Journal of Clinical Orthopaedics and Trauma 75 (2026) 103396

Contents lists available at ScienceDirect

Journal of Clinical Orthopaedics and Trauma

journal homepage: www.elsevier.com/locate/jcot

Original article

Impact of robotic assistance on early outcomes in adult spinal deformity surgery: A comparative analysis of inpatient and 30-day outcomes☆

R Dinesh Iyer [a,c], Vidyadhara S [a,b,c,*], Abhishek Soni [a], Balamurugan T [a], Dhiyanesh Krishnamurthy [a]

[a] Manipal Institute of Robotic Spine Surgery, Manipal Comprehensive Spine Care Centre, Manipal Hospital, Bangalore, India
[b] Department of Orthopaedics, Kasturba Medical College Manipal, Manipal Academy of Higher Education, Manipal, India

ARTICLE INFO

Keywords:
Adult spinal deformity
Degenerative scoliosis
Long segment fusion
Robotic spine surgery
Mazor X

ABSTRACT

Background: Robotic assistance in adult spinal deformity (ASD) surgery has been associated with improved pedicle screw accuracy and reduced blood loss and radiation exposure. However, evidence regarding early postoperative outcomes, complication profiles, and short-term readmissions in long-segment adult spinal deformity(ASD) surgeries remains limited. This study compared perioperative parameters and early functional outcomes between robotic-assisted and conventional open long-segment fusion for ASD.

Methods: We conducted a retrospective review of consecutive patients undergoing long-segment fusion for ASD (upper instrumented vertebra T10–T12, lower instrumented vertebra pelvis) at a tertiary spine center from June 2022 onward. Patients undergoing upper thoracic fixation, three-column osteotomies, non-instrumented procedures, or surgery for non-degenerative pathologies were excluded. Robotic-assisted minimally invasive fixation was compared with conventional open instrumentation. Estimated blood loss (EBL), operative duration, hospital length of stay, Visual Analog Scale (VAS) scores, Oswestry Disability Index (ODI), complications, 30-day readmissions, and mortality were analyzed.

Results: Seventy-four patients were included (34 robotic, 40 open), with comparable baseline characteristics. The robotic group demonstrated significantly lower EBL (745 ± 168 vs. 1026 ± 266 mL, $p < 0.001$), shorter operative time (227.6 ± 28.3 vs. 290.2 ± 30.5 min, $p < 0.001$), and reduced hospital stay (median 3 vs. 5.5 days, $p < 0.001$). Both groups showed significant 30-day improvements in ODI and VAS scores. ODI improvement was greater in the robotic cohort (6.9 ± 2.8 vs. 4.8 ± 2.5, $p = 0.002$; Cohen's $d = 0.81$), while VAS improvements were comparable. Complication rates, 30-day readmissions (8.1%), and mortality (0%) did not differ between groups.

Conclusion: Robotic-assisted long-segment fusion for ASD was associated with reduced blood loss, shorter operative time, and decreased hospital stay, with improved early functional recovery and no increase in short-term complications.

1. Introduction

Adult spinal deformity (ASD) has garnered significant interest over the past decade, as evidenced by the steady increase in scientific publications on the subject since 2005, peaking in 2021.[1] With rising global life expectancy, clinicians are increasingly encountering geriatric patients presenting with spinal pathologies. The prevalence of ASD has been reported to range between 20% and 32%, though it varies depending on age group and geographic region [2–4]. Surgical management in this high-risk, frail population is associated with substantial morbidity. In a prospective 2-year study, J. S.Smith et al.[5] reported a 28.2% reoperation rate and 270 peri-operative complications, including 145 minor and 125 major events. Similarly, Acosta et al.[6] found that patients ≥75 years old receiving severe deformity treatment had an

☆ Institution of Research: Manipal Institute of Robotic Spine Surgery, Manipal Hospital, Bangalore, India.

* Corresponding author. Spine Surgery, Consultant Robotic Spine Surgeon, Manipal Institute of Robotic Spine Surgery & Manipal Comprehensive Spine Care Center, Manipal Hospital, Old Airport Road, Bangalore, 560017, India.
E-mail address: vidya007@gmail.com (V. S).

[c] Authors 1 & 2 contributed equally to this manuscript.

https://doi.org/10.1016/j.jcot.2026.103396
Received 21 December 2025; Received in revised form 11 February 2026; Accepted 22 February 2026
Available online 23 February 2026

overall peri-operative complication rate of 62% and a long-term post-operative complication rate of 52%.

Minimally invasive surgery (MIS) has emerged as an alternative approach to address these conditions, demonstrating comparable clinical and radiographic outcomes to open surgery, but with fewer complications [7–9]. A multicentre study by Than KD et al.[10] comparing the complications of MIS with open/hybrid surgeries showed that the MIS group had significantly fewer surgical, neurological and minor complications in the MIS group.

However, the clinical outcomes and re-operation rates were similar in both the groups despite complications. Building on this foundation, the use of robot assisted spine surgeries has increased steadily in the past decade and is supported by multiple studies reporting high accuracy in screw insertion even in degenerative scoliosis[11–13]. The potential advantages of robotics in long-segment deformity correction include percutaneous screw placement, reduced intraoperative blood loss, decreased soft-tissue trauma, lower postoperative pain, and earlier mobilisation.

