

Assessment of the Learning Curve for Robotic-Assisted Microvascular Anastomosis Using the Symani Surgical System: A Prospective Training Study Across Different Levels of Surgical Experience

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Abstract

Background

Robotic-assisted microsurgery introduces specific psychomotor demands that may require dedicated training. This study aimed to propose a structured, stepwise training protocol for robotic-assisted microvascular anastomosis using the Symani Surgical System and to prospectively characterize early skill acquisition across different levels of baseline surgical experience.

Methods

Six participants were divided into experienced microsurgeons, non-experienced surgeons, and medical students. The proposed protocol included a 15-minute robotic familiarization followed by three end-to-end anastomoses on 2-mm synthetic vessels at 7-day intervals. Surgeons subsequently progressed to three 1-mm anastomoses. Performance was assessed through overall anastomosis time, individual suture time, and the Anastomosis Lapse Index (ALI).

Results

During 2-mm anastomoses, procedural and individual suture times decreased across all groups, with the greatest improvement observed among medical students. During 1-mm exercises, non-experienced surgeons progressively narrowed the initial performance gap with experienced microsurgeons. ALI scores generally decreased with repeated training, indicating that improved efficiency was accompanied by improved anastomotic quality.

Conclusions

The proposed stepwise protocol provides a structured framework for training and objectively assessing robotic microsurgical skills under progressively increasing technical difficulty. Repeated training was associated with early improvements in both procedural efficiency and technical quality, including among participants with limited baseline experience. Validation in larger cohorts and over longer training sequences is required to define reproducible learning trajectories, proficiency thresholds, skill retention, and transfer to biological and clinical settings.

Introduction

Microsurgical vascular anastomosis is a technically demanding procedure that requires precise hand movements, visuomotor coordination, fine instrument control, and consistent execution of repetitive surgical steps. Acquisition of these skills traditionally depends on extensive practice and progressive exposure under expert supervision[1, 2]. The learning process may be particularly challenging when

working with small-caliber vessels, in which minor technical inaccuracies may have a greater impact on the quality of the anastomosis[3, 4].

Robotic-assisted microsurgery has emerged as a potential means of facilitating the acquisition and execution of microsurgical skills. By providing articulated instruments, motion scaling, and tremor reduction, robotic platforms may improve instrument control and allow precise manipulation of small anatomical structures[5].

The Symani Surgical System was developed specifically for open microsurgery and supermicrosurgery and incorporates NanoWrist technology to facilitate manipulation of small-caliber tissues and vessels. Despite these technical advantages, effective use of a robotic microsurgical platform requires the acquisition of new psychomotor and instrument-specific skills, which may differ substantially from those required for conventional microsurgery[6–9].

Understanding the learning process associated with robotic-assisted microvascular anastomosis is therefore important for the development of standardized training programs and for determining the extent to which previous microsurgical experience influences the acquisition of robotic skills[6]. Objective assessment of performance should ideally encompass not only the overall time required to complete an anastomosis, but also the efficiency of individual procedural steps and the occurrence of technical errors. Such measures may provide a more comprehensive characterization of skill acquisition and help identify differences in learning trajectories among operators with different levels of baseline surgical experience[10–12].

The present study was designed to prospectively assess the learning curve associated with robotic-assisted microvascular anastomosis using the Symani Surgical System in participants with different levels of previous surgical and microsurgical experience. It aimed to characterize the acquisition of robotic microsurgical skills and to investigate the influence of previous microsurgical experience on performance during repeated training exercises.

Methods

Training Protocol

The training protocol is designed to provide a standardized and reproducible framework for acquiring and assessing robotic microsurgical skills using the Symani Surgical System. The primary objective is to evaluate progressive acquisition of technical proficiency in end-to-end microvascular anastomosis under increasing levels of procedural difficulty, progressing from 2-mm to 1-mm synthetic vessels.

This stepwise approach is intended to assess adaptation to robotic manipulation, precision of needle handling, suture placement, knot tying, tissue-edge approximation, and overall anastomotic quality.

All procedures are timed, and each individual suture and completed anastomosis is systematically evaluated using predefined technical performance criteria.

Training Environment and Equipment

Training should be performed under standardized laboratory conditions using the same robotic platform, visualization system, instruments, silicone vessel models, and suture materials throughout the training session.

