Minimally invasive surgery in adult degenerative scoliosis: a systematic review and meta-analysis of decompression, anterior/lateral and posterior lumbar approaches

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Background: Minimally invasive approaches for the treatment of adult degenerative scoliosis have been increasingly implemented. However, little data exists regarding the safety and complication profiles of minimally invasive lumbar interbody fusion (LIF) for adult degenerative scoliosis. This study aimed to greater understand different minimally invasive surgical approaches for adult degenerative scoliosis with respect to clinical outcomes, changes in radiographic measurements, and complication profiles via meta-analytical techniques.

Methods: A systematic search of six databases from inception to September 2015 was performed by two independent reviewers. Relevant studies were those that described the safety and/or effectiveness of minimally invasive anterior or lateral LIF (LLIF), transforaminal LIF (TLIF), and decompression only. Meta-analytical techniques and meta-regression were used to pool overall rates, and compare the different techniques. There was no financial funding or conflict of interest.

Results: A total of 29 studies (1,228 patients) were included in this meta-analysis. Total pooled fusion rate was 95.9% (95% CI: 92.7–98.2%) for the anterior/lateral approach. The pooled construct or hardware-related complications was 4.3%, and was similar among anterior/lateral (4.4%) and posterior (5.2%) techniques. The total pooled pseudoarthrosis rate was 4.3% for the lateral approach. The overall pooled rate of motor deficit was 2.7% (95% CI: 1.7–4.0%). Subgroup meta-regression demonstrated that the anterior/lateral approach had the highest rate of motor deficits (3.6% LLIF *vs.* 0.7% TLIF *vs.* 0.5% decompression, P=0.004). The overall pooled rate of sensory deficit was 2.4%, highest for the anterior/lateral technique (3.3%) compared to TLIF (0.7%) and decompression (0.5%). The infection rate, dural tears/CSF leak, cardiac and pulmonary events were similar among the techniques, with a pooled value of 2.6%, 3.9%, 1.7%, and 1.4%, respectively. Similarly satisfactory radiological outcomes were obtained amongst the different approaches.

Conclusions: Minimally invasive spine technologies may be used for the surgical treatment of lumbar degenerative scoliosis with acceptable complication rates, functional and radiological outcome. Future studies, specifically multi-centered longitudinal, examining the adequacy of minimally invasive spine surgery is warranted to compare long-term outcomes with the traditional procedure.

Keywords: Minimally invasive; lumbar spine fusion; degenerative spine; scoliosis; adult; meta-analysis; review

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Introduction

Open surgery has traditionally been employed for adult lumbar degenerative deformities, often with multi-level decompression and fusion to stabilize the columns and reduce neural compression. However, there has been a surge in the use of minimally invasive approaches for the treatment of multi-level pathology including adult degenerative scoliosis. Minimally invasive approaches were introduced to address approach-related morbidity associated with open spine surgery, with increasing applications to more complex patient pathologies (1). Less invasive surgery has the potential to minimize blood loss, reduce surgical trauma and stress to muscles and paraspinal structures, reduce analgesic use and reduce hospital stay. Minimally invasive approaches for degenerative scoliosis reported in the literature includes decompression only, lateral minimally invasive thoracolumbar instrumentation, minimally invasive posterior, transforaminal and anterior fusion approaches.

Though minimally invasive fusion has been associated with good initial results, most series discussing minimally invasive spinal (MIS) fusion have been in the presence of short-segment fusion (2-6). However, direct comparison of the safety and complication profiles of different minimally invasive surgical approaches for adult degenerative scoliosis remain scarce. Given that lateral LIF (LLIF) is a transpsoas approach, it is expected that there may be higher rates of motor and sensory deficits. Decompression alone approaches may be expected to yield higher revision rates with lower rates of satisfaction. Given the limited comparative evidence on this topic, this study aims to use meta-analytical techniques to compare the different minimally invasive surgical approaches for adult degenerative scoliosis with respect to clinical outcomes, changes in radiographic measurements including Cobb angle and lumbar lordosis, and complication profiles.

Methods

Literature search strategy

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were followed for the present systematic review. Electronic searches were performed using Ovid Medline, PubMed, Cochrane Central Register of Controlled Trials (CCTR), Cochrane Database of Systematic Reviews (CDSR), ACP Journal Club, and Database of Abstracts of Review of Effectiveness (DARE), from their dates of inception to September 2015. To achieve maximum sensitivity of the search strategy, we combined the terms "minimally invasive" or "fusion" or "decompression" and "degenerative scoliosis" and "adult" which were searched as text words and exploded as MeSH headings where possible. Two authors performed the search independently, and any discrepancies were resolved by discussion. The reference lists of all retrieved articles were reviewed for further identification of potentially relevant studies, assessed using the inclusion and exclusion criteria. Expert academic spinal surgeons were consulted as to whether they knew of any unpublished data (7).

Selection criteria

Eligible studies for the present systematic review and meta-analysis included those in which patient cohorts underwent minimally invasive surgery for adult degenerative scoliosis. When institutions published duplicate studies with accumulating numbers of patients or increased lengths of follow-up, only the most complete reports were included for quantitative assessment. All publications were limited to those involving human subjects and in the English language. Abstracts, case reports, conference presentations, editorials, reviews and expert opinions were excluded.

Data extraction and critical appraisal

All data including baseline characteristics, operational parameters, and safety and efficacy outcomes were extracted from article texts, tables and figures. The primary outcome was fusion rate at follow-up as well as change in Cobb angle. Other outcomes extracted included: change in visual analogue scale (VAS) back pain score, change in Oswestry disability index (ODI) score, change in lumbar lordosis angle, and complication rates. Two investigators independently reviewed each retrieved article. Discrepancies between the two reviewers were resolved by discussion and consensus. The quality of studies was assessed using criteria recommended by the National Health Service Centre for Reviews and Dissemination case series quality assessment criteria (University of York, Heslington, United Kingdom). The final results were reviewed by the senior investigators.

