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Title:

The learning curve in robotic colorectal surgery compared to laparoscopic colorectal surgery: A systematic review.

Running title: Robotic vs laparoscopic learning curve

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Abstract:

Background:

Learning curve has implications for efficient surgical training. Robotic surgery is perceived to have a shorter learning curve than laparoscopy, however detailed analysis is lacking. We analysed studies comparing robotic and laparoscopic colorectal learning curves. Simulation studies comparing novices' learning curves were analysed in order to surmise applicability to colorectal surgery.

Methods:

A systematic search of Medline, PubMed, EMBase, and Cochrane Library identified colorectal papers (01/01/2000 to 03/03/2021) comparing robotic learning curves to laparoscopic where surgeons lacked laparoscopic colorectal experience. Simulation studies comparing learning curves were also included. Learning curve was defined as the period of ongoing improvements in speed and/or accuracy.

Results:

From 576 abstracts reviewed, three operative and 16 simulation studies were included. Robotic learning curve for right colectomy was significantly faster in one study (16 versus 25 cases), and equal for anterior resection in two studies (44 versus 41 cases and 55 versus 55). One study showed less complications for robotic patients (14.6% vs 0%, p-0.013). Ten simulation studies reported faster times and eight recorded error rates favouring robotic surgery. Seven studies measured learning curve. Four favoured laparoscopic surgery, but operating times were faster using the robotic platform.

Conclusion:

Operating times for robotic surgery may be faster than laparoscopy when surgeons are inexperienced with both platforms. This may be related to a superior baseline performance rather than a shorter learning curve. Whether a shorter learning curve on the laparoscopic platform will persist long enough to enable skills to overtake robotic ability needs further investigation.

Key words:

Robotic surgery; colorectal surgery; learning curve

What does this paper add to the literature?

Comparisons between robotic and laparoscopic colorectal surgery learning curves are scarce. This study shows that robotic surgery may allow a superior baseline performance rather than a faster learning curve. Contrary to common belief, robotic surgery may be as fast as laparoscopy when surgeon experience levels are similar. This furthers understanding of the cost-effectiveness and safety of robotic colorectal surgery.

Introduction:

Robotic assisted colorectal surgery confers the benefits of conventional laparoscopy, including smaller incisions, reduced pain, faster recovery and reduced intra-abdominal adhesions. Benefits specific to robotic surgery include 3-dimensional views, wristed instruments and better surgeon ergonomics [1]. While clinical outcomes generally seem to be equivalent to laparoscopy [2], the platform requires significant initial and ongoing costs, with longer operating times in most studies. It is also an additional modality requiring further training.

A survey of early career US surgeons [3] found that many lack confidence to independently perform laparoscopic colorectal procedures due to insufficient experience during training. A platform offering more rapid skill acquisition may ameliorate this, increasing the number of patients benefitting from minimally invasive surgery. A more rapidly acquired technique is particularly significant for surgical training programs, in an era of restricted working hours with greater emphasis on efficient training. Common consensus is that robotic learning curves are shorter than laparoscopic. There is a paucity of supporting data.

True comparison of robotic learning curves to laparoscopy requires surgeons with equal levels of experience with each platform. Most studies, however, involve experienced laparoscopic surgeons who are relatively robotically naive. Lab-based simulations can compare true learning curves for both platforms in total novices, but simulation tasks may not predict results in the clinical setting.

We reviewed studies comparing learning curves for robotic and laparoscopic colorectal surgery. The number of cases required to achieve proficiency as well as patient related outcomes such as post-operative recovery and complication profiles are analysed. Given the small number of studies which address this, laboratory simulation studies comparing true novices' learning curves were also reviewed in order to surmise applicability to colorectal surgery.

Method:

A systematic search of Medline, PubMed, EMBase and Cochrane Library (01/01/2000 to 03/03/2021) identified papers comparing learning curves for robotic and laparoscopic procedures by surgeons with no prior laparoscopic colorectal experience. Simulation studies comparing learning curves were also included. Learning curve was defined as the period of ongoing improvements in speed and/or accuracy. The review protocol was prospectively registered in the Prospero database (registration number: CRD42020222512).

Search strategy

Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were followed. The search strategy was designed to identify articles comparing learning curves in robotic and laparoscopic colorectal surgery. MeSH and key terms used were 'anterior resection' OR 'rectal neoplasms' OR 'colorectal surgery' OR 'colectomy' OR 'colon resection' OR 'colonic neoplasms' AND 'robotic surgery' OR 'robotic surgical procedures' OR 'robot assisted surgery' AND 'learning curve'. For simulation-based comparisons, MeSH and key terms used were 'robotic surgery' OR 'robotic surgical procedures' OR 'robot assisted surgery' AND 'laparoscopic surgery' OR 'laparoscopy' AND 'learning curve' OR 'simulation training' or 'simulat*'

Medline (Ovid:1946-present), PubMed (NCBI), EMBase (Ovid:1966-present) and Cochrane Library were searched from 1st January 2000, with the final search on 3rd March, 2021. Reference lists of relevant articles were searched for additional studies. The full research question and search strategy can be reviewed in Appendix S1.

Inclusion & exclusion criteria

Studies comparing the learning curve of robotic surgery to laparoscopy, relevant to colorectal surgery, either because they examined colorectal procedures, or because tasks were simulations equally applicable to any surgical specialty. At least 50% of participants in simulation studies were to have no experience in laparoscopic surgery, unless there was separate analysis for novices. For studies directly assessing colorectal surgery procedures, surgeons were to have as little laparoscopic experience as practical.

Case reports or series of ≤5 patients were excluded. Studies where learning curve was not analyzed or not compared to laparoscopy due to inclusion of experienced laparoscopic surgeons were excluded. Studies using robotic platforms which are no longer available were considered irrelevant and therefore excluded.

