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ORIGINAL ARTICLE

Comparative evaluation of postoperative outcomes and expenditure between robotic and conventional single-level lumbar fusion surgery: a comprehensive analysis of nationwide inpatient sample data

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Abstract

Introduction In this study, we investigate the evolution of lumbar fusion surgery with robotic assistance, specifically focusing on the impact of robotic technology on pedicle screw placement and fixation. Utilizing data from the Nationwide Inpatient Sample (NIS) covering 2016 to 2019, we conduct a comprehensive analysis of postoperative outcomes and costs for single-level lumbar fusion surgery. Traditionally, freehand techniques for pedicle screw placement posed risks, leading to the development of robotic-assisted techniques with advantages such as reduced misplacement, increased precision, smaller incisions, and decreased surgeon fatigue. However, conflicting study results regarding the efficacy of robotic assistance in comparison to conventional techniques have prompted the need for a thorough evaluation. With a dataset of 461,965 patients, our aim is to provide insights into the impact of robotic assistance on patient care and healthcare resource utilization. Our primary goal is to contribute to the ongoing discourse on the efficacy of robotic technology in lumbar fusion procedures, offering meaningful insights for optimizing patient-centered care and healthcare resource allocation.

Methods This study employed data from the Nationwide Inpatient Sample (NIS) spanning the years 2016 to 2019 from USA, 461,965 patients underwent one-level lumbar fusion surgery, with 5770 of them having the surgery with the assistance of robotic technology. The study focused primarily on one-level lumbar fusion surgery and excluded non-elective cases and those with prior surgeries. The analysis encompassed the identification of comorbidities, surgical etiologies, and complications using specific ICD-10 codes. Throughout the study, a constant comparison was made between robotic and non-robotic lumbar fusion procedures. Various statistical methods were applied, with a p value threshold of < 0.05, to determine statistical significance.

Results Robotic-assisted lumbar fusion surgeries demonstrated a significant increase from 2016 to 2019, comprising 1.25% of cases. Both groups exhibited similar patient demographics, with minor differences in payment methods, favoring Medicare in non-robotic surgery and more private payer usage in robotic surgery. A comparison of comorbid conditions revealed differences in the prevalence of hypertension, dyslipidemia, and sleep apnea diagnoses—In terms of hospitalization outcomes and costs, there was a slight shorter hospital stay of 3.06 days, compared to 3.13 days in non-robotic surgery, showcasing a statistically significant difference ($p = 0.042$). Robotic surgery has higher charges, with a mean charge of $154,673, whereas non-robotic surgery had a mean charge of $125,467 ($p < 0.0001$). Robotic surgery demonstrated lower rates of heart failure, acute coronary artery disease, pulmonary edema, venous thromboembolism, and traumatic spinal injury compared to non-robotic surgery, with statistically significant differences ($p < 0.05$). Conversely, robotic surgery demonstrated increased post-surgery anemia and blood transfusion requirements compared to non-robotic patients ($p < 0.0001$). Renal disease prevalence was similar before surgery, but acute kidney injury was slightly higher in the robotic group post-surgery ($p = 0.038$).

Conclusion This is the first big data study on this matter, our study showed that Robotic-assisted lumbar fusion surgery has fewer post-operative complications such as heart failure, acute coronary artery disease, pulmonary edema, venous thromboembolism, and traumatic spinal injury in comparison to conventional methods. Conversely, robotic surgery demonstrated increased post-surgery anemia, blood transfusion and acute kidney injury. Robotic surgery has higher charges compared to non-robotic surgery.

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Keywords Robotic surgery · Lumbar fusion · Robotic lumbar fusion · Clinical outcomes · NIS · National inpatient sample · Big data

Introduction

Lumbar fusion surgery, a pivotal intervention for diverse spinal conditions, has undergone significant evolution with the integration of robotic assistance. The transformative impact of robotic-assisted spine surgery on pedicle screw placement and fixation has gained considerable attention, particularly in addressing challenges associated with freehand techniques [1–6]. This paper initiates a comprehensive comparative analysis of postoperative outcomes and expenditures related to single-level lumbar fusion surgery, utilizing an extensive dataset from the Nationwide Inpatient Sample (NIS) covering the years 2016–2019 from USA.