Statistical analysis

Data are presented as mean ± standard deviation. For

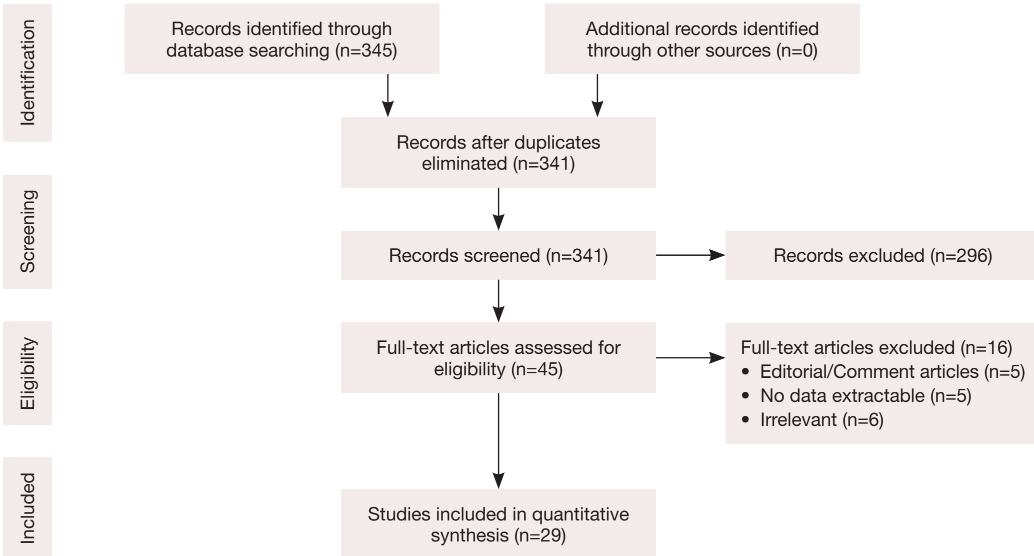

Figure 1 PRISMA flow chart of systematic review and meta-analysis of minimally invasive surgery in adult degenerative scoliosis. PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses.

weighted pooled means, a meta-analysis of proportions was conducted. Firstly, to establish variance of raw proportions, a transformation was applied. To incorporate heterogeneity (anticipated among the included studies), transformed proportions were combined using DerSimonian-Laird random effects models. Finally the pooled estimates were back-transformed. Heterogeneity was evaluated using Cochran Q and I^2 test. Weighted means were calculated by determining the total number of events divided by total sample size.

A formal statistical comparison was performed between decompression, anterior, lateral and transforaminal fusion approaches using mixed-effects meta-regression with a fixed-effect moderator variable for interventional technique. All analyses were performed using the metafor package for R version 3.02. P values <0.05 were considered statistically significant.

Results

Search strategy

A total of 345 references were identified from the electronic databases search. After exclusion and exclusion criteria were applied, 45 references remained for full text evaluation (*Figure 1*). Manual reference list searches did not yield additional studies. After final application of criteria, there were 29 studies (8-20) (1,228 patients) (21-36) included for qualitative and quantitative analysis in the present study. All studies were observational studies, with mean follow-up range of 4.75 to 68.4 months (*Table 1*). Risk of bias assessment for each included study is summarized in *Table S1*.

Baseline characteristics

Patient age ranged from 54 to 77 years. Inclusion and exclusion criteria varied between studies. All required at minimum a diagnosis of adult degenerative lumbar scoliosis at some level with disability, and have undergone a minimally invasive lumbar fusion. The mean operative time ranged from 137 to 401 minutes. The mean hospital stay ranged from 1.4 to 7.6 days. The blood loss ranged from 54 to 480 mL. These characteristics for each study are shown in *Table 2*.

Functional outcomes: VAS & ODI scores

All the studies demonstrated a decrease in pain post-operation compared to pre-operation, as measured by the VAS. The mean decrease in VAS was 34.5 points. The mean pre-operative VAS ranged from 43.5 to 95. Mean post-operative VAS ranged from 15.7 to 70 points. Tormenti and colleagues (32) demonstrated the decrease in VAS pain scores was similar between the LLIF and posterior approach

Table 1 Study characteristics of manuscripts included in the present systematic review and meta-analysis

First author	Year	Study period	Country	Study design	Study type	Patient, n	No. of levels	Follow-up average (months)
Flouzat-Lachaniette	2015	2000–2010	France	R	OS	47	64.0	36.00 (12.0–120.0)
Ahmadian	2015	2008–2012	USA, Australia	R	OS	59	96.0	14.60
Waddell	2014	2008–2013	USA	R	OS	11	37.0	12.00
Sclafani	2014	2011–2012	USA	P	OS	98	122.0	NS
Manwaring	2014	2009–2012	USA	R	OS	27	110.0	22.90 (6.0–37.1)
Khajavi	2014	2005–2009	USA	P	OS	21	70.0	24.00 (12.0–36.0)
Haque	2014	NS	USA	R	OS	22	NS	NS
Castro	2014	2004–2008	Brazil	R	OS	35	107.0	24.00
Wang	2013	NS	USA	P	OS	25	132.0	12.00
Phillips	2013	NS	USA	P	OS	107	451.0	NS–minimum 24 months
Johnson	2013	2009–2011	Italy	R	OS	30	41.0	NS–minimum 6 months
Deukmedjian	2013	2007–2012	USA	R	OS	27	NS	17.00
Caputo	2013	NS	USA	R	OS	30	127.0	14.30
Anand	2013	2007–2009	USA	R	OS	71	NS	39.00 (24.0–60.0)
Wang	2012	NS	USA	R	OS	10	69.0	NS
Marchi	2012	2009–2010	Brazil	R	OS	8	17.0	NS–minimum 6 to max 24 months
Deukmedjian	2012	2010–2012	USA	R	OS	7	51.0	9.10
Caputo	2012	NS	USA	R	OS	30	NS	14.30
Karikari	2011	2005–2009	USA	R	OS	22	47.0	16.40 (3.0–50.0)
Acosta	2011	NS	USA	R	OS	36	66.0	"21 months in 21 patients"
Wang	2010	NS	USA	R	OS	23	86.0	13.40 (6.0–34.0)
Transfeldt	2010	1999–2005	USA	R	OS	85	NS	4.75 (2.0–8.1)
Tormenti	2010	2007–2009	USA	R	OS	12	XLIF group: 22.0, posterior group: 5.0	XLIF: 10.50 (3.0–16.0), Posterior: 11.50 (10.0–12.0)
Matsumura	2010	NS	Japan	R	OS	50	45.0	43.60 (24.0–89.0)
Kelleher	2010	2002–2006	Canada	R	OS	75	102.0	36.50 (18.0–68.0)
Isaacs	2010	NS	USA	R	OS	107	451.0	NS–minimum 24 months
Dakwar	2010	2007–2009	USA	R	OS	25	76.0	11.00 (3.0–20.0)
Liu	2009	2001–2006	China	R	OS	112	NS	68.40
Benglis	2008	NS	USA	R	OS	4	9.0	10.00±1.40
Anand	2008	NS	USA	P	OS	12	3.5 (mean)	2.20

