A Systematic Review on the Role of Robotic Microsurgery for Brachial Plexus Reconstruction

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Abstract

Robotic microsurgery has revolutionized surgical practices, offering unprecedented precision and minimally invasive techniques. This article presents an updated overview of the role of robotic microsurgery in brachial plexus reconstruction. Robotic systems provide unique advantages, including high-resolution 3D visualization with magnification up to 40X, precise movements magnified up to 10X, ergonomic work conditions, and elimination of physiological tremors. While brachial plexus injuries pose significant surgical challenges, early diagnosis and treatment are crucial for optimal outcomes. Robotic-assisted procedures offer minimally invasive options, reducing morbidity and improving patient prognosis.

A historical perspective traces the evolution of robotic surgery from its inception in the 1980s to the development of advanced systems like the da Vinci Surgical System and the Versius Surgical Robotic System. Notable milestones include the application of robotics in microsurgery, with successful arterial and venous anastomoses and nerve grafting procedures demonstrated in animal models and cadavers.

Methods A systematic literature search was performed using appropriate search terms in databases to identify all applications of robotic assistance in brachial plexus surgery. Two authors reviewed all articles, and a qualitative synthesis was performed of those articles that met the inclusion criteria. The systematic review and results were conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines.

Results Seventeen studies met the inclusion criteria. These studies were reviewed, and the data were synthesized.

Recent studies have explored robotic techniques for brachial plexus exploration and nerve reconstruction, showcasing promising outcomes in both experimental and clinical settings. Surgeons have successfully performed nerve repair procedures using robotic systems, overcoming challenges such as oversized instruments and lack of proprioceptive feedback.

Keywords
- brachial plexus injury
- brachial plexus reconstruction
- minimally invasive surgery
- nerve surgery
- robotic brachial plexus reconstruction
- robotic microsurgery

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Large-scale studies with long-term follow-up are warranted to assess the superiority of robotic techniques over conventional approaches in nerve and brachial plexus surgeries.

Introduction

Robot-assisted surgery is a relatively new advancement in surgery. It helps a surgeon to perform surgeries minimally invasively, overcoming the limitations of conventional minimally invasive surgeries. While its utilization in different surgical specialties like urology, gastroenterology, endocrinology, cardiology, and aerodigestive tract surgery has been well established, recent years have witnessed its integration into plastic and reconstructive surgery. Several properties of the surgical robot are adapted for microsurgery, including high-resolution three-dimensional (3D) visualization, up to 40X magnification, 10X magnification of surgical movements, ergonomic work conditions, and elimination of physiological tremors.

Brachial plexus injuries pose a surgical challenge for various reasons, including their complex anatomy.[1] In many of these cases caused by traction, there could be no physical disruption of the neural structures. In such cases, spontaneous recovery can occur with time. So, a wait-and-watch strategy for spontaneous recovery is universally followed for closed brachial plexus injuries. These injuries are observed for the first 6 to 12 weeks, during which the clinical progression of signs and symptoms is monitored.[2,3] Conventionally, the brachial plexus requires exploration through longer incisions for better access, which leads to scar formation in both the skin and neural structures. Often, intervention is delayed in cases of closed injuries in adults as well as in obstetric trauma because of a lack of anatomical delineation between normal and injured nerves at the time of exploration. A period of waiting for spontaneous recovery is therefore advised to allow for this differentiation to become clear, both anatomically and physiologically.

Background

A historical perspective traces the evolution of robotic surgery from its inception in the 1980s to the development of advanced systems like the da Vinci Surgical System and the Versius Surgical Robotic System. Notable milestones include the application of robotics in microsurgery, with successful arterial and venous anastomoses and nerve grafting procedures demonstrated in animal models and cadavers.