Traditionally, pedicle screw placement relied on anatomical landmarks and freehand techniques, entailing risks such as misplacement, spinal trauma, loss of fixation, and other complications [1–7]. The anatomical complexities of the spine contribute to the challenges associated with freehand techniques [7–10]. In response, technological advances have given rise to various techniques, including computed tomography-based image-navigation, fluoroscopy-based navigation, and robot-assisted techniques. Studies indicate that robotic-assisted techniques offer a significant reduction in pedicle screw misplacement, providing benefits such as increased degrees of freedom during surgery, decreased incision size, elimination of hand tremors, and reduced surgeon fatigue [1, 4–7].

However, the debate persists regarding the efficacy of robot-assisted lumbar spinal fusion surgery compared to conventional techniques, with conflicting study results [1–10]. Some studies report notable improvements with robotic assistance, while others suggest no significant benefits or even inferior results compared to freehand placement [1–3, 8–10]. This controversy underscores the need for a comprehensive evaluation of immediate postoperative outcomes and costs associated with robotic and conventional lumbar fusion surgery.

Our study leverages an extensive dataset comprising 461,965 patients, offering valuable insights into the impact of robotic assistance on patient care and healthcare resource utilization. With the primary objective of contributing to the ongoing discourse on the efficacy of robotic technology in lumbar fusion procedures, our investigation aims to enhance understanding of the practical implications, benefits, and disadvantages associated with the integration of robotic technology in this surgical context. Through this, we seek to provide meaningful insights that can guide future directions in this field, ultimately optimizing patient-centered care and healthcare resource allocation.

Methods

This study was conducted using data from the Nationwide Inpatient Sample (NIS), a prominent public database for inpatient care that is part of the Healthcare Cost and Utilization Project (HCUP). The NIS captures approximately 20% of inpatient stays from HCUP-associated hospitals, representing approximately 7 million unweighted admissions annually, there for we can reflect national estimates using discharge.

Sample weights provided by the NIS. The dataset, spanning between January 1st, 2016 and December 31st, 2019, is the latest available information within the NIS system at the time of this study.

Each dataset entry, referred to as a "case", encapsulated a group of 5 patients, meticulously matched in general parameters. The resulting extensive dataset (using the most recent available version of the NIS dataset).

This numerical distinction reflects the NIS discharge weight, signifying that each case extrapolates to five patients. A total of 92,393 cases related to lumbar fusion surgery were analyzed, representing 461,965 patients. All of these 461,965 patients underwent one-level minimal invasive lumbar fusion surgery, with 5770 of them having the surgery with the assistance of robotic technology identify by the ICD10 Procedure codes (8E0W8CZ, 8E0W4CZ, 8E0W3CZ). This represents 1.25% of the total lumbar fusion patients. The study received approval from the relevant institutional review board, and the need for informed consent was waived due to the de-identified nature of the data sourced from the NIS database.

The focus of this study was on patients undergoing one-level lumbar fusion surgery, identified based on specific ICD-10 procedure codes related to this procedure. The detailed list of included codes will be available in the "Appendix" section. Patients with non-elective admissions, those who underwent surgery prior to admission, and individuals who had surgery using navigation-guided technology were excluded from the analysis.

Comorbidities and complications were identified and validated through a careful review of patient-specific ICD-10 codes. Cases with reported hospital costs of $0 were excluded from the analysis. Various analytical studies were performed to visualize annual cases, identify year-over-year trends, and derive key statistical insights. Clinical outcomes, including in-hospital mortality, length of stay (LOS), in-hospital complications, and the overall cost of hospitalization, were examined.

All analyses, including cross-tabulations and independent sample *t* tests, were conducted, adopting a *p* value threshold of less than 0.05 to establish statistical significance. The comprehensive list of ICD-10 procedure codes used in this study and specific codes related to robotic-assisted one-level lumbar fusion will be included in the "Appendix" for reference.

Results

Data on lumbar fusion procedures from the years 2016 to 2019 were retrospectively collected and categorized based on the use of robotic assistance. For each calendar year, the number of procedures performed with and without robotic assistance was summarized, and the percentage of robotic-assisted lumbar fusion relative to the total number of lumbar fusion procedures was calculated. To assess the growth trend of robotic-assisted procedures over this period, a linear regression analysis was conducted with the calendar year as the predictor variable and the count of robotic-assisted procedures as the dependent variable. Results showed a progressive increase in the number of robotic-assisted lumbar fusion procedures, as depicted in Fig. 1, which presents the annual trend from 2016 to 2019. Additionally, Fig. 2 illustrates the proportion of robotic-assisted lumbar fusion in comparison to the total lumbar fusion procedures conducted for each year. The statistical analysis revealed a significant upward trend in the adoption of robotic assistance for these procedures, with a *p* value of 0.0232, indicating that the growth in the use of robotic assistance for lumbar fusion procedures between 2016 and 2019 was statistically significant.

