



The application of robotics in plastic and reconstructive surgery: A systematic review

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Abstract

Background: Robotic assisted surgery (RAS) has seen significant advancement in many surgical specialties, although the application of robotics in plastic and reconstructive surgery remains to be widely established. This systematic review aims to assess the role of RAS in plastic and reconstructive surgery.

Methods: The review protocol was published and registered a priori as CRD42024507420. A comprehensive electronic search for relevant studies was performed in MEDLINE, Embase and Google scholar databases.

Results: Overall, 132 studies were initially identified, of which, 44 studies satisfied the eligibility criteria with a cumulative total of 239 patients. RAS demonstrated a high degree of procedural success and anastomotic patency in microvascular procedures. There was no significant difference in periprocedural adverse events between robotic and manual procedures.

Conclusion: RAS can be feasibly implemented in plastic and reconstructive surgery with a good efficacy and safety profile, particularly for microsurgical anastomosis and trans-oral surgery.

KEYWORDS

microvascular surgery, plastic surgery, reconstructive surgery, robot, trans-oral robotic surgery

Francesca Ruccia and Akash Mavilakandy are joint first authors.

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1 | INTRODUCTION

The advancement and advocacy for robotic-assisted surgery (RAS) has occurred due to a combination of increased demand for minimally invasive procedures alongside significant progression in computing power and robotic engineering.^{1–4} RAS is a subcategory of computer-assisted surgery and facilitates the use of a motorised system to control its end-effectors and offer greater accuracy and precision. In recent years, various robotic systems have secured Federal Drug Agency approval for application in the abdominal, urological, and gynaecological surgical disciplines in addition to others.^{5–7} In contrast, the application of robotics in plastic and reconstructive surgery remains to be widely established.

The *da Vinci*® surgical system (Intuitive Surgical, Inc.) has been widely implemented across numerous surgical specialties in view of the advantages offered to overcome inherent issues well known to minimally invasive surgery. The human wrist facilitates seven degrees of freedom in contrast to laparoscopic surgery that is limited to four.⁸ Other impediments relevant to laparoscopic surgery include restricted vision in two dimensions, exaggeration of physiologic hand tremors and inconvenient positioning of the surgeon and patient.^{9,10} RAS offers versatility in the context of these challenges by providing visualisation in three dimensions and greater relation to the human wrist through the number of end-effectors and movement capabilities of the manipulators. Furthermore, the scaling down of surgical movements at the end-effectors enables better control and potentially efficacious application in meticulous approaches such as microvascular surgery.

Plastic and reconstructive surgery is a speciality that embodies innovation, particularly from a technical standpoint and actively collaborates with numerous surgical specialties that are currently implementing RAS as a standard of care. As a result, it is becoming increasingly pertinent to gain an understanding of RAS and explore its potential application in plastic and reconstructive surgery. There have been systematic reviews assessing the role of RAS in plastic and reconstructive surgery^{11,12} however an appraisal of these studies through the AMSTAR criteria, a comprehensive critical appraisal instrument that enables evaluation of systematic reviews, emphasised various methodological limitations that consequently hindered meaningful interpretation of the findings.¹³ Furthermore, given the topical nature of RAS, several new studies have been published that warrant a comprehensive review with a robust methodological approach to evaluate clinical outcomes.

This systematic review aims to provide a comprehensive summary and evaluation of the literature that has investigated the application of RAS in plastic and reconstructive surgery.

2 | MATERIAL AND METHODS

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were adhered to in conducting this systematic review. The protocol was published a priori on PROSPERO (CRD42024507420).

2.1 | Data sources and searches

EMBASE, MEDLINE and Google Scholar were searched from inception to 15 September 2023. Additional articles were identified from the references of the reviewed articles. The complete search strategies are available in Digital Content 1. Cross references of the included articles were also used to extract further relevant articles. Only articles written in English were considered.

2.2 | Study selection

Studies with a patient population undergoing robotic assisted plastic surgery for various indications were considered for inclusion. Comparison groups included conventional nonrobotic surgical approaches, and outcomes of interest included procedural success, procedural duration and incidence of adverse events and complications.

Pre-clinical and clinic studies were eligible for inclusion. Clinical studies include RCTs, prospective studies, retrospective studies, case-series, and case studies. Patients of all ages who underwent RAS in plastic and reconstructive surgery were included. The exclusion criteria were studies investigating the application of robot assisted surgery in other surgical disciplines. The abstracts were initially screened by four authors: AM, JB, HI and MO. The shortlisted studies underwent further screening by the same four independent authors based on full texts. Discrepancies between the authors were resolved by reading the full text and involving the senior author, AK.

2.3 | Outcomes

The primary outcome was procedural success in participants of the included clinical studies. Secondary outcomes included incidence of peri-operative adverse events and complications, procedural duration, anastomotic patency, anastomosis time, harvest time, and patient-related outcomes measures (PROM).

2.4 | Data collection and analysis

Four reviewers (AM, JB, HI, MO) independently extracted data from the included studies. Study characteristics included authors, year of study, country of study, study methodology, sample size, surgical procedure, specific robotic system utilised, and treatment arms. Patient demographics that were collated included age, gender, body-mass index, and comorbid burden. Surgical specific details included a category of procedure, specific operation, clinical indication, procedural methodology and steps, anatomical contour and specific robotic system utilised. Outcome data included procedural success, incidence of adverse events, robot docking time, anastomosis time, anastomotic patency, harvest time, surgical time, duration of follow-up, and PROM data. Any discrepancies between the reviewers were



resolved by consensus with a fifth reviewer. Grading of Recommendations, Assessment, Development and Evaluation (GRADE) was utilised to assess study quality.

2.5 | Risk of bias in individual studies

Risk of bias was assessed by two reviewers (YW and AM). Discrepancies between the reviewers at different stages of the review were resolved by consensus with the senior author AK. Randomised control trials were evaluated with Version 2 of the Cochrane risk of bias tool for randomised trials (RoB2)¹⁴ while non-randomised trials were evaluated with the ROBINS-I tool.¹⁵ The quality of the included case reports was assessed using the Joanna Briggs Institute Critical Appraisal Checklist for Case Reports, which consists of eight yes/no/unclear questions.¹⁶ The quality of the included case series was assessed using the Joanna Briggs Institute Critical Appraisal Checklist for Case Series, which consists of ten yes/no/unclear questions.¹⁶

To summarise the overall quality of case reports and case series, the studies were grouped into the following categories: low risk of bias (studies that satisfied at least 75% of the quality criteria), moderate risk of bias (studies that satisfied between 50% and 74% of the quality criteria), and high risk of bias (studies that satisfied under 50% of the quality criteria).

3 | RESULTS

3.1 | Study characteristics

The search retrieved 132 potentially relevant references. The following title and abstract reviews, 102 studies were eligible and included for full-text assessment with a cumulative sample size of 239 patients. Of the remaining full-text articles, 58 were excluded for the reasons outlined in Figure 1 with a residual 44 studies included for data extraction.^{17–60} The number of pre-clinical and clinical studies was 10(20, 35–37, 39, 42, 47, 51, 55, 57) and 34(17–19, 21–34, 38, 40, 41, 43–46, 48–50, 52–54, 56, 58–60), respectively. Of the clinical studies, there were two RCTs,^{58,59} one prospective study,⁵² eight retrospective studies,^{18,21,28,30,33,38,46,53} eleven case series,^{17,19,22,25,26,40,41,43,49,50,60} and twelve case reports.^{23,24,27,29,31,32,34,44,45,48,54,56} Characteristics of the included studies are provided in Tables 1 and 2. A total of six studies compared three treatment arms^{26,35,37,41,53,57} while the number of double and single arm studies were 18(17–19, 21, 23, 28, 30, 38, 42, 43, 47, 50, 51, 54, 55, 58, 59) and 20(22, 24, 25, 27, 29, 31–34, 36, 39, 40, 44–46, 48, 49, 52, 56, 60), respectively. The surgical procedures of the respective studies were subcategorised in to microvascular surgery,^{20,21,23,30,34–36,38,54,55,57} flap harvest surgery,^{19,22,25–29,32,42,44–46,50,52} trans-oral robotic surgery,^{18,31,33,37,38,47,49,53} nerve surgery,^{24,43,48} lymphatic surgery,^{41,58–60} and miscellaneous procedures.^{17,39,40,51,56}

The overall quality of the studies using the GRADE approach was moderate. Of the included case reports, four studies each demonstrated low risk,^{24,32,44,56} moderate risk^{23,29,34,45} and high risk.^{27,31,48,54} From the case studies, 4 studies^{17,22,25,41} and 7 studies^{19,26,40,43,49,50,60} demonstrated moderate and high risk, respectively. Of the included retrospective studies, 2 studies^{28,38} and 6 studies^{18,21,30,33,46,53} demonstrated moderate and high risk, respectively.

3.2 | Microvascular surgery

Eleven studies^{20,21,23,30,34–36,38,54,55,57} evaluated the role of robotics in microvascular plastic and reconstructive surgery (Table 3). Five^{20,35,36,55,57} and six^{21,23,30,34,38,54} of the included studies were preclinical and clinical studies, respectively. Of the clinical studies, there were 3 case reports^{23,34,54} and 3 retrospective studies,^{21,30,38} respectively. Robotic systems used include the da Vinci Surgical System (Intuitive Surgical),^{36,38,54} the Symani Surgical System (Medical Microinstruments, S.p.A, Calci),^{20,21,34} the MicroSure Robot ((TuE) (Maastricht University Medical Centre),^{55,57} RoboticScope® (BHS Technologies®),^{23,30} and the Computer Motion Zeus Robotic Surgical System (Computer Motion, Inc).³⁵

From pre-clinical studies, the anastomotic patency was typically ranging from 90%–100%^{35,36,55,57} although one study reported a patency of 75% for femoral artery anastomosis in a rat model.⁵⁷ The anastomosis time with RAS ranged from 11 to 40 min^{20,36,55,57} while one pre-clinical study reported a robot setup time of 33.7 min. The manual anastomosis time was less than the robotic cohort.^{20,55,57}

For case-reports, the surgical anatomical targets for anastomosis included the deep inferior epigastric vein with mammary vein,⁵⁴ the superior thyroid artery with radial artery,²³ and ALT flap perforator vessels with medial tarsal artery and vein.³⁴ The 3 studies reported procedural success while the reported arterial anastomosis time for two studies was approximately 22 min^{23,34} and the venous anastomosis time ranged from 11 to 32 min^{23,34}. There were no reported adverse outcomes and complications with a mean follow up of 7–10 months noted.