Robot-assisted microsurgery has the potential to provide a minimally invasive approach.[1] Robot-assisted microsurgery has the potential to provide a minimally invasive approach with better access to the brachial plexus. Other features of robotic surgery, like tremor elimination, high-resolution 3D visualization with up to 40X magnification, and precise motion scaling, augment surgical precision, which is particularly crucial when operating on delicate neural structures. The potential benefits of robot-assisted microsurgery for brachial plexus reconstruction include reduced scarring, faster recovery, and improved patient outcomes. Hence, robot-assisted microsurgery holds the potential to revolutionize the approach to brachial plexus reconstruction, providing a minimally invasive and effective therapeutic alternative. It is hopeful to look forward to the ongoing research and developments happening in this field, which might transcend the management of brachial plexus injuries in the future.

Methodology

Search Strategy

A review was conducted of the literature from PubMed, Medline, and Virtual Health Library, focusing on articles published on robotic brachial plexus surgery up to October 28, 2024. We have done a search combining the terms “brachial plexus,” “surgery,” “robot,” “nerve repair,” “nerve graft,” and “reconstruction” in their title/abstract/keyword and considered them for inclusion.

Additional articles were searched using citations from Google Scholar and other Web sites.

Study Selection

The articles included met the following criteria:

- The study should be published in the English language.
- The study design should be one of the following: case reports, case cohorts, case control, and reviews. Both prospective and retrospectively designed studies were included.
- Studies that report the use of a robotic surgical system for brachial plexus–related surgeries.

Studies published in languages other than English were excluded.

Participants

Articles with studies on animal models, cadavers, and humans with a brachial plexus injury or with an artificially created brachial plexus lesion were included.

Intervention

Studies involving procedures related to brachial plexus performed using a surgical robot were included.

Comparison and Outcomes

Outcomes assessed included the feasibility of the procedure using the surgical robot. Studies were compared with open surgeries where applicable.

Two independent reviewers screened each study based on its title and abstract. The full text of the selected studies was