Table 1 offers data about the demographic and clinical characteristics in both robotic and non-robotic lumbar fusion procedures, with a total of 461,965 patients included in the analysis. Notably, non-robotic surgeries accounted for a substantial majority at 98.75%, with robotic procedures making up just 1.25% of cases. Patient age showed minimal differences, with averages of 62.11 years for robotic surgery and 61.9 years for non-robotic surgery. Gender distribution was relatively balanced, with approximately 56–57% of patients being female in both groups. Significant variations appeared in payment methods, with non-robotic surgery patients utilizing Medicare more (49%) compared to the 47.7% in the robotic surgery group. Conversely, private payer usage was slightly higher in robotic surgery (40.6%) than non-robotic surgery (37.6%). These key findings provide insights into the shifting landscape of lumbar fusion surgeries, with robotic procedures dominating the field.

In Table 2, we examine the prevalence of comorbid conditions among patients who have undergone lumbar fusion procedures, comparing those who received robotic surgery to those who underwent traditional non-robotic surgery. Notable observations include higher percentages of hypertension, dyslipidemia, and sleep apnea diagnoses in the robotic surgery group.

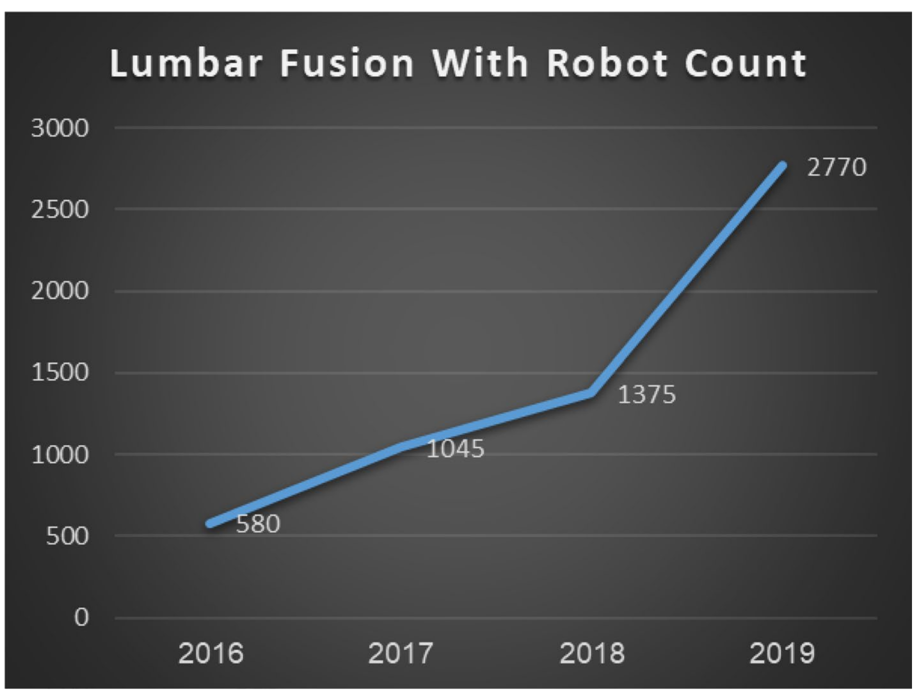

Fig. 1 Annual trend of robotic-assisted lumbar fusion procedures (2016–2019)