Studies available in English or Spanish were considered in accordance with the languages spoken by our team.

Study selection

Two authors (JF, JL) independently assessed study titles and abstracts against inclusion criteria, with full text review for the final decision. A third assessor (AH) independently reconciled any differences in study selection.

Data Extraction & Outcomes

Data was extracted by two authors (JF, JL) with discrepancies checked against the original papers and/or discussed with a third author (AH) to resolve.

Variables assessed included study design, operative technique, surgical time and learning curve as well as postoperative recovery. Simulation study variables included type of simulation, error rates and operating times.

Operating time was defined as time from the first incision until skin closure. Docking time was time to position the robot and secure arms to ports. Conversion included any unintended conversion to an open incision. Complications were graded according to the Clavien-Dindo scale [4] as minor (grades 1 and 2) or major (grades 3 and 4).

The inherent heterogeneity (use of different operations and simulation tasks) of the studies precluded pooling of data for meta-analysis.

Risk of Bias

Two authors (JF, JL) assessed risk of bias independently with a third author (AH) resolving any discrepancies, using the Newcastle Ottawa Scale [5] and Cochrane Risk of Bias in Non-Randomised Studies- of Interventions (ROBINS- I) [6] for non-randomised studies and the Jadad scale [7] and Revised Cochrane Risk of Bias Tool (ROB-2) [8] for Randomised Controlled Trials (RCT).

Results:

The initial search yielded 576 studies (figure 1). After assessment, 19 papers were included in the final analysis (Appendix S2 shows reasons for exclusion of considered papers). Study quality scores are shown in tables 1 and 4, with bias assessments presented in figures 2-4. Risk of bias in the randomized studies (figure 3) showed some concerns, mostly related to limited information regarding the randomization process. The non-randomised studies all showed serious concern (figures 2 and 4), mostly due to the potential for confounding when allocating to arms of the study, with experienced surgeons allocated to the robotic platform and novices to laparoscopy in several studies.

Operative (in vivo) studies:

Two studies involved low anterior resection [9,10]; one assessed right colectomy [11] (table 1). Park et al [9] present a case-matched study of 89 robotic and 89 laparoscopic low anterior resections. Melich et al [10] report 92 robotic and 106 laparoscopic consecutive low anterior resections. De'Angelis et al [11] present 30 robotic and 50 laparoscopic consecutive right colectomies.

Surgeon experience:

All three surgeons had trained in laparoscopic general surgery operations, with some prior assisting in laparoscopic colorectal surgery, while robotic experience was largely described as simulation and course-based.

Learning curves according to operating time (figure 5):

Park et al's CUSUM analysis of operating times demonstrates a robotic learning curve of 44 cases, versus 41 cases. They stratified patients to the learning curve or post-learning curve phase. Melich et al arbitrarily divided cases into three phases of about 31 patients. Improvements in robotic operating times plateaued after phase 2, while laparoscopic times continued to improve, suggesting an ongoing learning curve.

Park et al's CUSUM analysis of robotic docking times showed a plateau after 21 cases.

Operating times (table 2):

Park et al demonstrated shorter robotic operating times in phase 1 (mean 229.8 versus 242.3 minutes) but longer in phase 2 (187.9 versus 168.8 minutes).

Melich et al reported longer robotic operating times in phase 1 (median 397 versus 308 minutes), but shorter in phase 2 (median 253 versus 275 minutes) and in phase 3 (median 204 versus 220) (.

De'Angelis et al found that robotic operations were slightly faster, but not statistically significant, across three phases (arbitrarily defined as 10 cases each), with mean operating times for phases one to three: 237.8, 193.8 and 180 minutes for robotic cases versus 240, 214.5 and 188.6 for laparoscopy.

Return of bowel function:

Park et al found no significant difference in time to flatus. Time to soft diet was shorter for robotic patients in phase 1 (4.8 ± 1.3 versus 5.5 ± 1.6), but equal in phase 2 (4.9 ± 1.2 versus 4.9 ± 1.6). De'Angelis et al found no significant difference in time to flatus, return to diet or length of stay in hospital.

Conversion:

Park et al and De'Angelis et al did not convert any robotic cases to open, but did convert five and two laparoscopic cases respectively. This was statistically significant only in phase 1 of Park et al's study (four of five conversions occurred in phase 1, p=0.05). Melich et al also report lower conversion rates for robotic surgery (1.1 vs 3.8%) with all conversions for both platforms occurring in the first phase.

Complications:

Park et al encountered increased major postoperative complications in laparoscopic patients, which was significant in phase 2 (14.6% vs 0%, p-0.013) (table 3). There were no significant differences in complications rates in the other two operative studies.

Oncological resection:

None of the studies demonstrated significant differences in pathological outcomes such as resection margins and lymph node harvest.

Simulation studies:

16 studies [12-27] compared learning curves of novices in robotic versus laparoscopic simulation activities, incorporating 350 participants in total (table 4). Most participants were novices, with some studies [12,14,17,19-21,25,27] including a mix of novice and experienced laparoscopic surgeons including five studies which compared results between novices and experienced surgeons [12,15,19-21]. Three studies took place over multiple sessions [21,24,25], and one [19] allowed a 24-hour rest period between platforms. The remainder took place over a single day, with one [22] also bringing participants back one month later for a delayed retention test. All studies used operating time as a primary outcome measure. Ten also utilised other performance measures, such as precision or error rates (Table 5).

Operating times (14 studies):

Twelve studies reported faster times using a robotic platform [12-14,16-18,20,22-26] (table 6). Two studies, both including some experienced surgeons, showed no significant difference [21,27]. Subgroup analysis in one [21] showed that novices were significantly faster using a robotic platform, with no significant difference for experienced surgeons.