For retrospective studies, the surgical anatomical targets for anastomosis included the comitant vein/left radial artery to superior thyroid veins/branches of the right external jugular veins/facial vein, vessels involving breast reconstruction with deep inferior epigastric perforators (DIEP) or PAP flap, and omental lymphatic tissue flap perforator to posterior tibial artery. Anastomotic patency was reported to be 100%³⁸ with the anastomotic time ranging from 25 to 38 min^{21,30,38}. The manual anastomotic time for all the control populations was less than the robotic cohorts. The incidence of adverse events in the robotic cohorts ranged from 0% to 6.7% with one case of a thrombosis during breast reconstruction that was likely due to the holding of the vessel lumen with a dilator resulting in uncontrolled force application and subsequent intimal damage.²¹ Another adverse event was the development of a haematoma post-operatively due to

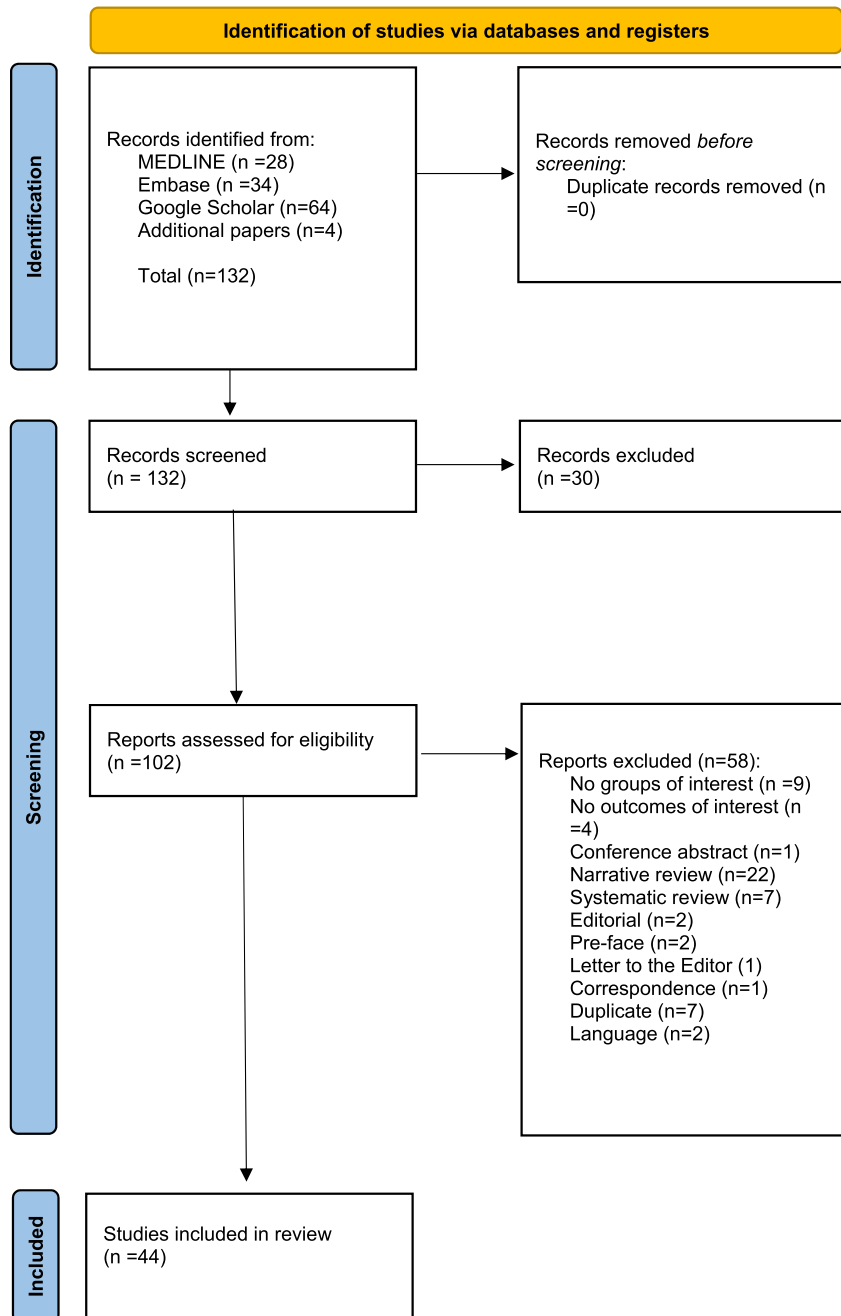


FIGURE 1 PRISMA flowchart for identification of studies.

abrupt hypertension, which was subsequently treated with a haematoma removal that confirmed flap survival.³⁸

3.3 | Flap harvest

Fourteen studies reported outcomes of RAS in the process of flap harvesting for reconstruction (Table 4). Of the included literatures, six^{27,29,32,42,44,45} and eight^{19,22,25,26,28,46,50,52} studies were pre-clinical and clinical studies, respectively. The da Vinci® system was utilised in majority of the studies^{25-29,32,42,44-46,50,52} while the robotic system used in the remaining two studies was unspecified. The

harvested flaps included DIEP,^{22,25,32,42} omentum,^{29,44} right gastro-epiploic lymph node (RGE-LNF),²⁷ pedicled myocutaneous latissimus dorsi,^{45,50} rectus abdominis,^{19,46} and latissimus dorsi^{26,28,52} for which they were used for the purposes of autologous breast reconstruction,^{22,26,28,32,42,50,52} near total anterior chest wall coverage,²⁹ distal pretibial coverage,⁴⁴ lymphedematous recipient coverage site,²⁷ shoulder reconstruction,⁴⁵ pelvic surgery,^{19,46} chest wall deformity,²⁶ scalp reconstruction,⁵⁰ lower extremity free coverage.⁴⁶

For the pre-clinical cadaveric study,⁴² trans-abdominal preperitoneal (TAPP) robotic assisted DIEP flap harvest had a shorter harvest time than the total extraperitoneal (TEP) approach (56.4 ± 8.60 vs. 65.4 ± 8.10 , $p = 0.049$) and a greater number of



TABLE 1 Descriptive characteristics of studies.

Study	Year	Country	Study methodology	Sample size	Age (Mean ± SD)	Category of procedure	Specific robot	Intervention arm 1	Intervention arm 2	Intervention arm 3
Pre-clinical studies										
Lei et al. ³⁹	2023	China	Feasibility study	5—model experiments on CT data of 5 children + 3 Bama minipigs	N/A	Miscellaneous—Craniofacial	Craniofacial plastic surgery robot (Universal robots, Odense, Denmark).	Craniofacial plastic surgery robot	N/A	N/A
Ballestin et al. ²⁰	2022	France	Preclinical study	40	N/A	Microvascular surgery	The symani surgical system (medical microinstruments, S.p.A, Calci, Pisa, Italy)	Robotic	Manual	N/A
Manrique et al. ⁴²	2020	USA	Cadaveric feasibility study	8 Cadavers (16 hemi DIEP flaps)	N/A	Flap harvest	The da Vinci Xi surgical system (intuitive surgical, sunnyvale, Calif.)	Robotic-assisted DIEP flap harvest for autologous breast reconstruction—trans- abdominal preperitoneal (TAPP)	Robotic-assisted DIEP flap harvest for autologous breast reconstruction—totally extraperitoneal (TEP)	N/A
Van Mulken et al. ⁵⁵	2018	USA	Feasibility study	60 (3 × (10 + 10))	N/A	Microvascular surgery	MicroSure robot (TuE, Eindhoven, The Netherlands) + (Maastricht University medical Centre) (Maastricht, The Netherlands)	Robot assisted anastomosis	Conventional (hand) anastomosis	N/A
Van Mulken et al. ³⁶	2018	The Netherlands	In-vitro/animal studies	8 (Wistar rats)	N/A	Microvascular surgery	MicroSure robot (MSR) first generation (GEN-1) (TuE, Eindhoven, The Netherlands) + (Maastricht University Medical Centre) (Maastricht, The Netherlands)	MSR - Aorta	Hand—Aorta	MSR—femoral artery
Podolsky et al. ⁴⁷	2017	Canada	Feasibility study	1	N/A	Trans-oral robotic surgery	Da Vinci (da Vinci S, intuitive surgical, sunnyvale, CA)	Da Vinci (da Vinci S, intuitive surgical, sunnyvale, CA) - Si	Da Vinci (da Vinci S, intuitive surgical, sunnyvale, CA)—Xi	N/A
Shi et al. ⁵¹	2017	Canada	Feasibility study	N/A	N/A	Miscellaneous—Craniofacial	Experimental robot	Experimental robot group	Control group (drilling by hand)	N/A
Khan et al. ³⁷	2016	UK	Cadaveric feasibility study	1	N/A	Trans-oral robotic surgery	Da Vinci (da Vinci S, intuitive surgical, sunnyvale, CA)	Angle of robot in relation to the operating table	The degree of head up or down tilt of the operating table	The endoscope and airway model used
Karamanoukian et al. ⁵³	2006	USA	Animal study/benchmark study	N/A	N/A	Microvascular surgery	Computer motion Zeus robotic surgical system (computer motion, inc, goleta CA, USA)	8-O Prolene -continuous	8-O Prolene -interrupted	Nitinol U clips
Katz et al. ³⁶	2006	USA	Animal study/benchmark study	N/A	N/A	Microvascular surgery	da Vinci surgical system (intuitive surgical, sunnyvale, CA)	Interrupted, end-to-end microvascular anastomosis using 8-0 nylon sutures.	N/A	N/A
Clinical studies										
Schafer et al. ⁴⁸	2023	Germany	Case report	1	16	Nerve surgery	Symani surgical system (medical microinstruments, S.p.A, Calci, Pisa, Italy)	Robotic epineural coaptation	N/A	N/A
Weinzierl et al. ⁶⁰	2023	Switzerland	Case series	8	51.5	Lymphatic surgery	Symani surgical system (medical microinstruments, S.p.A, Calci, Pisa, Italy)	Robot-assisted lymphatic microsurgery for ommental flap transfer to the axilla and lympho-venous anastomosis: Vascularised lymph node transfer (VLNT) to the axilla and lympho-venous anastomosis (LVA)	N/A	N/A

(Continues)



TABLE 1 (Continued)

Study	Year	Country	Study methodology	Sample size	Age (Mean \pm SD)	Category of procedure	Specific robot	Intervention arm 1	Intervention arm 2	Intervention arm 3
Van Mulken et al. ²⁶	2023	The Netherlands	Case report	1	72	Miscellaneous - lower limb surgery	MUSA robot (MicroSure B.V., son, The Netherlands)	2-Stage masquetelet approach - First stage with MUSA robot	N/A	N/A
Bishop et al. ²²	2022	USA	Case series	21	54.6 \pm 7.6	Flap harvest	Unspecified	Robotic harvest of the deep inferior epigastric perforator flap for breast reconstruction	N/A	N/A
Boehm et al. ²³	2022	Germany	Case report	1	N/A	Microvascular surgery	RoboticScope® (BHS Technologies®, Innsbruck, Austria)	Transoral tumour resection, with tissue defect sealed using radial forearm free flap - RoboticScope system used for visualisation and anastomosis	Conventional microscope (reference values for certain outcomes)	N/A
Dermietzel et al. ³⁰	2022	Germany	Retrospective study	10	N/A	Microvascular surgery	RoboticScope® (BHS Technologies®, Innsbruck, Austria)	Autologous breast reconstruction via free tissue transfers with DIEP and PAP flap with a robotic microscope	Conventional operating microscope (Zeiss, Opmi, Vario)	N/A
Innocenti et al. ³⁴	2023	Italy	Case report	1	15	Microvascular surgery	The symani surgical system (medical microinstruments, SpA, Calci, Pisa, Italy)	Robot assisted microsurgical free flap reconstruction using a perforator-to-perforator technique	N/A	N/A
Barbon et al. ²¹	2022	Switzerland	Retrospective study	22	46.1 \pm 19.2	Microvascular, nerve surgery, muscle flap harvest	The symani surgical system (medical microinstruments, SpA, Calci, Pisa, Italy)	Robot-assisted anastomosis	Hand sewn anastomosis	N/A
Shuck et al. ⁵²	2022	USA	Prospective study	15	49.6 \pm 10.3	Flap harvest	The da Vinci surgical system (intuitive surgical, sunnyvale, Calif.)	Robotic latissimus muscle harvest and breast reconstruction	N/A	N/A
Lindenblatt et al. ⁴¹	2022	Switzerland	Case series	5 patients (10 anastomoses)	50.8	Miscellaneous - lymphatic surgery	The symani surgical system (medical microinstruments, SpA, Calci, Pisa, Italy) with Pentero 900 microscope (Carl Zeiss meditec AG, Jena, Germany) or the VITOM 3D system (Karl storz SE & Co. KG, tuttlingen, Germany)	Robotic-assisted lymphatic anastomosis	Robotic-assisted lymphatic anastomosis + robot-assisted arterial anastomosis	Robot-assisted lymphatic anastomosis + conventional anastomosis
Van Mulken et al. ⁵⁹	2022	The Netherlands	RCT	20	N/A	Miscellaneous - lymphatic surgery	The MUSA (MicroSure, Eindhoven, The Netherlands)	Robotic-assisted lymphatic-venous anastomosis	Manual lymphatic-venous anastomosis	N/A
Asaad et al. ¹⁹	2021	USA	Case series	102 (7 robotic, 95 open)	65.9 (robotic group)	Flap harvest	Unspecified	Robotic rectus abdominis muscle flap following robotic Extrirpative surgery	Open rectus abdominis muscle harvest	N/A
Chang et al. ²⁴	2021	Taiwan	Case report	1	59	Nerve surgery	The da Vinci Xi surgical system (intuitive surgical, sunnyvale, Calif.)	Bilateral sympathetic trunk reversal reconstruction with an interpositional sural nerve graft	N/A	N/A
Choi et al. ²⁵	2021	South Korea	Case series	17	N/A	Flap harvest	The da Vinci SP (intuitive surgical, sunnyvale, Calif.)	Robotic DIEP flap harvest through a totally extraperitoneal approach	N/A	N/A
Day et al. ²⁹	2021	USA	Case report	1	68	Flap harvest	The da Vinci system (intuitive surgical, Sunnyvale, California, USA)	Robotic epineural coaptation	N/A	N/A