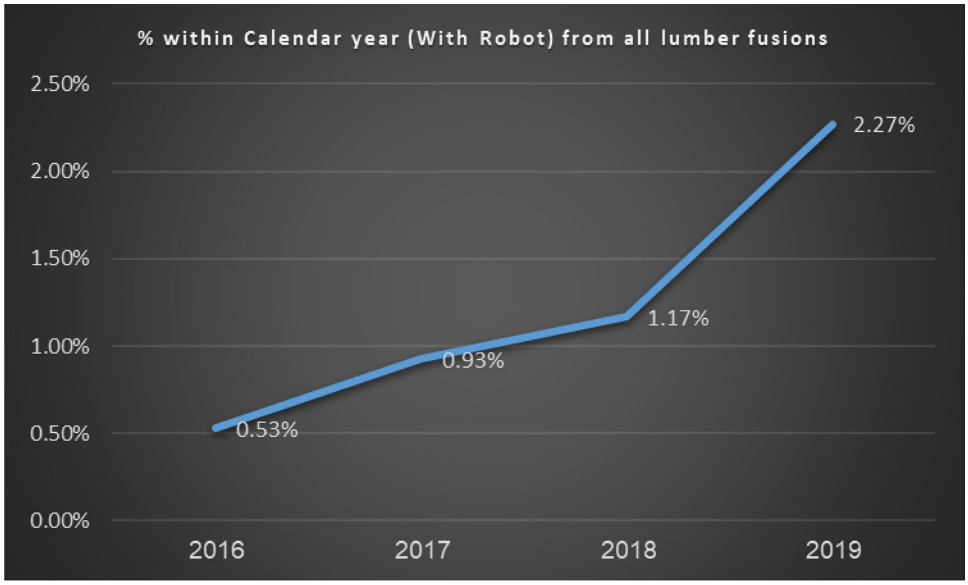

Fig. 2 proportion of robotic-assisted lumbar fusion within total lumbar fusion procedures by calendar year (2016–2019)

Table 1 Comparative analysis of demographic and clinical characteristics in robotic and non-robotic lumbar fusion procedures

Parameter	Non-robotic surgery (%)	Robotic surgery (%)	Significance
Total surgeries (%)	1.25	98.75	
Average age (y)	61.9	62.11	0.201
Female (%)	56.7	57.2	0.413
Payer—medicare (%)	49	47.7	$p < 0.0001$
Payer—medicaid (%)	6.1	2.9	
Payer—private (%)	37.6	40.6	
Payer—other (including self-pay) (%)	7.3	8.8	

Table 2 Prevalence of comorbid conditions in patients undergoing robotic and non-robotic lumbar fusion procedures

	Non-robotic surgery (%)	Robotic surgery (%)	Significance
Hypertension diagnosis	53.1	55	0.003
Dyslipidemia diagnosis	40	43.7	$p < 0.0001$
Sleep apnea diagnosis	11.2	13..3	$p < 0.0001$
Chronic anemia	4.8	3.5	$p < 0.0001$
Alcohol abuse	1.1	0.6	0.001
Mental disorders	38	36.8	0.059
Alzheimer disease	0.1	0.3	0.002
Parkinson disease	0.8	1	0.104
Type 2 diabetes	21.6	19.2	$p < 0.0001$
Renal disease	5.7	5.5	0.536
CHF	1.1	1.1	0.813
Chronic lung disease	7.7	5.8	$p < 0.0001$

Conversely, the non-robotic surgery group had a higher prevalence of alcohol abuse. While there was no statistically significant difference in the occurrence of mental disorders or congestive heart failure between the two groups, the prevalence of Alzheimer's disease was slightly higher in the robotic surgery group. Furthermore, the non-robotic surgery group exhibited a higher percentage of patients with type 2 diabetes and chronic lung disease.

Table 3 provides an overview of surgical etiologies in both robotic and non-robotic lumbar fusion surgeries, involving a total of 461,965 patients. Notably, spondylolisthesis and spinal stenosis are the prevalent conditions, with minor distinctions between the two surgical methods. Other conditions, such as disk degeneration, spondylosis, radiculopathy, and scoliosis, exhibit varying prevalence. Spondylolysis is

Table 3 Comparison of surgical etiologies in robotic and non-robotic lumbar fusion surgery: significance and patient distribution

Etiologies	Non-robotic surgery	Robotic surgery	Significance
Spondylolisthesis	114,725 (25.1%)	1640 (28.4%)	$p < 0.0001$
Spinal stenosis	176,955 (38.8%)	2305 (39.9%)	
Disk degeneration	81,580 (17.9%)	795 (13.8%)	
Spondylosis	32,175 (7.1%)	460 (8.0%)	
Radiculopathy	5600 (1.2%)	45 (0.8%)	
Scoliosis	3470 (0.8%)	50 (0.9%)	
Spinal instabilities	2335 (0.5%)	45 (0.8%)	
Spondylolysis	1725 (0.4%)	10 (0.2%)	
Other	37,630 (8.2%)	420 (7.3%)	