Error rates (10 studies):

Eight studies demonstrated superior scores using the robotic platform [13,15-17,22,23,26,27] (table 6); one found laparoscopy to be superior [18]. One study [19] found that robotic scores were better for the more difficult intracorporeal suturing, but no significant difference during easier tasks (peg transfer and circle cutting).

Learning curve (11 studies):

Three studies found no significant differences in learning curve [21,23,24] (table 6). Three demonstrated shorter robotic learning curves [12,15,17]; one found a robotic approach to be superior when accuracy was used to calculate the learning curve, but no significant difference when using speed [22]. Four studies found shorter learning curves for laparoscopy [16,18,25,26]. Average completion times in these studies were faster on the robotic platform, with laparoscopic times failing to overtake robotic times by the end of two of these studies [16,25] despite the faster learning curve. Anderberg et al showed that by the end of the study, laparoscopic times had overtaken robot times for continuous suturing, but robotic knot tying was still faster [18].

Ergonomics (7 studies):

All studies [14,15,19,21,24,26,27] demonstrate a preference for the robotic platform (table 7).

Effects of 3-D vision:

Hubens et al [13] demonstrated superior robotic results with 3-D compared to 2-D views, but 2-D robotic performances were superior 2-D laparoscopy. Shakir et al [23] found that participants performed better using the robotic approach than with 3-D laparoscopy.

Discussion:

We identified three studies comparing results and learning curves of surgeons new to both robotic and laparoscopic colorectal surgery. Anterior resection learning curves were similar; 44 and 55 cases for robotic surgery versus 41 and 55 [9,10]. Right colectomy learning curve [11] was significantly different;16 cases for the robotic platform versus 25. Previous reports of learning curve for anterior resection range from 15-114 for robotic procedures and 18-250 for laparoscopy [28-30].

Longer operating time forms a key criticism of the robotic platform. However, these studies all show significantly shorter robotic operating times at some point in the study. Simulations showed greater time advantages for more complex tasks, such as knot tying [19,18]. This is mirrored in the operative study, where TME was performed more rapidly using the robot, while there was no difference in operating times for splenic flexure mobilisation and IMA ligation [10].

The three operative studies showed only one conversion to open in a robotic case, compared to 11 laparoscopic cases, with 9 of these occurring within the initial phase. While many previous studies showed lower conversion rates for robotic surgery there was no significant difference in conversions in the ROLARR trial [31]. Our findings suggest reduced conversion rates are significant early in the learning curve, when laparoscopic conversions are more common. When the ROLARR authors adjusted for operating surgeon experience [32], risk of conversion was reduced using the robotic platform as surgeons gained more experienced with robotic surgery, regardless of laparoscopic experience, suggesting that the overall lack of difference in conversion rates related to the much greater laparoscopic experience of most of their surgeons. Even without accounting for this, robotic procedures on obese and male patients, generally accepted to be more difficult, had significantly lower conversion rates.

Although Park et al showed lower complication rates for robotic surgery, the other two operative studies found no significant differences. There were no significant differences in other post-operative and pathological outcomes. This is in line with the literature, confirming that early robotic practice does not infer increased risk to patients [2,33,31].

The 16 simulation studies universally depicted superior performances for novices using the robotic platform compared to laparoscopy. Surprisingly, learning curve trends were less convincing. Equal numbers favoured robotic and laparoscopic tasks, with no significant difference in three studies. There was also little difference in anterior resection learning curve [9,10], though right colectomy learning curve favoured robotic surgery [11]. The advantage in early practice on the robotic platform may result from a better baseline performance rather than a shorter learning curve, contrary to previous beliefs.

The benefits of superior baseline skills are illustrated in Marecik et al's study, where 15 novices performed an anastomosis on a porcine intestinal model. Operating times were no different despite increased suture breakage and a significantly higher number of sutures per centimetre for robotic anastomoses. The anastomoses were subjected to pneumatic pressure, to quantify the 'leak pressure'. Only six of 12 laparoscopic anastomoses were testable, compared to 11 of 12 robotic anastomoses, which showed significantly higher leak pressures. The benefit of being able to perform a higher quality anastomosis on the initial procedure is clear.

The question yet to be answered, is whether those who gain expertise in both robotic and laparoscopic surgery will maintain some superiority in their robotic performance, or whether a steeper laparoscopic learning curve means that, over time, laparoscopic performance will equal or overtake robotic performance.

Questionnaires in seven simulation studies showed a preference for the robotic platform, which caused less frustration, physical discomfort and pain. This may improve performance, and has clearly influenced the ongoing growth in robotic colorectal surgery [1,3] which is largely driven by surgeon preference. The subjective sense that the robotic platform makes surgery easier may lead surgeons to perform more complex procedures using a robotic as opposed to a laparoscopic approach [34] with a preference for the robotic platform in the more challenging confines of the pelvis being well documented [1,3].

Some of the advantages of robotic surgery can be incorporated into laparoscopic surgery. These include wristed instruments, 3-D views and immersive views, which may improve laparoscopic performances, but don't fully account for the superiority of robotic simulations. Subjects achieve better scores on the robotic platform even with two-dimensional views [13,35] or using 3-D laparoscopy [23]. Moorthy et al calculated that the transition from two-dimensional to three-dimensional robotic views only accounted for 10-15% of the overall advantage of the robotic platform [35].

Limitations:

The operative studies are not randomized, with selection of robotic surgery based on patient preference and/or insurance coverage, leading to potential bias based on how the surgeons explained the platforms and the patients' underlying attitudes. At least two of the three surgeons had prior laparoscopic experience and therefore will have acquired some skill in compensating for limitations of laparoscopy such as two-dimensional views and straight instruments, though the resulting bias towards laparoscopy is less pronounced than in most studies. The learning curves of just three surgeons is too small a group to draw firm conclusions, given the significant variation that can exist between individuals' capabilities, prior training and experience. Pooling of results was not possible given all three performed different operations (hybrid anterior resection, totally robotic anterior resection and right colectomy).