NS, not reported; R, retrospective; P, prospective; OS, observational study; XLIF, extreme lateral lumbar interbody fusion; n, number.

Table 2 Baseline and operative characteristics

First author	Mean age [range]	Males (%)	Patient selection/ inclusion criteria	Surgical technique	Biologics used	Operation duration (min)	Hospital stay (days)	Blood loss (mL)
Flouzat-Lachaniette[A]	64.00 [43–80]	19.1	ADS	ALIF with: HMA cage (4 stand alone, 5 with vantage plate), ROI-A cage (23 stand alone, 6 with vantage plate), 9 Avenue L cage (9 stand-alone)	rhBMP-2	166.0	NS	410.00
Ahmadian[L]	60.00 [31–86]	39.0	DDD, ADS spondylolisthesis	MIS-LLIF	rhBMP-2 (for 19 patients)	NS	3.3	NS
Waddell[L]	66.60 [42–83]		ADS (n=11)	LLIF with posterior correction and augmentation	BMP	NS	NS	NS
Sclafani[T]	64.50 [25–91]	42.9	Spondylolisthesis (27%), central stenosis (25%), foraminal stenosis (14%), degenerative scoliosis (6%)	MIS-TLIF	No	NS	NS	NS
Manwaring[L]	64.30 [32–80]	48.1	ADS	Anterolateral MI-LIF with no ACR, staged percutaneous posterior spinal instrumentation	Osteocel plus allograft	NS	NS	NS
Khajavi[L]	70.10±8.20	33.3	ADS	MI anterior/lateral lumbar interbody fusion	rh-BMP-2	218.0 [100–360]	2.2 [1–8]	68.00 [25–150]
Haque[L]	66.37		ADS	MIS-LIF with staged posterior instrumentation	No	NS	NS	NS
Castro[L]	68.20±9.80	25.7	ADS	LLIF	No	137.0 [80–240]	1.4 [1–4]	54.00
Wang[T]	72.00±7.00	32.0	ADS	MI-TLIF	rh-BMP-2	273±50	5 [3–8]	415.60±149.00
Phillips[L]	68.00 [45–87]	27.1	ADS	XLIF	NS	177.9 [43–458]	3.8 (3 median)	NS
Johnson[L]	56.00±10.60	66.7	Lumbar spondylosis (n=15), ADS (n=15)	XLIF	NS	NS	NS	NS
Deukmedjian[L]	61.00	40.7	ADS	3 cohorts-limited MIS-LLIF, MIS-LLIF + ALLR, MIS-LLIF +/– ALLR	NS	NS	NS	NS
Caputo[L]	65.90 [53–76]	36.7	ADS	XLIF	Osteocel plus allograft	NS	NS	NS
Anand[L]	64.00 [20–84]	47.9	ADS, idiopathic scoliosis, iatrogenic scoliosis	3 approaches-DLIF, percutaneous pedicle screw and presacral approach	rh-BMP-2	stage 1: 291.0, stage 2: 183.0	7.6 [2–26]	Stage 1: 412.00, stage 2: 314.00
Wang[L]	73.00 [62–80]	30.0	ADS	MI-LLIF with percutaneous iliac screw	NS	302.0	5.6 [4–7]	480
Marchi[L]	71.80±7.80	0.0	DDD (n=4), failed back syndrome (n=4)	MIS-LLIF	NS	210.0±127.0	NS	131.30±92.30
Deukmedjian[L]	64.70 [58–71]	42.9	Adult thoracolumbar degenerative deformity	Mix of MI-LLIF, ALIF staged with pedicle screws	NS	NS	8.3 (5 days minimum between the two stages)	Stage 1: 125.00, stage 2: 530.00

Table 2 (*continued*)

