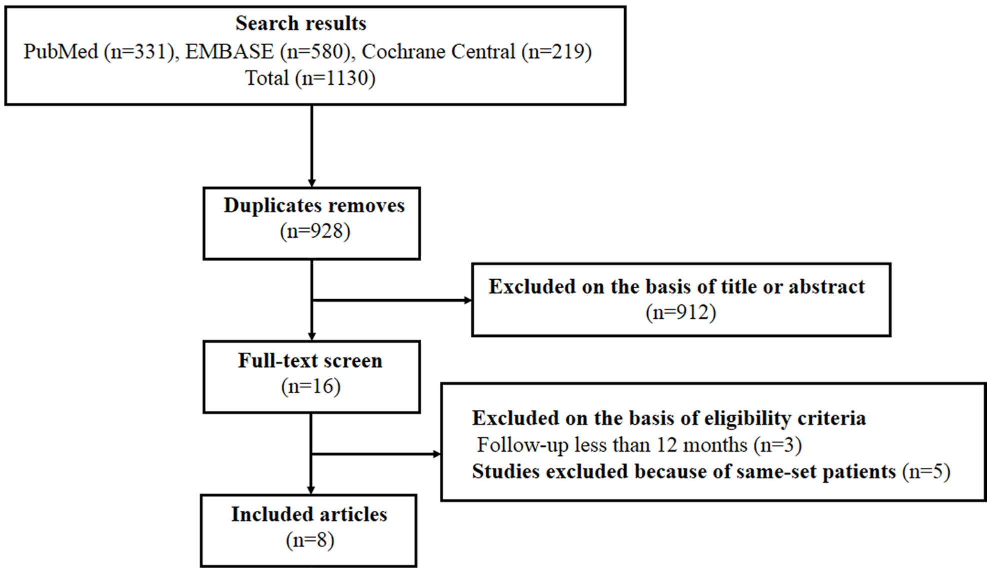

Fig. 1 Flow diagram of the study selection process for the meta-analysis

Table 1 Characteristics of the included studies

Study	Study type	Preoperative diagnosis	Surgical Intervention	Sample size	Mean age (year)	Follow-up (month)	Outcomes
Ryang 2008	RCT	Lumbar disc herniation	OMD TMD	30 30	39.1 38.2	16	VAS, ODI, complications, OT, LHS, reoperation
Arts 2009	RCT	Lumbar disc herniation	OMD TMD	159 166	41.6 41.3	13	VAS, ODI, complications, OT, LHS, reoperation
Franke 2009	RCT	Lumbar disc herniation	OMD TMD	48 52	44.0 44.0	12	VAS, ODI, complications, OT, LHS, reoperation
Hermantin 1999	RCT	Lumbar disc herniation	OMD TED	30 30	40.0 39.0	31	complications
Mayer 1993	RCT	Lumbar disc herniation	OMD TED	20 20	39.8 42.7	24	complications, OT, reoperation
Ruetten 2008	RCT	Lumbar disc herniation	OMD TED	87 91	39.0 39.0	24	VAS, ODI, complications, OT, reoperation
Gibson 2016	RCT	Lumbar disc herniation	OMD TED	70 70	39.0 42.0	24	VAS, ODI, complications, OT, LHS, reoperation
Gadjradj 2022	RCT	Lumbar disc herniation	OMD TED	309 179	45.7 45.3	12	VAS, ODI, OT, LOS, reoperation, complications

OMD: open microdiscectomy; **TMD**: tubular microdiscectomy; **TED**: percutaneous transforaminal endoscopic discectomy; **RCT**: randomized controlled trial; **VAS**: visual analogue scale for back and/or leg pain; **ODI**: Oswestry disability index; **OT**: operative time; **LHS**: length of hospital stay

None of the trials mentioned the use of the blinding method because none of the researchers in the studies could perform blinding. Six studies found no other significant sources of bias.

Pooled weighted outcomes and direct meta-analysis

Compared with OMD, TMD was no significant difference in any other aspects (Figs. 2, 3, 4 and 5). Compared with OMD, TED was associated with better functional outcomes (SMD=-5.17 95% CI – 8.04 to -2.31, Fig. 2), better pain relief (SMD=-1.10 95% CI – 1.85 to -0.34, Fig. 3), and shorter hospital stays (SMD=-0.70 95% CI – 1.05 to -0.35). There was no significant difference in any other outcomes (Figs. 4 and 5).

Network meta-analyses and rank probabilities

We conducted a network meta-analysis to compare OMD, TMD, and TED. According to our results, OMD, TMD, and TED were no significantly different in terms of VAS score, ODI score, complications, reoperation rate, operation time, and length of hospital stay (Table 2).