Table 4 Comparison of hospitalization outcomes and costs between non-robotic and robotic surgery in lumbar fusion procedures

	Non-robotic surgery	Robotic surgery	Significance
Died during hospitalization	0.047%	0.000%	0.099
Length of stay mean in days	3.13	3.06	0.042
Total charges mean in $	$125,467	$154,673	$p<0.0001$

Table 5 Incidence of postoperative complications in non-robotic and robotic lumbar fusion procedures without statistically significant differences

	Non-robotic surgery (%)	Robotic surgery (%)	Significance
Stroke	0.007	0	0.506
Pulmonary embolism	0.184	0.087	0.085
Pneumonia	0.414	0.260	0.069
Surgical site Infection	0.2959	0.1733	0.088

relatively rare, and other etiologies show minor differences in patient distribution.

Table 4 provides a comparison of hospitalization outcomes and costs between non-robotic and robotic surgery in lumbar fusion procedures. There were no reported deaths during hospitalization in the robotic surgery group, while a minimal percentage (0.047%) was noted in non-robotic surgery, with no statistical significance ($p=0.099$). The mean length of stay was shorter in the robotic surgery group (3.06 days) compared to non-robotic surgery (3.13 days) with a statistically significant difference ($p=0.042$). Additionally, the total charges in dollars showed a variance, with robotic surgery displaying higher mean charges ($154,673) compared to non-robotic surgery ($125,467), indicating statistical significance ($p<0.0001$). The total charges calculated in the study reflect the hospital stay cost, without adding the cost of ambulatory care of the patient.

Table 5 provides insights into the incidence of postoperative complications in both non-robotic and robotic lumbar fusion procedures, with a specific focus on identifying areas where statistically significant differences were absent. This analysis aims to highlight instances where the two surgical approaches exhibited comparable rates of postoperative complications.

Figure 3 highlights the significant advantages of robotic lumbar fusion procedures over non-robotic methods in reducing postoperative complications. Data analysis shows that patients undergoing robotic surgery experienced notably lower rates of complications, including heart failure, acute coronary artery disease, pulmonary edema, venous thromboembolism, and traumatic spinal injury. This table reflects the Postoperative Complications during initial hospitalization.

Figure 4 provides a comparative analysis of renal complications in patients undergoing robotic and non-robotic lumbar fusion procedures, emphasizing the similarity of the two groups before surgery and the notable distinctions in post-surgical outcomes. Prior to the surgery, both groups demonstrated a similar prevalence of renal disease, with no statistically significant difference observed. However, post-surgery data reveals a significant difference in the incidence of acute kidney injury, with the robotic

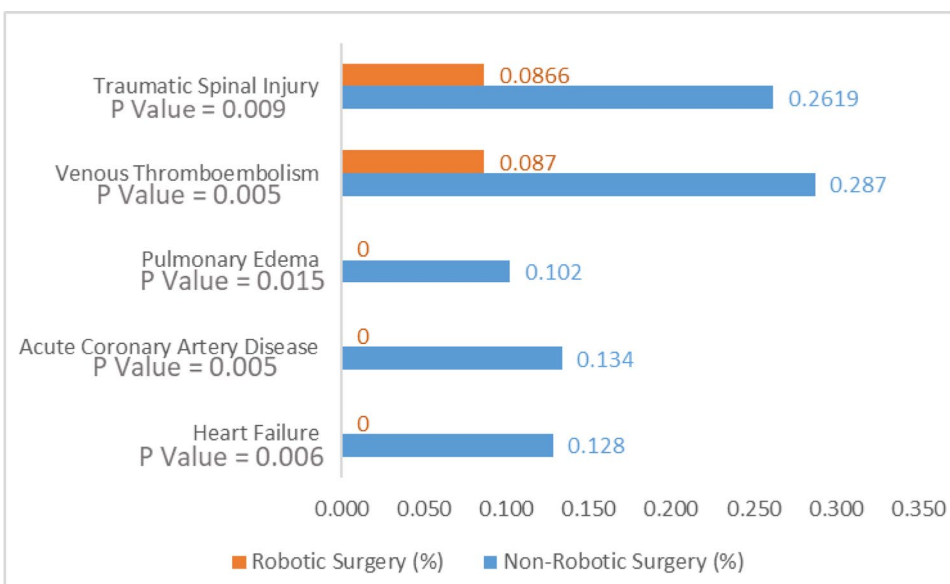

Fig. 3 Advantages of robotic lumbar fusion: lower incidence of postoperative complications

