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Review

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# The MUSA robot and its applicability in lymphatic surgery

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## Abstract
The development of surgical treatment of lymphedema has been a challenging endeavor. Various surgical modalities have been proposed, but the results are often unsatisfactory. The lymphaticovenous anastomosis (LVA) revolutionized by Koshima *et al*. with the introduction of super microsurgery has gained traction in the treatment of lymphedema and has shown favorable results. However, super microsurgery requires excellent hand-eye coordination, meticulous tissue handling, dexterity, and operative flow, which are subject to multiple factors. Robot-assisted microsurgery (RAMS) has the potential to increase safety for clinicians and patients and create new possibilities in the field of super microsurgery. Therefore, plastic surgeons of the Maastricht University Medical Center (Maastricht, the Netherlands) teamed up with engineers from the Eindhoven University of Technology (Eindhoven, the Netherlands) and developed the first dedicated robotic platform for (super)microsurgery, the MUSA. The development of MUSA, from inception to the first clinical study in patients with lymphedema, has yielded promising results. This review aims to elucidate the development of the MUSA and its role in lymphatic surgery.

**Keywords:** Lymphatic surgery, super microsurgery, robotic-assisted surgery

## INTRODUCTION

The development of surgical treatment of lymphedema has been challenging. The first attempt was described in the early 20th century when ablative procedures such as Charles and Homans were introduced[1]. Since then, a variety of surgical modalities have been proposed, but often with unsatisfactory results[1-3]. The first lymphaticovenous anastomosis (LVA) was described in 1960[4]. But it was not until the 1990s, when Koshima revolutionized the technique by introducing the concept of super microsurgery, that the LVA gained traction for the surgical management of lymphedema[5,6]. Since then, the success of the LVA increased with the introduction of designated microsurgical instruments and novel diagnostic imaging techniques such as Near Infrared Lymphography (NIRF) and high-frequency ultrasound[7,8].

Super microsurgery typically demands exceptional hand-eye coordination, meticulous tissue handling, dexterity, and operative flow[9]. These qualities can be influenced by various internal and external factors, such as the surgeons' capabilities, tremors, fatigue, and/or aging. Furthermore, super microsurgery can have a detrimental effect on the surgeon due to prolonged static, awkward positioning, repetitive motions, and overall generalized muscular fatigue[10]. To ameliorate these factors, the logical next step in advancing super microsurgery is the development of robotic assistance.

Robotic-assisted microsurgery (RAMS) has the potential to enhance safety for clinicians and patients by improving super microsurgical procedures, providing ergonomic designs and enhancing instrument handling. In turn, it can provide physical relief, and standardize the quality of therapy, notwithstanding the surgeons' capabilities, ultimately leading to improved patient outcomes[11].

The MUSA is a robotic platform designed specifically for (super)microsurgery, capable of overcoming human limitations and seamlessly integrating into the existing infrastructure of the operating theatre. This review aims to provide an overview of the development of the MUSA and its role in lymphatic surgery.

## HISTORY OF ROBOT ASSISTANCE IN MICROSURGERY

The exact origin of robot assistance in surgery is difficult to trace. In the 1970s, the National Aeronautics and Space Administration started developing telerobotic systems to facilitate surgery in space and sparked a new interest in utilizing robotics for surgical purposes[12]. Since then, the development of systems to aid microsurgeons has become a growing field in research, facilitating effective cooperation among surgeons, IT experts, engineers, and scientists from diverse fields[13].

The first master-slave system for microsurgery was developed by Jet Propulsion Laboratories in collaboration with MicroDexterity Systems and Dr. Steve Charles, a vitreo-retinal surgeon[14]. Ultimately, it was tested in a clinical setting and was successful in completing an end-to-end anastomosis on a rat's carotid artery[15].