Using a ranking system that indicates the best treatment probability, we developed a histogram figure (Supplemental Fig. 1) to show the probability of being the best, the second best, and the third best treatment

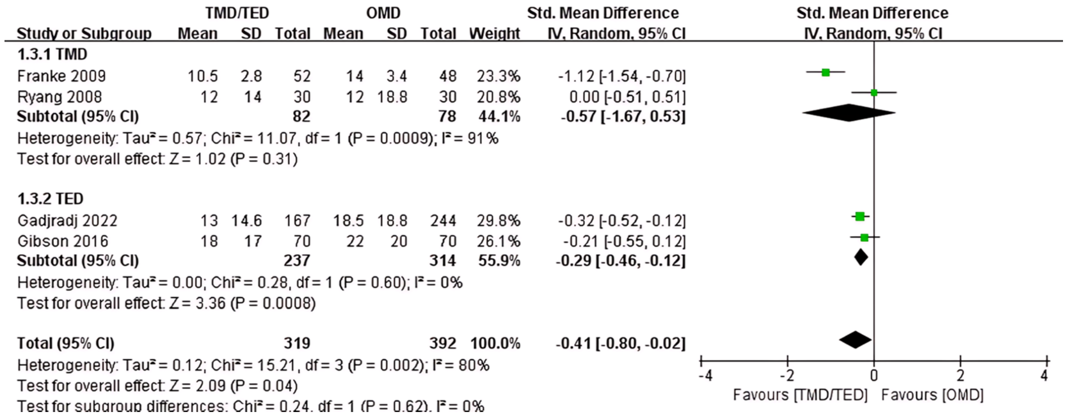

Fig. 2 Forest plot for the meta-analysis of ODI scores. [**ODI**: Oswestry disability index, **Std mean differences**: standardized mean differences, **95% CI**: 95% confidence intervals, **Random**: random effects model, **OMD**: open microscope discectomy; **TMD**: tubular microdiscectomy, **TED**: percutaneous transforaminal endoscopic discectomy]

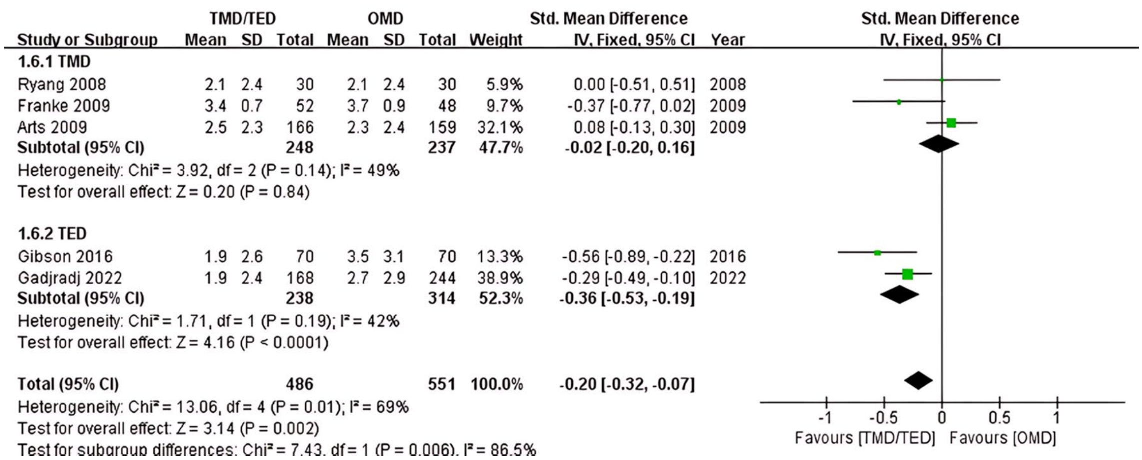

Fig. 3 Forest plot for the meta-analysis of VAS scores. [**VAS**: visual analogue scale, **Std mean differences**: standardized mean differences, **95% CI**: 95% confidence intervals, **Fixed**: fixed effects model, **OMD**: open microscope discectomy; **TMD**: tubular microdiscectomy, **TED**: percutaneous transforaminal endoscopic discectom]

modality. It was found that the treatment with higher values in the histogram had higher probabilities for better outcomes. The cumulative probabilities of TED (95%), TMD (4%), and OMD (1%) and their associations with high levels of pain relief were calculated with the help of the network meta-analysis (Supplemental Fig. 1A). TED (77%), TMD (22%), and OMD (1%) were associated with the highest cumulative probabilities of disability prevention (Supplemental Fig. 1B). In other words, the most likely treatment modality that would have the best clinical efficacy was TED, followed by TMD, and finally OMD. TMD (54%), TED (23%), and OMD (23%) were associated with the lowest cumulative probability of reoperation (Supplemental Fig. 1C). According to the cumulative probabilities, TED (58%), TMD (36%), and OMD (6%) were associated with the lowest complication rates (Supplemental Fig. 1D). That is, TED was the most likely to have the highest safety, followed by TMD and then OMD. TED (56.3%), TMD (39.3%), and OMD (4.4%) were associated with the lowest cumulative probability of a prolonged operation time. TED (87.7%), TMD (10.3%), and OMD (2%) were associated with the lowest cumulative probability of a prolonged hospital stay. These probabilistic rankings, while not achieving statistical significance in direct comparisons, reveal clinically meaningful hierarchies in therapeutic performance. The following discussion contextualizes these findings within surgical biomechanics and patient stratification paradigms, elucidating how procedural nuances may drive observed outcome differentials.