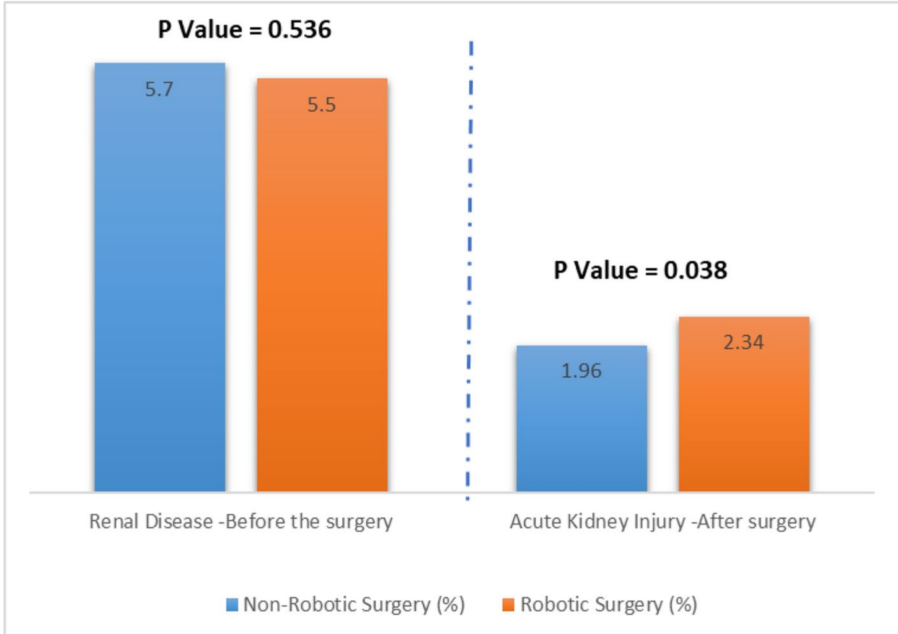

Fig. 4 Comparison of renal complications in robotic vs. non-robotic lumbar fusion procedures: pre-surgery parity and post-surgery differences

surgery group exhibiting a slightly higher rate than the non-robotic group (2.34% compared to 1.96%, $p = 0.038$). This figure reflects the Postoperative Complications during initial hospitalization.

Figure 5 presents a dynamic analysis of anemia and blood-related complications in patients undergoing lumbar fusion surgeries. Notably, the data reveals distinct patterns in the non-robotic and robotic surgery groups. Before the surgery, the non-robotic surgery group had a higher prevalence of chronic anemia compared to the robotic surgery group, and this difference was statistically significant (4.8% vs. 3.5%, $p < 0.0001$).

However, after the surgery, the scenario shifted. The robotic surgery group experienced a notable increase in anemia and a greater need for blood transfusions. The rates of blood transfusions and blood loss anemia were both higher in the robotic surgery group compared to the non-robotic surgery group, and these differences were statistically significant (2.9% vs. 2.1% for blood transfusion, and 16.0% vs. 11.7% for blood loss anemia, both $p < 0.0001$).