While there is abundant literature on the outcomes of MIS in surgeries for ASD, studies specifically evaluating robot-assisted techniques in ASD surgeries remain limited. With this background, we compared robotic-assisted and traditional open techniques for ASD surgery in a retrospective analysis focussing on the perioperative complications and early postoperative outcomes.

2. Materials and methods

This study was performed at a tertiary-level spine referral center following approval from the Institutional Review Board (IRB No. ECR/34/Inst/KA/2013/RR-24). Aim of the study was to assess the peri-operative, 30-day post-discharge outcomes and early complications rates among patients who underwent surgery for adult spinal deformity. Written informed consent was obtained from all participants for the use of their intraoperative and follow-up data for research and publication purposes.

Consecutive patients with adult spinal deformity who underwent surgery at our center from June 2022 onward were included if they demonstrated at least one of the following radiographic criteria: coronal Cobb angle $>20^{\circ}$, sagittal vertical axis >5 cm, pelvic tilt $>20^{\circ}$, pelvic incidence–lumbar lordosis mismatch $>10^{\circ}$, or thoracic kyphosis $\geq 60^{\circ}$. All patients underwent long segment fusion surgeries (either open or robotic assisted) in which the upper instrumented level (UIV) was between T10-T12 and lower instrumented vertebra (LIV) being pelvis/ilium for all cases. The study period began in June 2022. Robotic-assisted spine surgery was introduced at our institution in October 2023. All eligible patients treated prior to this date underwent conventional open surgery. After introduction of robotic surgery, eligible patients were counseled regarding both approaches, and the final surgical technique was determined through shared decision-making. Treatment allocation was not randomized. All procedures were performed by the same senior surgeon.

We excluded patients for which the UIV was in upper thoracic spine (T2-T4), patients who underwent 3 column osteotomies, revision surgeries, non-instrumented surgeries (decompression alone) or limited/short segment surgeries and patients with non-degenerative pathologies like infections, trauma and tumors.

Surgical technique (Open surgery) - All surgeries were performed by the senior author (VS). Standard midline exposure was done followed by pedicle screw instrumentation at the chosen levels. Decompression was done at the stenotic segments based on MRI. Contoured rods were inserted and correction of deformity was achieved by a combination of posterior releases, facetectomies, cantilevering and de-rotation maneuvres. Interbody fusion was done at L4-L5 or L5-S1 levels using transforaminal approach in all the cases to provide anterior column support.

Surgical technique (Robot assisted MIS surgery) - Robot-assisted procedures were performed using the Mazor X Stealth Edition system coupled with O-arm™ imaging (Medtronic Ltd., Dublin, Ireland) and a standardized scan-and-plan protocol.[14] Following sterile preparation, system calibration and registration were completed using a fiducial star-marker array. Orthogonal radiographs were obtained to verify marker visibility, after which a 3D scan was acquired and transferred to the robotic workstation for planning of pedicle screw trajectory, dimensions, and incision sites.

All planned levels were instrumented percutaneously under robotic guidance. Proximal fixation (T10/T11–L2) employed reduction screws with long detachable tulips. Limited midline exposure was restricted to L3–S1, with lateral exposure of screw heads. Rods were passed through a submuscular tunnel, preserving proximal midline structures. Neural decompression and interbody fusion were performed using standard open techniques. A representative case is illustrated in Fig. 1.

2.1. Data Collection

Clinical records were examined from admission through 30 days following surgery using the institutional electronic database. Patient-related variables included age, sex, body mass index(BMI), American Society of Anesthesiologists(ASA) class, and Charlson Comorbidity Index(CCI). Surgical metrics comprised operative time and estimated blood loss(EBL). Outcomes assessed after surgery included hospital length of stay, Oswestry Disability Index(ODI), Visual Analog Scale (VAS) scores for back and leg pain, postoperative complications, 30-day readmissions, and mortality.

2.2. Complications were categorized into two groups

1. Surgery-related complications which included wound dehiscence or superficial infection, deep surgical site infection (SSI), neurological deficits or radiculopathy, and dural tear/cerebrospinal fluid (CSF) leak.
2. Medical complications included pulmonary embolism (PE), myocardial infarction (MI), congestive heart failure (CHF), deep vein thrombosis (DVT), urinary tract infection (UTI), paralytic ileus, delirium, and sepsis.

Additionally, 30-day readmission rates, reoperation rates, and mortality were documented. All variables were compared between the two cohorts: Group 1 – robotic-assisted surgeries and Group 2 – open/non-robotic surgeries.

2.3. Data and statistical analysis

Continuous variables were summarized as means with standard deviations, and categorical data as frequencies. As data was non-parametric, between-group comparisons were performed using the Mann–Whitney U and chi-square test. Within-group pre-to postoperative changes were assessed using the Wilcoxon signed-rank test. Statistical significance was set at $p < 0.05$.