By using the 12 criteria recommended by the Cochrane Back Review Group, we assessed the risk of bias in all the original studies [34]. Figures 6 and 7 show the ratings from all the included studies. An analysis of the funnel

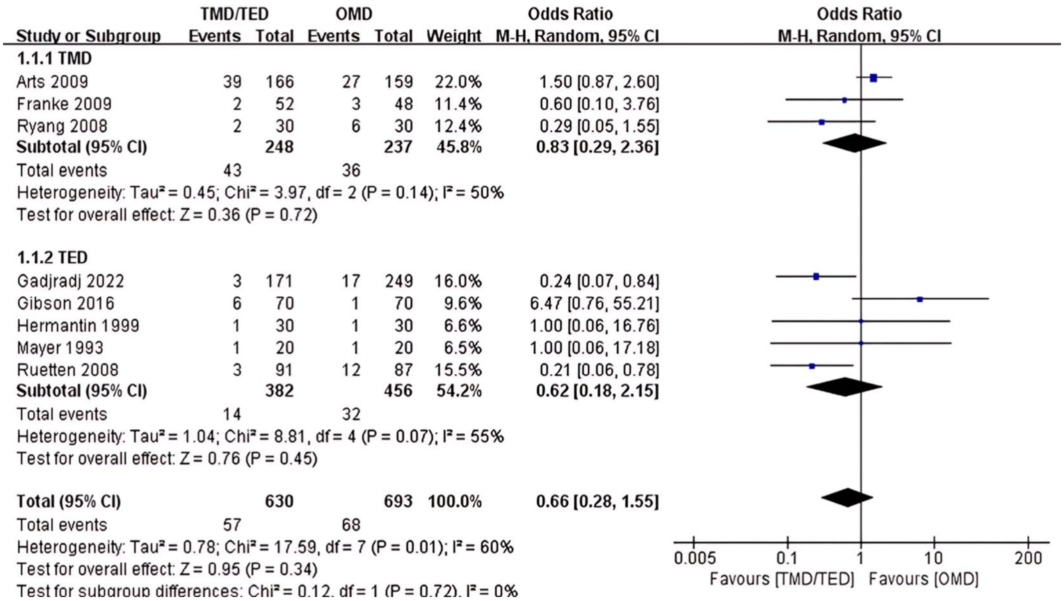

Fig. 4 Forest plot for the meta-analysis of complication. [**95% CI**: 95% confidence intervals, **Random**: random effects model, **OMD**: open microscope discectomy; **TMD**: tubular microdiscectomy, **TED**: percutaneous transforaminal endoscopic discectom]

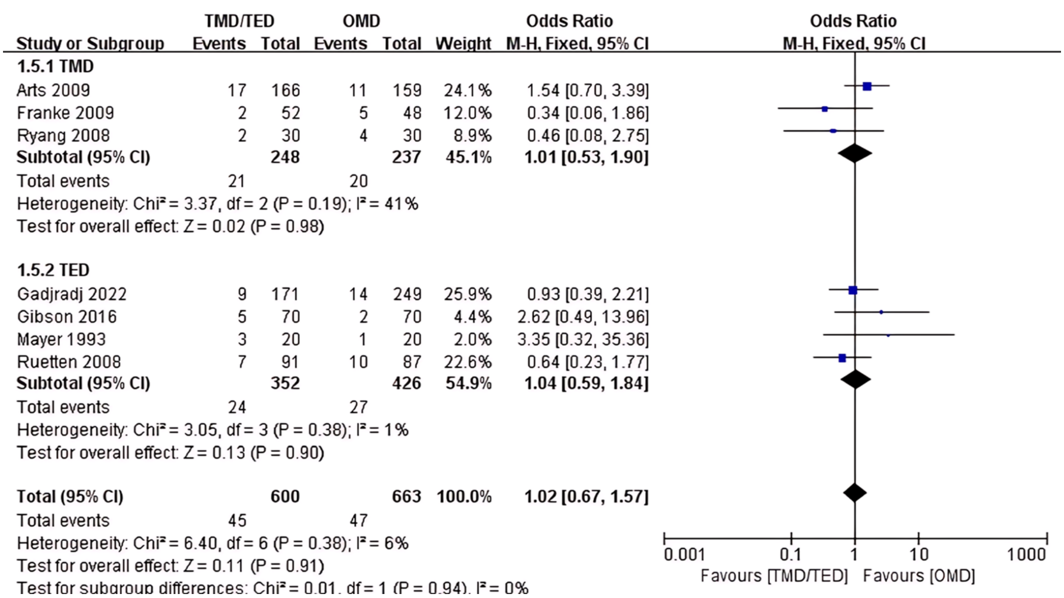

Fig. 5 Forest plot for the meta-analysis of reoperation. [**95% CI**: 95% confidence intervals, **Fixed**: fixed effects model, **OMD**: open microscope discectomy; **TMD**: tubular microdiscectomy, **TED**: percutaneous transforaminal endoscopic discectom]

plot (Supplemental Fig. 2) revealed no apparent publication bias. As our study had a small sample size, no sensitivity or scenario analysis was conducted.