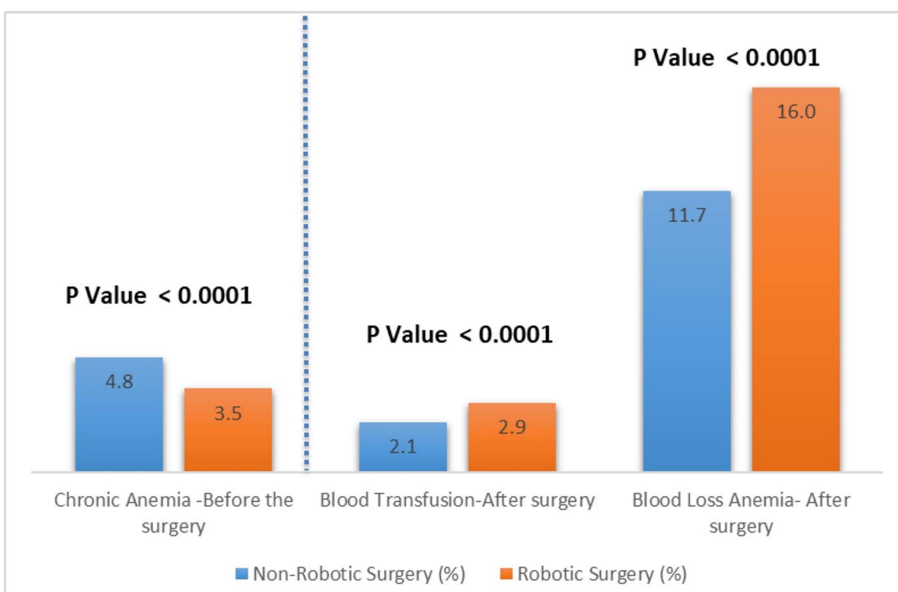

Fig. 5 Evolution of anemia and blood-related complications in lumbar fusion surgeries

Discussion

A critical revelation from our research is the remarkable surge in the adoption of robotic technology, a fivefold increase within a few short years, with a discernible and enduring impact. This escalating trend underscores the urgency and importance of delving deeper into the comparative efficacy of robotic versus non-robotic lumbar fusion surgeries.

Addressing the central question of whether robotic surgery surpasses non-robotic alternatives, our study provides multifaceted insights that unravel the complexities of this evolving landscape. Notably, we observe a substantial discrepancy in total charges between the two approaches, with robotic surgeries incurring an average cost nearly $30,000 higher. Our findings on cost diverge significantly from earlier published studies, as a considerable number of them predates the last decade. Subsequent to these studies, both inflationary trends and policy advancements have transpired, influencing the current landscape of medical expenditures [11]. This economic divergence, while considerable, can be rationalized by the substantial upfront investment required for robotic systems, typically priced around $1 million [9, 12]. The economic considerations raise pivotal questions about the cost-effectiveness of robotic surgery, prompting a nuanced evaluation of its benefits against the financial investment [12, 13].

Spinal fusion is a surgical procedure known for its significant perioperative blood loss, ranging from 0.5 to 2 L [14]. Our study reveals higher blood loss among patients undergoing robotic in comparison to non-robotic surgery group. Although a small case highlighted the opposite [15], according to large retrospective analysis of 4185 elective robotic surgeries revealed correspond with our result and revealed higher postoperative anemia [16]. Robotic surgeries have been associated with extended operative durations [17, 18], prompting us to postulate that the heightened incidence of blood loss in robotic procedures is most likely attributed to the prolonged operation time.

Our analysis of current research aligns with prevailing evidence regarding complication rates in robotic versus non-robotic single-level lumbar fusion surgery. Propensity-matched studies [19, 20] found no significant difference in complication rates, including surgical site infections, at various follow-up periods (30, 90 days, and 1 year) between the two groups [19, 20]. This finding is further supported by multicenter analyses like Mazor Robotic-Guided Versus Fluoroscopic-Guided Spinal Fusions: The MIS ReFRESH Prospective Comparative Study by Amundsen et al. [21], which reported no association between robotic-assisted surgery and 1-year reoperation rates [21]. However, they did observe a potential increase in blood loss requiring transfusion in the robotic surgery group [21].

While some studies suggest potential benefits of robotic surgery like improved visualization and potentially more precise screw placement [1, 22], these may be offset by the observed increase in blood loss in our study and potentially longer operative times reported elsewhere [20, 21]. Understanding the long-term impact of robotic surgery on complication rates, fusion rates, and patient functionality remains an area for future research.

Our findings indicate no significant variance in patient mortality between the two groups. However, a subtle difference in the duration of hospital stay comes to light. Notably, patients undergoing robotic surgery experienced only a marginally shorter hospital stay, suggesting that this small-time difference may not hold substantial clinical importance. While this efficiency over time could potentially alleviate the economic burden associated with robotic procedures, it does not negate the higher overall costs linked to robotic lumbar fusion surgeries. Therefore, a thorough consideration of benefits versus economic implications is essential [12].

Further exploration into postoperative complications paints a nuanced picture. Complications such as stroke, pulmonary embolism, pneumonia, and surgical site infection exhibit no significant disparity between patients undergoing robotic and non-robotic lumbar fusion surgeries. While there is a paucity of research on robotic-spine surgeries in the existing literature, our findings align with previously published studies conducted in the realm of non-robotic surgical interventions [23]. This suggests that, at least in our dataset, the selection between these surgical approaches does not substantially impact the incidence of these complications.