Table 2 *(continued)*

First author	Mean age [range]	Males (%)	Patient selection/ inclusion criteria	Surgical technique	Biologics used	Operation duration (min)	Hospital stay (days)	Blood loss (mL)
Caputo[L]	65.90 [53–76]	36.7	ADS	XLIF	Osteocel plus allograft	NS	NS	NS
Karikari[L]	64.60 [50–81]	31.8	ADS (n=11), prior fusion adjacent disease (n=5), thoracic disc herniation (n=3), pathologic fractures (n=2), discitis (n=1)	XLIF	rh-BMP-2	NS	4.8 [2–8]	227.50 [25–1,200]
Acosta[L]	62.00 [43–84]	25.0	Lumbar spondylosis (n=20), degenerative scoliosis (n=7), adjacent segment degeneration (n=5), spondylolisthesis (n=3), pseudoarthrosis (n=1)	DLIF with supplemental posterior fixation	rh-BMP-2	NS	NS	NS
Wang[L]	64.40 [42–84]	26.1	Adult thoracolumbar spinal deformities	Mini-open direct lateral with posterior supplementation	rh-BMP-2	401.0 [200–660]	NS	477.00 [200–3,500]
Transfeldt[D]	Group I: 77.00 [52–85], group II: 70.00 [50–93], group III: 63.00 [51–80]		ADS	Decompression alone (I), decompression with limited fusion (II), decompression with long fusion (III)	NS	NS	Group I: 2.3, group II: 4.6, group III: 8.2	Group I: 108.00, group II: 450.00, group III: 1,538.00
Tormenti[L,P]	XLIF: 60.00 [48–69], posterior: 61.00 [48–81]		ADS	Group I-XLIF with posterior pedicle screw, group II-posterior only	NS	NS	NS	NS
Matsumura[D]	DLS: 69.60 [53–82], LCS: 70.10 [54–84]	20.0	ADS	Microscopic bilateral decompression via a unilateral approach	NS	NS	NS	NS
Kelleher[D]	68.00 [40–89]	52.0	Focal stenosis with and without deformity	MIS lumbar laminoplasty	NS	NS	NS	NS
Isaacs[L]	68.00 [45–87]	27.1	ADS	XLIF	NS	177.9 [43–458]	3.8	NS
Dakwar	62.50 [35–77]	40.0	ADS	Discectomy and lateral interbody graft	rh-BMP-2	108.0 per level	6.2	53.00 per level
Liu[D]	54.70 [43–67]	42.0	ADS	Group 1: Short fusion, group 2: long fusion, group 3: decompression only	NS	NS	NS	NS
Benglis[L]	58.75 [49–75]	25.0	ADS	XLIF	rh-BMP-2	NS	3.5±1.9	NS
Anand	72.80 [50–85]	58.3	ADS	Circumferential fusion	rh-BMP-2	240.6±112.8	NS	163.89±105.41

[L], lateral transpsoas lumbar interbody fusion (XLIF or DLIF or LLIF); [P], posterior lumbar interbody fusion (PLIF); [A], anterior lumbar interbody fusion (ALIF); [T], transforaminal lumbar interbody fusion (TLIF); [D], decompression. XLIF, extreme lateral lumbar interbody fusion; LLIF, lateral lumbar interbody fusion; NS, not reported; ADS, adult degenerative scoliosis; MIS, minimally invasive surgery; ALIF, anterior lumbar interbody fusion; TLIF, transformainal lumbar interbody fusion; DDD, degenerative disc disease; ACR, anterior column release; ALLR, anterior longitudinal ligament release.

(53 *vs*. 55). In the four studies (14,19,25,36) which separately measured back and leg pain, back pain was consistently reported to be worse than the leg pain pre-operatively (range: 3 to 29.5 points difference). A greater degree of pain reduction was reported for back pain compared to leg pain (33.6 & 28.5 points, respectively) (*Table 3*).

In terms of disability, all studies demonstrated a decrease after the operation, as measured by the ODI (range: 8 to 37.5). The mean decrease in ODI was 22.5 points. The mean pre-operative ODI ranged from 24.8 to 82 points (*Table 3*).

Radiological outcomes: Cobb angle & Lumbar lordosis

All the studies, except one, demonstrated a decrease in the Cobb angle (range: –20.2 to +1.4) post-operatively. Liu demonstrated the decrease in Cobb angle was greatest for long fusion (–11.5), followed by short fusion (–6.3), and least for decompression only (–0.4). Tormenti demonstrated the decrease in Cobb angle was greater for LLIF than the posterior approach (28.5 *vs*. 8). The pre-operative Cobb angle ranged from 12.7 to 38.5. The post-operative Cobb angle ranged from 5.6 to 32 (*Table 4*).

All studies, except four, demonstrated an increase in the lumbar lordosis angle (range: –6.9 to 25.1). Tormenti and colleagues (32) demonstrated LLIF achieved a mean decrease of 6.9°, whilst the posterior approach increased the lumbar lordosis angle by 7.7°. Transfeldt and colleagues (33) demonstrated decompression with long fusion achieved an increase of 10° for lumbar fusion, however, no change was seen for decompression alone or decompression with limited fusion.

Fusion rates

Fusion rate (by proportion of patients) was reported only in studies, which used a minimally invasive lateral or LLIF approach. The pooled fusion rate was 95.9% (95% CI: 92.7–98.2%). Fusion rate according to proportion of levels was reported for the LLIF technique in six studies. Pooled fusion rate according to per level was 94.1% (95% CI: 87.1–98.5%) (*Table 5*).

Construct and hardware complications

Total pooled rates for all minimally invasive approaches used was 4.3% (95% CI: 2.4–6.7%). Rate of construct or hardware complication was similar among the different surgical approaches for adult degenerative scoliosis. Pooled construct or hardware complication rate was 4.4% (95% CI: 2.5–6.9%) for LLIF and 5.2% (95% CI: 0.1–28.5%) for transforaminal LIF (TLIF).

Pseudoarthrosis

Pseudoarthrosis was reported in six included studies in this meta-analysis. The pooled pseudoarthrosis rate from the four LLIF studies and two decompression studies was 4.3% (95% CI: 1.7–7.9%).

Subsidence

Subsidence rates were also reported in four LLIF studies. There was significant heterogeneity (I^2=77%, P=0.005) detected between the studies, with Castro *et al*. (29%), Johnson *et al*. (22) (3.3%), Karikari *et al*. (23) (4.5%), and Dakwar *et al*. (16) (4.0%) reporting different rates. This is likely because Castro *et al*. (15) had a longer follow-up period of up to 24 months, which may have captured higher rates of subsidence. The pooled subsidence rate for LLIF studies was 8.5% (95% CI: 1.0–22.1%).