Sensitivity analysis and quality assessment

Sensitivity analyses were conducted for primary outcomes exhibiting substantial heterogeneity. Our principal methodological approach involved sequential exclusion of lower-quality studies through individual trial removal. Notably, in the complication outcome analysis, exclusion of the study by Gibson et al. [31] resulted in marked reduction of heterogeneity (I^2 decreased from 55 to 0%). A plausible explanation emerges from procedural variability: Gibson's TED protocol utilized local anesthesia, whereas other included studies employed general anesthesia for TED procedures. This observation suggests potential associations between anesthetic modality selection and complication risk profiles. All pooled outcomes were evaluated using the GRADE quality assessment. The results are shown in Table 3.

Table 2 Multiple-treatment comparisons based for ODI, VAS, complication, reoperation, OT, LHS on the network

Parameter	The NMA of consistency/ Inconsistency			Inconsistency Standard Deviation
ODI[a]	OMD	-5.05 (-9.93, 0.06)	-3.08 (-7.26, 2.36)	2.73 (0.14, 5.37)
	5.05 (-0.06, 9.93)	TED	-2.05 (-4.43, 9.64)	
	3.08 (-2.36, 7.26)	-2.05 (-9.64, 4.43)	TMD	
VAS[a]	OMD	-1.09 (-2.21, -0.11)	-0.07 (-0.90, 0.86)	0.80 (0.04, 1.56)
	1.09 (0.11, 2.21)	TED	1.03 (-0.25, 2.52)	
	0.07 (-0.86, 0.90)	-1.03 (-2.52, 0.25)	TMD	
Complication[a]	OMD	0.54 (0.12, 2.49)	0.72 (0.15, 3.06)	0.77 (0.04, 1.50)
	1.86 (0.40, 8.20)	TED	1.36 (0.14, 11.05)	
	1.38 (0.33, 6.52)	0.73 (0.09, 7.17)	TMD	
Reoperation[b]	OMD	1.15 (0.51, 2.88)	0.86 (0.29, 2.09)	0.48 (0.03, 0.93)
	0.87 (0.35, 1.97)	TED	0.75 (0.18, 2.42)	
	1.16 (0.48, 3.44)	1.33 (0.41, 5.68)	TMD	
OT[a]	OMD	-10.69 (-35.83, 14.40)	-7.48 (-28.29, 12.96)	12.21 (0.57, 23.84)
	10.69 (-14.40, 35.83)	TED	2.98 (-29.54, 35.60)	
	7.48 (-12.96, 28.29)	-2.98 (-35.60, 29.54)	TMD	
LHS[b]	OMD	-0.70 (-1.62, 0.19)	-0.07 (-0.86, 0.63)	0.35 (0.02, 0.68)
	0.70 (-0.19, 1.62)	TED	0.63 (-0.57, 1.74)	
	0.07 (-0.63, 0.86)	-0.63 (-1.74, 0.57)	TMD	

The number in the cell represents the standardized mean difference (95% confidence interval) of the column defining treatment relative to the row defining treatment. [a: consistency model; b: inconsistency model; **NMA**: network meta-analysis **OMD**: open microdiscectomy; **TMD**: tubular microdiscectomy; **TED**: percutaneous transforaminal endoscopic discectomy; **RCT**: randomized controlled trial; **VAS**: visual analogue scale for back and/or leg pain; **ODI**: Oswestry disability index; **OT**: operative time; **LHS**: length of hospital stay]