3. Results

3.1. Baseline characteristics

A total of 74 patients were included in the study, comprising 34 in the robotic-assisted group and 40 in the non-robotic group. Baseline demographic and clinical parameters, including age (68.4 ± 6.3 vs. 66.8 ± 4.7 years, $p = 0.210$), sex distribution (41 males and 33 females; no between group difference, p value = 0.87), body mass index (overall BMI 26.5 ± 4.7 with no significant between group differences, p value = 0.74), ASA grade distribution and Charlson Comorbidity Index, were comparable between robotic and non-robotic cohorts (Table 1). Baseline radiographic parameters were comparable in both the groups (Table 2).

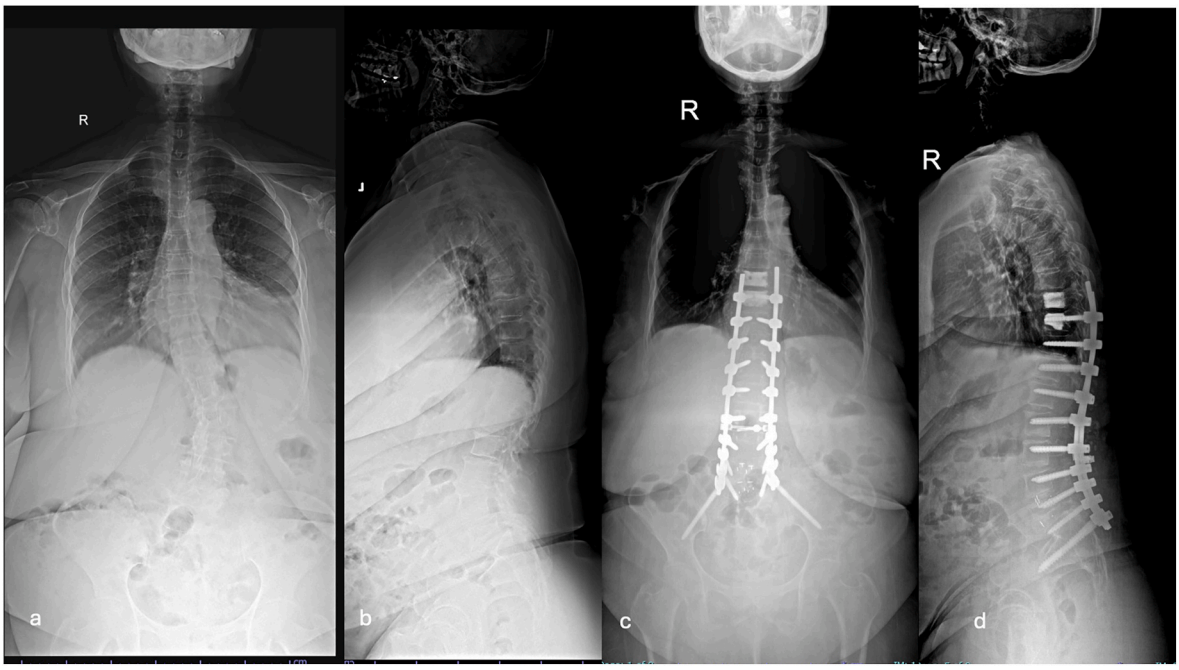

Fig. 1. A 65 year old lady with degenerative scoliosis, multilevel lumbar stenosis (L1–L5), and L4–L5/L5–S1 spondylolisthesis treated with T10–ilium posterior instrumented deformity correction, interbody fusion at L4–L5 and L5–S1, L1–L5 decompression, and cement augmentation at T9–T10.

Table 1
Baseline demographic and clinical characteristics.

Variable	Overall (n = 74)	Robotic (n = 34)	Non-robotic (n = 40)	p-value
Age (years)	67.51 ± 5.5	68.41 ± 6.3	66.75 ± 4.7	0.21[a]
Gender (Male/ Female)	41 males 33 females M:F ratio = 1.24	18 males 16 females M:F ratio = 1.12	23 males 17 females M:F ratio = 1.35	0.87**
BMI (kg/m^2)	26.5 ± 4.7	26.3 ± 4.5	26.7 ± 4.9	0.74[a]
ASA Grade	ASA grade 1 - 21 ASA grade 2 - 36 ASA grade 3 - 17	ASA grade 1 - 11 ASA grade 2 - 18 ASA grade 3 - 5	ASA grade 1 - 10 ASA grade 2 - 18 ASA grade 3 - 12	0.88**
Charlson Comorbidity Index (CCI)	Low risk (0-1 point) - 47 Moderate risk (2-3 points) −19 High risk (≥4 points) - 8	Low risk (0-1 point) - 22 Moderate risk (2-3 points) - 9 High risk (≥4 points) - 3	Low risk (0-1 point) - 25 Moderate risk (2-3 points) - 10 High risk (≥4 points) - 5	0.54[#]
VAS Score (Back pain)	6.69 ± 0.9	6.7 ± 0.9	6.67 ± 0.91	0.88[a]
VAS score (Leg pain)	5.31 ± 1.23	5.47 ± 1.41	5.17 ± 1.03	0.318[a]
ODI score (out of 45 - excluding sex life)	28.36 ± 4.14	27.85 ± 4.63	28.8 ± 3.68	0.33[a]

[a] Independent *t*-test; ** - Chi square test; # - Mann-Whitney test; VAS - Visual analog score; ODI - Oswestry Disability Index.