Dural tears or CSF leak

The total pooled rate of dural tears and CSF leaks across the included studies was 5.8% (3.5–8.6%). In the LLIF group, pooled rates of tears and CSF leak was 5.4% (95% CI: 1.7–10.9%), compared to 3.1% (0.6–7.4%) in the TLIF group and 8.1% (2.9–15.6%) in the decompression group. No significant difference was detected among the rate of infections reported (P=0.232).

Infections

Pooled infection rates across 25 studies was 2.6% (95% CI: 1.7–3.7%). When subgrouped according to surgical approach, the anterior/lateral approach rate was 3.6% compared to minimally invasive TLIF (2.0%) and decompression (1.1%). These differences were trending towards significance (P=0.065).

Motor and sensory deficits

The overall pooled rate of motor deficit for all minimally invasive surgery for degenerative lumbar scoliosis was 2.5% (95% CI: 1.5–3.7%). From 21 anterior/lateral minimally invasive approaches, the pooled motor deficit rate was

Table 3 Functional outcomes: visual analogue scale & Oswestry disability index

First author	Visual analogue scale (mean)			Oswestry disability index (mean)		
	Preop	Postop	Change	Preop	Postop	Change
Flouzat-Lachaniette[A]	Back: 63.0, leg: 60.0	Back: 31.0, leg: 23.0	Back: ↓32.0, leg: ↓37.0	51.0	25.0	↓26.0
Ahmadian[L]	69.1	37.8	↓31.1	51.8	31.8	↓20.0
Waddell[L]	NS	NS		NS	NS	
Sclafani[T]	Back: 65.0±155.0, leg: 54.0±28.0	32.0±25.0		46.5±15.2	26.2±20.4	↓20.3
Manwaring[L]	NS	NS		NS	NS	
Khajavi[L]	Back: 70.0, leg: 56.0	Back: 29.0, leg: 33.0	Back: ↓41.0, leg: ↓23.0	48.4	24.4	↓24.0
Haque[L]	NS	NS		NS	NS	
Castro[L]	NS	NS		NS	NS	
Wang[T]	NS	NS		44.9±11.8	24.1±11.6	↓20.8
Phillips[L]	NS	NS		NS	NS	
Johnson[L]	NS	NS		NS	NS	
Deukmedjian[L]	Green: 74.0, yellow: 89.0, red: 85.0	Green: 39.0, yellow: 53.0, red: 70.0	Green: ↓35.0, yellow: ↓36.0, red: ↓15.0	Green: 47.0, yellow: 64.0, red: 70.0	Green: 30.0, yellow: 31.0, red: 60.0	Green: ↓17.0, yellow: ↓33.0, red: ↓10.0
Caputo[L]	NS	NS		NS	NS	
Anand[L]	64.3	35.0	↓29.3	50.3	29.8	↓20.5
Wang[L]	NS	NS		NS	NS	
Marchi[L]	88.0	37.0	↓51.0	82.0	49.0	↓33.0
Deukmedjian[L]	73.0	47.0	↓26.0	60.0	42.0	↓18.0
Caputo[L]	Back: 68.0, leg: 54.0	Back: 46.0, leg: 28.0	Back: ↓22.0, leg: ↓26.0	24.8	19.0	↓5.8
Karikari[L]	73.0	46.0	↓27.0	42.0	34.0	↓8.0
Acosta[L]	77.0	29.0	↓48.0	43.0	21.0	↓22.0
Wang[L]	Back: 73.0, leg: 43.5	Back: 33.5, leg: 15.7	Back: ↓39.5, leg: ↓27.8	NS	NS	
Transfeldt[D]	NS	NS		NS	Group I: 39.5±17.7, group II: 33.9±19.5, group III: 39.5±18.7	
Tormenti[L,P]	XLIF: 88.0, posterior: 95.0	XLIF: 35.0, posterior: 40.0	XLIF: ↓53.0, posterior: ↓55.0	NS	NS	
Matsumura[D]	NS	NS		NS	NS	
Kelleher[D]	NS	NS		49.1	23.9	↓25.2
Isaacs[L]	NS	NS		NS	NS	
Dakwar	81.0	24.0	↓57.0	53.6	29.9	↓23.7
Liu[D]	NS	NS		Group 1: 50.5±6.5, group 2: 53.3±5.8, group 3: 45.3±7.7	Group 1: 17.3±4.9, group 2: 15.8±6.9, group 3: 15.9±5.4	Group 1: ↓33.2, group 2: ↓37.5, group 3: ↓29.4
Benglis[L]	NS	NS		NS	NS	
Anand	71.0±28.0	48.0±19.0	↓23.0	NS	NS	
Mean change			↓34.5			↓22.5

[L], lateral transpsoas lumbar interbody fusion (XLIF or DLIF or LLIF); [A], anterior lumbar interbody fusion (ALIF); [T], transforaminal lumbar interbody fusion (TLIF); [D], decompression; [P], posterior lumbar interbody fusion (PLIF). NS, not reported; XLIF, extreme lateral lumbar interbody fusion.

