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Diffusion of robotic-assisted laparoscopic technology across specialties: a national study from 2008 to 2013

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Abstract

Introduction Robotic-assisted procedures were frequently found to have similar outcomes and indications to their laparoscopic counterparts, yet significant variation existed in the acceptance of robotic-assisted technology between surgical specialties and procedures. We performed a retrospective cohort study investigating factors associated with the adoption of robotic assistance across the United States from 2008 to 2013.

Methods Using the Nationwide Inpatient Sample database, patient- and hospital-level variables were examined for differential distribution between robotic-assisted and conventional laparoscopic procedures. Multilevel logistic regression models were constructed to identify independent factors associated with robotic adoption. Furthermore, cases were stratified by procedure and specialty before being ranked according to proportion of robotic-assistance adoption. Correlation was examined between robotic-assistance adoption and relative outcome in comparison with conventional laparoscopic procedures.

Results The national robotic case volume doubled over the five-year period while a gradual decline in laparoscopic case volume was observed, resulting in an increase in the proportion of procedures performed with robotic assistance from 6.8 to 17%. Patients receiving robotic procedures were more likely to be younger, males, white, privately insured, more affluent, and with less comorbidities. These differences have been decreasing over the study period. The three specialties with the highest proportion of robotic-assisted laparoscopic procedures were urology (34.1%), gynecology (11.0%), and endocrine surgery (9.4%). However, no significant association existed between the frequency of robotic-assistance usage and relative outcome statistics such as mortality, charge, or length of stay.

Conclusion The variation in robotic-assistance adoption between specialties and procedures could not be attributable to clinical outcomes alone. Cultural readiness toward adopting new technology within specialty and target anatomic areas appear to be major determining factors influencing its adoption.

Keywords Robotic-assisted · Laparoscopic · Minimally-invasive surgery · Temporal trend

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Diffusion is defined as the process by which innovations are communicated over time among members of a social system [1], e.g., surgeons, in the case of adopting a new operative technology [2]. The diffusion of robotic-assisted laparoscopic technology began with urologic case reports of robotic-assisted laparoscopic prostatectomy [3, 4] in the early nineties. Due to its hypothesized benefits relating to three-dimensional visualization, improved ergonomics, tremor filtration, motion scaling, and enhanced dexterity [5], robotic-assisted technology has spread rapidly [6]. However, some recent studies actually pointed to an association between its early adoption in prostatectomy and diminished perioperative patient safety [7, 8], as could be expected with the advent of any new surgical technology.

As robotic-assisted technology was gradually adopted for various procedures across nearly all surgical disciplines [9–13], it has come to pass that its benefits vary with the surgical procedure [14–16]. For most procedures, it affords similar efficacy and safety to its laparoscopic counterpart [17–20], and in the hands of an experienced minimally-invasive surgeon, the indications for robotic-assisted laparoscopic operation are often similar to those for conventional laparoscopic operation. Many of the structural barriers that may have initially obstructed the adoption of robotic-assisted technology have also abated, as evidenced by its prevalent use among urologists [21] and gynecologists [22] in most medical centers. However, the diffusion of robotic-assisted technology for some surgical specialties has remained comparatively gradual. While robotic-assisted technology is not unique among novel medical technologies in this diffusion pattern [23–27], where its adoption outpaced evidence-based clinical advantage, it remains unexamined what factors influenced its uneven adoption across specialties.

In order to concentrate resources on future laparoscopic procedures most likely to adopt and benefit from robotic-assisted technology, it is important to understand factors influencing the variation in robotic-assisted technology adoption in currently prevalent robotic procedures. With this in mind, we performed a study to better understand the diffusion of robotic-assisted technology across surgical specialties in a contemporary cohort using national hospital discharge abstracts. Quantifying the uptake of robotic-assisted technology by surgical specialty and procedure would help elucidate the factors responsible for the differential adoption of robotic-assisted technology. In addition, it would facilitate future efforts in improving the diffusion of robotic-assisted technology on the appropriate target.

Materials and methods

This is a retrospective cohort study of the most commonly performed robotic-assisted laparoscopic procedures in the United States from October 2008 to December 2013.