3.2. Intra-operative parameters and early post-operative outcomes (Table 3)

1. **Estimated blood loss (EBL)** - Mean EBL was significantly lower in the robotic group (745 ± 168 ml) than in the non-robotic group (1026 ± 266 ml), reflecting a mean reduction of approximately 281 ml ($p < 0.001$, Mann–Whitney U).

Table 2
Pre-operative radiographic parameters.

Pre-operative parameters	Robotic assisted (n = 34)	Non-robotic (n = 40)	p-value[a]
Pelvic Incidence (PI)	52.17° (17.6°)	52.43° (12.56)	0.964
Pelvic Tilt (PT)	26.2°(9.72°)	30.43° (5.74)	0.277
Sacral Slope (SS)	26° (16.4)	22° (8.4)	0.544
Lumbar Lordosis (LL)	22.33° (14.6)	18.71° (6.6)	0.318
SVA (cm)	6.2 (3.6)	5.1 (2.8)	0.470
Coronal cobbs	22.5° (13.32)	31.7° (10.31)	0.150

[a] Independent *t*-test.

2. **Duration of Surgery -** Robotic-assisted procedures had a shorter mean operative time (227.6 ± 28.3 min) compared with non-robotic surgery (290.2 ± 30.5 min), corresponding to a mean reduction of 62.6 min (95% CI −76.2 to −49.0; $p < 0.001$).
3. **Length of stay -** The robotic group demonstrated a shorter hospital stay (mean 2.97 ± 0.9 days; median 3 days, IQR 2–4) compared with the open group (mean 5.12 ± 0.9 days; median 5.5 days, IQR 5–6), with a significant reduction of approximately 2–3 days ($p < 0.001$).

3.3. Functional outcomes (Table 3)

1. **VAS score (Back pain) -** Both cohorts showed significant within-group improvement at 30 days ($p < 0.01$). Back pain VAS improved from 6.7 ± 0.9 to 2.6 ± 0.9 in the robotic group and from 6.67 ± 0.91 to 2.97 ± 0.86 in the non-robotic group, with no significant between-group difference ($p = 0.055$).
2. **VAS score (Leg pain) -** Leg pain VAS scores improved significantly in both groups, decreasing from 5.47 ± 1.41 to 1.65 ± 0.73 in the robotic cohort and from 5.17 ± 1.03 to 1.45 ± 0.87 in the non-robotic cohort, with no intergroup difference ($p = 0.44$, Mann Whitney U).
3. **ODI score -** Both groups demonstrated significant improvement in ODI scores at 30-day follow-up compared to baseline. Improvement was greater in the robotic group (6.94 ± 2.8) than in the non-robotic

group (4.8 ± 2.5), with a mean difference of 2.1 (95% CI 0.9–3.4; p = 0.002) and a large effect size (Cohen's d = 0.81).

A consolidated summary of peri-operative and functional outcomes are presented in Table 3.

3.4. Peri-operative complications

Medical complications were recorded in 14 patients, accounting for 19 events, involving 8 patients in the robotic group and 6 in the non-robotic group. Urinary tract infection (UTI) was the most common complication, occurring in six patients (2 robotic, 4 non-robotic; p = 0.415). Other medical events included paralytic ileus (2 patients, one per group), acute kidney injury (1 robotic), pulmonary embolism (2 non-robotic), myocardial infarction (1 non-robotic), deep vein thrombosis (1 robotic), delirium (4 patients, two per group), and sepsis (2 patients, one per group). Both sepsis cases followed postoperative UTI and required readmission for intravenous antibiotics. Cardiopulmonary events were identified prior to discharge and managed without residual morbidity. Multiple complications occurred in five patients, including combined pulmonary embolism and myocardial infarction, UTI progressing to urosepsis, and delirium with paralytic ileus. No between-group differences were statistically significant.

Surgical complications occurred in 14 patients (6 robotic, 8 non-robotic). Wound dehiscence was most frequent (4 patients, two per group), followed by CSF leak (3 patients), deep surgical site infection (3 patients), and neurological deficit (4 patients). Deep surgical site infections occurred in three patients (one in the robotic group and two in the non-robotic group), while cerebrospinal fluid leaks were observed in three patients (one robotic and two non-robotic). No statistically significant differences were noted between groups. Complications and their distribution are summarized in Table 4.

3.5. Readmission and mortality

Six patients were readmitted within 30 days due to urosepsis (2 patients - one robotic and one non-robotic), deep surgical site infection (3 cases - one robotic and two non-robotic), or persistent CSF leak(one patient in non-robotic group). No cases of 30-day mortality was observed in any of the cohorts.

Table 3
Comparison of peri-operative parameters and functional outcomes.