TABLE 1 (Continued)

Study	Year	Country	Study methodology	Sample size	Age (Mean ± SD)	Category of procedure	Specific robot	Intervention arm 1	Intervention arm 2	Intervention arm 3
Lin et al. ⁴⁰	2021	China	Case series	6	22.5 +/- 4.30	Miscellaneous— Craniofacial surgery	CPSP-1 surgical robot (Institute of forming technology & Equipment, Shanghai Jiao Tong University, China)	Robot-assisted lymphatic microsurgery for orontal flap transfer to the axilla and lympho-venous anastomosis; Vascularised lymph node transfer (VLNT) to the axilla and lympho-venous anastomosis (LVA)	N/A	N/A
Van Mulken et al. ⁵⁸	2020	The Netherlands	RCT	20	N/A	Microvascular surgery	MUSA (MicroSure, Eindhoven, The Netherlands)	2-Stage masquetelet approach - First stage with MUSA robot	Manual LVA	N/A
Lai et al. ³⁸	2019	China	Retrospective study	15 patients (17 anastomoses)	59.2 +/- 8.27	Microvascular surgery	Da Vinci (da Vinci S, intuitive surgical, sunnyvale, CA)	Robotic harvest of the deep inferior epigastric perforator flap for breast reconstruction	Hand sewn	N/A
Arora et al. ¹⁸	2018	India	Retrospective study	11	53.1	Trans oral robotic surgery	Da Vinci (da Vinci S, intuitive surgical, sunnyvale, CA)	Transoral tumour resection, with tissue defect sealed using radial forearm free flap	Wide local excision + robotic selective neck dissection (WLE + RSND)	N/A
Ozkan et al. ⁴⁴	2019	Turkey	Case report	1	58	Flap harvest	Da Vinci Xi (da Vinci S, intuitive surgical, sunnyvale, CA)	Autologous breast reconstruction via free tissue transfers with DIEP and PAP flap with a robotic microscope	N/A	N/A
Ahn et al. ¹⁷	2019	South Korea	Case series	4	N/A	Miscellaneous - mastectomy + immediate reconstruction	The da Vinci Xi surgical system (intuitive surgical inc., sunnyvale, CA)	Robot assisted microsurgical free flap reconstruction using a perforator-to-perforator technique	Control group: Age and cancer stage-matched patients who underwent nipple-sparing mastectomy with a conventional method and reconstruction with 2-staged prosthetic reconstruction without a contralateral balancing procedure	N/A
Hatten et al. ³³	2018	USA	Retrospective study	42	57.5	Trans-oral robotic surgery	Da Vinci (da Vinci S, intuitive surgical, sunnyvale, CA)	Robot-assisted anastomosis	N/A	N/A
Gundlapalli et al. ³²	2018	USA	Case report	1	55	Flap harvest	Da Vinci (da Vinci S, intuitive surgical, sunnyvale, CA)	Robotic latissimus muscle harvest and breast reconstruction	N/A	N/A
Ciudad et al. ²⁷	2016	Taiwan	Case report	1	55	Flap harvest	Da Vinci (da Vinci S, intuitive surgical, sunnyvale, CA)	Robotic-assisted lymphatic anastomosis	N/A	N/A
Chung et al. ²⁶	2015	South Korea	Case series	12	35.8	Flap harvest	Da Vinci (da Vinci S, intuitive surgical, sunnyvale, CA)	Robotic-assisted lymphatico-venous anastomosis	Immediate reconstruction (nipple sparing mastectomy, breast conserving surgery)	Chest wall deformity correction surgery
Clemens et al. ²⁸	2014	USA	Retrospective study	12	54.3	Flap harvest	da Vinci Surgical system (intuitive surgical, inc, sunnyvale, US)	Robotic rectus abdominis muscle flap following robotic Extrirpative surgery	Traditional open technique (TOT)	N/A
Pedersen et al. ⁴⁶	2014	USA	Retrospective study	10	Patient 1—30 years old Patient 2—62 years old Patient 3—10 - unspecified	Flap harvest	da Vinci Surgical system (intuitive surgical, inc, sunnyvale, US)	Bilateral sympathetic trunk reversal reconstruction with an interpositional sural nerve graft	N/A	N/A

(Continues)



TABLE 1 (Continued)

Study	Year	Country	Study methodology	Sample size	Age (Mean \pm SD)	Category of procedure	Specific robot	Intervention arm 1	Intervention arm 2	Intervention arm 3
Song et al. ⁵³	2013	South Korea	Retrospective study	5	55	Free flap reconstruction + Oropharyngeal surgery + transoral robotic surgery + microvascular surgery	da Vinci Surgical system (intuitive surgical, inc, sunnyvale, US)	Robotic DIEP flap harvest through a totally extraperitoneal approach	TORS + CND + RFFF + flap inseting (robotic procedure in reconstruction)	TORS + RAND + ALT free flap + flap inseting (robotic procedure in reconstruction)
Naito et al. ⁴³	2012	France	Case series	4	31.3	Nerve surgery + upper limb surgery	da Vinci Surgical system (intuitive surgical, inc, sunnyvale, US)	Robotic omental flap harvest for near-total anterior chest wall coverage	Elbow flexion restoration - Oberlin procedure - technique 2 (min-invasive)	N/A
Patel et al. ⁴⁵	2012	USA	Case report	1	55	Flap harvest	da Vinci Surgical system (intuitive surgical, inc, sunnyvale, US)	Robot assisted genioplasty	N/A	N/A
Selber et al. ⁵⁰	2012	USA	Case series	8	N/A	Flap harvest	da Vinci Surgical system (intuitive surgical, inc, sunnyvale, US)	Robot-assisted LVA	Clinical series	N/A
Garfein et al. ³¹	2011	USA	Case report	1	66	Transoral robotic reconstructive surgery + microvascular component (anastomoses) performed with robot	da Vinci Surgical system (intuitive surgical, inc, sunnyvale, US)	da Vinci surgical system	N/A	N/A
Selber et al. ⁴⁹	2010	USA	Case series	5	70.8	Transoral robotic surgery + microvascular surgery	da Vinci Surgical system (intuitive surgical, inc, sunnyvale, US)	Transoral robotic surgery (TORS) \pm traditional neck dissection	N/A	N/A
van der Hulst et al. ⁵⁴	2007	The Netherlands	Case report	1	58	Microvascular surgery	da Vinci Surgical system (intuitive surgical, inc, sunnyvale, US)	Robot assisted omental flap harvest	Standard technique (referred to in manuscript - population not specified)	N/A

Abbreviations: ALT, anterolateral thigh; CND, central neck dissection; DIEP, deep inferior epigastric perforators; LVA, lympho-venous anastomosis; MSR, microSure robot; N/A, not applicable/available; PAP, profunda artery perforator; RAND, robot-assisted neck dissection; RFFF, radial forearm free flap; SD, standard deviation; TAPP, trans-abdominal preperitoneal; TEP, totally extraperitoneal; TORS, transoral robotic surgery; TOT, traditional open technique; VLNT, vascularised lymph node transfer; WLE + RSND, wide local excision + robotic selective neck dissection.



TABLE 2 Patient demographics in clinical studies.

Study	Category of procedure	Operation	Anatomical contour	Intervention 1				Intervention 2				Intervention 3			
				Intervention 1	Sample size	Age	Gender (male prevalence (0))	Intervention	Sample size	Age	Gender (male prevalence (0))	Intervention	Sample size	Age	Gender (male prevalence (0))
Case reports															
Schafer et al. ⁴⁸	Nerve surgery	Epineural coaptation of 3 donor nerves (intercostal nerves 4–6) to the long thoracic nerve and the thoracodorsal nerve as recipient nerves	Brachial plexus	Robotic epineural coaptation	1	16	0 (0)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Van Mulken et al. ⁵⁵	Miscellaneous - lower limb surgery	2-Stage masquetelet approach First operation is debridement of all infected and necrotic tissue to result in clean cavity and then temporarily fill with a cement block and cover with vascularised soft tissue coverage Second part is removal of the cement spacer and filling of the cavity with the bone graft that surrounded by the well-vascularised membrane and soft tissue envelope	Harvest: Anterolateral thigh Transfer: Tibia	2-Stage masquetelet approach First stage with MUSA robot	1	72	1 (100)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Boehm et al. ²³	Microvascular surgery	Transoral tumour resection, with tissue defect sealed using radial forearm free flap - RoboticScope system used for visualisation and anastomosis	Anastomosis - superior thyroid artery and radial artery	Transoral tumour resection, with tissue defect sealed using radial forearm free flap–RoboticScope system used for visualisation and anastomosis	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Innocenti et al. ³⁴	Microvascular surgery	Robot assisted microsurgical free flap reconstruction using a perforator-to-perforator technique	Harvest: Anterolateral thigh Transfer: Right foot	Robot assisted microsurgical free flap reconstruction using a perforator-to-perforator technique	1	15	0 (0)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Chang et al. ²⁴	Nerve surgery	Bilateral sympathetic trunk reversal reconstruction with an interpositional sural nerve graft	Harvest: Sural nerve Transfer: Thoracic cavity	Bilateral sympathetic trunk reversal reconstruction with an interpositional sural nerve graft	1	59	0 (0)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Day et al. ²⁹	Flap harvest	Robotic omental flap harvest for near-total anterior chest wall coverage	Harvest: Omentum Transfer: Chest wall	Robotic omental flap harvest for near-total anterior chest wall coverage	1	68	0 (0)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Ozkan et al. ⁴⁴	Flap harvest	Robot assisted omental flap harvest	Harvest: Omental flap Transfer: Distal pretibial region	Robot assisted omental flap harvest	1	58	1 (100)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Gundlapalli et al. ³²	Flap harvest	Robotic-assisted deep inferior epigastric artery perforator flap abdominal harvest for autologous breast reconstruction	Harvest: Deep inferior epigastric artery Transfer: Breast	Robotic-assisted deep inferior epigastric artery perforator flap abdominal harvest for breast reconstruction	1	55	0 (0)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Ciudad et al. ²⁷	Flap harvest	Robotic harvest of a right Gastroepiploic lymph node flap (RGE-LNF)	Harvest: Right gastroepiploic lymph node Transfer:	Robotic harvest of a right gastroepiploic lymph node flap	1	55	0 (0)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