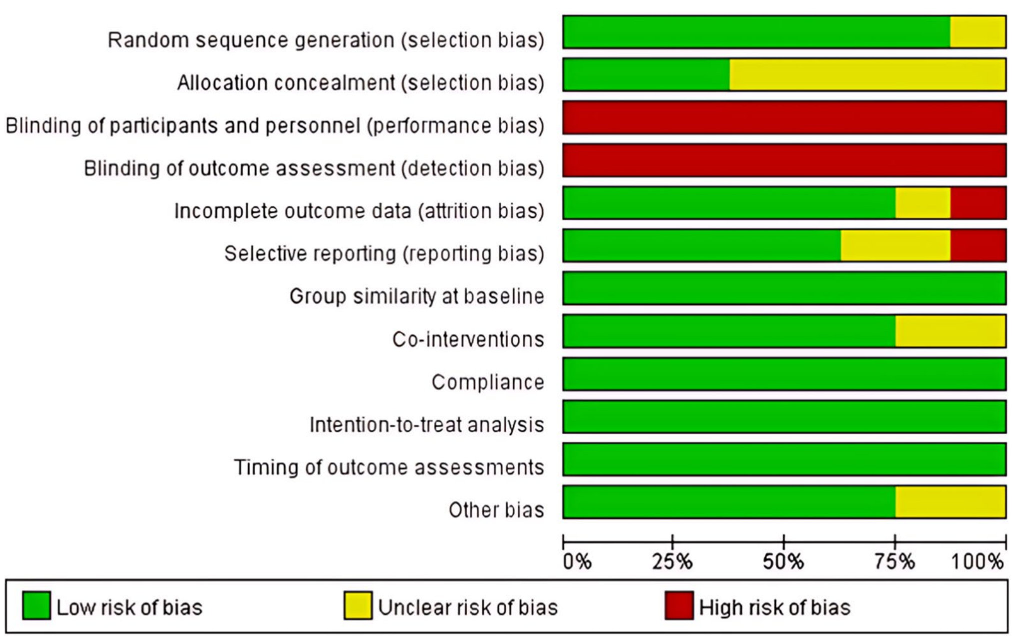

Fig. 6 Risk of bias summary. This risk of bias tool incorporates assessment of randomization (sequence generation and allocation concealment), blinding (participants, personnel and outcome assessors), completeness of outcome data, selection of outcomes reported, and other sources of bias. The items were scored with "yes", "no", or "unclear"

Discussion

The discordance between statistical equivalence and probabilistic superiority underscores the need to contextualize these findings through biomechanical rationales and patient-specific considerations, as explored in the following discussion. In this study, we performed a NMA to compare the clinical efficacy and safety of OMD, TMD and TED for LDH. Based on data from eight RCTs, we evaluated the efficacy (in terms of VAS, ODI) and safety (in terms of complication and reoperation rates) of three treatment options for patients with LDH in this study. The NMA indicated that the outcomes of TED and TMD