Variable	Robotic (n = 34)	Non-robotic (n = 40)	p-value
Estimated Blood Loss (ml)	**Mean(SD)** - 745 (168) **Median(IQR)** - 740 (650–828)	**Mean(SD)** - 1026 (266) **Median(IQR)** −1000(845–1163)	p < 0.01*
Duration of Surgery (min)	**Mean(SD)** - 227.64 (28.3) **Median(IQR)** - 220(210–240)	**Mean(SD)** - 290.25 (30.5) **Median(IQR)** - 295 (268–320)	p < 0.01*
Length of Stay (number of days)	**Mean(SD)** - 2.97 (0.90) **Median(IQR)** - 3.0 (2–3.75)	**Mean(SD)** - 5.12 (0.91) **Median(IQR)** - 5.5 (5–6)	p < 0.001*
30 day post op VAS score (back pain)	2.6 ± 0.9	2.97 ± 0.86	p = 0.055*
△VAS - Back pain	4.12 ± 0.97	3.7 ± 0.85	p = 0.06*
30 day post op VAS score (leg pain)	1.65 ± 0.73	1.45 ± 0.87	p = 0.224 *
△VAS - Leg pain	3.82 ± 1.31	3.72 ± 1.15	p = 0.44*
30 day post op ODI score	20.91 ± 2.76	24 ± 3.85	p < 0.01*
△ODI score	6.94 ± 2.83	4.8 ± 2.48	p < 0.01*

SD - Standard Deviation; IQR - Inter-quartile range; * - Mann Whitney *U* test.

Table 4
Overview of complications.

Variable	Overall (n = 74)	Robotic (n = 34)	Non-robotic (n = 40)
Medical complications (no. of patients)	**14** (19 complications in 14 patients) UTI - 6 AKI - 1 PE - 2 MI - 1 Sepsis - 2 DVT - 1 Ileus - 2 Delirium - 4	**8** UTI - 2 AKI - 1 PE - 0 MI - 0 Sepsis - 1 DVT - 1 Ileus - 1 Delirium - 2	**6** UTI - 4 AKI - 0 PE - 2 MI - 1 Sepsis - 1 DVT - 0 Ileus - 1 Delirium - 2
Surgical complications (no. of patients)	**14** Wound Dehiscence - 4 CSF leak - 3 Deep SSI - 3 Neurological deficit - 4	**6** Wound Dehiscence - 2 CSF leak - 2 Deep SSI - 1 Neurological deficit - 1	**8** Wound Dehiscence - 2 CSF leak - 1 Deep SSI - 2 Neurological deficit - 3
Re-admissions	**6 readmissions** UTI and sepsis - 2 (Managed with supportive care and IV antibiotics) Deep SSI - 3 (wound debridement done) CSF Leak - 1 (re-exploration and repair of dural defect)	**3 readmissions** UTI and sepsis - 1 CSF Leak - 1 Deep SSI - 1	**3 readmissions** UTI and sepsis - 1 Deep SSI - 2
Mortality	Nil	Nil	Nil

UTI - Urinary tract infection; AKI - Acute Kidney Injury; PE - Pulmonary embolism; CSF - Cerebrospinal fluid.
MI - Myocardial infarction; DVT - Deep Vein Thrombosis; SSI - Surgical site infection.

Comparisons between groups were performed using the chi-square test for overall complication rates and Fisher's exact test for individual complication subtypes, depending on expected cell counts. A two-tailed $p < 0.05$ was considered statistically significant.

4. Discussion

Adult spinal deformity (ASD) surgery requiring long-segment fusion represents one of the complex procedures in spine surgery and is associated with substantial perioperative morbidity, including high blood loss, prolonged operative time, and extended hospitalization.[15,16] Robotic-assisted surgery has emerged as a potential strategy to address these challenges by improving instrumentation accuracy while facilitating minimally invasive fixation. By limiting soft tissue disruption and optimizing screw placement, robotic assistance may mitigate several perioperative risks inherent to ASD surgery.

In our cohort, robotic-assisted surgery was associated with significantly lower intraoperative blood loss, shorter operative duration, and reduced length of hospital stay compared with conventional open techniques. These findings align with a systematic review by Sun et al., which demonstrated an approximate 30% reduction in estimated blood loss with robotic pedicle screw insertion in deformity surgery.[17] Similarly, our study demonstrated a 27% reduction in blood loss in the robotic group. Given the established association between blood loss, operative duration, and postoperative complications, these findings are clinically meaningful.

Operative time is a critical determinant of perioperative morbidity. Monetta et al. reported a marked increase in both medical and surgical complications as operative duration increased, with complication rates rising from 2.4% for procedures under 2 h to nearly 70% for surgeries exceeding 4 h.[18] In our study, robotic-assisted surgery reduced operative time by approximately 1 h. While earlier reports suggested longer operative times with robotic spine surgery compared to

navigation-based or freehand techniques,[19,20] many of these studies reflected early adoption phases, limited-level fusions, and less standardized workflows. In contrast, our experience demonstrates that for long-segment constructs involving 9–12 levels, robotic assistance—particularly with percutaneous screw placement—can meaningfully reduce operative duration compared with open midline exposure used in most prior series.

Length of hospital stay was also significantly reduced in the robotic group. Kantelhardt et al. reported a mean reduction of four days with percutaneous robotic-assisted procedures compared to non-robotic surgery,[21] while Hyun et al. demonstrated shorter hospital stays in a randomized trial comparing robotic-assisted and conventional open techniques (6.8 vs. 9.4 days).[22] A meta-analysis by Li et al. similarly reported reduced postoperative hospitalization with robotic pedicle screw placement compared to freehand methods.[23] Consistent with these findings, patients in our robotic cohort experienced a shorter hospital stay, averaging approximately three days versus nearly five days in the open group, with potential implications for reduced healthcare costs.