(Continues)

(Continues)



TABLE 2 (Continued)

Study	Category of procedure	Operation	Anatomical contour	Intervention 1				Intervention 2				Intervention 3			
				Intervention 1	Sample size	Age	Gender (male prevalence (0))	Intervention	Sample size	Age	Gender (male prevalence (0))	Intervention	Sample size	Age	Gender (male prevalence (0))
Patel et al. ⁴⁵	Flap harvest	Harvest of a pedicled myocutaneous latissimus dorsi flap (robotic component) and subsequent shoulder reconstruction following sarcoma resection	Lymphoedematous recipient site - ankle level	Harvest of a pedicled myocutaneous latissimus dorsi flap (robotic component) and subsequent shoulder reconstruction following sarcoma resection	1	55	1 (100)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
				Transoral robotic reconstructive surgery - surgical debridement of the necrotic tissue and bone - microvascular component (anastomoses) performed with robot	1	66	1 (100)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Garfein et al. ⁵¹	1. Transoral robotic reconstructive surgery + microvascular component (anastomoses) performed with robot	Transoral robotic reconstructive surgery - surgical debridement of the necrotic tissue and bone - microvascular component (anastomoses) performed with robot	Oropharyngeal	Transoral robotic reconstructive surgery - surgical debridement of the necrotic tissue and bone - microvascular component (anastomoses) performed with robot	1	66	1 (100)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
van der Hulst et al. ⁵⁴	Microvascular surgery	Breast reconstruction with muscle sparing free TRAM-flap—robot utilised for arterial adventectomy and anastomosis	Mammary vessel	Arterial adventectomy and anastomosis was performed using 9/0 nylon sutures	1	58	0 (0)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Case series	Lymphatic surgery	Robot-assisted lymphatic microsurgery for omental flap transfer to the axilla and lympho-venous anastomosis: Vascularised lymph node transfer (VLNT) to the axilla and lympho-venous anastomosis (LVA)	Harvest: Omentum Transfer: Axilla	*Robot-assisted lymphatic microsurgery for omental flap transfer to the axilla and lympho-venous anastomosis: Vascularised lymph node transfer (VLNT) to the axilla and lympho-venous anastomosis (LVA)*	8	51.5	0 (0)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
				Robotic harvest of the deep inferior epigastric perforator flap for breast reconstruction	21	54.6 +/- 7.6	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Bishop et al. ²²	Flap harvest	Robotic harvest of the deep inferior epigastric perforator flap for breast reconstruction	Harvest: Deep inferior epigastric artery perforator	Robotic harvest of the deep inferior epigastric perforator flap for breast reconstruction	2	57	N/A	Robot-assisted lymphatic anastomosis + robot-assisted arterial anastomosis	1	57	N/A	Robot-assisted lymphatic anastomosis + robot-assisted arterial anastomosis	1	34	N/A
Lindenblatt et al. ⁴¹	Miscellaneous - lymphatic surgery	1. Patient	Groin lower limb	Robotic lymphatic reconstruction surgery:	2	57	N/A	Robot-assisted lymphatic anastomosis	1	57	N/A	Robot-assisted lymphatic anastomosis + robot-assisted arterial anastomosis	1	34	N/A
		2. 2 × Lymphovenous anastomosis, vascularised lymph node transfer from right axilla to right groin		Robotic lymphatic reconstruction surgery:	2	57	N/A	Robot-assisted lymphatic anastomosis	1	57	N/A	Robot-assisted lymphatic anastomosis + robot-assisted arterial anastomosis	1	34	N/A
		3. 9 × lymphovenous anastomosis		Robotic lymphatic reconstruction surgery:	2	57	N/A	Robot-assisted lymphatic anastomosis	1	57	N/A	Robot-assisted lymphatic anastomosis + robot-assisted arterial anastomosis	1	34	N/A
		4. 2 × lymphovenous anastomosis, vascularised lymph node transfer from left axilla to right groin		Robotic lymphatic reconstruction surgery:	2	57	N/A	Robot-assisted lymphatic anastomosis	1	57	N/A	Robot-assisted lymphatic anastomosis + robot-assisted arterial anastomosis	1	34	N/A
		5. Tumour resection, lympho-		Robotic lymphatic reconstruction surgery:	2	57	N/A	Robot-assisted lymphatic anastomosis	1	57	N/A	Robot-assisted lymphatic anastomosis + robot-assisted arterial anastomosis	1	34	N/A



TABLE 2 (Continued)

Study	Category of procedure	Operation	Anatomical contour	Intervention 1				Intervention 2				Intervention 3			
				Intervention 1	Sample size	Age	Gender (male prevalence (0))	Intervention	Sample size	Age	Gender (male prevalence (0))	Intervention	Sample size	Age	Gender (male prevalence (0))
Asaad et al. ¹⁹	Flap harvest	lymphatic anastomosis and microscopical lymphatic ligation	Harvest: Rectus abdominis Transfer: Pelvis	Robotic rectus abdominis muscle flap following robotic Extrinsic surgery	7	65.9	7 (100)	Open rectus abdominis muscle harvest (comparator cohort—No specifics mentioned aside from outcomes)	95	N/A	N/A	N/A	N/A	N/A	N/A
		6. Tumour resection, turn-over superficial circumflex iliac perforator flap, lymphovenous anastomosis and microscopical lymphatic ligation													
Choi et al. ²⁵	Flap harvest	Robotic DIEP flap harvest through a totally extraperitoneal approach—single port	Harvest: Deep inferior epigastric artery perforator	Robotic DIEP flap harvest through a totally extraperitoneal approach	17	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lin et al. ⁴⁰	Miscellaneous—Craniofacial surgery	Robot assisted genioplasty	Mandible	Robot assisted genioplasty	6	22.5 +/- 4.30	1 (16.7)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Ahn et al. ¹⁷	Miscellaneous—mastectomy + immediate reconstruction	Robot-assisted nipple-sparing mastectomy and immediate reconstruction using expanders	Breast	Robot-assisted nipple-sparing mastectomy and immediate reconstruction using expanders	4	N/A	0 (0)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Chung et al. ²⁶	Flap harvest	Robot assisted latissimus dorsi muscle flap using transaxillary gasless technique associated with the following procedures: 3 cases: Delayed reconstruction following tissue expander insertion or breast conserving surgery, with a mastectomy scar on the inferolateral border of the breast 4 cases: Immediate reconstruction following nipple sparing mastectomy, with a mastectomy incision on the lateral side of the breast 5 cases: Chest wall deformity correction surgery in patients with Poland syndrome	Harvest: Latissimus dorsi Transfer: Breast and chest wall	Delayed reconstruction following tissue expander insertion (breast conserving surgery, capsular contracture)	3	49	0 (0%)	Immediate reconstruction (nipple sparing mastectomy, breast conserving surgery)	4	40.3	0 (0%)	Chest wall deformity correction surgery	5	24.2	4 (80%)
Naito et al. ⁴³	Nerve surgery + upper limb surgery	Elbow flexion restoration—Oberlin procedure—technique 1	Elbow	Elbow flexion restoration—Oberlin procedure - technique 1	3	33	N/A	Elbow flexion restoration—	1	26	N/A	N/A	N/A	N/A	N/A

(Continues)



TABLE 2 (Continued)

Study	Category of procedure	Operation	Anatomical contour	Intervention 1				Intervention 2				Intervention 3			
				Intervention 1	Sample size	Age	Gender (male prevalence (0))	Intervention	Sample size	Age	Gender (male prevalence (0))	Intervention	Sample size	Age	Gender (male prevalence (0))
Arora et al. ¹⁸	Trans oral robotic surgery	free flap construction following tumour extirpation		free flap reconstruction											
		(1) Transoral robotic surgery (TORS) ± traditional neck dissection (9)	Harvest: Free arm radial artery forearm, rectus femoris, anterolateral thigh flap	Transoral robotic surgery ± traditional neck dissection	9	55.1	9 (100%)	Wide local excision + robotic selective neck dissection (WLE + RSND)	2	44	2 (100)	N/A	N/A	N/A	N/A
		(2) Wide local excision + robotic selective neck dissection (WLE + RSND) (2)	Transfer: Oral cavity, neck												
Hatten et al. ³³	Trans-oral robotic surgery	(3) All patients required free-flap reconstruction for the residual defects following tumour resection													
		Trans-oral robotic surgery (TORS) resection with lateral pharyngotomy followed by microvascular reconstruction	Head and neck	Trans-oral robotic surgery (TORS) resection with lateral pharyngotomy followed by microvascular reconstruction	42	57.5	35 (83.3)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Clemens et al. ²⁸	Flap harvest	Robotic-assisted latissimus dorsi harvest (RALDH)	Harvest—latissimus dorsi	RALDH	12	54.3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pedersen et al. ⁴⁶	Flap harvest	Robotic, intraperitoneal harvest of the rectus abdominis muscle 4 of the harvested muscles used as free flaps for lower extremity 6 of the harvested muscles used as pedicled flaps in minimally invasive pelvic surgery requiring soft tissue reconstruction	Harvest: Rectus abdominis muscle Transfer: Lower extremity free flaps (4) and pelvis (6)	Robotic, intraperitoneal harvest of the rectus abdominis muscle	10	Patient 1—30 years old Patient 2—62 years old Patient 3—10 - unspecified	Patient 1 - F Patient 2 - M Patient 3 - 10 - unspecified	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		1. Conventional wide excision (CWE) + robotic assisted neck dissection (RAND) + radial forearm free flap (RFFF)	Head and neck	CWE + RAND + RFFF	2	51.5	0 (0)	TORS + CND + RFFF + flap inseting (robotic procedure in reconstruction)	1	50	0 (0)	TORS + RAND + ALT free flap + flap inseting (robotic procedure in reconstruction)	1	68	1 (100)
Song et al. ^{53*}	Free flap reconstruction + Oropharyngeal surgery + transoral robotic surgery + microvascular surgery	2. Conventional wide excision (CWE) + robotic assisted neck dissection (RAND) + radial forearm free flap (RFFF)													
		3. Transoral robotic surgery (TORS) + conventional neck dissection (CND) + radial													

(Continues)



TABLE 2 (Continued)

Study	Category of procedure	Operation	Anatomical contour	Intervention 1				Intervention 2				Intervention 3			
				Intervention 1	Sample size	Age	Gender (male prevalence (0))	Intervention	Sample size	Age	Gender (male prevalence (0))	Intervention	Sample size	Age	Gender (male prevalence (0))
		forearm free flap (RFFF) + flap insetting (robotic procedure in reconstruction)													
		4. Transoral robotic surgery (TORS) + robotic assisted neck dissection + anterolateral thigh free flap (ALT) + flap insetting (robotic procedure in reconstruction)													
		5. Transoral robotic surgery + robotic assisted neck dissection + right forearm free flap + flap insetting and microanastomosis (robotic procedure in reconstruction)													
Prospective study															
Shuck et al. ⁵²	Flap harvest	Robotic latissimus muscle harvest and breast reconstruction	Harvest: Latissimus dorsi Transfer: Breast	Robotic latissimus muscle harvest and breast reconstruction	15	49.6 +/- 10.3	0 (0)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Randomised controlled trials															
Van Mulken et al. ²⁰²² ⁵⁹	Lymphatic surgery	Robotic-assisted lymphatico-venous anastomosis (LVA)	Pre-determined sites assessed from NIRF lymphography	Robot-assisted LVA	8	58 (52.8–69.3)	0 (0)	Manual LVA	12	59.5 (55.5–66.0)	0 (0)	N/A	N/A	N/A	N/A
Van Mulken et al. ²⁰²⁰ ⁵⁸	Lymphatic surgery	Robot assisted lymphatico-venous anastomosis (LVA)	Pre-determined sites assessed from NIRF lymphography	Robot-assisted LVA	8	60 +/- 11	0 (0)	Manual LVA	12	60 +/- 7	0 (0)	N/A	N/A	N/A	N/A

Abbreviations: ALT, anterolateral thigh.; ALT, anterolateral thigh; CND, central neck dissection; CND, central neck dissection; CWE, conventional wide excision; DIEP, deep inferior epigastric perforators; LVA, lympho-venous anastomosis; N/A, not applicable/available; PAP, profunda artery perforator; RALDH, robotic-assisted latissimus dorsi harvest; RAND, robot-assisted neck dissection; RAND, robot-assisted neck dissection; RFF, radial forearm free flap; RFF, radial forearm free flap; RGE-LNF, robotic harvest of a right gastroepiploic lymph node flap; TORS, transoral robotic surgery; TOT, traditional open technique; VLNT, vascularised lymph node transfer.



intraabdominal content manipulation (2 (25%) vs. 0 (0), $p < 0.05$), while both approaches had an adverse event each. The TAPP approach observed intestinal injury, whereas the TEP approach necessitated a conversion to the open conventional approach due to violation of the peritoneum.