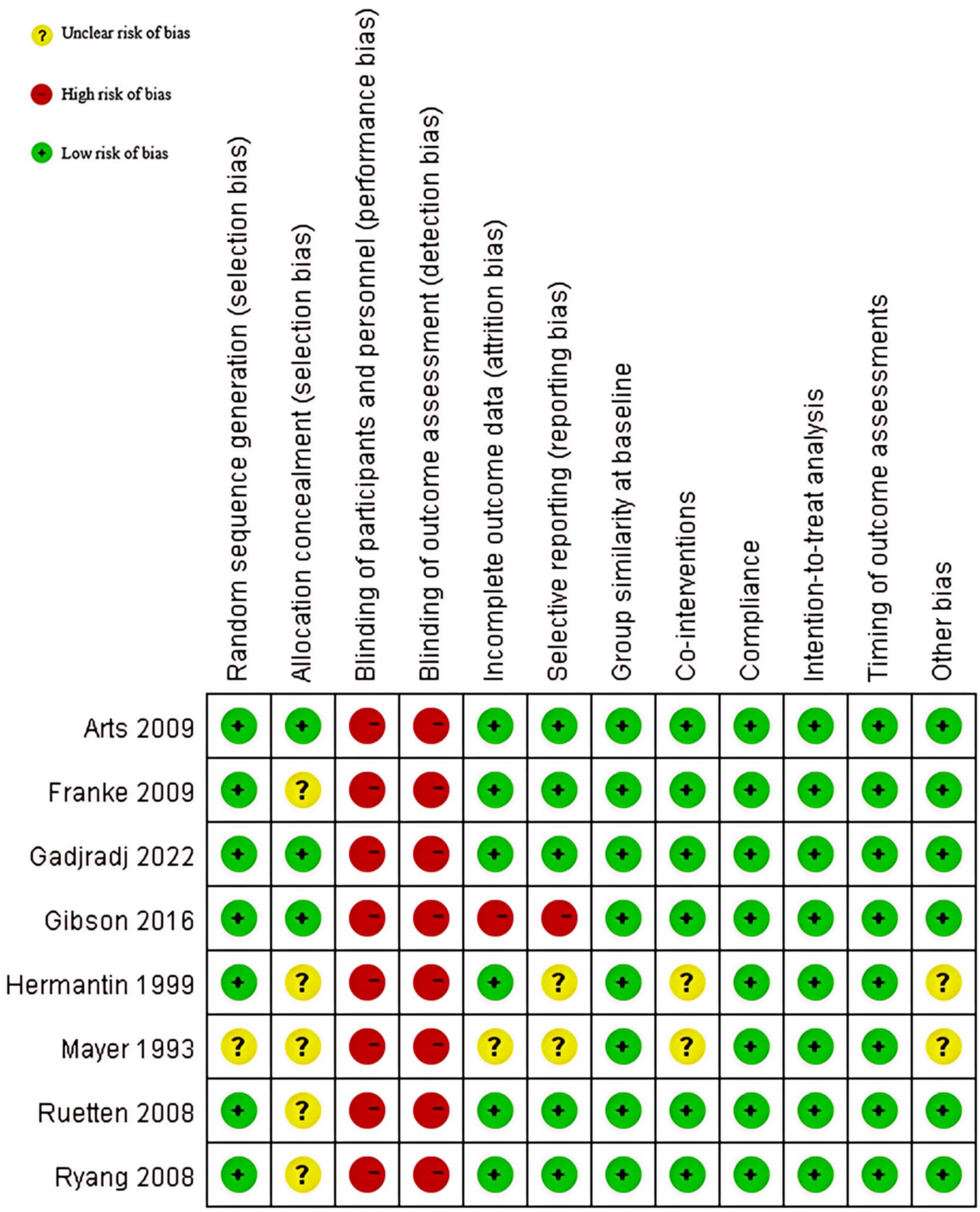

Fig. 7 Risk of bias graph: judgments about each risk of bias item presented as percentages across all included studies

were not significantly different. When relative values fail to reach statistical significance, rank probabilities can be used to analyze a treatment group's position among certain treatments. It can tell us which treatment would be the most likely option to achieve the best outcomes or if one treatment might be better than another [56]. Our NMA concluded that TED had the greatest probability of ranking first among all three surgical options regarding VAS score, ODI score, complication rate, and operation time, while TMD had the greatest probability of ranking best in terms of reoperation rate.

The ultimate goals for LDH treatments are to eliminate or reduce pain and restore or improve limb function. The direct meta-analysis shows that TMD has no advantages over OMD in terms of pain relief. This conclusion is consistent with the results of previous meta-analyses [28]. Notably, patient-reported VAS score following TED were better than those following OMD. This is in contrast to the findings of Qin's study [57]. However, although there

Table 3 Summary of findings for the main comparison

Outcomes	Comparison of inteventions	Direct estimate		Indirect estimate		Network estimate	
		OR/SMD (95%CI)	Certainty direct estimate	OR/SMD (95%CI)	Certainty indirect estimate	OR/SMD (95%CI)	Certainty network estimate
ODI	TMD vs. OMD	-3.43 (-4.64, -2.21)	⊕⊕⊕⊕ HIGH	Not evaluated [a]	Not evaluated [a]	-3.08 (-7.26, 2.36)	⊕⊕⊕⊕ HIGH
	TED vs. OMD	-5.17 (-8.04, -2.31)	⊕⊕◯◯ LOW [c]	Not evaluated [a]	Not evaluated [a]	-5.05 (-9.93, 0.06)	⊕⊕◯◯ LOW
	TED vs. TMD	Not evaluated [a]	Not evaluated [a]	-2.05 (-9.64, 4.43)	⊕⊕◯◯ LOW [d]	-2.05 (-9.64, 4.43)	⊕⊕◯◯ LOW
VAS	TMD vs. OMD	-0.11 (-0.46, 0.24)	⊕⊕⊕◯ MODERATE [b]	Not evaluated [a]	Not evaluated [a]	-0.07 (-0.90, 0.86)	⊕⊕⊕◯ MODERATE
	TED vs. OMD	-1.10 (-1.85, -0.34)	⊕⊕◯◯ LOW [c]	Not evaluated [a]	Not evaluated [a]	-1.09 (-2.21, -0.11)	⊕⊕◯◯ LOW
	TED vs. TMD	Not evaluated [a]	Not evaluated [a]	-1.03 (-2.52, 0.25)	⊕⊕◯◯ LOW [d]	-1.03 (-2.52, 0.25)	⊕⊕◯◯ LOW
Complications	TMD vs. OMD	0.83 (0.29, 2.36)	⊕⊕⊕◯ MODERATE [b]	Not evaluated [a]	Not evaluated [a]	0.72 (0.15, 3.06)	⊕⊕⊕◯ MODERATE
	TED vs. OMD	0.62 (0.18, 2.15)	⊕⊕⊕◯ MODERATE [b]	Not evaluated [a]	Not evaluated [a]	0.54 (0.12, 2.49)	⊕⊕⊕◯ MODERATE
	TED vs. TMD	Not evaluated [a]	Not evaluated [a]	0.73 (0.09, 7.17)	⊕⊕⊕◯ MODERATE [e]	0.73 (0.09, 7.17)	⊕⊕⊕◯ MODERATE
Reoperation	TMD vs. OMD	0.81 (0.29, 2.23)	⊕⊕⊕◯ MODERATE [b]	Not evaluated [a]	Not evaluated [a]	0.87 (0.29, 2.13)	⊕⊕⊕◯ MODERATE
	TED vs. OMD	1.02 (0.56, 1.85)	⊕⊕⊕◯ MODERATE [b]	Not evaluated [a]	Not evaluated [a]	1.09 (0.51, 2.82)	⊕⊕⊕◯ MODERATE
	TED vs. TMD	Not evaluated [a]	Not evaluated [a]	1.24 (0.38, 5.69)	⊕⊕⊕◯ MODERATE [e]	1.24 (0.38, 5.69)	⊕⊕⊕◯ MODERATE
Operation time	TMD vs. OMD	-7.70 (-33.72, 18.32)	⊕⊕⊕◯ MODERATE [b]	Not evaluated [a]	Not evaluated [a]	-7.48 (-28.29,12.96)	⊕⊕⊕◯ MODERATE
	TED vs. OMD	-10.91 (-24.13, 2.32)	⊕⊕⊕◯ MODERATE [b]	Not evaluated [a]	Not evaluated [a]	-10.69 (-35.83, 14.40)	⊕⊕⊕◯ MODERATE
	TED vs. TMD	Not evaluated [a]	Not evaluated [a]	-2.98 (-35.60, 29.54)	⊕⊕⊕◯ MODERATE [e]	-2.98 (-35.60, 29.54)	⊕⊕⊕◯ MODERATE
Length of hospital stay	TMD vs. OMD	-0.01 (-0.26, 0.23)	⊕⊕⊕◯ HIGH	Not evaluated [a]	Not evaluated [a]	-0.05 (-0.88, 0.64)	⊕⊕⊕◯ HIGH
	TED vs. OMD	-0.70 (-1.05, -0.35)	⊕⊕⊕◯ LOW [c]	Not evaluated [a]	Not evaluated [a]	-0.70 (-1.64, 0.20)	⊕⊕⊕◯ LOW
	TED vs. TMD	Not evaluated [a]	Not evaluated [a]	-0.64 (-1.78, 0.57)	⊕⊕◯◯ LOW [d]	-0.64 (-1.78, 0.57)	⊕⊕◯◯ LOW