Robotic platform

- Symani® Surgical System (Medical Microinstruments [MMI]).
- NanoWrist® Micro and SuperMicro instrument sets.
- Microsurgical visualization system with adequate magnification (ORBEYE™ 4K 3D exoscope, Olympus)

The magnification and motion-scaling settings should not be standardized and should be selected by each operator according to individual preference.

Vascular models

Two silicone vessel diameters are to be used:

- 2-mm internal diameter silicone vessels
- 1-mm internal diameter silicone vessels

The vessels should be secured on a stable training platform without excessive longitudinal tension or rotation.

Suture material

- 2-mm vessels: 8 – 0 microsurgical suture
- 1-mm vessels: 10 – 0 microsurgical suture

Anastomotic Technique

A standardized interrupted-suture technique consisting of eight sutures is to be adopted by all participants, beginning from the polar aspect of the vessel.

Two approaches to manipulation of the free suture end can be indifferently applied during the training (Fig. 1):

- Technique A: the free end of the suture was consistently grasped from the same side.
- Technique B: the free end of the suture was alternately grasped from both sides.

Training Sequence

The training session consists of three consecutive phases:

Phase 0 – Robotic familiarization

15-minute manual dexterity exercise using the Symani robotic arms.

Phase 1–2-mm vessel anastomosis

Three end-to-end anastomoses using 8 – 0 sutures, performed at 7-day intervals.

Phase 2–1-mm vessel anastomosis

Three end-to-end anastomoses using 10 – 0 sutures, performed at 7-day intervals.

The progression from 2-mm to 1-mm vessels introduces increasing technical difficulty while maintaining the same basic anastomotic configuration and number of sutures.

Robotic Familiarization and Manual Dexterity

Before performing vascular anastomoses, each participant undergoes a standardized 15-minute familiarization session with the Symani robotic arms.

The purpose of this phase is to allow adaptation to robotic motion scaling, instrument control, depth perception, bimanual coordination, needle manipulation, and robotic knot-tying movements before formal performance assessment.

The participant should perform repetitive exercises involving:

- bimanual manipulation;
- object grasping and transfer;
- fine instrument positioning;
- controlled opening and closing of the robotic instruments;
- needle grasping and reorientation;
- needle passage through a synthetic target;

Study Design and Training Protocol Application

This prospective experimental training study was designed to evaluate the learning curve associated with robotic-assisted microvascular anastomosis using the Symani Surgical System.

A total of six participants were enrolled in the training protocol and divided into three groups according to their baseline surgical experience:

- Group 1 – Experienced microsurgeons: two surgeons with previous experience in manual microvascular anastomosis;
- Group 2 – Non-experienced surgeons: two surgeons without previous experience in manual microvascular anastomosis;
- Group 3 – Medical students: two medical students with no previous experience in any type of surgical suturing.

The inclusion of participants with progressively lower levels of baseline surgical experience allowed the assessment of the influence of previous microsurgical skills on the acquisition of robotic-assisted anastomotic skills.

All three participant groups underwent the familiarization session and the initial 2mm-vessel training phase.

Each participant performed three consecutive end-to-end anastomoses on 2-mm synthetic vessels, for a total of six anastomoses per participant group and 18 anastomoses overall.

Following completion of the 2mm-vessel phase, the two surgeon groups proceeded to the small-vessel phase. Each surgeon performed three additional end-to-end anastomoses on 1-mm synthetic vessels, for a total of 12 anastomoses.

Performance Assessment

The learning curve was evaluated using three main performance parameters: Overall anastomosis time, Individual suture time and Anastomosis Lapse Index.

Overall anastomosis time

The total anastomosis time was recorded for each procedure and represented the time required to complete the entire end-to-end anastomosis.

Individual suture time

The time required to complete each individual suture was recorded separately. This parameter allowed assessment of changes in procedural efficiency at the level of individual sutures and across successive sutures within the same anastomosis.

Anastomosis Lapse Index

Anastomotic quality was assessed using the Anastomosis Lapse Index (ALI), a validated end-product assessment tool developed for the evaluation of microvascular anastomoses performed during microsurgical simulation training. The ALI is based on a predefined list of technical errors that may compromise anastomotic integrity and potentially result in leakage or thrombosis[11, 12].