For the case reports, all studies demonstrated feasibility and procedural success,^{27,29,32,44,45} while only one adverse event was noted. This was a sloughing of the skin graft on the left lateral chest wall that was successfully treated with gauze application and topical antibiotics.²⁹ Flap harvest time was reported at a range of 55–60 min.^{27,44}

For the case series,^{19,22,25,26,50} all studies demonstrated procedural success with no conversions to the open approach. The incidence of perioperative adverse events (16–24 weeks F/U) ranged from 0% to 31%^{19,22,50} and included infection,²² ureteral anastomotic leak,¹⁹ pelvic abscess,¹⁹ and hernia recurrence.¹⁹ No donor site complications were reported.¹⁹

For the retrospective studies,^{28,46} both studies demonstrated procedural success with no conversions to the open approach. The robotic harvest time ranged from 45 to 92 min, which was higher than the control/non-robotic approach. The incidence of perioperative adverse events ranged from 10% to 16.7% with surgical complications including the development of a seroma (8.3%), infection (14.1%), unplanned reoperation (8.3%), and a stage I decubitus ulcer (10%).

The overall incidence of adverse events was lower than the control/non-robotic approach.

One prospective study⁵² was conducted and reported complete procedural success with a procedural duration of 300.3 ± 82.2 min and an improvement in the QuickDASH score at 36 weeks of follow-up (-31.8 (41.7 to 18.2), $p < 0.05$). The incidence of adverse events was 33.3% with one case of a donor site seroma/haematoma and 4 cases where drain insertion was required.

3.4 | Trans-oral robotic surgery

Eight studies reported outcomes of RAS in transoral plastic and reconstructive surgery (Table 5). Two^{37,47} and six^{18,31,33,38,49,53} of the included studies were pre-clinical and clinical studies, respectively. The da Vinci® system was utilised for the entirety of the studies.

For the pre-clinical studies, Khan et al. focused on the optimum angle of the robot and operating table along with the endoscope³⁷ while Podolsky et al. evaluated the number of intra-operative arm repositioning, instrument-instrument collisions, and instrumental-oral aperture collisions when comparing the da Vinci® Si system to the da Vinci® Xi system.⁴⁷ Khan et al. recommended the following: robotic base unit parallel to the operating table, the head down tilt of the operating table at 10° from neutral, and zero-degree endoscope. Podolsky et al. reported that the Xi system required no arm repositioning and exhibited fewer events of instrument-instrument and instrument-oral aperture collisions while maintaining a similar procedural duration in comparison to the Si system.

For the case report³¹ and case series,⁴⁹ transoral robotic surgery was performed for the treatment of oropharyngeal malignancies. Both studies reported complete procedural success with no perioperative adverse events. For the retrospective studies,^{18,33,38,53} procedural success and feasibility were demonstrated throughout all the studies with the procedural duration ranging from 913 to 1132 min depending on the type of operation performed. The incidence of adverse events ranged from 0% to 21%.

3.5 | Nerve surgery

Three clinical studies^{24,43,48} evaluated the outcomes of RAS in nerve associated plastic and reconstructive surgery (Table S3). All three studies were of anecdotal evidence comprising 2 case reports^{24,48} and a case series.⁴³ The da Vinci® system was used for two of the studies^{24,43} while the Symani® system was used for one case.⁴⁸ Schaffer et al. conveyed procedural success for robotic epineural coaptation of 3 intercostal nerves to the long thoracic and thoracodorsal nerves in order to treat a brachial plexus palsy.⁴⁸ Chang et al. also reported procedural success and improvement in PROMS for a bilateral sympathetic trunk reversal reconstruction using an interposition sural nerve graft.²⁴

Naito et al. compared open and minimally invasive RAS for treating elbow flexion deformities and reported complete procedural success of the open cohort, while one case of the minimally invasive approach required a conversion to open due to challenging insufflation secondary to leaks.⁴³ Follow-up of the patients at 12 months confirmed recovery of elbow flexion and absence of sensory-motor deficits in the ulnar nerve territory.

3.6 | Lymphatic surgery

Four clinical studies reported outcomes of RAS in lymphatic based plastic and reconstructive surgery (Table 6). Two^{41,60} of the studies were case series, while the remaining^{58,59} were randomised control trials. Both case series reported complete procedural success and feasibility for robot-assisted lymphatic microsurgery and conveyed 100% patency of the lymphatic anastomosis performed.

The included RCTs^{58,59} compared a robotic assisted approach with a manual approach for lymphaticovenous anastomosis to treat breast-cancer related lymphoedema. Van Mulken et al. (2022) reported a significant improvement in the Lymphoedema Functioning, Disability and Health Questionnaire (Lymph-ICF) at 12 month follow-up (Change: -20 , $p = 0.045$), which was also comparable to the manual cohort (Change: -23 , $p = 0.001$).⁵⁹ Both robotic and manual cohorts also recorded a non-statistically significant improvement in the Upper Extremity Lymphoedema Index at 12 months (Change: $+6.99$, $p = 0.094$ vs. Change: $+7.20$, $p = 0.240$). Van Mulken et al. (2020) reported a higher quality of anastomosis for the robotic cohort in comparison to the manual cohort when assessing with the Structured Assessment of Microsurgery Skills (4.0 ± 0.3 vs. 3.2 ± 0.4 ,



TABLE 3 Robotic application in microvascular surgery.

Study	Intervention	Robot	Anatomical contour	Clinical indication	Follow-up period	Outcome 1	Result 1	Outcome 2	Result 2	Outcome 3	Result 3	Surgical procedure duration/min
Pre-clinical studies												
Karamanoukian et al. (2004)	8-0 Prolene -continuous	Computer motion Zeus robotic surgical system (computer motion, inc, goleta CA., USA)	Coronary artery anastomosis—explanted pig heart	N/A	N/A	Anastomotic patency/%	94%	N/A	N/A	N/A	N/A	N/A
Katz et al. (2006)	8-0 Prolene -interrupted Nitinol U clips	da Vinci surgical system (intuitive surgical, sunnyvale, CA)	Femoral vessel—canine	N/A	N/A	Anastomotic patency (%)	6 (100)	Anastomosis time/min	39.7 min	Robot setup time/min	33.7 min	N/A
Van Mulken et al. (2018)	Interrupted, end-to-end, microvascular anastomosis using 8-0 nylon sutures. Robot assisted anastomosis	MicroSure robot (TuE, Eindhoven, The Netherlands) + (Maastricht University Medical Centre) (Maastricht, The Netherlands)	2-mm-diameter synthetic polyurethane vessels of 3 cm length, which were secured to a foam platform with needles and double-opposing microvascular clamps	N/A	N/A	—	Session 1: 2.3 (1.8–2.5) Session 10: 3.0 (2.8–3.5) Session 1: 2.8 (2.0–3.5) Session 10: 3.6 (3.0–4.0)	Anastomotic leakages (%)	2 (6.67%)	N/A	N/A	Session 1: 119 Session 10: 35.0
Ballestin et al. (2022)	1. Robotic 2. Manual	The symani surgical system (Medical Microinstruments, S.p.A, Calci, Pisa, Italy)	N/A	N/A	N/A	Needle passage test—difference between the entry and exit needle passage/mm	Intervention 1: 0.17 +/- 0.02-mm Intervention 2: 0.22 +/- 0.02-mm p = 0.02	Needle passage test - angle of incidence in needle passage	Intervention 1: 6.37 +/- 0.64 Intervention 2: 10.2 +/- 0.97 p < 0.01	Anastomosis test: Anastomotic time/min	Intervention 1: Novice: 15 +/- 1.18 min Expert: 11 +/- 0.87 min Intervention 2: Novice: 12 +/- 0.25 min Expert: 6.5 +/- 0.58 min p > 0.5	N/A
Van mulken et al. (2018)	MSR—Aorta Hand—Aorta MSR—femoral artery Hand—femoral artery	MicroSure robot (MSR) first generation (GEN-1) (TuE, Eindhoven, The Netherlands) + (Maastricht University medical Centre) (Maastricht, The Netherlands)	Abdominal aorta Femoral artery	N/A	N/A	Anastomosis time/min	69 (53–87) 19 27 (26–29) 12	Anastomotic patency (%)	3 (100) 1 (100) 3 (75) 1 (100)	N/A	N/A N/A N/A N/A	N/A
Clinical studies												
Case report												
van der Hulst et al. (2007)	Robotic-arterial adventectomy and anastomosis was performed using 9/0 nylon sutures Standard technique	da Vinci Surgical system (intuitive surgical, inc, sunnyvale, US)	Anastomosis: Deep inferior epigastric vein Mammary vessel	Precise underlying pathology not specified	N/A	Procedural time	40 min	N/A	N/A	N/A	N/A	40 min
							15 min	N/A	N/A	N/A	N/A	15 min



TABLE 3 (Continued)