Table 4 Radiological outcomes

First author	Cobb angle (°)			Lumbar lordosis (°)		
	Preop	Postop	Change	Preop	Postop	Change
Flouzat-Lachaniette[A]	23.10 (10.0–60.0)	17.90 (0.0–73.0)	↓5.90	43.0 [7–75]	49.0 [10–64]	↓6.0
Ahmadian[L]	NS	NS		NS	NS	
Waddell[L]	NS	NS		NS	NS	
Sclafani[T]	NS	NS		NS	NS	
Manwaring[L]	28.90	12.90	↓16.00	43.7	45.9	↑2.2
Khajavi[L]	27.70	16.60	↓11.10	31.8	44.0	↑12.2
Haque[L]	27.28	8.51	↓18.77	20.1	19.9	↓0.2
Castro[L]	21.00	12.00	↓9.00	32.0±7.0	41.0±6.0	↑9.0
Wang[T]	29.20±9.30	9.00±5.00	↓20.20	27.8±12.9	42.6±12.1	↑14.8
Phillips[L]	20.90±10.40	Postop: 13.50±9.20, 24 months FU: 15.20±10.60	Postop: ↓7.00, 24 months FU: ↓5.20	NS	NS	
Johnson[L]	13.00±4.70	7.10±3.70	↓5.90	42.8±10.6	44.4±9.8	↑1.6
Deukmedjian[L]	Green: 23.00, yellow: 22.00, red: 44.00	Green: 11.00, yellow: 11.00, red: 22.00	Green: ↓12.00, yellow: ↓11.00, red: ↓22.00	Green: 55.0, yellow: 37.0, red: 32.0	Green: 56.0, yellow: 44.0, red: 47.0	Green: ↑1.0, yellow: ↑7.0, red: ↑15.0
Caputo[L]	20.20±7.00	5.60±3.40	↓14.60	43.5±11.1	48.5±8.0	↑5.0
Anand[L]	24.70 (8.3–65.0)	9.50 (0.6–28.8)	↓15.20	NS	NS	
Wang[L]	35.00	8	↓27.00	27.0	48.0	↑21.0
Marchi[L]	NS	NS		14.9±7.4	40.0±8.2	↑25.1
Deukmedjian[L]	NS	NS		24.0	48.0	↑24.0
Caputo[L]	20.20 (10.1–42.0)	NS		NS	NS	
Karikari[L]	22.00 (10.0–47.0)	14.00 (4.0–22.0)	↓8.00	NS	NS	
Acosta[L]	21.40	9.70	↓11.70	42.1	46.2	↑4.1
Wang[L]	31.40	11.50	↓19.90	37.4	45.5	↓8.0
Transfeldt[D]	NS	NS		Group I: 46.0, group II: 46.0, group III: 40.0	Group I: 46, group II: 46, group III: 50	Group I: 0.0, group II:0.0, group III: ↑10.0
Tormenti[L,P]	XLIF: 38.50 (18.0–80.0), posterior: 19.00 (17.0–25.0)	XLIF: 10.00, posterior: 11.00	XLIF: ↓28.50, posterior: ↓8.00	XLIF: 47.3, posterior: 30.0	XLIF: 40.4, posterior: 37.7	XLIF: ↓6.9, posterior: ↑7.7
Matsumura[D]	DLS: 12.70±3.20	DLS: 14.10±4.30	DLS: ↑1.40	NS	NS	
Kelleher[D]	13.90 (10.0–32.0)	NS		NS	NS	
Isaacs[L]	20.90±10.40	Postop:13.50±9.20, 24 months FU: 15.20±10.60		NS	NS	
Dakwar	NS	NS		NS	NS	
Liu[D]	Group 1: 17.60±2.80, group 2: 24.30±4.50, group 3: 15.30±3.70	Group 1: 11.30±2.40, group 2: 12.80±3.90, group 3: 14.90±2.80	Group 1: ↓6.30, group 2: ↓11.50, group 3: ↓0.40	Group 1: 30.6, group 2: 21.7, group 3: 28.7	Group 1: 31.7, group 2: 29.5, group 3: 29.3	Group 1: ↑1.1, group 2: ↑7.8, group 3: ↑0.6
Benglis[L]	32.00, 26.00, 20.00, 36.00	16.00, 8.00, 17.00, 32.00		NS	NS	
Anand	18.93±10.48	6.19±7.20	↓12.70	NS	NS	

[L], lateral transpsoas lumbar interbody fusion (XLIF or DLIF or LLIF); [A], anterior lumbar interbody fusion (ALIF); [T], transforaminal lumbar interbody fusion (TLIF); [D], decompression; [P], posterior lumbar interbody fusion (PLIF). NS, not reported; XLIF, extreme lateral lumbar interbody fusion.

Table 5 Fusion outcomes and complications

Parameter	Subgroup	Number of studies	Pooled rate (95% CI)	I^2 (%)	P value for heterogeneity	P value for subgroup difference
Fusion	Anterior/lateral	6	95.9 (92.7–98.2)	4	0.3910	NA
	Posterior	0	—	—	—	
	Decompression	—	—	—	—	
	Overall	6	95.9 (92.7–98.2)	4	0.3910	
Fusion (by level)	Anterior/lateral	5	94.1 (87.1–98.5)	86.31	<0.0001	NA
	Posterior	0	—	—	—	
	Decompression	—	—	—	—	
	Overall	5	94.1 (87.1–98.5)	86.31	<0.0001	
Construct or hardware-related	Anterior/lateral	19	4.4 (2.5–6.9)	31.64	0.0920	0.934
	Posterior	2	5.2 (0.1–28.5)	89.19	0.0020	
	Decompression	—	—	—	—	
	Overall	21	4.3 (2.5–6.6)	42.61	0.0170	
Pseudoarthrosis	Anterior/lateral	4	4.3 (1.7–7.9)	0	0.9190	NA
	Posterior	0	—	—	—	
	Decompression	—	—	—	—	
	Overall	4	4.3 (1.7–7.9)	0	0.9190	
Subsidence	Anterior/lateral	4	8.5 (1.0–22.1)	76.78	0.0050	NA
	Posterior	0	—	—	—	
	Decompression	0	—	—	—	
	Overall	4	8.5 (1.0–22.1)	76.78	0.0050	
CSF leak or dural tear	Anterior/lateral	5	3.4 (1.7–6.9)	0	0.6830	0.232
	Posterior	1	3.1 (0.6–7.4)	NA	NA	
	Decompression	2	8.1 (2.9–15.6)	61.46	0.1070	
	Overall	9	3.9 (3.5–8.6)	7.28	0.3750	
Infection	Anterior/lateral	20	3.6 (2.2–5.2)	0	0.9480	0.065
	Posterior	3	2.0 (0.3–5.2)	0	0.9690	
	Decompression	2	1.1 (0.2–2.7)	0	0.4790	
	Overall	25	2.6 (1.7–3.7)	0	0.8440	
Motor deficit	Anterior/lateral	21	3.6 (2.3–5.1)	0	0.6290	0.004
	Posterior	2	0.7 (0.0–3.0)	0	0.5370	
	Decompression	2	0.5 (0.0–2.1)	0	0.8440	
	Overall	25	2.5 (1.5–3.7)	17.03	0.2230	
Sensory deficit	Anterior/lateral	20	3.3 (2.0–5.0)	6.18	0.3800	0.014
	Posterior	2	0.7 (0.0–3.0)	0	0.5370	
	Decompression	2	0.5 (0.0–2.1)	0	0.8440	
	Overall	24	2.4 (1.4–3.7)	21.76	0.1670	
Cardiac-related	Anterior/lateral	20	2.4 (1.4–3.8)	0	0.9960	0.091
	Posterior	2	1.2 (0.0–4.9)	26.15	0.2450	
	Decompression	2	0.5 (0.0–2.1)	0	0.8440	
	Overall	24	1.7 (0.1–2.7)	0	0.9540	
Pulmonary-related	Anterior/lateral	20	2.0 (1.0–3.2)	0	0.9120	0.189
	Posterior	2	0.7 (0.0–3.0)	0	0.5370	
	Decompression	2	0.5 (0.0–2.1)	0	0.8440	
	Overall	24	1.4 (0.8–2.3)	0	0.8920	