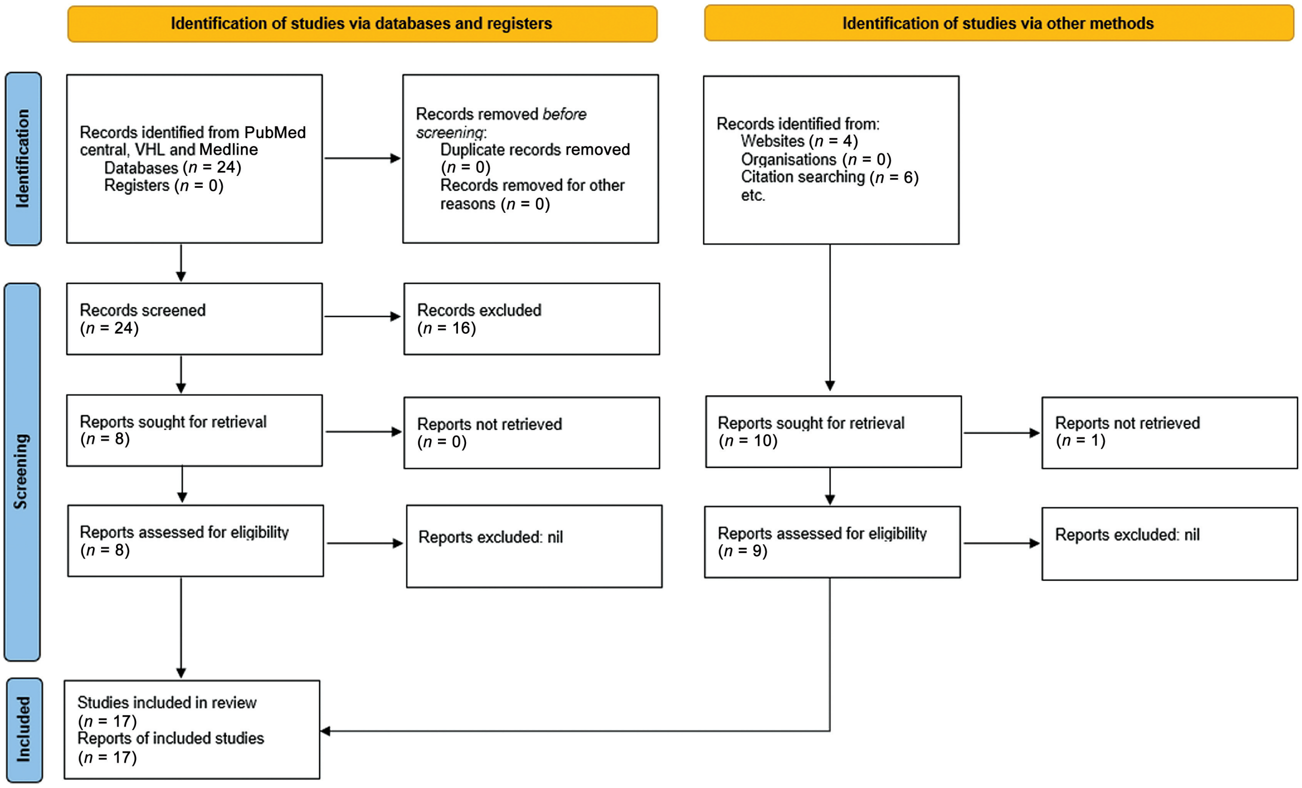

Fig. 1 Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram for systematic reviews, which included searches of database and other sources. VHL, von Hippel–Lindau. (Adapted from Page MJ, Bossuyt PM, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372(71):1–9.) It is an Open Access article distributed in accordance with the terms of the Creative Commons Attribution (CC BY 4.0) license, which permits others to distribute, remix, adapt and build upon this work, for commercial use, provided the original work is properly cited. http://creativecommons.org/licenses/by/4.0/.)

then examined to assess the eligibility. The included studies were subsequently reviewed independently for final inclusion by a third reviewer. References were checked for further unidentified articles, and these were added if appropriate. ►**Fig. 1** shows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram of the search done in databases and other sources.

A data extraction sheet was developed to extract the following data from studies: author, date of publication, study design, number of operations performed, robot used, operations/techniques performed, and outcomes measured. All data were extracted and tabulated using Microsoft Word and Excel.

Results

Seventeen articles, including three relevant review articles, were identified.[4–6] We identified and included seven more studies in the review article published on the application of robotics for brachial plexus surgery.

Fourteen articles showed the feasibility of various procedures using robotic systems, which are summarized in ►**Tables 1** and **2**.[5–18]

The first ever reported nerve surgery performed using a robotic system was by Latif et al[5,19] in 2008 in an animal model for thoracic sympathectomy reversal by intercostal nerve grafting. It was an effective procedure without any adverse events.

The use of a robotic system for brachial plexus reconstruction was first reported[5,20] in 2009 by Taleb et al from France. They assessed the feasibility of peripheral nerve repair using telemicrosurgery on anatomical specimens derived from three distinct species: rats, pigs, and humans, using a da Vinci Robot. Their results demonstrated that robotic surgery allows safe and precise peripheral nerve repair by counteracting physiological tremors and improving the view of the surgical field when done with an anatomical and neurotrophic technique.

This study was followed by another study demonstrating the utility of robotic systems for brachial plexus exploration and reconstruction, which was conducted by Mantovani et al[1] in 2011. Through an endoscopic approach utilizing the da Vinci robotic system, they successfully dissected the brachial plexus in human cadavers. Furthermore, they achieved successful reconstruction of an artificially induced lesion in the upper trunk using a nerve graft and an epineural microsurgical suturing technique exclusively facilitated by the robotic system. Notably, they observed no inadvertent macroscopic damage to the neurovascular structures involved. In conclusion, the feasibility of an endoscopic approach for the brachial plexus reconstruction was affirmed. Their study also suggested that the minimally invasive procedure with low morbidity may justify a diagnostic surgery in the acute setting, avoiding scarring of the skin and nerve tissue.