The core objective of employing robotic assistance in lumbar fusion surgery is to enhance precision, particularly in pedicle screw placement [24–26]. In this pursuit, our study highlights a significant advantage associated with the use of robotic systems—a notably reduced incidence of traumatic spinal injuries. While the absolute numbers are low, less than 0.26% of cases without robotic assistance experienced traumatic spinal injuries, this difference is statistically significant and holds paramount clinical significance. Traumatic spinal injuries can lead to severe long-term neurological deficits [27], making the observed reduction a noteworthy advantage of robotic-assisted procedures.

However, a nuanced consideration is warranted as our study also reveals certain drawbacks associated with robotic surgeries. Patients undergoing robotic lumbar fusion surgeries exhibited a higher incidence of acute kidney injuries and increased blood loss necessitating transfusions. While the exact cause is challenging to ascertain from our extensive dataset, a plausible explanation may lie in the potential prolongation of surgeries associated with robotic assistance, leading to increased blood loss and subsequent renal implications. This prompts a critical reevaluation of the purported benefits of robotic systems, especially when confronted with adverse outcomes such as heightened post-operative complications [2].

Synthesizing these findings with existing research on the topic, a complex narrative emerges. Some studies indicate no substantial performance improvement with robotic assistance, while others suggest enhanced outcomes. This diversity in findings further complicates the decision-making process for clinicians and underscores the need for more nuanced research methodologies [3–11].

In addition to the variability in study outcomes, our investigation reveals that robotic-assisted lumbar fusion surgeries remain a relatively novel method, utilized in less than 2% of the cases in our dataset. This highlights the need for cautious interpretation of the results, considering the evolving nature of this technology and the learning curve associated with its implementation [2].

Looking ahead, future studies should explore the efficacy of robotic assistance in multilevel lumbar fusion surgeries, a scenario not extensively addressed in our current investigation focused on single-level procedures. Understanding the applicability and potential advantages of robotic systems in more complex spinal surgeries will be crucial for informing clinical decisions and advancing patient care.

Acknowledging the limitations of our methodology, characterized by the use of extensive ICD codes from a large dataset, our study provides a macro-level perspective. While lacking granularity at the individual patient level, the sheer volume of cases lends statistical power to our findings. It is essential to recognize the inherent trade-off between detailed patient-level insights and the strength derived from a comprehensive analysis involving more than 400,000 one level lumbar fusions.

In conclusion, our expansive investigation sheds light on the escalating trend of robotic-assisted lumbar fusion surgeries and their comparative outcomes. The economic implications, nuanced clinical advantages, and potential drawbacks uncovered in our study present a comprehensive foundation for future research, policy considerations, and clinical decision-making in the ever-evolving landscape of spinal surgeries.

Appendix

ICD 10 codes/procedure code	
8E0W0CZ, 8E0W3CZ, 8E0W4CZ	Robotic assisted procedure
I5021, I5031, I5033, I5041, I5043	Heart failure
N170, N171, N172, N178, N179	Acute kidney injury
I2101, I2102, I2109, I211, I2119, I2111, I212, I2129, I213, I214, I219	Acute coronary artery disease
I60, I61, I62, I63, I650, I688, O873, O2250, O2251, O2252	Stroke
J810, J811, I501	Pulmonary edema
I10 (start with)	Hypertension
D62 (start with)	Blood loss anemia
J189, J159, J22	Pneumonia
I2602, I2609, I2692, I2699	Pulmonary embolism
I82401, I82402, I82403, I82409, I82411, I82412, I82413, I82419, I82421, I82422, I82423, I82429	DVT
E78 (start with)	Dyslipidemia
G473	Obstructive sleep apnea
D64 (start with)	Chronic anemia
F10	Alcohol abuse history
M81, M82	Osteoporosis
F (start with)	Mental disorders
G20 (start with)	Parkinson disease
E11 (start with)	Type 2 diabetes mellitus
N18 (start with)	Chronic kidney disease
I500, I501, I509	Congestive heart failure
J44 (start with)	Chronic lung disease

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Declarations

Conflict of interest The authors have no commercial associations or sources of support that might pose a conflict of interest.

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