The simulation studies provide a more even comparison, with a greater number of participants. However, extrapolating results of a simulation task to a complex, multi-stage colorectal procedure is imprecise. These studies were also unsuitable for pooling, given the use of different simulation tasks between the studies.

Funding source was not specified in most papers, but industry funding is likely in at least some and this is a potential source of bias. In general, all robotic surgery studies tend to be undertaken by enthusiasts, which may bias any study towards the robotic platform.

Operating time is the key variable used to assess learning curve. Clearly speed is not the only indicator of a surgeon's proficiency. However, many other outcomes, such as technical finesse, complication rates and pathological outcomes are either too subjective, too heterogeneous or differences are harder to demonstrate. As a result, operating time is likely to continue to be considered a key indicator of proficiency.

Conclusions:

Contrary to common perceptions, robotic surgery can be associated with faster operating times than laparoscopy when experience levels are similar. The advantages of the robotic platform seem to be most evident with more complex tasks, and early in the learning curve. This may be due to better initial baseline ability, rather than a shorter learning curve as has previously been proposed and suggests superior patient safety for inexperienced surgeons. Whether the shorter learning curve of the laparoscopic platform will persist long enough to enable skills to overtake robotic ability needs further investigation.

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35. Moorthy K, Munz Y, Dosis A, Hernandez J, Martin S, Bello F, Rockall T, Darzi A (2004) Dexterity enhancement with robotic surgery. Surg Endosc 18 (5):790-795. doi:10.1007/s00464-003-8922-2

Figure 1: PRISMA flow chart of studies selection

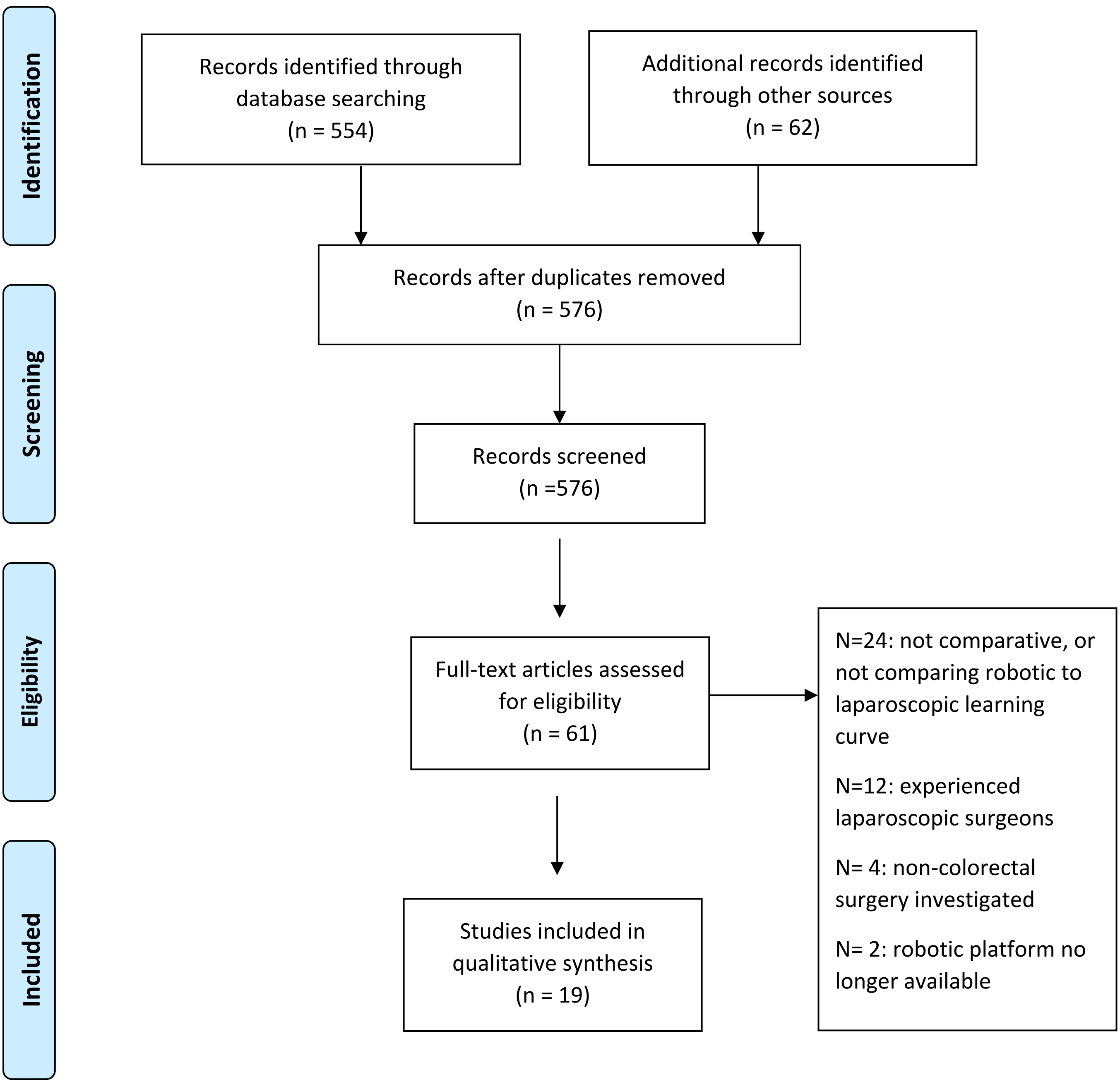


Figure 2: Bias Assessment* for operative studies

Low risk of bias

Moderate risk of bias

Serious risk of bias

Critical risk of bias

D1: Confounding

D2: Selection of participants

D3: Classification of interventions

D4: Deviations from intended interventions

D5: Missing data

D6: Measurement of outcomes

D7: Selection of the reported result

*ROBINS-I Cochrane Risk-of-Bias Tool for non-randomised trials

Figure 3: Bias Assessment* for Randomised Simulation Studies:

Study ID	Weight	D1	D2	D3	D4	D5	Overall
Blavier et al (2007)	1	!	+	+	+	+	!
Heemskerk et al (2007)	1	!	+	+	+	+	!
Rashid et al (2010)	1	!	+	+	+	+	!
Anderberg et al (2010)	1	!	+	+	+	+	!
Moore et al (2015)	1	!	+	+	+	+	!
Shakir et al (2016)	1	+	+	+	+	+	+
Dewaele et al (2019)	1	!	+	+	+	+	!
Leijte et al (2020)	1	-	+	+	+	+	-
Moncayo et al (2020)	1	!	+	+	+	+	!
Marecik et al (2007)	1	!	+	+	+	+	!

+ Low risk

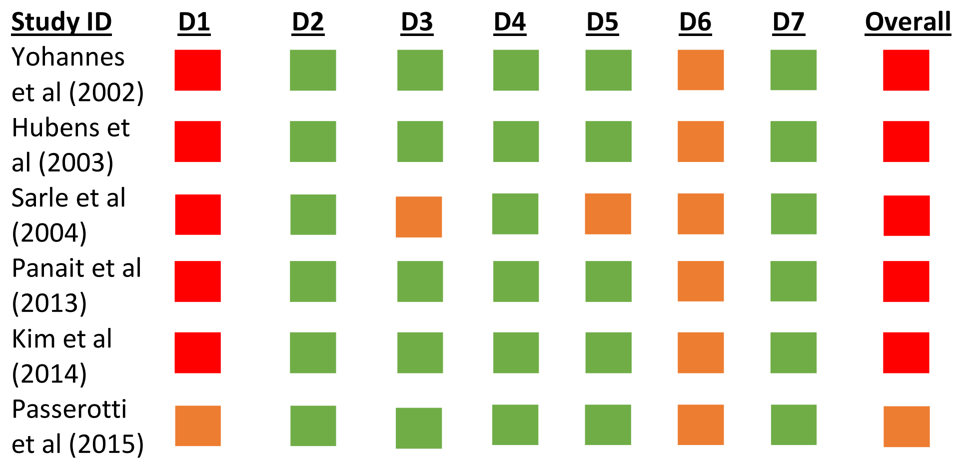
! Some concerns

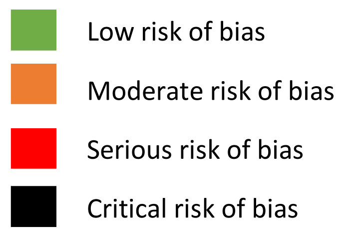
- High risk

D1	Randomisation process
D2	Deviations from the intended interventions
D3	Missing outcome data
D4	Measurement of the outcome
D5	Selection of the reported result

* ROB-2: Revised Cochrane Risk-of-Bias Tool for randomised trials

Figure 4: Bias Assessment* for Non-Randomised Simulation Studies





D1: Confounding

D2: Selection of participants

D3: Classification of interventions

D4: Deviations from intended interventions

D5: Missing data

D6: Measurement of outcomes

D7: Selection of the reported result

*ROBINS-I Cochrane Risk-of-Bias Tool for non-randomised trials

Figure 5: Operative Studies: Learning Curve (number of cases to achieve plateau in operating times).

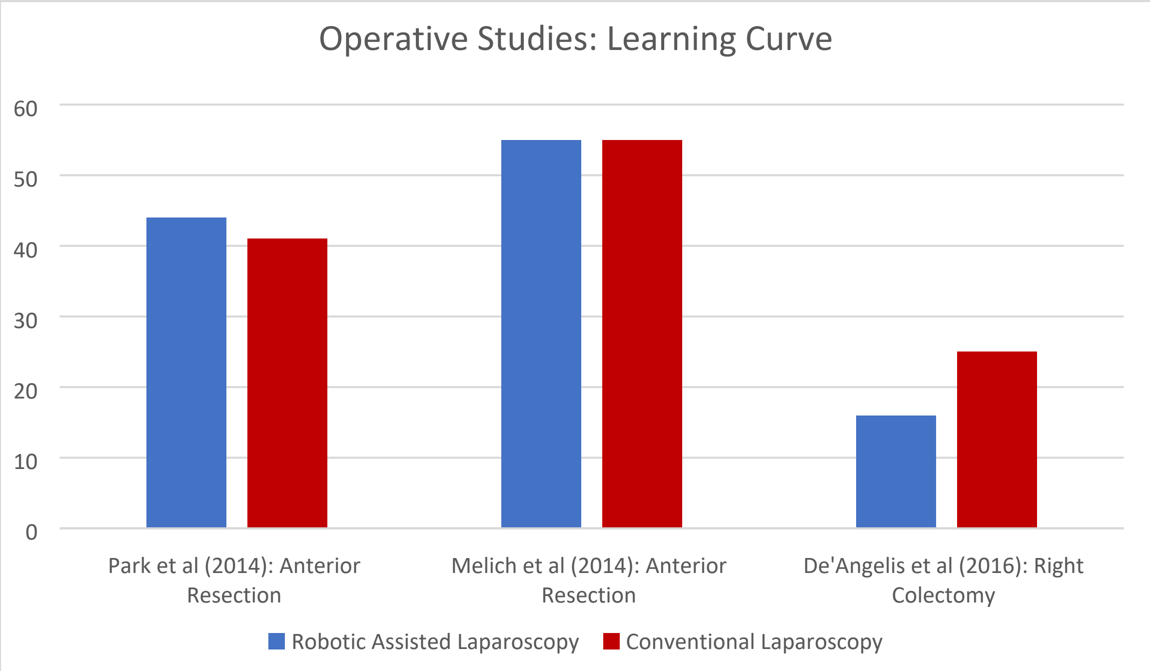


Table 1: In vivo study characteristics

Author (year)	Funding	Surgical steps using RL subjected to analysis	Choice of platform & study design.	RL: sample size	CL: sample size	Parameters learning	Outcome	Study Quality**