Following completion of each anastomosis, the vascular specimen was collected and longitudinally opened to expose the internal surface of the anastomotic site. Standardized photographs of the opened anastomosis were obtained for subsequent assessment. Each specimen was evaluated according to the predefined ALI error list, and the number of identified errors was recorded as the ALI score, with lower ALI scores representing higher anastomotic quality and greater technical proficiency.

The assessment was performed on the final anastomotic product rather than during the procedure, thereby providing an independent measure of anastomotic quality complementary to the time-based performance parameters.

Data Collection

All procedural times were prospectively recorded by the trainer during each exercise and subsequently entered into a dedicated Excel database.

For each anastomosis, the following variables were recorded:

- total anastomosis time;
- time required to complete each individual suture;
- ALI score;
- participant group;
- vessel diameter;
- suture caliber;
- number of sutures;
- magnification setting;
- motion-scaling setting;
- suture manipulation technique (Technique A or B).

The sequential nature of the exercises allowed assessment of changes in performance across repeated attempts and characterization of individual learning trajectories.

Results

Study Cohort and Training Completion

Overall, all 30 planned anastomoses were completed and assessed: 18 during the 2-mm phase and 12 during the 1-mm phase. Each participant performed three anastomoses within the respective training phase (T1, T2, and T3), with each attempt performed at a 7-day interval from the preceding one.

Learning Curve for 2-mm Vessel Anastomoses

The learning curve for 2-mm vessel anastomosis was assessed using overall anastomosis and individual suture times. Both measures decreased across the three consecutive attempts in all participant groups.

Mean anastomosis time in experienced surgeons decreased from 31.20 minutes (T1) to 22.18 (T2) and 24.36 (T3), while non-experienced surgeons improved from 31.53 to 23.47 and 21.27 minutes, respectively. Medical students showed the greatest reduction, from 41.45 minutes at T1 to 31.19 at T2 and 23.44 at T3. Despite longer initial times, students showed a steeper learning curve, with between-group differences narrowing by T3.

Individual suture time followed a similar pattern. Mean times decreased from 3.58 to 2.27 and 2.36 minutes in experienced surgeons, from 3.50 to 2.44 and 2.37 minutes in non-experienced surgeons, and from 5.02 to 3.44 and 2.55 minutes in medical students across T1–T3, respectively.

Analysis of individual suture performance across the three consecutive anastomoses further illustrated the learning trajectory (Fig. 2).

Overall, both procedural measures showed improvement with repeated practice, with the greatest relative improvement observed among medical students.

Mean individual suture completion time is plotted according to suture sequence for experienced surgeons, non-experienced surgeons, and medical students. Each data point represents the mean completion time for the corresponding suture across the two participants within each group. Sutures 1–8, 9–16, and 17–24 correspond to the first (T1), second (T2), and third (T3) anastomosis, respectively, performed at 7-day intervals.

Learning Curve for 1-mm Vessel Anastomoses

The four surgeons subsequently performed three 1-mm vessel anastomoses using SuperMicro instrumentation. Learning curves were assessed using overall anastomosis and individual suture times.

Mean anastomosis time among expert surgeons was 19.41 minutes at T1, 23.13 at T2, and 21.29 at T3. Non-expert surgeons showed a progressive reduction from 31.29 to 26.06 and 19.50 minutes, respectively, reaching comparable times to experts by T3.

Individual suture time followed a similar pattern (Fig. 3). Mean times remained relatively stable among experts (2.18, 2.50, and 2.41 minutes at T1–T3), whereas non-experts progressively improved from 3.55 to 3.12 and 2.24 minutes.

Overall, non-expert surgeons showed a more pronounced learning curve, with improvements in both measures progressively narrowing the initial performance gap.

Mean individual suture completion time is plotted according to suture sequence for experienced surgeons and non-experienced surgeons. Each data point represents the mean completion time for the corresponding suture across the two participants within each group. Sutures 1–8, 9–16, and 17–24 correspond to the first (T1), second (T2), and third (T3) anastomosis, respectively, performed at 7-day intervals.

Anastomosis Lapse Index

Qualitative assessment of the microvascular anastomoses using the Anastomosis Lapse Index (ALI) showed an overall improvement in anastomotic quality over repeated robotic training sessions.

For 2-mm vessels, the mean ALI score decreased from 5.0 at the first anastomosis to 3.0 at the second and 3.5 at the third attempt in expert surgeons. Non-expert surgeons showed a reduction from 4.5 at both the first and second attempts to 3.5 at the third, while medical students demonstrated a progressive decrease from 5.0 to 4.5 and 4.0 across the three consecutive anastomoses (Fig. 4).