Nationwide Inpatient Sample Database

The Healthcare Cost and Utilization Project Nationwide Inpatient Sample (HCUP-NIS) was the largest all-payer healthcare administrative database in the United States, with a weighted sampling of approximately 20% of hospitalizations from non-federal acute-care hospitals in sampled states [28]. It included patient- and hospital-level variables from each hospital discharge, including demographics, up to 15 primary and secondary diagnoses, procedures performed, demographics, payment source, length of stay, hospital characteristics (bed size, urban/rural, geographic region, and teaching status), and total charges. Due to the retrospective nature of the administrative database, no information regarding disease severity for the surgical indication was available. Weighted discharge data were used so the national estimates of case volume were comparable across years in which participating hospitals and states varied. Due to the de-identified nature of the data, this study was deemed exempt by the Institutional Review Board.

Case identification

Adult patients (>18 years old) were included in the study if they have undergone laparoscopic surgery as their primary procedure or have one of the following additional International Classification of Diseases, 9th revision (ICD-9) codes (54.21, 54.51, or 65.63) denoting laparoscopic procedure. They were subsequently categorized as conventional laparoscopic procedures or robotic-assisted laparoscopic procedures, which were identified using ICD-9 codes including 17.41, 17.42, 17.32, 17.44, 17.45, and 17.49. Data was excluded if it entailed rarely performed robotic-assisted laparoscopic procedures with frequency in the bottom 10% or open robotic surgeries, such as those used in orthopedic (ICD-9 76–84×) surgeries. The corresponding ICD-9 procedure codes were tabulated in Supplemental Table 1. The Procedures were grouped by specialties into "colorectal," "endocrine," "general surgery," "cardiac," "thoracic," "gynecology," and "urology."

Statistical analysis

The primary outcome of interest was adoption of robotic assistance in laparoscopic procedures. The fraction of laparoscopic surgeries performed with robotic assistance was calculated for each year-quarter. Patient- and hospital-level variables were examined for association with adoption of robotic-assistance individually. Patient-level variables of interest included age, gender, race, payer (Medicare, Medicaid, private including HMO, other), comorbidity and median household income, while hospital-level variables of interest included bed size (small, medium, large), location/teaching status (rural vs urban/non-teaching vs urban/teaching), and geographical region (northeast, midwest, south, west). All of these variables were defined and coded by NIS. Baseline comorbidity was quantified using the Elixhauser Index, a summary statistic of comorbidities based on presence or absence of thirty diagnoses in the patient and combined together in a weighted formula [29, 30]. Subsequently, the temporal shift in relative makeup of these patient- and hospital-level variables among robotic-assisted procedures was tabulated across the study period to identify potential temporal patterns. Statistical trend significance was examined using a modified Wilcoxon rank-sum test for trend across ordered groups [31]. Multilevel models were used to examine the relative contribution of hospital- and patient-level variables to the propensity for adoption of robotic-assistance technology. The multilevel approach considered the complex sampling scheme of the data, with multiple discharges being clustered within hospitals, and allowed for an explicit examination of hospital-level effects. Generalized linear mixed models with a logit link function [32], assuming a binomial error distribution, were used. Starting with an empty model, hospital- and patient-level variables were gradually introduced in addition to operative year, as fixed effects, in an attempt to explain the observed variance in the data.

Subsequently, procedures were stratified by specialty and procedure type. This was then ranked and analyzed over the study time period according to proportion of laparoscopic cases performed with robotic assistance. Outcome measures such as mortality, length of stay, and charge per hospitalization were compared between procedures with and without robotic assistance and summarized in ratios. Pearson correlation test was then done to examine the association between prevalence of robotic adoption and ratios of these outcome measures.

Data was stored and analyzed using Stata 13.0 software (StataCorp, College Station, TX). Continuous variables were reported as mean ± standard deviation when the underlying distribution assimilates normal distribution and as median ± interquartile range when the underlying distribution appears skewed. Wilxocon-Mann–Whitney test was utilized for continuous and ordinal variables; while Fisher's exact test and Pearson's Chi square were used for categorical variables. All tests were unpaired with significance level defined as a two-tailed *p*-level less than 0.05.