The impact of robotics on functional outcomes remains less clear. Hyun et al. reported superior improvement in ODI scores with robotic assistance,[22] whereas Park et al. and Keric et al. found no significant differences.[24,25] Notably, these studies primarily involved short-segment fusions performed through open approaches in both groups. In contrast, our study focused on long-segment constructs and employed percutaneous fixation for proximal segments in the robotic cohort, preserving midline musculature which likely contributed to the superior ODI improvement observed in our robotic group. Although the robotic-assisted group demonstrated a statistically greater improvement in ODI at 30 days, this difference did not consistently exceed commonly reported thresholds for the minimal clinically important difference (MCID), which typically range from 8 to 12 points in adult spinal deformity populations.[26] However, given the early postoperative time point evaluated in this study, these findings likely reflect accelerated functional recovery rather than definitive long-term superiority. Longer-term follow-up is necessary to determine whether these early advantages translate into clinically meaningful differences at later time points.

Improvements in VAS scores for back and leg pain were comparable between groups, underscoring the multifactorial nature of axial back pain, which is influenced by factors such as sarcopenia, osteoporosis, frailty, and psychosocial variables that may not be directly modified by robotic assistance alone. It is important to acknowledge that the observed perioperative advantages likely reflect the combined effect of robotic guidance and a minimally invasive fixation strategy, as these two components are inherently integrated in the robotic workflow used in this study.

Despite these perioperative and functional benefits, safety remains a key concern. In our series, overall complication rates, 30-day readmissions, and mortality were comparable between robotic and non-robotic groups, with no deaths observed within 30 days. These findings are consistent with those of Vengsarkar et al., who reported similar surgical complication rates but fewer pulmonary and systemic events in robotic ASD surgery, potentially attributable to reduced surgical stress.[27]

Urinary tract infection (UTI) was the most common medical complication in our cohort, occurring in 8.1% of patients. UTIs in the postoperative period carry significant systemic implications. Núñez-Pereira et al. reported that over one-third of Gram-negative surgical site infections originated from urinary sources.[28] In our study, both cases of deep surgical site infection were preceded by UTIs with concordant *E. coli* cultures. Additionally, Bohl et al. demonstrated that UTIs substantially increase the risk of systemic sepsis,[29] a finding reflected in our cohort, where both patients who developed sepsis had preceding UTIs.

Pulmonary complications, historically common in deformity surgery—particularly with combined anterior approaches—have decreased with the predominance of posterior-only techniques. Jules-Elysee et al. reported radiographic pulmonary abnormalities in 64% of patients undergoing combined anteroposterior fusion.[30] While contemporary posterior approaches have reduced this risk, pulmonary complications continue to occur in 3–5% of frail or elderly patients due to aspiration or preexisting cardiopulmonary compromise.

Cardiovascular complications following spine surgery remain uncommon, with reported 30-day myocardial infarction rates ranging from 0.13% to 1.60%.[31,32] Identified risk factors include extensive fusion, prolonged operative duration, advanced age, transfusion, and chronic kidney disease. In our cohort, cardiopulmonary complications occurred in 4.05% of patients, including two pulmonary emboli and one myocardial infarction, reflecting the high-risk nature of ASD surgery rather than technique-specific factors.

Robotic integration in ASD surgery continues to evolve. Future advances may include enhanced navigation, augmented reality, and artificial intelligence–assisted planning to further improve efficiency and accuracy. Expanded use of minimally invasive deformity correction enabled by robotics may further reduce tissue trauma, blood loss, and postoperative pain. Cost-effectiveness remains a critical consideration; while robotic systems entail substantial capital investment, reductions in transfusion requirements, complications, and length of stay may offset initial costs. Identifying patient subgroups most likely to benefit—such as elderly or frail individuals and those with severe deformity—will be essential for optimizing utilization.

5. Limitations

This study is limited by its retrospective, single-center design and relatively small sample size, which restricts the ability to detect differences in rare complications. Only short-term outcomes were evaluated, and long-term radiographic correction, fusion rates, and implant durability were not assessed. Propensity matching and multivariable analyses were not performed due to sample size limitations, although baseline characteristics were comparable and effect-size estimates support the robustness of our findings. Because treatment allocation was not randomized and was influenced by the timing of robotic adoption and patient preference, selection bias cannot be excluded; however, baseline demographic, clinical, and radiographic characteristics were comparable between groups. Larger prospective multicenter studies with long-term follow-up and cost analyses are warranted.

6. Conclusion

Robotic-assisted long-segment fusion for adult spinal deformity was associated with reduced blood loss, shorter operative time, and decreased hospital stay compared with non-robotic open surgery, without increased complications or readmissions. These findings suggest that robotic assistance enhances perioperative efficiency and may translate into meaningful early clinical benefits.

Patient consent statement

Informed consent for participating in the study and use of their clinical and radiological data was taken from each participant.

Ethical statement

The study was conducted in a tertiary referral spine care center and was approved by the institutional review board of the institute (IRB no. **ECR/34/Inst/KA/2013/RR-24).**

Ethical approval

This retrospective study was approved by the Institutional Ethics Committee of Manipal Hospital, Bangalore (ECR/34/Inst/KA/2013/RR-24).