Study	Intervention	Robot	Anatomical contour	Clinical indication	Follow-up period	Outcome 1	Result 1	Outcome 2	Result 2	Outcome 3	Result 3	Surgical procedure duration/min
(referred to in manuscript – population not specified)												
Boehm et al. (2022)	Transoral tumour resection, with tissue defect sealed using radial forearm free flap – RoboticScope system used for visualisation and anastomosis	RoboticScope® (BHS Technologies®, Innsbruck, Austria)	Anastomosis – superior thyroid artery and radial artery	Squamous cell carcinoma of the lateral tongue	7 months	Anastomosis time/min	Arterial anastomosis – 22.8 min Venous anastomosis – 32.0 min	Ergonomics/ surgeon posture – rapid Upper limb assessment (RULA)	2 points	Perioperative adverse events (%)	0 (0)	N/A
Innocenti et al. (2022)	Robot assisted microsurgical free flap reconstruction using a perforator-to-perforator technique	The symani surgical system (medical microinstruments, S.p.A. Caldi, Pisa, Italy)	Harvest: Anterolateral thigh Transfer: Right foot ALT flap perforator vessels with medial tarsal artery and vein	Grade III open fracture of the right foot	10 months	Anastomosis time/min	Artery anastomosis – 22 min Venous anastomosis – 11 min	Procedural success (%)	1 (100)	Incidence of adverse outcomes (%)	0 (0)	N/A
Retrospective studies												
Lai et al. (2019)	da Vinci surgical system	Da Vinci (da Vinci S, intuitive surgical, sunnyvale, CA)	Head and neck Radial forearm	Oropharyngeal squamous Cell Ca – 15 (100%)	11.5 +/- 7.6 (3–25) months	Anastomosis time/min	38.4 +/- 10.4	Anastomotic patency (%)	100%	Incidence of vessel related complications (%)	Across both interventions – 1 (6.67%) – haematoma 2 weeks following post op due to abrupt rise in blood pressure and underwent haematoma removal – flap still survived	38.4 +/- 10.4 28.0 +/- 7.7
Dermietzel et al. (2022)	1. Autologous breast reconstruction via free tissue transfer with DIEP and PAP flap with a robotic microscope 2. Conventional operating microscope	RoboticScope® (BHS Technologies®, Innsbruck, Austria)	Breast	N/A	N/A	Anastomosis time/min	Arterial anastomosis: Intervention 1 – 31 +/- 7 min Intervention 2 – 25 +/- 7 min p = 0.30 Venous anastomosis: Intervention 1 –	Total flap ischaemia time/min and incidence of complications (%)	Intervention 1 – 54 +/- 8 min Intervention 2 – 52 +/- 22 min p = 0.87 Intervention 1: 0 (0%) Intervention 2: 0 (0%)	Length of hospital admission/days	Intervention 1: 7 +/- 3 days Intervention 2: 6 +/- 1 day p = 0.24	N/A

(Continues)



TABLE 3 (Continued)

Study	Intervention	Robot	Anatomical contour	Clinical indication	Follow-up period	Outcome 1	Result 1	Outcome 2	Result 2	Outcome 3	Result 3	Surgical procedure duration/ min	
Barbon et al. (2022)	1. Robot-assisted anastomosis	The symani surgical system (medical microinstruments, S.p.A, Calci, Pisa, Italy)	Upper extremity—1 (5)	N/A	N/A	Anastomosis time/min	5 +/- 1 min Intervention 2—4 +/- 3 min p = 0.51 Total anastomosis time: Intervention 1—31 +/- 7 min Intervention 2—25 +/- 7 min p = 0.87	Incidence of adverse events (%)	1 (0.03) —thrombosis on an irradiated vessel of the thorax during breast reconstruction. Procedural evaluation indicated that the thrombosis most likely occurred due to holding the vessel lumen with the dilator resulting in uncontrolled force application and intima damage.	Learning curve among robotic anastomosis— anastomotic time between first robotic group and second robotic group	Intervention 1: First group—23.9 +/- 6.8 min Intervention 2: 16.3 +/- 6.1 min p < 0.05	N/A	
	2. Hand sewn anastomosis		Lower extremity/inguinal region - 17 (77) Genital—1 (5) Face/neck—2 (9) Trunk—1 (5)										
								0 (0)					

Abbreviations: ALT, anterolateral thigh; DIEP, deep inferior epigastric perforators; MSR, microSure robot; N/A, not applicable/available; PAP, profunda artery perforator; RULA, rapid upper limb assessment.



TABLE 4 Robotic application in flap harvest.

Study	Intervention	Robot	Anatomical contour	Clinical indication	Follow-up period	Outcome 1	Result 1	Outcome 2	Result 2	Outcome 3	Result 3	Surgical procedure duration/min
Pre-clinical studies												
Manrique et al. (2020)	1. Robotic-assisted DIEP flap harvest for autologous breast reconstruction—trans- abdominal preperitoneal (TAPP) 2. Robotic-assisted DIEP flap harvest for autologous breast reconstruction—totally extraperitoneal (TEP)	The da Vinci Xi surgical system (intuitive surgical, sunnyvale, Calif)	Harvest—deep inferior epigastric perforators - Cadavers	N/A	N/A	Total harvest time/min	Intervention 1: 56.4 +/- 8.6 Intervention 2: 65.4 +/- 8.1 $p = 0.049$	Intra-abdominal content manipulation (%)	Intervention 1: 2 (25%) Intervention 2: 0 $p < 0.05$	Intra-operative adverse event (%)	Intervention 1: 1 (12.5)—injury to bowel Intervention 2: 1 (12.5)—conversion to conventional open approach to violation of peritoneum	N/A
Clinical studies												
Case reports												
Day et al. (2021)	Robotic omental flap harvest for near-total anterior chest wall coverage	The da Vinci system (intuitive surgical, sunnyvale, California, USA)	Harvest: Omentum Transfer: Chest wall	Recurrence secondary chest wall angiosarcoma	3 months - *succumbed to metastatic disease	Procedural success (%)	1 (100)	Perioperative adverse events (%)	1 (100%) - Sloughing of the skin graft on the left lateral chest wall—treated with gauze and topical antibiotics	N/A	N/A	N/A
Ozkan et al. (2019)	Robot assisted omental flap harvest	The da Vinci Xi system (intuitive surgical, sunnyvale, California, USA)	Harvest: Omental flap Transfer: Distal pretibial region	Patient that has underwent several operations due to Osteomyelitis, demonstrated a non-healing wound in the distal pre-tibial region with a 10 × 12 cm defect.	12 months	Procedural success (%)	1 (100)	Procedural duration/min	150 min (60 min—flap harvesting and 90 min for anastomosis, inset and skin grafting)	Incidence of adverse events(%)	0 (0%)	150 min
Gundlapalli et al. (2018)	Robotic assisted deep inferior epigastric artery perforator flap abdominal harvest for autologous breast reconstruction	The da Vinci system (intuitive surgical, sunnyvale, California, USA)	Harvest: Deep inferior epigastric artery Transfer: Breast	Right sided breast cancer—treated with neoadjuvant chemotherapy, right modified radical mastectomy, and adjuvant radiotherapy - patient presented 3 years following procedure for consideration of delayed autologous	9 months	Procedural success (%)	1 (100)	Incidence of adverse events (%)	0 (0)	N/A	N/A	8 h, 51 min

(Continues)



TABLE 4 (Continued)

Study	Intervention	Robot	Anatomical contour	Clinical indication	Follow-up period	Outcome 1	Result 1	Outcome 2	Result 2	Outcome 3	Result 3	Surgical procedure duration/min
Ciudad et al. (2016)	Robotic harvest of a right gastroepiploic lymph node flap (RGE-LNF)	The da Vinci system (intuitive surgical, sunnyvale, California, USA)	Harvest: Right gastroepiploic lymph node Transfer: Lymphoedematous recipient site - ankle level	Left lower extremity lymphoedema with refractory outcomes to conservative treatment	N/A	Procedural success (%)	1 (100)	Total harvest (time/min)	55	N/A	N/A	N/A
Patel et al. (2012)	Harvest of a pedicled myocutaneous latissimus dorsi flap (robotic component) and subsequent shoulder reconstruction following sarcoma resection	The da Vinci system (intuitive surgical, sunnyvale, California, USA)	Latissimus dorsi	Recurrent leiomyosarcoma of the right shoulder	N/A	Procedural success (%)	1 (100)	N/A	N/A	N/A	N/A	N/A
Case series												
Bishop et al. (2022)	Robotic harvest of the deep inferior epigastric perforator flap for breast reconstruction	Unspecified	Harvest: Deep inferior epigastric artery perforator	N/A	5 months	Conversion from robotic to open harvest (%)	0 (0)	Mean benefit – length of facial incision spared by robotic approach/cm	9.83 +/- 2.28	Incidence of surgical site occurrences (breast wound dehiscence, infection, skin flap necrosis, fat necrosis, in addition to seroma and haematoma) (%)	5 (31)	Unilateral: 425.3 ± 70.1 min Bilateral: 511.3 ± 67.2 min
Choi et al. (2021)	Robotic DIEP flap harvest through a totally extraperitoneal approach	The da Vinci SP (intuitive surgical, sunnyvale, Calif.)	Harvest: Deep inferior epigastric artery perforator	N/A	N/A	Procedure duration/min	487 +/- 93	Harvest duration/min	65 +/- 33	N/A	N/A	487 +/- 93 min
Asaad et al. (2021)	1. Robotic rectus abdominis muscle flap following robotic Extripative surgery 2. Open rectus abdominis muscle harvest	Unspecified	Harvest: Rectus abdominis Transfer: Pelvis	Prostate Ca - 7 (100) Patient 1. Radiation chronic haemorrhagic cystitis and recurrent UTI Patient 2. Recurrent UTI Patient 3. Recurrent UTI, incontinence Patient 4. Pelvic osteomyelitis/pelvic abscess, uro-cutaneous fistula, chronic pelvic pain Patient 5. Prostate Ca. Patient 6. High-	16 +/- 24 months	Number of donor site complications (%)	Intervention 1: 0 (0) Intervention 2: 18 (19) p = 0.35	Number of recipient site complications (%)	Intervention 1: 2 (29) - Ureteral anastomotic leak – treatment with bilateral nephrostomy - no reoperation performed - Pelvis abscess - interventional radiology guided drainage Intervention 2: 24 (25) p = 1.00	Incidence of hernia recurrence (%)	Intervention 1: 1 (7) Intervention 2: 3 (3) p = 0.25	N/A N/A



TABLE 4 (Continued)

Study	Intervention	Robot	Anatomical contour	Clinical indication	Follow-up period	Outcome 1	Result 1	Outcome 2	Result 2	Outcome 3	Result 3	Surgical procedure duration/min
Chung et al. (2015)	1. Delayed reconstruction following tissue expander insertion (breast conserving surgery, capsular contracture) 2. Immediate reconstruction (nipple sparing mastectomy, breast conserving surgery) 3. Chest wall deformity correction surgery	The da Vinci system (intuitive surgical, sunnyvale, California, USA)	Harvest: Latissimus dorsi Transfer: Breast and chest wall	grade prostate sarcoma, prostate-rectal fistula Patient 7: Urethral stricture and necrotic prostate following radiation therapy, chronic pelvic pain 1. Implant based reconstruction following breast surgery (7 patients (58.3%)) 2. Chest wall deformity in patients with Poland syndrome (5 patients (41.7%))	Total average F/U: 15.7 months Intervention 1: 1. 19.7 months Intervention 2: 2. 16.3 months Intervention 3: 3. 12.8 months	Satisfaction - general outcomes	10 9.5 9.8	Satisfaction - scar	9.9 10 9.8	Satisfaction - symmetry	8.67 9.0 9.6	Total average operation time: 400.4 min Intervention 1: 416.7 min Intervention 2: 367.5 min Intervention 3: 417 min
Selber et al. (2012)	Cadaveric latissimus dorsi muscle harvest Clinical series	The da Vinci system (intuitive surgical, sunnyvale, California, USA)	Harvest—latissimus dorsi. Transfer—breast (b) and scalp (2)	1. Latissimus dorsi flap harvest—pedicled flap usage for implant-based breast reconstruction (6 patients) 2. Latissimus dorsi flap harvest—free flap usage for scalp reconstruction (2 patients)	6 months	Procedural success (%)	8 (100%) 8 (100%)—No procedures converted to open	Robotic harvest time/min	N/A 1 h and 51 min	Incidence of adverse events (%)	N/A N/A	N/A