Results

Data on 936,188 patients were abstracted from the NIS, yielding a weighted national estimate of 4,517,590 patients who underwent laparoscopic procedures with (13.2%) and without (86.8%) robotic assistance between October 2008 and December 2013. Figure 1 shows estimated quarterly utilization rates for robotic assistance within laparoscopic procedures. The total annual number of laparoscopic procedures gradually declined from 956,304 cases in 2009 to 737,615 cases in 2013. The quarterly national robotic case volume doubled over the five-year period from 17,720 cases in 2008 winter to 33,530 cases in 2012 winter, contrasted with a gradual decline in national laparoscopic case volume from 244,333 cases in 2012 winter to 148,030 in 2013 spring. This resulted in the proportion of laparoscopic procedures performed with robotic assistance increasing from 6.8% in 2008 until this figure nearly tripled around 17% in 2012.

Factors influencing adoption of robotic-assisted laparoscopic technology

Table 1 displays the results of our bivariate analysis, in which comparisons were made between patients undergoing laparoscopic procedures with and without robotic assistance. Patients undergoing surgery with robotic assistance appeared to consist of less geriatric patients greater than 80 years old (2.4 vs 5.2%, $p < 0.01$), more males (54.4 vs 27.7%, $p < 0.01$), more whites (75.4 vs 71.6%, $p < 0.01$), more privately insured (61.4 vs 56.3%, $p < 0.01$), less Medicaid (4.6 vs 8.7%, $p < 0.01$) or self paid (1.4 vs 2.9%), less comorbidities (Elixhauser Index > 6: 2.2 vs 3.4%, $p < 0.01$), and more affluent (median household income at highest quartile 30.8 vs 24.7%, $p < 0.01$). Temporal trends documented that robotic-assisted technology was progressively adopted in older patients, females, nonwhites, Medicare- or Medicaid-covered patients, patients with higher comorbidities and lower median house hold incomes (summarized in Table 2). On the other hand, no significant difference was found in bed size ($p = 0.08$) or geographical region ($p = 0.59$) where laparoscopic cases were performed between those with and without robotic assistance. Robotic cases were performed more commonly in urban teaching hospitals than rural or urban nonteaching hospitals (66.9 vs 52.9%, $p < 0.01$). Contrary to anticipation of gradual diffusion from large to small and teaching to nonteaching hospitals, no consistent temporal trend was observed in hospital-level variables among robotic cases across the study period.

Multilevel logistic regression found that age category between 65 and 69 years, male gender, being privately insured, lower Elixhauser comorbidity score, residing in communities with the highest median household income and receiving operation in an urban teaching hospital were all significant predictors of robotic-assistance utilization during laparoscopic procedure (see Table 3 for regression model).

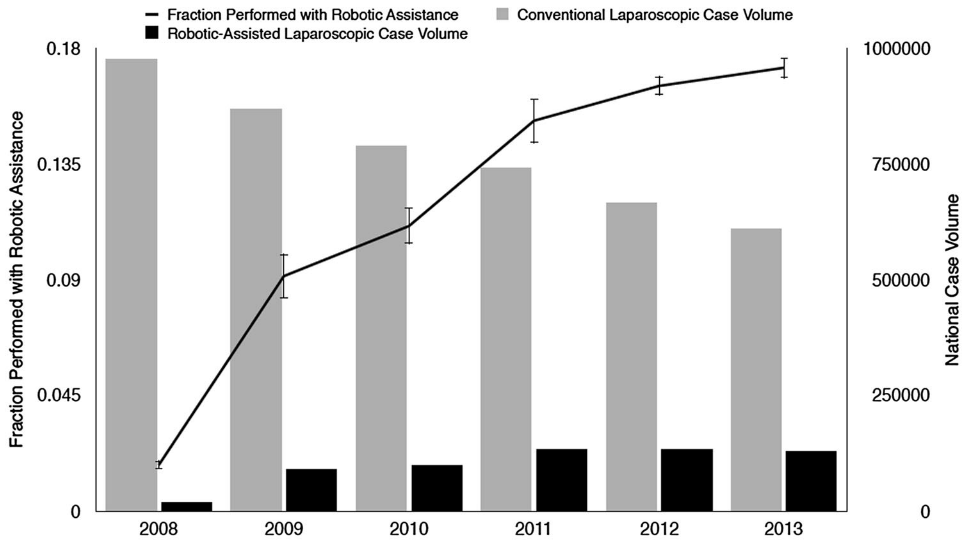

Fig. 1 The total annual number of laparoscopic procedures is gradually declining while the national robotic case volume is on the rise. This resulted in the proportion of laparoscopic procedures performed with robotic assistance almost tripling from 2008 to 2012

Diffusion of robotic-assisted laparoscopic technology across specialties

The top three specialties with the highest proportion of robotic-assisted laparoscopic procedures were urology (34.1%), gynecology (11.0%), and endocrine surgery (9.4%). On the other hand, the top three specialties with the most rapid adoption of robotic-assisted technology across the study period were colorectal surgery (from 0.3 to 8.5%, p-trend <0.01), thoracic surgery (from 0.4 to 9.4%, p-trend <0.01), and general surgery (from 0.7 to 5.0%, p-trend <0.01).