Table 1 Preclinical studies on robot-assisted brachial plexus reconstruction

Study	Year	Study design	Robot used	Procedure done	Outcome and observation
Mantovani et al[1,5]	2011	Human cadaver	Da Vinci system	Supraclavicular brachial plexus exploration and repair with a nerve graft ($N=2$)	The robot allowed microsurgery to be performed in a confined space endoscopically
Garcia et al[6,7]	2012	Human cadaver and case series ($n=3$)	Da Vinci system	Open dissection of the brachial plexus and robot-assisted microsurgical repair of the brachial plexus in cadaver and then in human subjects	Tremor filtration, motion scaling, and ergonomic positioning allowed for successful repair in all subjects; however, lack of adequate instrumentation was noted
Porto de Melo et al[8]	2013	Human cadaver	Da Vinci system	Microsurgical dissection of the branches of the axillary nerve and the nerve of the long head of the triceps brachii ($N=1$)	Endoscopic dissection of both the axillary nerve and nerve to the long head of the triceps was achieved successfully.
Facca et al[5,9]	2014	Human cadaver	Da Vinci S system	Sural nerve graft between the C5 root or spinal nerve, and the musculocutaneous nerve ($N=8$)	Endoscopic treatment of supraclavicular nerve palsy is feasible. However, a case requiring a sural nerve graft and a case with C5–C6 root avulsion were converted to open
Porto de Melo et al[5,10]	2014	Animal model	Da Vinci system	Phrenic nerve harvest and use in brachial plexus surgery ($N=1$)	Successful nerve harvest
Tetik et al[11]	2014	Human cadaver	Da Vinci system	Robot-assisted axillary exposure of the brachial plexus	The axillary approach was valuable and advantageous for lower roots, particularly for thoracic outlet syndrome
Miyamoto et al[5,12]	2016	Animal model (pig)	Da Vinci Model S	Intercostal nerve (4–6) harvest for brachial plexus reconstruction ($N=3$)	Physiological tremor was eliminated; there were no major complications. Free movement of joint-equipped robotic arms and amplification of the surgeon's hand motion by as much as 5 times were noted
Jiang et al[4,6,13]	2016	Human cadaver	da Vinci SI surgical robot	Contralateral C7 nerve root transfer procedure with the use of a prevertebral minimally invasive robot-assisted technique	They were able to eliminate the large incision and use a much shorter nerve graft
Bijon et al[4,14]	2018	Human cadaver	da Vinci SI surgical robot	Contralateral C7 nerve root transfer procedure for brachial plexus lesion	They performed a transfer of the right C7 root on the left C7 root by direct retropharyngeal suture without graft and by a minimally invasive technique

Table 2 Clinical studies on robot-assisted brachial plexus reconstruction

Study	Year	Study design	Robot used	Procedure done	Outcome and observation
Lequint et al[4,15]	2012	Case report	Da Vinci system	Mini-invasive robot-assisted biopsy of an intraneural perineurioma of the right brachial plexus	Feasibility of mini-invasive biopsy proven The patient had better cosmesis and decreased scarring without sensory or motor deficits postoperatively. Lack of sensory feedback was not a problem, but nerve biopsy was unable to be confirmed without electrical stimulation
Naito et al[4,17]	2012	Case cohort	Da Vinci system	The Oberlin procedure of nerve transfer for restoration of elbow flexion ($N = 4$)	At the mean follow-up12 mo, all patients had recovery of useful elbow flexion, with no sensory/motor deficit in the ulnar nerve territory
Facca et al[5,9]	2014	Case series	Da Vinci S	Robot-assisted surgery of the shoulder girdle and brachial plexus ($N = 8$)	The prospects of using telemicrosurgery in peripheral nerve surgery vary depending on the level of injury They performed six robot-assisted procedures
Naito et al[16]	2020	Case report	Da Vinci Xi	Robot-assisted intercostal nerve harvest for brachial plexus injury ($N = 1$)	Harvested sufficient length of the fifth intercostal nerve for robot-assisted nerve transfer
Schäfer et al[18]	2023	Case report	Symani Surgical System	The epineural coaptation of three donor nerves (intercostal nerves 4–6) to the thoracodorsal nerve and the long thoracic nerve of Bell ($N = 1$)	For the first time, a triple nerve transfer was performed with a dedicated microsurgical robotic system. The coaptations were performed precisely and accurately

In their 2012 study, Naito et al[17] demonstrated the feasibility of restoring elbow flexion utilizing the Oberlin technique with the assistance of a da Vinci robot. The authors' cohort comprised four patients who had elbow flexion paralysis, three of whom underwent surgery via an open approach. In contrast, the remaining patient initially underwent a minimally invasive procedure, which was subsequently converted to an open procedure. Following a 1-year follow-up period, all patients exhibited successful recovery of elbow flexion. The authors noted the potential for enhancing the minimally invasive approach through the refinement of specific retractors and instruments.