Consent for participation in research

Informed consent from individual participants was taken for using their intra-operative and follow up data for the purpose of research and publication.

Data availability statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request, subject to approval by the Institutional Ethics Committee.

Author contributions

All authors meet the ICMJE criteria for authorship and have approved the final manuscript. Contributions were:

- •Conceptualization: Vidyadhara S.
- •Methodology: R Dinesh Iyer, Vidyadhara S.
- •Data Collection: R Dinesh Iyer, Dhiyanesh Krishnamurthy.
- •Data Curation & Analysis: R Dinesh Iyer, Balamurugan T.
- •Surgical Procedures: Vidyadhara S, Abhishek Soni, Balamurugan T.
- • Writing – Original Draft: R Dinesh Iyer, Dhiyanesh Krishnamurthy.
- • Writing – Review & Editing: Vidyadhara S, Abhishek Soni.
- • Supervision: Vidyadhara S.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors acknowledge the technicians and nurses of the operation theatre at Manipal Hospital for their assistance in data collection.

References

1. Geng Z, Wang J, Liu J, Miao J. Bibliometric analysis of the development, current status, and trends in adult degenerative scoliosis research: a systematic review from 1998 to 2023. *J Pain Res*. 2024;17:153–169. https://doi.org/10.2147/JPR.S437575. Published 2024 Jan 6.
2. Kim HJ, Yang JH, Chang DG, et al. Adult spinal deformity: a comprehensive review of current advances and future directions. *Asian Spine J*. 2022;16(5):776–788. https://doi.org/10.31616/asj.2022.0376.
3. Ames CP, Scheer JK, Lafage V, et al. Adult spinal deformity: epidemiology, health impact, evaluation, and management. *Spine Deform*. 2016;4(4):310–322. https://doi.org/10.1016/j.jspd.2015.12.009.
4. Schwab F, Dubey A, Gamez L, et al. Adult scoliosis: prevalence, SF-36, and nutritional parameters in an elderly volunteer population. *Spine (Phila Pa 1976)*. 2005;30, 1082e5.
5. Smith JS, Klineberg E, Lafage V, et al. Prospective multicenter assessment of perioperative and minimum 2-year postoperative complication rates associated with adult spinal deformity surgery. *J Neurosurg Spine*. 2016;25(1):1–14. https://doi.org/10.3171/2015.11.SPINE151036.
6. Acosta FL Jr, McClendon Jr J, O'Shaughnessy BA, et al. Morbidity and mortality after spinal deformity surgery in patients 75 years and older: complications and predictive factors. *J Neurosurg Spine*. 2011;15(6):667–674. https://doi.org/10.3171/2011.7.SPINE10640.
7. Anand N, Rosemann R, Khalsa B, et al. Mid-term to long-term clinical and functional outcomes of minimally invasive correction and fusion for adults with scoliosis. *Neurosurg Focus*. 2010 Mar;28(3):E6. https://doi.org/10.3171/2010.1.FOCUS09272. PMID: 20192666.
8. Hamilton DK, Kanter AS, Bolinger BD, et al. Reoperation rates in minimally invasive, hybrid and open surgical treatment for adult spinal deformity with minimum 2-year follow-up. *Eur Spine J*. 2016;25(8):2605–2611. https://doi.org/10.1007/s00586-016-4443-2.
9. Eastlack RK, Srinivas R, Mundis GM, et al. Early and late reoperation rates with various MIS techniques for adult spinal deformity correction. *Glob Spine J*. 2019;9(1):41–47. https://doi.org/10.1177/2192568218761032.
10. Than KD, Mummaneni PV, Bridges KJ, et al. Complication rates associated with open versus percutaneous pedicle screw instrumentation among patients undergoing minimally invasive interbody fusion for adult spinal deformity. *Neurosurg Focus*. 2017;43(6), E7. https://doi.org/10.3171/2017.8.FOCUS17479.
11. Fan Y, Du JP, Liu JJ, et al. Accuracy of pedicle screw placement comparing robot-assisted technology and the free-hand with fluoroscopy-guided method in spine surgery: an updated meta-analysis. *Medicine (Baltim)*. 2018;97(22), e10970. https://doi.org/10.1097/MD.0000000000010970.
12. Kanhangad MP, Srinivasa V, Thirugnanam B, et al. Robotic spine systems: overcoming surgeon experience in pedicle screw accuracy: a prospective study. *Asian Spine J*. 2024;18(5):663–672. https://doi.org/10.31616/asj.2024.0191.
13. Ong V, Swan AR, Sheppard JP, et al. A comparison of spinal robotic systems and pedicle screw accuracy rates: review of literature and meta-analysis. *Asian J Neurosurg*. 2022;17(4):547–556. https://doi.org/10.1055/s-0042-1757628. Published 2022 Oct 18.
14. Vidyadhara S, Iyer RD, Soni A, et al. Risk factors of inaccurate screw placement in robotic spine surgeries: why do robots make error and how to avoid them? *J Robot Surg*. 2025;19(1):681. https://doi.org/10.1007/s11701-025-02884-3. Published 2025 Oct 11.