See Table 4 for the 90% most commonly performed robotic procedures and their relative outcome statistics in comparison with their conventional laparoscopic counterpart, sorted by frequency of robotic-assistance usage. Interestingly, no significant association existed between the frequency of robotic-assistance usage and relative outcome statistics such as mortality, charge, or length of stay (LOS). Mortality, charge, and LOS ratios were calculated by dividing the respective robotic procedure's outcome summary statistics by those associated with their laparoscopic counterparts. One can conclude that the differential procedure-specific adoption of robotic-assistance technology was not driven by these outcome measures.

Discussion

This report provides an initial description of national utilization trends for robotic-assisted technology in laparoscopic procedures. The introduction of robotic-assisted technology for laparoscopic procedures has caused a marked change in practice throughout the United States. We found that conventional laparoscopic case volume has declined by 39.4% whereas robotic-assisted laparoscopic procedures have increased by 250.0% over the course of 6 years. The introduction of less invasive surgical approaches, such as endovascular technology to vascular surgery [33] or laparoscopy to general surgery [34, 35], usually lowers threshold for receiving treatment and the total number of procedures are anticipated to increase. However, the total number of laparoscopic procedures actually decreased progressively since the introduction of robotic-assisted technology. Assuming that the national patient cohort eligible for laparoscopic surgery did not significantly decrease during the study period, we can conclude that robotic assistance did not lower thresholds for receiving laparoscopic surgery.

One interesting temporal trend that we have observed, in concurrence with other studies [36–39], was the plateauing of laparoscopic case volume in the early- to mid-2000s and its subsequent decrease. While our study represented the first effort to examine the robotic-adoption phenomenon across procedures, studies investigating individual procedures such as colectomy [37, 40] demonstrated that the increase in robotic case volume did not appear to compensate for the decrease in laparoscopic volume. The reasons for this plateauing and decrease in laparoscopic volume appeared to require further exploration.

There are few specific differences in the indication between conventional and robotic-assisted laparoscopic procedures in the hands of an experienced minimally-invasive surgeon [14, 41–45], yet significant differences in patient characteristics were observed in our study between the two surgical approaches. Patients receiving robotic procedures were found to be younger, more likely to be males, white, privately insured, more affluent, and with less

Table 1 Summary of patient- and hospital-level variables between patients undergoing conventional and robotic-assisted laparoscopic procedures

	Conventional laparoscopic procedures (n = 3,921,610, 86.8%)	Robotic-assisted laparoscopic procedures (n = 595,985, 13.2%)	p value
Patient-level variables			
Age (years)			
18–64	286,922 (73.2%)	410,630 (68.9%)	<0.01
65–69	361,056 (9.2%)	97,343 (16.3%)	
70–79	485,998 (12.4%)	73,722 (12.4%)	
80+	205,336 (5.2%)	14,288 (2.4%)	
Gender			
Male	1,084,230 (27.7%)	323,613 (54.4%)	<0.01
Female	2,826,350 (72.3%)	271,359 (45.6%)	
Race			
White	2,500,600 (71.6%)	402,781 (75.4%)	<0.01
Nonwhite	990,920 (28.4%)	131,305 (24.6%)	
Payer			
Medicare	1,103,570 (28.2%)	176,522 (29.7%)	<0.01
Medicaid	340,825 (8.7%)	27,577 (4.6%)	
Private insurance	2,201,800 (56.3%)	365,376 (61.4%)	
Self pay	112,531 (2.9%)	8293 (1.4%)	
Others	152,454 (3.9%)	17,260 (2.9%)	
Elixhauser			
0–2	2,718,550 (69.3%)	419,785 (70.4%)	<0.01
3–5	1,062,600 (27.1%)	163,227 (27.4%)	
>5	140,460 (3.4%)	12,973 (2.2%)	
Median household income			
First quartile (lowest)	916,554 (23.9%)	110,059 (18.8%)	<0.01
Second quartile	978,444 (25.5%)	132,680 (22.7%)	
Third quartile	999,227 (26.0%)	161,962 (27.7%)	
Fourth quartile (highest)	947,711 (24.7%)	179,958 (30.8%)	
Hospital-level variables			
Bed size			
Small	455,776 (11.7%)	64,910 (11.0%)	0.08
Medium	971,306 (25.0%)	129,326 (21.8%)	
Large	2,465,620 (63.3%)	397,811 (67.2%)	
Location/teaching status			
Rural	364,696 (9.4%)	12,639 (2.13%)	<0.01
Urban nonteaching	1,465,030 (37.6%)	183,307 (30.9%)	
Urban teaching	2,062,980 (52.9%)	396,102 (66.9%)	
Region			
Northeast	485,327 (18.3%)	63,458 (18.9%)	0.59
Midwest	624,584 (23.6%)	83,331 (24.8%)	
South	961,124 (36.3%)	111,182 (33.0%)	
West	574,037 (21.7%)	78,558 (23.3%)	