In 2013, Porto de Melo et al[8] reported that they conducted microsurgical nerve transfers on a human cadaver. Specifically, they successfully transferred branches of the axillary nerve onto the nerve of the long head of the triceps. They successfully demonstrated the feasibility of accessing the terminal branches of the axillary nerve and the nerve to the long head of the triceps brachii, dissecting adequate nerve lengths, and performing endoscopic microsurgical nerve transfers through minimally invasive ports with the assistance of the da Vinci robot. However, they emphasized the necessity of a detailed step-by-step description of the new surgical techniques due to the increased complexity of anatomical visualization through an endoscope compared with conventional approaches.

In 2014, Facca et al[9] reported an experimental, followed by a clinical case series on brachial plexus reconstruction around the shoulder girdle using the da Vinci S robot. In a fresh cadaver, endoscopic dissection of the supraclavicular brachial plexus was meticulously conducted. Subsequently, a segment of the C5 nerve root was grafted utilizing robotic techniques. This approach was further extended to encompass a series of eight clinical cases involving nerve injuries around the shoulder girdle, all of which were operated at the Strasbourg University Hospital. ►**Figs. 2** and **3** show the setup after docking the robot through this approach and view of the operative field. The spectrum of cases included 2 cases of complete brachial plexus palsies, 3 cases of partial C5–C6 brachial plexus palsies, 2 occurrences of lesions involving the axillary nerve, and 1 case with concomitant damage to both the axillary and musculocutaneous nerves. Surgeries performed robotically included repair of the C5 root to the musculocutaneous nerve through graft, the spinal accessory nerve to the musculocutaneous nerve transfer using a graft, two cases of neurolysis, three cases of Oberlin transfer, and one case of Somsak transfer with Oberlin transfer. Both cases of axillary nerve exploration using the robot were converted to an open approach due to the inability to access the operative field with robotic instrumentation. The rest of the cases were successfully performed endoscopically through robotic assistance. On follow-up, in the cases where

Fig. 2 Robotic setup after docking of supraclavicular ports.

the Oberlin procedure was performed, the recovery was commendable in terms of muscle power regained.

In an experimental study performed by Porto de Melo et al[10] in an anesthetized 20-kg female domestic pig, they proved the feasibility of transthoracic phrenic nerve harvest using a da Vinci S system. The transthoracic harvest allows the full-length harvest of the phrenic nerve, thereby surpassing the drawback of the procedure through the conventional open approach.

Miyamoto et al[12] showed the feasibility of robotic intercostal nerve neurolysis and harvest using the da Vinci S system transthoracically in three pigs. They were able to harvest the fourth, fifth, and sixth intercostal nerves from the posterior edges to the anterior axillary line. The anterior edges of the nerves were transected at the rib cartilage zone.

In 2014, Tetik and Uzun[11] from Turkey conducted an experiment on a human cadaver at Paris University, Ecole. They tried accessing the brachial plexus through a novel axillary approach using a da Vinci robotics system. They had made an incision in the axilla, dissection was performed, and the required working space was maintained using a Chang retractor. They did not use CO_2 insufflation. Through this approach, they were able to access the C7, C8, and T1 roots and the trunks of the brachial plexus. From their experience, they have noted that this approach provides a wider range of motion to manipulate the robot than through a supraclavicular exposure for the lower part of the brachial plexus. This approach is superior for managing brachial plexus involvement in cases of thoracic outlet syndrome where even the medial-most part of the first rib is accessible.