						curve is based on		
Park et al (2014)	None	Rectal dissection as part of low anterior resection (CL for left colon/splenic flexure)	Patient choice/ability to pay. Case matched.	89	89	CUSUM plots based on operating times	RL: initial learning curve: 44 CL: initial learning curve: 41	7/9
Melich et al (2014)	None	Low anterior resection. Dual docking, totally RL	Patient choice/ability to pay. Retrospective review.	92	106	Plateau of operative time curves	55 cases for RL and CL*	7/9
De'Angelis et al (2016)	None	Totally RL right hemicolectomy	Patient choice & availability (no extra cost to patient). Retrospective review.	50	30	CUSUM plots based on operating times	RL: 16 cases CL: 25 cases	7/9

* No plateau was reached for operating times during the study, but improvement in times slowed at this point

** Newcastle-Ottawa Assessment Scale (maximum score: 9)

Table 2: In vivo study operating times

Author (year)	Operation	Robot phase 1 operating times (phase 1 definition)	Laparoscopy phase 1 operating times (phase 1 definition)	Robot phase 2 operating times (phase 2 definition)	Laparoscopy phase 2 operating times (phase 2 definition)	Robot phase 3 operating times (phase 3 definition)	Laparoscopy phase 3 operating times (phase 3 definition)
Park et al (2014)	Low anterior resection	229.8±48.5* (Cases 1-44)	242.3±80.6* (Cases 1-41)	187.9±53.2* (Cases 45-89)	168.8±52.5* (Cases 42-89)	NA	NA
Melich et al (2014)	Low anterior resection	397 (373-420)** (Cases 1-31)	308 (291-325)** (Cases 1-31)	253 (238-268)** (Cases 32-62)	275 (263-288)** (Cases 32-62)	204 (196-211)** (Cases 63-106)	220 (212-229)** (Cases 63-92)
De'Angelis et al (2016)	Right colectomy	237.8±27.07 (Cases 1-10)	240±26.14) (Cases 1-10)	193.8±24.24 (Cases 11-20)	214.5±12.57 (Cases 11-20)	180±12 (Cases 21-30)	188.6±14.73 (Cases 21-50)

NA= not applicable

* Times in minutes expressed as mean ± standard deviation

**Times in minutes expressed as mean (95% confidence interval)

Table 3: Complication rates for operative studies

Author (year)	Cases per phase	RL Complications			CL Complications			p
		Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3	
Park et al (2014)	Phase 1: 41 (RL); 48 (CL) Phase 2: 44 (RL); 45 (CL)	Minor*: 2 (4.9%) Major*: 3 (7.3%)	Minor*: 4 (9.1%) Major*: 0	NA	Minor*: 4 (8.3%) Major*: 4 (8.3%)	Minor*: 8 (17.8%) Major*: 7 (15.6%)	NA	0.707 † 0.013 ‡
Melich et al (2014)	Phases 1 & 2: 31 Phase 3: 30 (RL); 44 (CL)	Minor*: 6 (19.4%) Major*: 1 (3.2%)	Minor*: 3 (9.7%) Major*: 2 (6.5%)	Minor*: 2 (6.7%) Major*: 3 (10%)	Minor*: 3 (9.7%) Major*: 2 (6.5%)	Minor*: 7 (22.6%) Major*: 1 (3.2%)	Minor*: 3 (6.8%) Major*: 2 (4.6%)	NS
De'Angelis et al (2016)	Phases 1 & 2: 10 Phase 3: 10 (RL); 30 (CL)	Minor*: 2 (20%) Major*: 0	Minor*: 1 (10%) Major*: 0	Minor*: 5 (16.7%) Major*: 0	Minor*: 2 (20%) Major*: 0	Minor*: 1 (10%) Major*: 1 (10%)	Minor*: 1 (10%) Major*: 1 (3.3%)	0.499

RL: robotic assisted laparoscopy (with 3D vision unless otherwise stated)

CL: conventional laparoscopy (with 2D vision unless otherwise stated)

NA: not applicable

NS: not statistically significant

* Complications graded according to Clavien-Dindo scale as minor (grades 1 and 2) or major (grades 3 and 4)

† Major complications, phase 1 RL vs CL

‡ Major complications, phase 2 RL vs CL

Table 4: Included simulation studies

Author (year)	**Funding**	**Simulation task**	**Repetitions ** **	**Number of subjects**	**Type of subjects**	**Study design**	**Comparison groups *** **	**Outcome measures**	**Quality***
Yohannes et al (2002)	NR	Suturing & non-surgical ‡‡‡	5	8	Mixed	All subjects: RL then CL	RL, CL, novice, experienced†	Speed	6/9
Hubens et al (2003)	NR	Knot tying & non-surgical ‡‡‡	2	6	Novice	All subjects: 3D RL then 2D RL	RL 3D, RL 2D, CL 2D	Speed, errors	7/9