The Da Vinci Surgical System (Intuitive Surgical, Inc.) was designed and is mainly used for endoscopic surgery. However, its use in reconstructive microsurgery has been widely documented. While the feasibility of the Da Vinci robot has been evidenced and surgeon users report a steep learning curve, no large-scale data have been published proving its efficacy in microsurgery[16-18]. Furthermore, multiple studies indicate that the Da Vinci robot disrupts operative workflow, has limited optic magnification for microsurgery, and lacks suitable instruments for (super)microsurgery[16,18-20].

### Development of a designated microsurgical robot

The aforementioned limitations and the increasing demand for super microsurgery resulted in a collaboration between technicians of the Technical University of Eindhoven (TU/e, Eindhoven, Eindhoven) and microsurgeons of the Maastricht University Medical Center to develop a surgical robot designated for super microsurgery.

The MUSA is a lightweight, small-sized master-slave system that can be incorporated into any surgical setting. It is compatible with existing surgical microscopes and exoscopes and uses conventional super micro instruments. The robot consists of slave manipulators that can be mounted on the operating table and can be adjusted in height according to the location of the operative field. The surgeon has a direct view of the operation site and is able to perform surgery using joystick-like master manipulators. Through the device software, the manipulators can filter out tremors and motion scaling is effectuated using the foot pedals.

The efficacy of the MUSA Gen-1 was tested in a preclinical setting using 2 mm-silicone vessels and *in vivo* rat models in previously reported studies[21,22]. In both studies, the time to perform an anastomosis was logged and the quality of the anastomosis was measured using the modified version of the Structured Assessment of Microsurgical Skills (SAMS)[23].

The SAMS score consists of four categories (dexterity, visuospatial ability, operative flow, and judgment), and each category contains three items that can be scored from 1 (bad) to 5 (excellent). Overall performance (1 bad-5 excellent) and indicative skill (1 novice-5 expert) were also evaluated[23].

During the preclinical studies with silicone vessels, conventional manual microsurgery had overall higher SAMS scores compared to robot-assisted procedures. Overall, a learning curve was reported for indicative skill and overall performance in both groups[22].

During the *in vivo* experiments with rat models, the abdominal aorta (1.8 to 2.4 mm) and femoral artery (0.7 to 0.8 mm) were used. While manual surgery had shorter anastomosis times and higher SAMS scores, the MUSA once more showed a steep learning curve, with surgery time gradually decreasing and overall quality per anastomosis improving. Furthermore, patency was confirmed in all anastomoses but one[21].

Even though manual surgery reported higher SAMS scores, the results of the first designated microsurgical robot were not disappointing. The steep learning curve in the robotic group indicates that with adequate training, the MUSA robot has the potential to supersede manual surgery. Based on this newly gained experience, a new generation MUSA was created with a more ergonomic design to improve manual dexterity[21,22].

## FIRST-IN-HUMAN ROBOTIC LVA

In 2017 the first LVA using a designated microsurgical robot (MUSA) was performed, followed by the first-in-human randomized pilot study to evaluate the feasibility of the MUSA in super microsurgery[24]. The study evaluated the efficacy of the MUSA in LVA surgery in patients suffering from breast cancer-related lymphedema (BCRL). From 2017, twenty females suffering from unilateral BCRL of the arm, stage 1 or 2, according to the International Society of Lymphology, with viable lymphatic vessels ICG stadium II-III (Narushima) as determined with NIRF were randomized to undergo robot-assisted or manual LVA[25]. In the video Supplement Materials, an LVA is demonstrated with the use of the MUSA robot. A minimum of 30 h of robot microsurgical training was required before the surgeon can participate in the study.

Preoperatively, NIRF was performed in the outpatient clinic to locate and mark the location for LVA. During surgery, using the photographs of the markings, the sites for incision are marked. The surgery was performed under local anesthesia. Incisions of 1.5 to 2 cm were made in the subdermal region to find the viable lymphatic vessels and subdermal veins. The dissection was performed manually. The anastomosis was performed either using a robot-assisted approach or manually, depending on the randomization. The LVAs were performed in an end-to-end fashion with an 11-0 Ethilon suture (Ethicon, Johnson & Johnson, USA). The patency of the anastomosis was checked by performing the milking test. The wound was closed using interrupted transcutaneous sutures with 4-0 Ethilon. The duration of anastomosis was recorded[26].