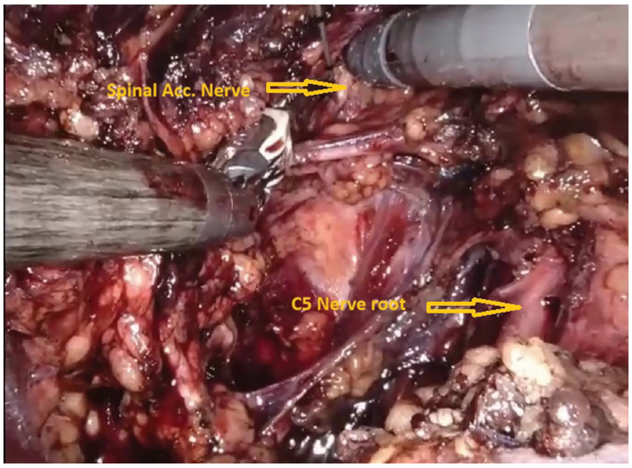

Fig. 3 Operative field showing the spinal accessory nerve (Acc N) and the C5 nerve root.

In 2014, Facca and colleagues[21] from France, Brazil, and Texas also performed brachial plexus exploration and surgery using a da Vinci robotic system for the shoulder girdle. They did a trial in a fresh human cadaver followed by the same in eight clinical cases. In all these cases, they used CO_2 insufflation to create space and perform supraclavicular dissection. In the trial case, they performed grafting for the C5 nerve root robotically. Then, a series of eight clinical cases with nerve damage around the shoulder girdle were operated on. Among the eight cases they performed, two were neurolysis, four were the Oberlin procedures with an added Somsak procedure in one of them, C7 root to the musculocutaneous nerve using a graft, and a spinal accessory nerve to musculocutaneous transfer using a graft. The results were promising in those who underwent neurolysis with a recovery of power of 05 as per the British Medical Research Council (BMRC) scale and recovery of power of 03 and 04 in two patients who underwent the Oberlin procedure, which was noticed after a minimum of 7 months of follow-up.

Naito et al,[16] in their 2020 study, reported their experience of robotic-assisted intercostal nerve harvest. They were able to successfully perform the first case of robot-assisted intercostal nerve harvest in Japan. They made a long longitudinal incision along the midline of the axilla, followed by transthoracically harvesting the nerve, maneuvering using the robotic instruments inserted through the ports inserted through the chest wall. They reported increased patient satisfaction along with reduced postoperative pain, shortened patients' hospital stays, lower complication rates, and better quality-of-life outcomes.

From the lessons learned from initial experiences, a dedicated robot for microsurgery, the Symani Surgical System, was developed, and it has been used after testing. A clinical case report published in August 2023 by Schäfer et al[18] mentioned the use of the Symani Surgical System (Medical Microinstruments, S.p.A, Calci, Pisa, Italy) for epineural coaptation of three donor nerves (intercostal nerves 4–6) to the long thoracic nerve and the thoracodorsal nerve as recipient nerves in a patient with brachial plexus palsy.

Discussion

In this comprehensive review, we have identified 10 feasibility studies, comprising 6 preclinical and 4 clinical investigations, focusing on the utilization of robotic systems for brachial plexus reconstruction. Despite the well-established application of robotics in certain surgical domains, such as prostatectomy, its use in plastic surgery continues to be an area of active exploration.

It was noted that the robot was used instead of a regular microscope during the initial nerve surgeries performed with a robot.[9] The robot was docked into the operating field when required, and then the surgeon controlled it from a console. The ability to perform nerve repair was confirmed, but the entire potential of robot-assisted microneural surgery was not realized during these initial cases.

Later, in 2009, Philippe Liverneaux was the first to succeed in endoscopically accessing the supraclavicular plexus using a robot in France, followed by Gustavo Mantovani Ruggiero in Brazil in 2011.[9] They could perform nerve dissection and coaptation within the confined space using minimally invasive techniques along with the telemanipulation offered by the robotic technology.[1] It is justifiable to perform such an endoscopic procedure with low morbidity as a diagnostic surgery in an acute setting of closed brachial plexus injury. An endoscopic repair could be executed in the same sitting. It will cut down the duration of neural recovery. It will translate to early and better outcomes for the patient and could offer a promising avenue for the management of closed brachial plexus injuries.