CI: confidence interval; **OR**: odds ratio; **SMD**: standardized mean difference; **VAS**: visual analogue scale; **ODI**: Oswestry disability index; **OMD**: open microdiscectomy; **TMD**: tubular microdiscectomy; **TED**: percutaneous transforaminal endoscopic discectomy

GRADE Working Group grades of evidence

High certainty: We are very confident that the true effect lies close to that of the estimate of the effect

Moderate certainty: We are moderately confident in the effect estimate: The true effect is likely to be close to the estimate of the effect, but there is a possibility that it is substantially different

Low certainty: Our confidence in the effect estimate is limited: The true effect may be substantially different from the estimate of the effect

Very low certainty: We have very little confidence in the effect estimate: The true effect is likely to be substantially different from the estimate of effect

Explanations

(a) Not evaluated, because there are no trials included in the network; (b) Due to risk of bias; (c) Only one study was available to elucidate the question; (d) Low direct evidence; (e) Moderate direct evidence

were 8 RCTs in total, a large portion of the studies did not provide SD values, and the inability to extract valid data led to limited data accuracy. Our NMA results showed no significant differences in VAS and ODI scores among TED, TMD, and OMD treatments, but the rank probabilities revealed a decreasing trend in potential advantages sequentially. One possible reason for this trend is that TED uses the anatomical space to gain access to the internal surgery site, and the musculoskeletal structure is rarely damaged [58]. There is also evidence that paravertebral muscle injuries are associated with poor clinical outcomes [29, 59]. A study that compared preoperative and postoperative serum creatine phosphokinase levels with postoperative low back pain between TED and OMD treatments confirmed that TED was associated with fewer muscle injuries [50]. A study comparing TMD and OMD found no reduction in the incidence of muscle injuries, and patients experienced more low-back pain a year after TMD [42]. Regarding surgical data, the NMA showed that TMD and TED did not differ significantly in terms of operation time and hospitalization days.

In terms of safety, common complications after surgical repair of LDH include cerebrospinal fluid leakage, nerve root injury, and incision-related complications. When OMD was compared with TMD or TED, our NMA showed no reduced risk of complications. These results are in line with previous studies. A meta-analysis found no significant difference in the clinical efficacy of TMD and OMD for LDH in terms of outcomes, reoperation rate or incidence of dural tears [28]. Zhang et al. reported no significant difference in the incidence of complications between TED and OMD for the treatment of LDH [29]. Our NMA found no significant difference in the rate of reoperation between TED and TMD; however, the rank probabilities revealed that compared with TED, TMD was associated with lower incidences of complications and reoperations. One possible reason for these trends is that limited surgical exposure increases the difficulty of surgery, making it easier to cause nerve damage and other complications [60]. Notably, recent technological breakthroughs in the Internet of Things (IoT) have introduced new dimensions in surgical practice. Smart surgical instruments with embedded sensors now enable real-time tissue feedback during discectomy procedures, while wearable IoT devices allow continuous postoperative monitoring of patients' rehabilitation progress. These innovations are reshaping the landscape of minimally invasive spine surgery [61].