comorbidities. These disparities have been echoed in multiple other case series [46–49]. We also noted that the differences in these patient characteristics tend to decrease over the study period. We hypothesized that these differences are most likely attributable to surgeons' preference for "safer" patients while embarking on the learning curve

Table 2 Temporal trends of patient characteristics among robotic procedures [shown in percentage (%)]

	2008	2009	2010	2011	2012	2013	*p*-trend
Age >80 years old	1.0	2.0	2.1	2.3	2.6	3.1	<0.01
Female: gender	31.1	37.2	43.1	47.8	50.9	47.6	<0.01
NonWhite Race	17.4	21.2	22.7	25.5	26.7	26.9	<0.01
Medicare-covered	24.9	27.9	28.6	28.1	30.7	32.9	<0.01
Medicaid-covered	3.4	3.3	4.4	4.7	5.2	5.2	<0.01
Elixhauser > 5	0.8	1.3	1.6	1.7	2.7	3.2	<0.01
Lowest quartile median household income	16.1	17.1	19.1	17.4	20.6	19.9	0.12

Table 3 Logistic regression model identifying significant factors for robotic adoption

	Odds ratio	95% confidence interval	*p* value
Patient-level variables			
Age (years)			
18–64	1 (baseline)		
65–69	1.48	1.36–1.61	<0.01
70–79	0.81	0.74–0.88	<0.01
80+	0.33	0.29–0.37	<0.01
Gender			
Male	1 (baseline)		
Female	0.28	0.25–0.32	<0.01
Race			
White	1 (baseline)		
Nonwhite	0.92	0.83–1.02	0.13
Payer			
Medicare	1.17	0.97–1.42	0.11
Medicaid	0.80	0.66–0.98	0.03
Private insurance	1.41	1.16–1.71	<0.01
Self pay	0.61	0.46–0.81	<0.01
Others	1 (baseline)		
Elixhauser			
0–2	1 (baseline)		
3–5	0.84	0.79–0.88	<0.01
>5	0.43	0.38–0.48	<0.01
Median household income			
First quartile (lowest)	1 (baseline)		
Second quartile	1.05	0.98–1.13	0.20
Third quartile	1.10	1.01–1.21	0.04
Fourth quartile (highest)	1.22	1.07–1.39	<0.01
Hospital-level variables			
Bed size			
Small	1 (baseline)		
Medium	0.83	0.53–1.30	0.41
Large	1.09	0.72–1.65	0.70
Location/teaching status			
Rural	1 (baseline)		
Urban nonteaching	4.02	2.24–7.20	<0.01
Urban teaching	6.07	3.44–10.70	<0.01
Region			
Northeast	1 (baseline)		
Midwest	1.20	0.89–1.61	0.22
South	1.06	0.79–1.42	0.71
West	1.24	0.87–1.76	0.23