Mean Anastomosis Lapse Index (ALI) values are shown for experienced surgeons, non-experienced surgeons, and medical students across three consecutive anastomosis attempts (T1–T3), performed at 7-day intervals. Each bar represents the mean ALI of the two participants within each group at the corresponding attempt.

For 1-mm vessels, evaluated only in surgeons, ALI scores remained relatively stable between the first two attempts and decreased at the third anastomosis. Expert surgeons showed mean scores of 3.5, 4.0, and 3.0 across the three attempts, respectively, whereas non-expert surgeons showed corresponding scores of 4.0, 4.5, and 3.5. Thus, both groups achieved their lowest ALI score at the third 1-mm anastomosis (Fig. 5).

Mean Anastomosis Lapse Index (ALI) values are shown for experienced and non-experienced surgeons across three consecutive anastomosis attempts (T1–T3), performed at 7-day intervals. Each bar represents the mean ALI of the two participants within each group at the corresponding attempt.

Overall, repeated robotic practice was associated with a reduction in technical errors and improved anastomotic quality, with the clearest progressive improvement observed in 2-mm anastomoses performed by participants without previous surgical experience.

The progressive reduction in ALI scores occurred in parallel with the reduction in overall anastomosis and individual suture times, indicating that the improvement in procedural speed was accompanied by an improvement in the technical quality of the final anastomotic product.

Discussion

This prospective training study investigated the early acquisition of robotic-assisted microvascular anastomotic skills using the Symani Surgical System across participants with markedly different levels of baseline surgical experience. Three main findings emerged. First, repeated robotic practice was associated with an early improvement in procedural efficiency, reflected by reductions in both overall anastomosis time and individual suture time. Second, this increase in efficiency occurred alongside a reduction in technical errors, suggesting that greater efficiency was achieved without compromising anastomotic quality. Third, baseline surgical and microsurgical experience appeared to influence initial performance and the shape of the learning trajectory, but did not preclude substantial improvement in less experienced participants. Indeed, medical students showed the greatest improvement during 2-mm anastomosis, while non-experienced surgeons progressively narrowed the initial performance gap with experienced microsurgeons during the more demanding 1-mm exercises. Taken together, these findings characterize an early learning effect for robotic-assisted microvascular anastomosis and suggest that adaptation to the robotic interface can occur rapidly across different levels of previous microsurgical experience.

Early learning curve

Procedural time decreased across repeated exercises, although improvement varied with baseline experience and task difficulty. During 2-mm anastomoses, all groups reduced both overall anastomosis and individual suture times, supporting an early improvement in procedural efficiency regardless of previous experience. As formal assessment followed only a 15-minute familiarization period, these changes likely reflect progressive adaptation to the visuomotor and psychomotor demands of robotic manipulation, including indirect instrument control, bimanual coordination, needle handling, and knot tying.

This pattern is consistent with previous preclinical studies of the Symani Surgical System. Von Reibnitz et al. reported improvements in anastomosis time and microsurgical performance during repeated 2-mm vessel training, with the influence of previous surgical experience diminishing by the final session[14]. Similar improvements across different experience levels were reported by Wessel et al.[15], while Struebing et al. demonstrated a pronounced learning effect among medical students without previous microsurgical training[16]. Clinical experience has likewise shown progressive reductions in robotic anastomosis time[5]. Together, these findings suggest that substantial adaptation to the robotic platform may occur after relatively limited training exposure.

The transition from 2-mm vessels with 8 – 0 sutures to 1-mm vessels with 10 – 0 sutures provided a controlled increase in technical difficulty. Experienced microsurgeons maintained relatively stable performance, whereas non-experienced surgeons progressively reduced both overall and individual suture times, narrowing the initial performance gap by the third exercise. This may reflect less room for improvement among experienced operators and greater adaptation among non-experienced participants. Given the small cohort and limited repetitions, however, these patterns should not be interpreted as evidence of a performance plateau.

Learning trajectories were not strictly linear, with fluctuations between attempts even among experienced operators. Such variability is expected during acquisition of complex psychomotor skills, where improvement is not necessarily monotonic. With only three exercises per vessel diameter, our findings therefore characterize early skill acquisition rather than the complete learning curve. Proficiency and mastery require greater procedural exposure[1]. Larger studies with additional repetitions could apply CUSUM, nonlinear regression, or plateau analyses to identify performance stabilization and objective proficiency thresholds.