15. Cheng T, Gerdhem P. Outcome of surgery for degenerative lumbar scoliosis: an observational study using the Swedish spine register. *Eur Spine J*. 2018 Mar;27(3):622–629. https://doi.org/10.1007/s00586-017-5248-7. Epub 2017 Aug 5. PMID: 28780620.
16. Hu SS. Blood loss in adult spinal surgery. *Eur Spine J*. 2004;13(Suppl 1):S3–S5. https://doi.org/10.1007/s00586-004-0753-x. Suppl 1.
17. Sun WX, Huang WQ, Li HY, et al. Clinical efficacy of robotic spine surgery: an updated systematic review of 20 randomized controlled trials. *EFORT Open Rev*. 2023;8(11):841–853. https://doi.org/10.1530/EOR-23-0125. Published 2023 Nov 1.
18. Monetta A, Griffoni C, Falzetti L, et al. Prolonged operative time significantly impacts on the incidence of complications in spinal surgery. *J Orthop Surg Res*. 2024;19(1):567. https://doi.org/10.1186/s13018-024-05066-3. Published 2024 Sep. 14.
19. Fan Y, Peng Du J, Liu JJ, et al. Radiological and clinical differences among three assisted technologies in pedicle screw fixation of adult degenerative scoliosis. *Sci Rep*. 2018;8(1):890. https://doi.org/10.1038/s41598-017-19054-7. Published 2018 Jan 17.
20. Chen X, Feng F, Yu X, et al. Robot-assisted orthopedic surgery in the treatment of adult degenerative scoliosis: a preliminary clinical report. *J Orthop Surg Res*. 2020;15(1):282. https://doi.org/10.1186/s13018-020-01796-2. Published 2020 Jul 25.
21. Kantelhardt SR, Martinez R, Baerwinkel S, et al. Perioperative course and accuracy of screw positioning in non-robotic, open robotic-guided and percutaneous robotic-guided, pedicle screw placement. *Eur Spine J*. 2011;20(6):860–868. https://doi.org/10.1007/s00586-011-1729-2.
22. Hyun SJ, Kim KJ, Jahng TA, et al. Minimally invasive robotic versus open fluoroscopic-guided spinal instrumented fusions: a randomized controlled trial. *Spine (Phila Pa 1976)*. 2017;42(6):353–358. https://doi.org/10.1097/BRS.0000000000001778.
23. Li Y, Wang Y, Ma X, et al. Comparison of short-term clinical outcomes between robot-assisted and freehand pedicle screw placement in spine surgery: a meta-analysis and systematic review. *J Orthop Surg Res*. 2023;18:359. https://doi.org/10.1186/s13018-023-03774-w.
24. Park SM, Kim HJ, Lee SY, et al. Radiographic and clinical outcomes of robot-assisted posterior pedicle screw fixation: two-year results from a randomized controlled trial. *Yonsei Med J*. 2018;59:438–444.
25. Keric N, Eum DJ, Afghanyar F, et al. Evaluation of surgical strategy of non-robotic vs. percutaneous robot-assisted spinal trans-pedicular instrumentation in spondylodiscitis. *J Robot Surg*. 2016;11:17–25.
26. Yoshida G, Hasegawa T, Yamato Y, et al. Minimum clinically important differences in oswestry disability index domains and their impact on adult spinal deformity surgery. *Asian Spine J*. 2019;13(1):35–44. https://doi.org/10.31616/asj.2018.0077.
27. Vengsarkar VA, Goudarzi A, Chi J, et al. Robotic-assisted versus free-hand techniques in adult spinal deformity surgery: a comparative analysis of postoperative outcomes. *J Robot Surg*. 2025;19(1):375. https://doi.org/10.1007/s11701-025-02543-7. Published 2025 Jul 11.
28. Núñez-Pereira S, Rodríguez-Pardo D, Pellisé F, et al. Postoperative urinary tract infection and surgical site infection in instrumented spinal surgery: is there a link? *Clin Microbiol Infect*. 2014;20(8):768–773. https://doi.org/10.1111/1469-0691.12527.
29. Bohl DD, Ahn J, Tabaraee E, et al. Urinary tract infection following posterior lumbar fusion procedures: an American college of surgeons national surgical quality improvement program study. *Spine (Phila Pa 1976)*. 2015;40(22):1785–1791. https://doi.org/10.1097/BRS.0000000000001003.
30. Jules-Elysee K, Urban MK, Urquhart BL, et al. Pulmonary complications in anterior-posterior thoracic lumbar fusions. *Spine J*. 2004;4(3):312–316. https://doi.org/10.1016/j.spinee.2003.11.008.
31. Patel SA, McDonald CL, Reid DBC, et al. Complications of thoracolumbar adult spinal deformity surgery. *JBJS Rev*. 2020;8(5), e0214. https://doi.org/10.2106/JBJS.RVW.19.00214.
32. Wang TY, Martin JR, Loriaux DB, et al. Risk assessment and characterization of 30-Day perioperative myocardial infarction following spine surgery: a retrospective analysis of 1346 consecutive adult patients. *Spine (Phila Pa 1976)*. 2016;41(5):438–444. https://doi.org/10.1097/BRS.0000000000001249.