						then CL			
Sarle et al (2004)	NR	Knot tying & non-surgical ‡‡‡	NR	21	Mixed	All subjects: RL & CL (order NR)	RL, CL	Speed	7/9
Blavier et al (2007)	Research grant‡	Non-surgical ‡‡‡	11	40	Novice	Randomised crossover	RL, CL Novice, experienced†	Speed, errors, ambidexterity	2/5
Heemskerk et al (2007)	NR	Suturing & non-surgical ‡‡‡	3	8	Novice	Randomised crossover	RL, CL	Speed, accuracy	2/5
Rashid et al (2010)	NR	Non-surgical ‡‡‡	10	6	Mixed	Randomised crossover	RL, CL	Speed, errors	1/5
Anderberg et al (2010)	None	Knot tying & non-surgical ‡‡‡	4	20	Novice	Randomised crossover	RL, CL	Speed, accuracy	2/5
Panait et al (2013)	NR	Suturing & non-surgical ‡‡‡	NR	28	Mixed	All subjects: CL then RL 24 hrs later	RL, CL, novice, experienced†	Speed, errors	7/9
Kim et al (2014)	Research grant ‡	Suturing & non-surgical ‡‡‡	2	20	Mixed	All subjects: RL & CL (order NR)	RL, CL, novice, experienced†	Speed	6/9
Passerotti et al (2015)	None	Suturing & non-surgical ‡‡‡	5 weekly sessions	43	Mixed	All subjects: RL & CL (order NR)	RL, CL, novice, experienced†	Speed	9/9

Moore et al (2015)	Industry	Non-surgical ‡‡‡	50	40	Novice	Randomised, no crossover	RL, CL	Speed, errors	2/5
Shakir et al (2016)	None	Knot tying & non-surgical ‡‡‡	10	20	Novice	Randomised crossover	RL 3D, CL 3D	Speed, errors	3/5
Dewaele et al (2019)	Industry	Suturing & non-surgical ‡‡‡	9 hours per platform over 3 weeks	16	Novice	Randomised crossover	RL, CL, CL with steerable instruments†††	Speed	2/5
Leijte et al (2020)	None	Suturing & non-surgical ‡‡‡	‘Multiple sessions’	47	Mixed	Novices: randomised. Experienced: robot. No crossover	RL, CL	Speed	1/5
Moncayo et al (2020)	None	Non-surgical ‡‡‡	5	12	Novice	Randomised crossover	RL, CL	Speed, OSATS scores ‡‡	2/5
Marecik et al (2007)	NR	Intestinal anastomosis (porcine model)	1 anastomosis per platform	15	Mixed	Randomised crossover	RL, CL, open surgery	Speed, errors, leak test	2/5

RL: robotic assisted laparoscopy (with 3D vision unless otherwise stated)

CL: conventional laparoscopy (with 2D vision unless otherwise stated)

NR: Not reported

*Quality assessment score out of 9 (Newcastle-Ottawa Quality Assessment Scale) for non-randomised studies; Score out of 5 (Jadad scale) for randomised studies

**Number of repetitions of each task

***When not otherwise specified, robot uses 3D vision & laparoscopy uses 2D vision.

**** Straight laparoscopic instruments used with the robotic platform as well as the laparoscopic in order to specifically isolate the immersive 3D vision of the robotic platform.

† Experienced laparoscopic surgeons with little/no robotic experience

††† Steerable instruments via the laparoscopic platform

‡ Research institution funding: not industry-based

‡‡ OSATS= Objective structured assessment of technical skills

‡‡‡ Non-surgical tasks: simulation tasks which don't directly imitate surgical procedures but test the dexterity and motor skills required to undertake minimally invasive surgery. Most involve picking up & placing objects, threading needles or rope, or cutting out a circle.

Table 5: Performance score definitions

Author	**Outcome**	**Definitions**	**Calculation of score**

(year)	measures used in performance score calculation		
Hubens et al (2003)	Errors	Research team defined errors for each task eg dropping object, multiple attempts to grasp a needle, inaccurate cutting	Number of errors counted per task, compared with Friedman test
Blavier et al (2007)	Error score, ambidexterity score	Errors: failure to grasp needle on first attempt, dropping the needle, missing the ring. Ambidexterity: alternative uses of left and right instruments	Accuracy evaluated by 3 independent observers. Error score: total number of failures per trial. Ambidexterity score: number of alternative uses of left and right instruments. Learning curves for each score analysed by repeated-measures analysis of variance.
Heemskerk et al (2007)	Accuracy	Inaccuracy: bead, needle or needle cap accidentally dropped or damaged by excessive force. Suture breakage. Loose knot	Number of dropped or damaged objects. That is, lower score equates to superior performance. Mean scores for each task calculated
Rashid et al (2010)	Errors	Circle cutting breach: disruption of border	Number of breaches counted. Median scores calculated, compared with Wilcoxon signed rank test.
Anderberg et al (2010)	Accuracy	Inaccuracy: damage to skin pad, dropped needle, tearing of thread	Damage to skin pad recorded as yes/no. Number of dropped needles or tearing of thread per set recorded. Mean values calculated to compare groups with Wilcoxon's signed rank test for paired samples and Mann-Whitney test of two independent samples before and after the crossover.

Panait et al (2013)	Errors	Precision and errors described as being assessed 'according to established methods', but no explicit definition given.	Penalty score applied for errors or lack of precision. This was subtracted from time to give overall score.
Moore et al (2015)	Errors	Errors: balls dropped and/or knocked off. Tone counting task errors: difference between actual number of tones played during task and participants' estimate of number of tones played.	Errors: number of balls dropped and/or knocked off Tone counting task error score: actual number of target tones subtracted from participants' estimates of number of target tones played.
Shakir et al (2016)	Errors	Error: grasping rope outside marked area, cut extending outside marked area, dropping of needle or needle cap, missed attempt to grasp suture	Mean error rates calculated, compared with Wicoxon signed-rank test.
Moncayo et al (2020)	OSATS scores	Validated scoring system allocating points for a number of domains, including respect for tissue (tissue handling/use of force), time and motion (economy of movement), instrument handling, flow of operation and forward planning, knowledge of instruments and use of assistants.	Validated scoring system, points range from 7-35
Marecik et al (2007)	Errors, leak test	Errors: suture break, obvious holes/defects in anastomosis. Leak test: Intestinal cylinder mounted and sealed on a connector attached to CO2 insufflation system. Submerged in water and tested for leak at increasing pressures.	Leak test: leak pressure, ie the pressure at which a leak was established. That is, the higher the leak pressure, the better the anastomosis. Mean leak pressures compared using analysis of variance 1-way test with post hoc analysis.