Other advantages identified included the elimination of physiological tremors, which commonly interfere with surgical precision, and the augmentation of movements, thereby enhancing overall precision. Additionally, researchers observed that the absence of haptic feedback did not impede the execution of robotic microsurgery.[8] Utilization of the surgical robot facilitated seamless dissection and enabled precise microsurgical suturing under optimal conditions. The enhanced range of motion and precision in the surgeon's maneuvers afforded by the technology permitted the surgeon to successfully perform an epineural suture within the confined space created by gas insufflation.[9] Miyamoto et al[12] noted the advantages of robotic microsurgery for intercostal nerve harvest, including the elimination of physiological tremors, free movement of joint-equipped robotic arms, and amplification of the surgeon's hand motion by as much as five times.

So far, supraclavicular plexus exploration, repair of lesion with nerve graft, Oberlin procedure, Somsak procedure, contralateral C7 nerve transfer, axillary nerve neurolysis, axillary approach to the caudal part of the plexus, transthoracic phrenic nerve harvest, intercostal nerve harvest, and a triple nerve transfer have been performed with robotic assistance. Out of these, only supraclavicular plexus exploration, contralateral C7 transfer, and intercostal nerve harvest in pigs were achieved endoscopically; all other surgeries were either done through an open approach or converted to an open technique.

Liverneaux et al[22] outlined several potential factors necessitating the conversion to open surgery, including difficulty maintaining the resection cavity (leakage of carbon dioxide through trocar holes), unsuitable instrumentation, blurring of the stereoscopic vision (due to a rapid increase in temperature in this small volume, which was solved with the aid of a suction device), and major difficulties in visual identification of anatomical landmarks.

The primary challenge associated with robotic surgery lies in the substantial investment necessary for the acquisition and maintenance of equipment. That said, a study by Ind et al[23] substantiates that in facilities where proficiency has been achieved, robotic surgery presents as a more cost-effective alternative to traditional open surgery in managing endometrial cancer. Nevertheless, further research is warranted to conduct comprehensive cost analyses pertaining to robotic brachial plexus surgery.

A 2024 study by Frieberg et al[24] on robotic microsurgery learning curves evaluated how the experience of the surgeon influences outcomes and learning curves in robotic-assisted microsurgery. They found no statistical difference in the mean time between groups for the robot-assisted anastomoses. All groups reduced their mean time in half through their 10 robotic sessions. They concluded that there were similarities in the learning curves for robot-assisted anastomosis among surgeons with varied experience levels. Experts excelled technically in manual anastomoses, but robot assistance enabled novice and intermediate surgeons to perform comparably to the experts. Robotic assistance may aid more novice learners in performing microsurgical anastomosis safely at earlier points in their education.

Porto de Melo et al[10] reported that the time needed for the robot setup and port placement was 30 minutes. The surgical time for harvesting 20 cm of the phrenic nerve in the console was 45 minutes. Less than 20 mL of blood was lost during the procedure. Bijon et al[14] were able to carry out a transfer of the right C7 root on the left C7 root by direct retropharyngeal suture without graft and by a minimally invasive technique in 2 hours and 40 minutes. Other studies that we reviewed did not specify the time taken for surgery. It can be noted that for a retropharyngeal Contralateral C7, the duration of nerve transfer is comparable to that of the open approach. These surgeries may take extra time for docking in addition to the operative time. However it is noted that there is lesser blood loss, shorter hospital stay and better post operative patient satisfaction. It is also noted that the total time taken to perform the robotic microsurgery reduces with training.[24]

Lack of haptic feedback is frequently identified as an additional limitation of robotic surgery. Nevertheless, findings from the study conducted by Hagen et al,[17,25] encompassing 52 participants, challenge this notion by revealing that visual signals can simulate the sensation of tactile feedback, notwithstanding its actual absence during robotic surgical procedures.

Conclusion

So far, every experimental study conducted on robotic nerve surgery has shown that it is technically possible to perform different conventional procedures for brachial plexus reconstruction with robot assistance. However, substantial evidence supporting the incorporation of the procedure into routine clinical practice is lacking and requires further research. Large-scale studies with long-term follow-up are warranted to assess the superiority of robotic techniques over conventional approaches in nerve and brachial plexus surgeries.

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Conflict of Interest
None declared.

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