Retrospective studies

Clemens et al. (2014)	Robotic-assisted latissimus dorsi harvest (RALDH)	The da Vinci system (intuitive surgical, sunnyvale, California, USA)	Harvest—latissimus dorsi. Transfer—breast	Invasive ductal carcinoma (85.5%) Invasive lobular carcinoma (14.5%)	Intervention 1: 12.3 months Intervention 2: 16.4 months	Procedural success (%)	12 (100%)	Latissimus dorsi harvest time/min	92 min (65–165 min)	Incidence of surgical complications (%)	16.7%—seroma 8.3%, infection 14.1%, unplanned reoperation 8.3%	N/A
	Traditional open technique (TOT)						64 (100%)		58 min (42–98 min)		37.5%—seroma 8.9%, delayed healing 7.8%, infection 8.3%, unplanned reoperation 12.5%	N/A

(Continues)



TABLE 4 (Continued)

Study	Intervention	Robot	Anatomical contour	Clinical indication	Follow-up period	Outcome 1	Result 1	Outcome 2	Result 2	Outcome 3	Result 3	Surgical procedure duration/min
Pedersen et al. (2014)	Robotic, intraperitoneal harvest of the rectus abdominis muscle	The da Vinci system (intuitive surgical, sunnyvale, California, USA)	Harvest: Rectus abdominis muscle Transfer: Lower extremity free flaps (4) and pelvis (6)	Case 1: Recticular cell sarcoma Case 2: High risk prostate cancer Case 3: 10 - Unknown	7 months	Procedural success (%)	100%—No conversions to open procedure and muscles completely viable following harvest	Robotic harvest time/min	45 (31–126)	Incidence of surgical complications (%)	1 (10%)—stage I decubitus ulcer resulting from a long, multiservice case	N/A
Prospective studies												
Shuck et al. (2022)	Robotic latissimus muscle harvest and breast reconstruction	The da Vinci system (intuitive surgical, sunnyvale, California, USA)	Harvest: Latissimus dorsi Transfer: Breast	Unspecified	105.7 +/- 103 days	Procedural success (%)	15 (100%)	Incidence of adverse event at week 13 (%)	Muscle flap failure —0 (0) Donor-site seroma/haematoma—1 (6.7) Drain required—4 (26.7)	Change in QuickDASH score (from 2 to 36 weeks)	−31.8 (−47.7 to −18.2) $p < 0.05$	300.3 +/- 82.2 min

Abbreviations: DIEP, deep inferior epigastric perforators; TAPP, trans-abdominal preperitoneal; TEP, totally extraperitoneal; N/A, not applicable/available; RGE-LNF, robotic harvest of a right; GLNF, gastroepiploic lymph node flap; RALDH, robotic-assisted latissimus dorsi harvest; TOT, traditional open technique.

$p < 0.001$) and University of Western Ontario Microsurgical Skills Acquisition Instrument (UWOMSA) (4.0 ± 0.5 vs. 3.4 ± 0.3 , $p < 0.001$). Scoring methods. The surgical time for the robotic assisted cohort was longer than that for the manual/control cohort.

3.7 | Miscellaneous

Five studies^{17,39,40,51,56} evaluating the outcomes of RAS in various plastic and reconstructive surgeries were included under the miscellaneous category (Table S4). Of the included studies, two^{39,51} and three^{17,40,56} studies were pre-clinical and clinical studies, respectively.

Of the pre-clinical studies, Lei et al. evaluated the efficacy of craniomaxillofacial plastic surgery robot for osteotomies,³⁹ while Shi et al. reported the outcomes on mandibular bone drilling with robotic assistance.⁵¹ Both studies utilised experimental/prototype robots. Lei et al. reported procedural success, while Shi et al. reported a reduced position error (1.07 ± 0.27 mm vs. 1.49 ± 0.13 mm) and angle error (5.59 ± 3.15 vs. 9.41 ± 2.13) for the experimental robot group in comparison to the control group.

Van Mulken et al. reported feasibility for the RAS MUSA robot (MicroSure B.V.) in the Masquelet approach and conveyed procedural success along with an absence of peri-operative adverse events and attainment of full weight bearing status on follow-up.⁵⁶ Ahn et al. reported outcomes for robot-assisted nipple-sparing mastectomy and immediate reconstruction in comparison to the conventional method and conveyed a superior BREAST Q Score for satisfaction for the robotic cohort along with an absence of significant perioperative adverse events.¹⁷ Lin et al. utilised the CPSR-I surgical robot (Institute of Forming Technology & Equipment, Shanghai Jiao Tong University, China) for genioplasty and reported feasibility with a distance error of 2.19 ± 0.48 mm between pre-operative and post-operative imaging.⁴⁰ The authors also reported maximum patient satisfaction at 6 months (5/5).

4 | DISCUSSION

Robot-assisted surgery has seen substantial advancement and is highly integrated in certain surgical disciplines. This incorporation has taken relatively longer in the plastic and reconstructive surgical discipline. However, despite the above, this systematic review has substantiated that RAS has made significant strides and developments in this speciality. RAS has been successfully implemented in various subdisciplines including microvascular, transoral and nerve surgery.

The advantages of robotic surgery have been well established even in the absence of large-scale studies with robust methodologies. These include decreased blood loss and optimised precision. Regarding plastic and reconstructive surgery, the nullification of tremors, augmented degree of freedom of instruments, and motion scaling are all promising merits for improvement of accuracy and



TABLE 5 Trans-oral robotic surgery in plastic surgery.

Study	Intervention	Robot	Anatomical contour	Clinical indication	Follow-up period	Outcome 1	Result 1	Outcome 2	Result 2	Outcome 3	Result 3	Surgical procedure duration/min
Pre-clinical studies												
Khan et al. (2016)	Angle of robot in relation to the operating table	da Vinci S, intuitive surgical, sunnyvale, CA	Cadaveric oral cavity: Posterior pharyngeal wall and palate	N/A	N/A	Angle of robot in relation to the operating table	Robotic base unit parallel to the operating table at the feet of the patient	The degree of head up or down tilt of the operating table	Head down at 10° from neutral	The endoscope and airway model used	The zero degrees endoscope	N/A
	The degree of head up or down tilt of the operating table											
	The endoscope and airway model used											
Podolsky et al. (2017)	Da Vinci (da Vinci S, intuitive surgical, sunnyvale, CA)—SI	da Vinci surgical system (intuitive surgical, sunnyvale, CA)	Simulator- oral cavity: Anterior oral cavity and posterior oral cavity	N/A	N/A	Arm repositioning during surgical steps	Arm repositioning required for all 12 steps	Instrument- instrument collisions	3 events of instrument - instrument collisions	Instrument- oral aperture collisions	11 events of instrument—oral aperture collision	3–4 h
	Da Vinci (da Vinci S, intuitive surgical, sunnyvale, CA)—XI						Arm repositioning required for 0 steps		2 events of instrument- instrument collision		9 events of instrument-oral aperture collision	3–4 h
Clinical studies												
Case report												
Garfein et al. (2011)	Transoral robotic reconstructive surgery - surgical debridement of the necrotic tissue and bone—microvascular component (anastomoses) performed with robot	da Vinci Surgical system (intuitive surgical, inc, sunnyvale, US)	Oropharyngeal	Squamous Cell Ca on tongue—stage IV + Osteoradionecrosis of the hyoid bone and soft-tissue radio-necrosis of the tumour bed	6 weeks	Procedural success (%)	1 (100%)	Post operative swallow function	Passed swallow evaluation after first week—started on oral diet on D8. Video esophagram conducted 6 weeks after, showed good function	N/A	N/A	N/A
Case series												
Selber et al. (2010)	Transoral robotic surgery and Oropharyngeal surgery—namely oropharyngeal tumour resection, robotic reconstruction with flaps and arterial anastomosis	da Vinci Surgical system (intuitive surgical, inc, sunnyvale, US)	Head and neck	Oropharyngeal malignancies	N/A	Procedural success (%)	5 (100%)	Incidence of intraoperative complications (%)	0 (0%)	N/A	N/A	8.9 h (total procedure - including non-robotic component - robotic component not recorded separately)
Retrospective studies												
Arora et al. (2019)	Transoral robotic surgery (TORS) ± traditional neck dissection	da Vinci Surgical system (intuitive surgical, inc, sunnyvale, US)	Harvest: Free arm radial artery forearm, rectus femoris, anterolateral thigh flap Transfer: Oral cavity, neck	Oropharyngeal squamous cell cancer—base of tongue Ca (2), tongue (mobile) Ca (2), buccal mucosa (BM) Ca (4), tonsil Ca (1), soft palate (1), gingivo-tonsillar sulcus (1)	N/A	Procedural success (%)	9 (100)	Robotic surgery time/min	32.8	Flap harvest time/min	49.4	N/A
	Wide local excision + robotic selective neck dissection (WLE + RSND)						2 (100)		63		40	N/A

(Continues)



TABLE 5 (Continued)

Study	Intervention	Robot	Anatomical contour	Clinical indication	Follow-up period	Outcome 1	Result 1	Outcome 2	Result 2	Outcome 3	Result 3	Surgical procedure duration/min
Hatten et al. (2018)	Trans-oral robotic surgery (TORS) resection with lateral pharyngotomy followed by microvascular reconstruction	da Vinci Surgical system (intuitive surgical, inc, sunnyvale, US)	Head and neck	Oropharyngeal malignancies (42%–100%)	3–30 months	Procedural success (%)	42 (100)	Incidence of adverse events (%)	9 (21)	N/A	N/A	N/A
Lai et al. (2019)	da Vinci surgical system Hand sewn	Da Vinci S, (da Vinci S, intuitive surgical, sunnyvale, CA)	Head and neck radial forearm	Oropharyngeal squamous Cell Ca - 15 (100%)	11.5 +/- 7.6 (3–25) months	Anastomosis time/min	38.4 +/- 10.4	Anastomotic patency (%)	100%	Incidence of vessel related complications (%)	Across both interventions—1 (6.67%)—haematoma 2 weeks following post op due to abrupt rise in blood pressure and underwent haematoma removal—flap still survived	38.4 +/- 10.4 28.0 +/- 7.7
Song et al. (2013)	CWE + RAND + RFFF TORS + CND + RFFF + flap inseting (robotic procedure in reconstruction) TORS + RAND + ALT free flap + flap inseting (robotic procedure in reconstruction) TORS + RAND + RFF + flap inseting and microanastomosis (robotic procedure in reconstruction)	da Vinci Surgical system (intuitive surgical, inc, sunnyvale, US)	Head and neck	1. Tongue Ca—T1N0M0—stage I 2. Base of tongue Ca—T1N0M01—stage I 3. Tonsil Ca—T2N2cM0—stage IVA 4. Tonsil Ca—T2N1M0—stage III 5. Tonsil Ca—T3N0M0—stage III	12.8 months (16, 15, 15, 10, 8)	Pedicle length/cm	9 10 10 6	Reconstructive operation time/min	541 540 661 673	Incidence of adverse events (%)	0 (0) 0 (0) 0 (0) 0 (0)	913 min 1126 min 1121 min 1132 min

Abbreviations: ALT, antero-lateral thigh; BM, buccal mucosa; CND, central neck dissection; CWE + RAND + RFFF, conventional wide excision + robot-assisted neck dissection + radial forearm free flap; N/A, not applicable/available; TORS, transoral robotic surgery; WLE + RSND, wide local excision + robotic selective neck dissection.



reproducibility of procedures along with an ergonomic and comfortable platform. Multiple pre-clinical studies have supported the expeditious attainment of RAS proficiency despite the steep initial learning curve.^{35,55}

RAS application in microvascular anastomosis has been feasible, efficacious, and safe although the anastomosis time was typically longer in comparison to the control/manual cohort. The prevalence of anastomotic patency and incidence of leaks were comparable across robotics enhanced and conventional techniques. Challenges include absence of haptic feedback although this can potentially be overcome with the use of other alternatives such as visual cues when determining if sufficient tension has been applied to the knots for anastomosis.⁵⁵ As previously mentioned, the operating time is notably and comparatively longer although this may be shortened with more experience and exposure.^{61,62} RAS was also successfully implemented in flap harvest procedures, particularly involving DIEP, omental and latissimus dorsi muscle flaps. Studies conveyed the feasibility and reproducibility of this approach as well as the technical advantages in comparison to the endoscopic approach along with the cosmetic advantages over the open approach, particularly for free flap harvest.⁵⁰ While the continuity of cutaneous tissue in skin flaps poses a unique surgical challenge, the integration of robotic assistance could provide a valuable tool in the armamentarium of plastic surgeons. Robotic assistance can facilitate precise dissection, which would enable surgeons to navigate complex anatomical structures with enhanced visualisation and control, thereby reducing the risk of tissue damage and improving surgical outcomes. By leveraging the precision, control, and innovative capabilities of robotic platforms, we can enhance our ability to perform skin flap procedures with greater efficiency, safety, and precision, ultimately benefiting patients through improved outcomes and enhanced surgical experience.