Table 6: Simulation study results:

Author (year)	**Type of subjects**	**Platform with greater speed of task completion**	**p**	**Platform with better performance scores****	**p**	**Platform with faster learning curve**	**p**	**Overall comments**
Yohannes et al (2002)	Mixed	CL (1st attempt) RL (final attempt)	NR	NR	NR	RL	<0.01	Learning curve greater in novices. Experienced surgeons outperformed novices on both platforms.
Hubens et al (2003)	Novice	RL	<0.05	RL	<0.05	NR	NR	RL performed better across all tasks, but more pronounced for more difficult tasks. 2D RL was superior to 2D CL.
Sarle et al (2004)	Mixed	RL	<0.001	NR	NR	NR	NR	All 8 tasks faster with RL, statistically significant for all but most simple task

Blavier et al (2007)*	Novice	NR	NR	RL*	NR	RL*	NR	
Heemskerk et al (2007)	Novice	RL (sig in ¾ tasks)	<0.009	RL (sig in 2/4 tasks)	<0.001	CL in 1/3 tasks (no difference in other tasks)	NS	3 attempts at each task
Rashid et al (2010)	Mixed	RL	<0.0001	RL	<0.0001	RL	NR	No improvement in lap over the 10 attempts
Anderberg et al (2010)	Novice	RL (difficult task) NS (all other tasks)	NR	CL	NR	CL	NR	Steeper for CL (but CL scores inferior to RL at all points on curve)
Panait et al (2013)	Mixed	NR	NR	RL (difficult task) NS (easier tasks)	<0.001	NR	NR	Experienced surgeons (subgroup): lower scores on RL for simpler tasks, equal scores on more complex tasks.
Kim et al (2014)	Mixed	RL	0.039	NR	NR	NR	NR	Novices scored better with RL in all tasks. Experienced surgeons only scored better in 1/3 tasks. The rest were NS
Passerotti	Mixed	RL (novices)	0.01	NR	NR	NS	NR	Novices did better on the

et al (2015)		NS (experienced surgeons)						RL, and performances were comparable to the expert surgeons by the end.
Moore et al (2015)	Novice	RL	0.006	RL	<0.001	Time: NS. Accuracy: learning curve shorter for RL	0.043	Superiority of RL more pronounced for more difficult tasks.
Shakir et al (2016)†	Novice	RL†	NR	RL†	<0.01	NS†	<0.01	RL times and error rates better at all points on learning curve
Dewaele et al (2019)	Novice	RL	NR	NR	NR	NS	NR	Steerable learning curve steeper than RL or CL.
Leijte et al (2020)	Mixed	RL	NR	NR	NR	CL	NR	
Moncayo et al (2020)	Novice	RL	<0.0001	RL	<0.001	CL	NR	Greater improvements with CL than RL (but scores remained lower to the end)
Marecik et al (2007)	Mixed	NS	NR	RL	NR	NR	NR	

CL: Conventional laparoscopy

RL: Robotic assisted laparoscopy

NS: No significant difference

NR: Not reported

*Robot with 3D compared to laparoscopy with 2D. See main text for results of robot with 2D and laparoscopy with 3D.

** A number of different performance scores were used, see Table 4 for definitions

†Compares robot with 3D laparoscopy

Table 7: Ergonomics and ease of use of platforms

Author (year)	Measure of subjective ease/comfort	Result	p
Sarle et al (2004)	Participants asked which platform was easier for each task	19/21 said RL was easier, increased with task difficulty	NR
Blavier et al (2007)	Questionnaire- self performance evaluation, feelings of mastery, familiarity, performance satisfaction, confidence, preference for platform (4 point Likert scale)	Higher scores with RL than CL across most questions (statistically significant), with CL perceived as more difficult	NR
Panait et al	NASA-TLX questionnaire: validated 20-point visual	No sig difference on peg transfer, but less demand with RL	<0.05

(2013)	analogue scale assessing six subscales: mental demand, physical demand, temporal demand, performance, effort, and frustration level. Total score by adding the six categories.	on the more difficult tasks.	
Passerotti et al (2015)	ISAT survey: baseline survey assessed demographics, previous experience and attitude toward RL and CL. After each session survey assessed level of frustration and impact of frustration. This used six items to quantify emotional, physical and cognitive aspects of stress with a 1-4 Likert scale (1, not at all … 4, very much). Mood was also assessed using a scale from 0-10	Experienced surgeons overall experienced less frustration. Easier tasks caused less frustration. RL resulted in less frustration for surgeons & novices.	<0.01
Dewaele et al (2019)	Pain scores based on a visual analogue scale to evaluate strain in wrist and shoulders	Most strain in CL. Some wrist pain in RL during early phases, none after final test.	NR
Moncayo et al (2020)	Satisfaction survey (no specific details provided)	12/12 preferred RL	NR
Marecik et al (2007)	Subjective difficulty scale (tasks rated as easy, moderate, hard, very hard by each subject)	CL: 66% very hard, 25% hard. RL: 66% mod, 17% hard	NR

NR: Not reported

CL: Conventional laparoscopy

RL: Robotic assisted robotic surgery

NASA-TLX survey: National Aeronautics and Space Administration Task Load Index

ISAT survey: Imperial Stress Assessment Tool