A detailed review of the surgical procedures and technical nuances of TED and TMD may enhance the interpretation of the aforementioned findings. In minimally invasive surgeries for LDH, TMD and TED exhibit distinct technical pathways and intraoperative risks. TMD is typically performed under general anesthesia with the patient prone on a Wilson frame. A 16–20 mm vertical incision is made two fingerbreadths lateral to the midline, followed by sequential dilation to the target intervertebral space using a tubular retractor (18–21 mm diameter). Under microscopic guidance, laminotomy, medial facetectomy, and ligamentum flavum removal are completed, with lateral decompression for severe foraminal stenosis achieved via 2-mm foraminal punches. While this technique minimizes paraspinal muscle dissection through intermuscular approaches, partial facet resection may compromise spinal stability [62]. In contrast, TED employs the TESSYS system (Joimax) through a 5 mm incision 8–14 cm lateral to the midline. The endoscopic channel is established via Kambin's triangle (bounded by the exiting nerve root, superior endplate of the inferior vertebra, and traversing nerve root), enabling direct visualization for laser or radiofrequency ablation of herniated nucleus pulposus and osteophytes with minimal osseous disruption [63]. However, grade III foraminal stenosis (nerve root collapse) may constrain endoscopic maneuverability, necessitating cautious lateral recess expansion [64].

Intraoperatively, TMD carries a 2–5% risk of dural tears and nerve root irritation due to adjustments in tubular retractor depth [62], while TED poses a 1–3% risk of thermal nerve root injury during laser/radiofrequency application in stenotic foramina [64]. Both techniques require intraoperative fluoroscopic confirmation of instrument trajectories to prevent vascular or visceral injuries. Although both adhere to minimally invasive principles and demonstrate comparable overall efficacy, TED may demonstrate advantages in pain scores (VAS/ODI) due to its avoidance of paraspinal muscle stripping, whereas TMD's thorough decompression in severe stenosis may reduce reoperation rates [62, 64]. Consequently, TED could be prioritized for younger patients with unilateral radiculopathy due to its potential for superior pain relief and shorter hospitalization, while TMD may be preferred for elderly patients with comorbidities to minimize reoperation risks. Future randomized controlled trials employing standardized surgical protocols are warranted to validate these differences.

Our study had a few potential limitations. First, although all the studies in our study were RCTs, the size of the studies was small, and the total sample size was small. Second, while our initial protocol included quality of life and intraoperative blood loss as exploratory endpoints, insufficient data availability precluded their inclusion in the formal analysis. Future studies should prioritize standardized reporting of these outcomes. Third, substantial heterogeneity emerged from four key sources: (1) Inconsistent postoperative surveillance intervals (12–24 months), compromising longitudinal complication profiling; (2) Technical variability in surgical execution, particularly between legacy (Mayer et al. [48], Hermantin et al. [47]) and contemporary full-endoscopic systems (Ruetten et al. [49], Gibson et al. [31]); (3) Non-standardized allocation concealment methods across trials; (4) Universal absence of independent outcome assessor blinding. Notably, Ruetten's study also included patients who were treated with an interlaminar endoscopic approach, which is a different procedure from TED. To mitigate these confounders, we implemented a Bayesian random-effects model in the network meta-analysis, which accounts for between-study variability by allowing true treatment effects to differ across studies [65]. Sensitivity analyses were further conducted by excluding studies with high risk of bias. Despite these measures, residual heterogeneity may downgrade the evidence level of this study to Grade II. Last, although this study's evidence network plot appears to be star-shaped, it does not have a closed loop, which indicates that there are no head-to-head comparisons; thus, the differences in the efficacy and safety of TED and TMD are not statistically significant. Consequently, more RCTs comparing TED with TMD should be conducted to obtain more robust results.

Conclusion

In the comparative analysis of clinical outcomes for LDH treatment, the TED demonstrated superior clinical efficacy over OMD, while TMD exhibited comparable efficacy to OMD. All three surgical modalities exhibited comparable postoperative complication rates and similar reoperation risks. Notably, no significant differences were observed between TED and TMD regarding overall therapeutic efficacy or safety profiles. Probabilistic ranking analyses indicated that TED may serve as the preferred option for younger patients with unilateral radicular symptoms due to its potential advantages in pain alleviation and reduced hospitalization duration. Conversely, TMD may be prioritized for elderly patients with comorbidities to minimize reoperation risks. This conclusion needs to be confirmed in additional well-designed and large-scale RCTs.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12893-025-02856-2.

Supplementary Material 1

Acknowledgements
We are grateful for the help and support provided by the Fujian Medical University.

Author contributions
Jingyu Zhou is the co-first author. Shichao Liu and Jingyu Zhou have contributed equally to this study. Shichao Liu and Jingyu Zhou participated in processes of study design, study selection, data extraction and analysis, writing, and quality evaluation. All authors read and approved the final manuscript.

Funding
This work was funded by Startup Fund for scientific research, Fujian Medical University (Grant number: 2021QH1037).

Data availability
All data generated or analyzed during this study are included in this published article and its supplementary information files.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Trial registration number
This study is not a clinical trial; therefore, it does not involve providing details of trial registration.

Competing interests
The authors declare no competing interests.

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Received: 24 December 2024 / Accepted: 17 March 2025
Published online: 28 March 2025

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