Procedural efficiency and technical quality

Procedural time alone provides an incomplete measure of microsurgical performance, as faster execution may compromise technical accuracy. We therefore assessed procedural efficiency alongside technical errors using the Anastomosis Lapse Index (ALI)[11, 12].

Rather than indicating a speed–accuracy trade-off, reductions in procedural time were generally accompanied by improved ALI scores. During 2-mm anastomoses, medical students showed the greatest reduction in both procedural time and technical errors, while non-experienced surgeons also improved by the third exercise and experienced microsurgeons maintained relatively low error rates. During 1-mm anastomoses, both surgeon groups achieved their lowest mean ALI scores at the third exercise. Thus, improved efficiency was accompanied by greater accuracy, supporting genuine early skill acquisition rather than faster task execution alone.

Robotic features such as motion scaling, tremor filtration, and articulated instrumentation may facilitate precise manipulation during skill acquisition[17]. Although their individual contributions cannot be determined from our study, adaptation to the robotic interface occurred without an evident speed–accuracy trade-off.

Nevertheless, ALI is an end-product assessment and does not capture patency, flow characteristics, endothelial injury, mechanical strength, or tissue trauma. Future studies should integrate error-based evaluation with functional endpoints, including leakage, patency, and flow assessment, and process-based measures such as instrument trajectory, economy of movement, and force analysis. Such multidimensional evaluation may better distinguish faster execution from true technical proficiency.

Influence of previous microsurgical experience on robotic skill acquisition

Baseline microsurgical experience did not appear to confer a persistent advantage during robotic skill acquisition. During 2-mm anastomoses, experienced and non-experienced surgeons showed similar initial performance, whereas medical students started with longer procedural times but demonstrated the greatest relative improvement, markedly narrowing between-group differences by the third exercise. Similarly, during 1-mm anastomoses, non-experienced surgeons progressively approached the performance of experienced microsurgeons, whose performance remained relatively stable. This may

reflect greater learning potential among less-experienced participants, while experienced operators started closer to their early performance ceiling[18].

These findings are consistent with previous robotic microsurgery studies. Von Reibnitz et al. reported a diminishing association between previous surgical experience and performance across successive training sessions[14]. Similarly, training with the MUSA-2 system showed improvement across different experience levels, with no significant differences in robotic procedural time between groups, whereas manual performance remained associated with previous microsurgical experience[19].

Robotic microsurgery preserves the principles of conventional microsurgery while introducing a distinct motor interface through motion scaling, tremor filtration, articulated instrumentation, and indirect visuomotor control. Experienced surgeons must adapt established motor patterns to this interface, whereas less-experienced participants may have fewer consolidated patterns to recalibrate. This may partly explain the substantial early gains observed among participants with limited or no previous microsurgical experience.

These findings do not imply that conventional microsurgical expertise becomes irrelevant. Experienced surgeons retain critical advantages in tissue handling, procedural planning, error recognition, anatomical knowledge, and intraoperative decision-making, which cannot be assessed in a synthetic anastomosis model. Rather, our findings suggest that robotic skill acquisition may represent a partially distinct psychomotor domain in which the influence of baseline manual experience may diminish after initial adaptation.

Implications for robotic microsurgical training and future directions

Taken together, these findings support the training protocol proposed in the present study as a structured framework for the early acquisition and objective assessment of robotic microsurgical skills. The protocol combines an initial familiarization phase with repeated standardized microvascular anastomoses of progressively increasing technical difficulty, moving from 2-mm vessels with 8 – 0 sutures to 1-mm vessels with 10 – 0 sutures, while assessing performance through complementary measures of procedural efficiency and technical quality. This stepwise design provides a reproducible training environment in which individual learning trajectories can be monitored across operators with different levels of baseline microsurgical experience.

Importantly, the proposed protocol should be regarded as a preliminary training framework rather than a validated curriculum. The present study was designed to characterize early performance changes and does not establish the number of repetitions required to achieve proficiency or the thresholds that should determine progression between training stages. Nevertheless, our findings provide a rationale for further developing this framework toward a proficiency-based approach to robotic microsurgical training[20]. Rather than defining progression exclusively by the number of procedures performed or by

the operator's previous surgical experience, advancement could ultimately be based on objective performance criteria combining procedural efficiency and technical quality.