RAS has been widely implemented in trans-oral procedures as it introduces an extra dimension into the technical capability of surgeons operating in limited access regions such as the aerodigestive tract. Stereotactic vision, augmented magnification, dexterity, improved illumination, and enhanced range of motion confer a conducive approach when operating in narrow confined fields. TORS has provided a surgical approach to early stage oropharyngeal malignancies that would have typically been reserved for chemoradiation. Previous concerns regarding open approach morbid incisions such lip-split incisions and mandibulotomy have been addressed with RAS as this approach utilises smaller incisions. RAS has also demonstrated aptitude for nerve based surgery with nerve coaptation successfully and safely performed⁴⁸ although the overall evidence base for this systematic review was highly limited to anecdotal and evidence. RAS has also demonstrated feasibility in lymphatic surgery, particularly lymphaticovenous anastomosis.^{58,59}

The widespread integration of RAS remains a challenge in view of monetary considerations with high costs required for both the acquisition and maintenance of the equipment. Furthermore, a robust infrastructure is required for facilitation along with specifically trained staff. Overall, cost optimisation is likely essential for market establishment.

The future of RAS in plastic and reconstructive surgery could potentially be substantial; however, further research might be needed to optimise the currently available robotic platforms along with the development of systems for specific indications. Microsurgical tools may require further development, especially for versatility towards size and degree of articulation. An intelligent robotic system might also be another area of development as robotic platforms can enable the registration and storage of movements and force. A combination of surgical data, robot registration, calibration and kinematic data could propel clinical care through intelligent robotic systems.

A large proportion of the included studies exhibited methodological concerns ranging from reported outcomes to statistical analysis. Majority of the studies retrieved and included were of a lower evidence base with very few prospective and randomised control trials published on this topic. This was not unexpected given the infancy of RAS application in plastic and reconstructive surgery. However, in view of the increasing dissemination of this approach, we can anticipate the facilitation of more robust studies to be conducted in the future. The overall sample size across the included studies was generally lower, with particularly seldom use of the statistical power calculation. Several studies did not exhibit a comparator arm and thus, it was difficult to assess the efficacy and safety of the robotic approach relative to the conventional approach. There was also significant variation in the primary and secondary outcomes reported. In view of significant clinical and methodological heterogeneity between the studies, meta-analysis was not pursued. Additionally, this limitation also precluded the feasibility of conducting meaningful subgroup analysis or meta-regression. As a result, there was a greater focus on providing a descriptive synthesis of the literature to highlight key findings and areas of consensus and divergence. Furthermore, the variation in study methodology, patient populations, and outcome measures precluded a meaningful examination of the impact of different methodological features on clinical findings and thus sensitivity analysis was not pursued.

Moving forward, as more data become available and methodological standards improve, the possibility of conducting meta-analysis with subgroup analysis or meta-regression to elucidate sources of heterogeneity should be explored.

Following rigorous methodological evaluation of the included studies, there was a degree of evidence supporting the use of RAS in certain areas of plastic and reconstructive surgery such as microsurgical anastomosis, trans-oral surgery, flap harvest, and lymphatic surgery, although the overall quality of the evidence base was found to be deficient.

In conclusion, the findings of our systematic review highlight the promising role of robotic-assisted surgery (RAS) in plastic and reconstructive procedures, particularly in microsurgical and trans-oral applications. While surgical operative time may initially be higher, increased experience and exposure have the potential to mitigate this limitation. However, the quality of evidence remains suboptimal, underscoring the need for further robust studies. Recommendations to enhance the implementation of RAS include the



TABLE 6 Robotic application in lymphatic based plastic surgery.

Study	Intervention	Robot	Anatomical contour	Clinical indication	Follow-up period	Outcome 1	Result 1	Outcome 2	Result 2	Outcome 3	Result 3	Surgical procedure duration/ min
Clinical studies												
Case series												
Lindenblatt et al. (2022)	Robotic-assisted lymphatic anastomosis	The symani surgical system (medical microinstruments, Sp.A. Calci, Pisa, Italy) with Pentero 900 microscope (Carl Zeiss meditec AG, Jena, Germany) or the VITOM 3D system (Karl storz SE & Co. KG, tuttlingen, Germany)	Groin lower limb	Patient 1. Secondary lymphoedema of the right leg	N/A	Procedural success (%)	2 (100)	Patency of anastomosis (%)	2 (100)	N/A	N/A	N/A
	Robotic-assisted lymphatic anastomosis + robot-assisted arterial anastomosis				1 (100)	2 (100)	N/A	N/A	N/A			
	Robot-assisted lymphatic anastomosis + conventional anastomosis				1 (100)	2 (100)	N/A	N/A	N/A			
	Robotic-assisted lymphatic anastomosis + robot-assisted arterial anastomosis + conventional anastomosis				1 (100)	3 (100)	N/A	N/A	N/A			
Weinzierl et al. (2023)	Robot-assisted lymphatic microsurgery for omental flap transfer to the axilla and lympho-venous anastomosis: Vascularised lymph node transfer (VLNT) to the axilla and lympho-venous anastomosis (LVA)	Symani surgical system (medical microinstruments, Sp.A. Calci, Pisa, Italy)	Harvest: Omentum Transfer: Axilla	Lymphoedema—8 (100%) Patient 1 - primary lymphoedema of right arm - stage II-III Patient 2-secondary lymphoedema (post mastectomy) of the right arm, stage II-III Patient 3-secondary lymphoedema of the left arm (post lumpectomy, post axillary dissection) Patient 4-secondary lymphoedema of the left arm, stage II-III (post mastectomy, post axillary dissection) Patient 5-secondary lymphoedema of the left arm, stage I, post mastectomy Patient 6-secondary lymphoedema of the left arm, stage II, post mastectomy Patient 7-secondary lymphoedema of the right arm, stage III, post mastectomy Patient 8-secondary lymphoedema of the right arm, stage II, post lumpectomy, post axillary dissection.	3 months	Procedural success (%)	8 (100)	Patency of anastomosis (%)	100%	Anastomotic time/min	22.6 +/- 26.2	N/A



TABLE 6 (Continued)

Study	Intervention	Robot	Anatomical contour	Clinical indication	Follow-up period	Outcome 1	Result 1	Outcome 2	Result 2	Outcome 3	Result 3	Surgical procedure duration/min
Randomised controlled trial												
Van Mulken et al. (2022)	Robotic-assisted lymphatico-venous anastomosis	The MUSA (MicroSure, Eindhoven, The Netherlands)	Pre-determined sites assessed from NIRF lymphography	Breast-cancer related lymphoedema	378 days	Lymphoedema functioning, disability and Health questionnaire (Lymph-ICF) - Baseline to 12 months	B/L: 38 12 months: 18 Change: (-) 20 $p = 0.045$	Upper extremity lymphoedema (UEL) index - Baseline to 12 months	Change: +6.99 $p = 0.094$	Arm dermal backflow (ADB) stage - Baseline and 12 months	ADB stage 2 B/L-3 (37.5) 12 months- 2 (33.3) ADB stage 3 B/L-5 (62.5) 12 months- 3 (50)	115 min
	Manual lymphatico-venous anastomosis				376 days		B/L: 48 12 months: 25 Change: (-) 23 $p = 0.001$		Change: +7.20 $p = 0.240$		ADB stage 2 B/L-1 (8.3) 12 months - 6 (54.5) ADB stage 3 B/L- 11 (91.7) 12 months- 5 (45.5)	81 min
Van Mulken et al. (2020)	Robotic-assisted lymphatico-venous anastomosis Manual lymphatico-venous anastomosis	The MUSA (MicroSure, Eindhoven, The Netherlands)	Pre-determined sites assessed from NIRF lymphography	Breast-cancer related lymphoedema	90 days	Mean lymph-ICF total score at 3 months compared to baseline	Intervention 1: B/L-38 +/- 16 3 months - 22 +/- 16 Intervention 2: B/L-49 +/- 16 3 months - 29 +/- 19 $p = 0.69$ for comparisons at 3 months	Mean UEL index of affected arm at 3 months compared to baseline	Intervention 1: B/L-116 +/- 24 3 months - 113.01 +/- 21 Intervention 2: B/L-122 +/- 20 3 months - 125 +/- 19 $p = 0.91$ for comparison at 3 months	Quality of anastomosis using SAMS and UWOMSA scores	Intervention 1: SAMS-4.0 +/- 0.3 UWOMSA- 4.0 +/- 0.5 Intervention 2: SAMS-3.2 +/- 0.4 UWOMSA - 3.4 +/- 0.3 Comparisons of SAMS- $p < 0.001$ Comparisons of UWOMSA $-p < 0.001$	115 min 81 min

Abbreviations: ADB, arm dermal backflow; B/L, baseline; LVA, lymphaticovenous anastomosis; N/A, not applicable/available; NIRF, near-infrared fluorescence; SAMS, structured assessment of microsurgery skills; UEL, upper extremity lymphoedema; UWOMSA, university of western ontario microsurgical skills acquisition; VLNT, vascularised lymph node transfer.



development of standardised training programs, and prioritisation of multicentre collaborative studies. Long-term outcome assessment, cost-effectiveness analysis, and clear patient selection criteria will also guide future research and clinical practice. Continued research and innovation are essential to advance the field and optimise patient outcomes in plastic and reconstructive surgery.

AUTHOR CONTRIBUTIONS

Conception and design: Francesca Ruccia, Akash Mavilakandy and Ankur Khajuria; acquisition and interpretation of the data: Francesca Ruccia, Akash Mavilakandy, Hassan Imtiaz, John Erskine, Yong Yie Liew, Meyada Ali; Writing and editing: Francesca Ruccia, Akash Mavilakandy, Ankur Khajuria; critical revisions and final approval: Ankur Khajuria.

ACKNOWLEDGEMENTS

I have no acknowledgement to declare. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST STATEMENT

Francesca Ruccia, Akash Mavilakandy, Hassan Imtiaz, John Erskine, Yong Yie Liew, Meyada Ali, and Ankur Khajuria declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Ruccia F, Mavilakandy A, Imtiaz H, et al. The application of robotics in plastic and reconstructive surgery: a systematic review. *Int J Med Robot*. 2024;e2661. <https://doi.org/10.1002/rcs.2661>