The clinical outcomes were health-related quality of life (HRQOL) measured by Lymphedema Functioning, Disability, and Health Questionnaire (Lymph-ICF), arm circumference measured by the upper extremity lymphedema (UEL) index, the use of compression garments, patency of the anastomosis and adverse and severe adverse events were reported[27].

Furthermore, technical outcomes such as the amount of anastomosis per procedure, the total time of the procedure, and the total duration of the anastomosis were recorded. The quality of the microsurgical technique was compared between the two groups by two independent experienced microsurgeons using the SAMS and University of Western Ontario Microsurgical Skills Acquisition Instrument (UWOMSA) assessment methods[28].

The Lymph-ICF is a validated questionnaire for patients with lymphedema, consisting of 29 questions based on function, activity limitations, and participation restrictions divided into five domains. Items are scored on a Visual Analog Scale (VAS) from 0 to 100 mm[29]. Higher scores indicate worsening HRQOL. The UEL index uses circumference measurement of five points on the affected arm and is corrected for body mass index. A decrease in arm circumference results in a lower UEL index[27].

The UWOMSA assesses microsurgical skills in preparation, suturing, and final product. Patient satisfaction was assessed using a VAS score, and a higher score indicates higher patient satisfaction. The surgeon's overall satisfaction with the procedure was assessed, and a higher score indicates higher surgeon satisfaction[28].

There was an improvement in quality of life after LVA surgery for both the manual and the robot-LVA group after 3, 6, and ultimately 12 months. However, there was no statistically significant difference in quality of life between the two groups during follow-up (3; 95%CI: -11 to 16, $P = 0.679$).

The arm circumference measured by the UEL-index showed no statistically significant difference during follow-up, (Robot-LVA, -0.93 and manual-LVA, 0.36, $P = 0.66$). Furthermore, a decrease in circumference measured by UEL-index could not be evidenced for both groups (0.6; 95%CI: -10.3 to 11.4; $P = 0.913$)[26].

After 12 months, a reduction in the use of compression garments was reported in both groups (Robot-LVA 42.9% *vs*. manual-LVA 45.4% reduction). Additionally, patency was confirmed in 66.6% of patients in the robot-LVA group, whereas 81.8% in the manual-LVA group[26].

None of the patients developed wound infections after surgery. During follow-up, four episodes of erysipelas occurred in three patients at 6 months postoperatively; these were treated with oral antibiotics[26].

A total of 14 anastomoses were completed using robot assistance, with a mean number of 1.75 anastomoses per patient; in the manual group, 26 anastomoses were performed with a mean number of 2 anastomoses per patient. The mean duration per anastomoses was significantly higher in the robot-LVA group compared to the manual-LVA group [respectively, 25 ± 6 min, range 16-33 min and 9 ± 6 min, range 4-36 min, ($P < 0.001$)]. The mean surgical time in the robot-LVA group was 115 min (range 69 min to 185 min) *vs.* 81 min in the manual-LVA group (range 48 min to 140 min), but the difference was not significant. Interestingly, the surgical time in the robot-LVA group decreased after every procedure, indicating a reasonable learning curve[24].

Ultimately, the quality of the microsurgical techniques measured by the SAMS and UWOMSA was significantly higher in the manual-LVA group compared to the robot-LVA groups (SAMS; 4.0 ± 0.3 and 3.2 ± 0.4, respectively ($P < 0.001$), (UWOMSA; 4.0 ± 0.5 and 3.4 ± 0.3, respectively ($P < 0.001$)[24].