Table 4 Laparoscopic procedures with most frequent robotic-assistance usage

Procedure	Specialty	Cases with robotic assistance (%)	Mortality ratio	LOS ratio	Charge ratio
Prostatectomy	Urology	48.48	0.10	0.74	1.63
Uretero-pelvic junction correction	Urology	42.22	<0.01	0.86	1.32
Nephrectomy	Urology	38.16	0.39	0.68	1.10
Vaginal suspension	Gynecology	24.42	1.57	0.79	1.45
Cystectomy	Urology	15.49	0.60	0.86	1.07
Ovarian/fallopian tube resection	Gynecology	12.85	0.31	0.55	1.33
Esophagomyotomy	Thoracic	10.76	<0.01	0.75	1.08
Hysterectomy	Gynecology	10.50	0.71	0.67	1.53
Adrenalectomy	Endocrine	9.36	<0.01	0.79	1.10
Nephroureterectomy	Urology	9.04	0.67	0.82	1.19
Ureteroneocystostomy	Urology	8.15	<0.01	0.79	1.36
Mitral valvuloplasty	Cardiac	7.16	0.58	0.65	0.91
Lysis of adhesions	General surgery	5.26	<0.01	0.69	1.62
Hiatal hernia repair	General surgery	4.96	0.69	1.06	1.15
Coronary artery bypass graft	Cardiac	4.88	0.20	0.73	0.85
Enterostomy	General surgery	4.76	0.54	0.83	1.17
Nissen fundoplasty	General surgery	4.26	1.05	0.92	1.26
Lung resection	Thoracic	4.23	1.02	0.91	1.33
Colectomy	Colorectal	3.39	0.61	0.88	1.32
Sleeve gastrectomy	General surgery	3.19	<0.01	1.10	1.38
Urinary stress incontinence repair	Urology	2.95	<0.01	1.06	2.07
Gastroenterostomy	General surgery	2.36	1.84	1.12	1.41
Cholecystectomy	General surgery	0.93	1.35	0.85	1.65

for a new procedural approach. As our nation's surgeons gradually mature in the learning curve process, these differences are likely going to continue to decrease in the future. In addition, the initial robotic patient profile was heavily skewed by prostatectomies, but as other competing procedures increased in case volume, the dominance of the prostatectomy patient characteristics gradually diminished.

Furthermore, we saw that procedures with a higher robotic-adoption rate were not necessarily experiencing a relatively beneficial outcome from the use of robots, such as lower mortality, shorter length of stay, or lower charge. In contrast to the disruptive changes to open surgery brought about by laparoscopic technology, the addition of robotic-assisted technology were often found to be equivalent in outcome to its conventional laparoscopic counterparts [15, 17–20, 42, 44]. No novel evidence suggesting superiority of robotic-assisted over conventional laparoscopic approach has surfaced in the past decade regarding colectomy [17], esophagomyotomy [50], or hiatal hernia [51], yet colorectal, thoracic, and general surgery represented the three specialties with the most rapid increase in robotic adoption. Interestingly, five of the top ten most frequently performed robotic procedures were done by urologists. This could mean that the adoption of robot-assisted technology were heavily individual- and culture-dependent [52, 53], with urologists [54, 55] and gynecologists [56] historically being the early adopters in this technology. In addition, nine out of ten most commonly performed robotic procedures occurred in the retroperitoneum. Surgeons may find the main attraction of robotic assistance to lie in technical ease in approaching certain anatomical areas due to its multi-articulated instruments [57] instead of actual clinical outcomes [58].

We recognize several limitations to our current study, mainly stemming from the administrative nature of the database used for analyses. NIS is ideal for studying population-based adoption of new technology, but detailed clinical information on operative indication, disease severity, and postoperative complications were not available. If such were available, a more thorough examination of the relative outcome summary statics between laparoscopic procedures with and without robotic assistance could be performed. Nevertheless, the purpose of this study is to gain an updated overview of our nation's surgical practice in the adoption of robotic technology instead of examining individual procedures. Second, our examined outcomes may be confounded by inadequate clinical risk adjustment as detailed information on comorbidities were lacking in NIS. Surgeons are known to preferentially select "safer" patients during the initial adoption of new technology; this may lead to an overestimation of robotic procedure's clinical benefit in our simple outcome measure ratios.

Although robotic-assisted technology has seen progressive increase in prevalence, its adoption is conspicuously uneven across specialties and procedures. Moreover, it appears that the expanding use of robotic-assisted technology did not correlate well with frequently examined clinical outcomes in the literature. The next step in this body of work is to identify specific perceived technical advantages by surgeons working in certain anatomic areas in order to optimize target procedures for the uptake of robotic technology in the future.

Compliance with ethical standards

Disclosures Drs. Juo, Lin, Dutson, Ahmad, and Aditya have no conflicts of interest or financial ties to disclose.

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