3.6% (95% CI: 2.3–5.1%). This was significantly higher compared to minimally invasive TLIF (0.7%, 95% CI: 0–3.0%) and decompression (0.5%, 95% CI: 1.5–3.7%) (P=0.004).

The total pooled rate of sensory deficit from all minimally invasive surgical approaches used including fusion and decompression was 2.4% (95% CI: 1.4–3.7%). For the minimally invasive LLIF approach, the pooled sensory deficit rate was 3.3% (95% CI: 2.0–5.0%). Minimally invasive TLIF had a pooled sensory deficit rate of 0.7% (95% CI: 0–3.0%), whilst decompression-only resulted in pooled rate of 0.5% (95% CI: 0–2.1%). Meta-regression analysis demonstrated significant difference between the approaches used (P=0.014).

Cardiac events

The total pooled rates for all minimally invasive approaches used were 1.7% (95% CI: 0.1–2.7%). The rate of cardiac complications was similar (P=0.091) among the different surgical approaches for adult degenerative scoliosis.

Pulmonary events

Total pooled rates for all minimally invasive approaches used was 1.4% (95% CI: 0.8–2.3%). Rate of pulmonary complications was similar (P=0.189) among the different surgical approaches for adult degenerative scoliosis.

Discussion

Lumbar degenerative scoliosis is a common degenerative condition of the lumbar spine associated with considerable morbidity. Although the etiology of this condition is not clear, the most commonly implicated causes include asymmetrical degeneration of discs, osteoporosis and vertebral body compression fractures (37). Radiological features include facet hypertrophy, loss of lumbar lordosis and increasing deformity in sagittal and coronal planes. Affected patients most commonly complain of axial low back pain with or without radiculopathy, with stenotic symptoms localized to the primary lumbar curve, generally without neurologic deficit (38-40). This pain may be generated directly by the facet joints or due to nerve root impingement or traction.

The surgical treatment for symptomatic adult scoliosis remains controversial, namely due to the extensive morbidity associated with the conventional, open, surgical approaches (41-44). These open approaches have reported complication rates ranging from 28.1% to 66% with extensive operative time, hospitalization, recovery and return to normal activity (45,46). Despite the risks, these surgical interventions have shown greater benefits over non-surgical treatment in decreasing pain and disability, whilst increasing the health-related quality of life (HRQOL) (41,47). However, major open surgery is often limited by the patients' age, medical comorbidities, as well as the considerable blood loss expected during open surgery.

MIS fusion has been increasingly used as it has been associated with decreased blood loss, decreased hospital stays, and decreased pain compared to open fusion (5). One minimally invasive approach is the decompression procedure such as decompressive laminectomy with or without foraminotomy. Fusion is also an option, which has an increasing array of surgical approaches available. The majority of surgical approaches involved anterior column support with the fusion, and posterior instrumentation. Approaches for lumbar fusion include the: lateral transpsoas interbody fusion [LLIF/DLIF/extreme lateral lumbar interbody fusion (XLIF)], anterior lumbar interbody fusion (ALIF), TLIF and posterior lumbar interbody fusion (PLIF).

Deformity correction

This review demonstrates minimally invasive surgery for adult lumbar scoliosis was able to correct for deformities, with outcomes similar to open surgery. The greatest improvement in the Cobb angle and lumbar lordosis is seen with fusion techniques compared to decompression alone. Liu and colleagues examined minimally invasive short fusion, long fusion and decompression alone. Patients with decompression alone had the lowest change in Cobb angle (decrease of 0.4°) and lumbar lordosis (increase of 0.6°), whilst long fusion had the greatest change in Cobb angle (decrease of 11.5°) and lumbar lordosis (increase of 7.8°). Wang and colleagues, who investigated 23 patients, reported one of the highest decreases in Cobb angle of 27° (pre-operative: 35° to post-operative: 8°). This study used a mini-open direct lateral approach with posterior supplementation. Tormenti and colleagues evaluated patients who underwent XLIF with posterior pedicle screw, and those with the posterior approach only. They identified the group with XLIF with the posterior pedicle screw achieved a greater decrease in Cobb angle of 28.5° compared to the posterior approach alone (decrease of

8°). However, this may be due the large Cobb angle pre-operatively for the XLIF group (38.5°) compared to the posterior approach alone (19°). Both approaches achieved a similar post-operative Cobb angle (10° & 11°). To date there is evidence that suggests minimally invasive lateral procedures are more effective in correcting coronal deformities than sagittal deformities such as regional lordosis, which is more clinically significant (48). While studies are still limited, there are newer minimally invasive techniques such as anterior column realignment (ACR), which can effectively correct sagittal deformities with potentially less surgical complications (49,50). Nevertheless, the current evidence suggests that minimally invasive fusion approaches may be associated with improved deformity correction. However, further long-term studies are required to determine the differences in deformity progression between the anterior, lateral, and posterior fusion techniques.