This was the first clinical study using robotic assistance in LVA surgery. The prospects might be optimistic due to favorable results when comparing manual *vs.* robot LVA. However, large-scale data are still needed to corroborate these results. Momentarily, a continuation of the current study with a larger population is being conducted.

## VALUE OF THE ROBOTIC-ASSISTED MICROSURGERY

### Developing the first robotic platform for microsurgery

Our Department of Plastic, Reconstructive and Hand Surgery in the Netherlands was honored to start and pursue the endeavor of creating a robot for microsurgery in 2009. Through continuous collaboration with the technicians of TU Eindhoven, the MUSA robot was created primarily for scientific purposes. Ultimately, this collaboration resulted in the establishment of Microsure®.

Our first experience with robot assistance in microsurgery using the Da Vinci provided valuable insights into the properties required for a designated microsurgical robot[20]. Although the Da Vinci is able to accommodate microsurgical instruments, its main focus is intra-abdominal procedures[30]. Due to the requisites of microsurgery, a custom platform with specific features was required.

Through the development of the MUSA, the preclinical and clinical trials by plastic surgeons using the robotic platform continuously provide the engineers with valuable feedback and have been able to expand the use of the MUSA[21,22,24,26]. Aside from LVA surgery, the MUSA is being used for digital nerve repairs and free tissue transplantation. In 2019, MUSA got the Conformité Européenne certification, allowing its use outside clinical trials.

### Distinctive characteristics of MUSA robot

MUSA robot distinguishes itself from other RAMS due to its ability to integrate well into the conventional surgical setting and, more importantly, to use current supermicrosurgical instruments. This enhances its versatility to perform both microsurgical and super microsurgical procedures, limiting the introduction of new disposable materials and thus reducing costs[26].

### Meaningful technology development for patients

Nowadays, there has been a large influx of new medical gadgets and devices, with the intention (at least in theory) to improve the quality of care and obtain better clinical outcomes. Skepticism and rejection are sometimes warranted, as patients' well-being and high-quality medical care should be the main goals of clinicians and researchers. Clinicians should remain critical and continuously ask: what are the potential benefits for patients? Do I foresee the application of this new device? Robotic assistance in microsurgery has the potential to improve current techniques to standardize care and support surgeons during surgery. Studies have shown that robot assistance is easier for inexperienced surgeons to master compared to conventional manual techniques and our current research supports this finding. Adopting an innovation such as robotic assistance in microsurgery will require incorporating robotic microsurgical training in the curriculum of plastic surgery residents.

Surgeons have always been known to be innovators because the integration of new concepts into current surgical practices is a fundamental principle[31]. So far, the field of robotic microsurgery is relatively new and RAMS represents a new enabling technology that has the capacity to advance microsurgery even further. However, to effectively disseminate innovation, it is essential to test the boundaries of the innovation. In the case of robotic assistance in microsurgery, large-scale quantitative data in the form of comparative randomized controlled trials are required.

Currently, the 3rd generation of the MUSA is being developed, which will be commercially available. The new MUSA will be mounted on a wheeled cart and will facilitate the use of 3D digital microscopes.

## CONCLUSION

The development of the MUSA robot, from its inception to the first clinical study, has produced encouraging results. However, its clinical value has not yet been evidenced on a large scale. Through randomized controlled trials, comparative studies, and cost-effectiveness analysis, the value of robotic assistance in microsurgery will become evident. When promising results are proven, it might facilitate the use of the MUSA robot in general practice.

## DECLARATIONS

### Author's contributions

Participated equally in this manuscript's conception, design, drafting, writing, and revision: Jonis YMJ, Profar JJA, van Mulken TJM, Qiu S

### Availability of data and materials

Not applicable.

### Financial support and sponsorship

None.

### Conflicts of interest

Tom J. M. van Mulken is a shareholder in the company Microsure. The other authors declare that they have no conflicts of interest.

### Ethical approval and consent to participate

Not applicable.

### Consent for publication

Not applicable.

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