Clinical outcome

The results from this review demonstrated that minimally invasive surgical approaches are effective at improving the functional outcomes of degenerative scoliosis patients, with rates similar to open, conventional procedures. All the included studies demonstrated a decrease in back pain and disability post-operation compared to pre-operation, as measured by the VAS and the ODI respectively. The pooled absolute decrease in the VAS back pain score was 34.5 points (pre-operative range, 43.5–95 points & post-operative range, 15.7–70 points). The pooled absolute decrease in ODI was 22.5 points (range, 8–37.5). Tormenti *et al*. demonstrated the decrease in VAS pain scores was similar between XLIF and posterior approach (53 *vs*. 55 points). Liu and colleagues investigated 112 patients and demonstrated the average improvement in the ODI was 32.6, 26.3 and 13.5 for long segment fusion, short segment fusion and simple decompression without fusion (mean of 5.7 years follow-up). However, as seen from *Table 3*, there are several studies that have not reported VAS or ODI data. Therefore, it is difficult to make firm definitive conclusions. Further research is warranted to compare the clinical outcome differences between the different minimally invasive approaches.

Complications

The total pooled fusion and pseudoarthrosis rates for all minimally invasive surgery for degenerative lumbar scoliosis were 95.9% and 6.0%, respectively. Meta-regression demonstrated that pseudoarthrosis rates were similar between anterior/lateral approaches compared to decompression (4.3% *vs*. 7.5%, respectively) (P=0.189).

The mean overall pooled rate of motor deficit and sensory deficit was 2.5% and 2.4% respectively. Significantly higher motor deficits were seen in the anterior/lateral approach compared to the transforaminal approach and decompression alone. Similar trends were also seen for sensory deficit, which was significantly higher in the anterior/lateral subgroup. The significantly higher rate of motor deficits for the anterior/lateral can be justified by the fact that LLIF requires dissection of the psoas major, which may injure the nerves of the lumbar plexus or cause significant trauma to the psoas major. A possible explanation for the higher rates of motor deficits for ALIF may be related to the violation or retraction of great vessels, whereby undetected injury or intraoperative ischemia (51,52) may result in post-operative motor deficits. This may be further compounded by the increased operative time for ALIF compared to XLIF (53,54). Closer examination into the studies which used a more anterior corridor demonstrates the motor deficit reported in one study (25) was foot drop in 1 patient (4.8%), and in the other study (19), a persisting, complete, L5 palsy without residual compression on CT scan in 1 patient (2.1%) and acute urinary retention in 6 patients (12.8%). If the patients who developed acute urinary retention were removed, the rates of motor deficits for ALIF would be 3.45%, which would be similar to a purely lateral approach.

The total pooled rate of infections, dural tears/CSF leaks, hardware complications, cardiac and pulmonary events were 2.6%, 5.8%, 4.3%, 1.7% and 1.4%, respectively. There were no significant differences between the different minimally invasive interbody fusion techniques. The rates of complication in this review are substantially lower than open approaches, which have reported rates ranging from 28.1% to 66% (45,46).

Learning curve and comparison with open surgery

MIS fusions have been associated with steep learning curves, increased surgical times, and increased radiation exposure. However, Anand and colleagues (11) have demonstrated otherwise, where MIS approaches were technically feasible, had shorter hospital stays, able to be accomplished within very reasonable operative times, and associated with much less blood loss than open procedures (when compared with the literature). Additionally, this review illustrates the lengths of surgery, hospital stay and blood loss associated with MIS fusions for lumbar degenerative scoliosis is relatively lower than open procedures (*Table 2*). Furthermore, the clinical outcomes, both in terms of VAS and ODI demonstrate excellent results for minimally invasive procedures.

Limitations

Limitations of the current review include the lack of direct comparative studies between the different minimally invasive surgical approaches (1,55). This resulted in significant heterogeneity and selection bias unaccounted for. In order to minimise heterogeneity, subgroup analysis was performed based on the type of fusion and separated decompression only studies out. However, there still remains a significant level of heterogeneity regarding the techniques used by different surgeons and centres (e.g., type of posterior instrumentation, graft types, additional posterior instrumentation). Additionally, the follow-up duration was variable between studies and limited for some studies [2.2 months (11)]. This may undermine the true rate of complications in studies which have a relatively shorter follow up compared to those with a longer follow up, such as the rate of pseudoarthrosis, changes in Cobb angle and lumbar lordosis. However, the effect of this is reduced by having a majority of pooled studies into the meta-regression having more than 12 months follow-up. Poor reporting of key outcomes from the included studies also limited assessment of surgical approaches. For example, few studies reported SVA as a marker of sagittal correction, and it was difficult to compare statistically blood loss, operative time, and length of stay among the approaches. Despite these limitations, this review has several strengths such as thoroughly evaluating and assessing the functional and clinical outcome of the available literature for minimally invasive surgery for adult degenerative scoliosis.

Conclusions

Minimally invasive spine technologies may be used for the surgical treatment of lumbar degenerative scoliosis. The current review adds to the growing literature examining minimally invasive techniques in adult scoliosis, suggesting that the procedure may have acceptable complication rates, radiological outcomes and clinical outcomes. Anterior and particularly lateral approaches are likely associated with increased motor and sensory deficit compared to posterior approaches. Similar rates of hardware/constructed-related complications, CSF leak, cardiac and pulmonary complications were found among LLIF, TLIF and decompression techniques. Future studies, specifically multi-centered longitudinal, examining the adequacy of MIS is warranted to compare long-term outcomes with the traditional procedure.

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Footnote

Conflicts of Interest: The authors have no conflicts of interest to declare.

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