Within such a framework, trainees could progress from robotic familiarization to standardized 2-mm anastomosis and subsequently to smaller-caliber vessels after reaching predefined performance thresholds[21]. Increasingly demanding biological models could then be introduced to assess whether skills acquired in standardized synthetic tasks transfer to environments that reproduce vessel compliance, adventitial dissection, tissue fragility, bleeding, and other features of clinical microsurgery[22, 23]. Importantly, the present data do not establish such proficiency thresholds; rather, they provide preliminary evidence that individual learning trajectories can be captured using the proposed protocol through combined time- and quality-based assessment.

Future validation should determine whether these early performance gains are retained over time, transferable to biological tissues, and ultimately reflected in clinical performance. Skill retention and transfer should therefore represent key endpoints when the proposed training protocol is evaluated in larger prospective cohorts.

Limitations

Several limitations should be acknowledged. First, the study included only six participants, with two individuals in each experience group. The observed between-group differences and learning trajectories should therefore be regarded as exploratory and descriptive, and no definitive conclusions can be drawn regarding the independent effect of previous microsurgical experience.

Second, only three repetitions were performed for each vessel diameter. Although sufficient to identify early changes in performance, this exposure is insufficient to characterize a complete learning curve, establish a plateau, or define proficiency. Longer training sequences and longitudinal assessment will be necessary to determine both the number of repetitions required to achieve stable performance and the retention of acquired skills over time.

Third, medical students participated only in the 2-mm phase. Consequently, the study cannot determine whether the pronounced improvement observed among participants without any previous surgical experience would persist when procedural difficulty increases.

Fourth, synthetic vessels provide a reproducible environment for standardized performance assessment but cannot replicate the biological characteristics of living vessels, including tissue compliance, adventitial dissection, pulsatility, fragility, bleeding, and thrombogenicity. Progression toward biological and ultimately clinical models will therefore be necessary to evaluate transferability.

Fifth, magnification and motion-scaling settings were selected according to operator preference rather than standardized across participants. Although this reflects individualized use of the robotic platform, it

introduces an additional source of variability and may influence comparisons between individual learning trajectories.

Finally, ALI provides a structured assessment of technical errors in the final anastomotic product but does not capture all dimensions of microsurgical performance. Future studies should integrate functional measures such as leakage and patency testing with objective robotic performance metrics and, where possible, blinded video-based assessment.

Larger prospective studies incorporating more participants, repeated procedures, formal learning-curve modeling, retention testing, and progressive transition from synthetic to biological models will be required to determine whether the early convergence observed here translates into sustained robotic proficiency. In particular, clarifying the extent to which robotic assistance modifies the dependence of microsurgical technical performance on previous manual experience may have important implications for the design of future robotic microsurgical curricula.

Conclusions

This prospective training study demonstrates an early learning effect during robotic-assisted microvascular anastomosis with the Symani Surgical System and proposes a structured, stepwise training protocol for the acquisition and objective assessment of robotic microsurgical skills. Repeated training was associated with improved procedural efficiency together with a reduction in technical errors, suggesting that faster execution was not achieved at the expense of anastomotic quality. Baseline surgical experience influenced initial performance and learning trajectories, particularly as task difficulty increased; however, participants with limited or no previous microsurgical experience demonstrated substantial improvement over repeated exercises, progressively narrowing initial performance differences.

These findings suggest that acquisition of robotic-assisted microsurgical skills may involve a partially distinct psychomotor learning process and support further development of structured, proficiency-based robotic training. The proposed protocol now requires validation in larger cohorts and over longer training sequences to define reproducible learning trajectories and objective proficiency thresholds, assess skill retention and transfer, and determine whether performance acquired in standardized synthetic models translates to biological models and, ultimately, clinical microsurgery.

Declarations

Conflicts of Interest:

None

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None

Author Contribution

Conceptualization: S.P., R.S. ; Methodology: D.C. , M.B. , A.C. ; Data curation: M.B. , M.S. , D.C. ; Formal analysis: M.B. , M. S. ; Writing – original draft: M.S. , V.M. ; Writing – review & editing: M.S. , V.M. , D.C. ; Supervision: R.S., S.P. M.S. and D.C. contributed equally to this work.All authors reviewed and approved the final version of the manuscript.

Data Availability

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

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Figures

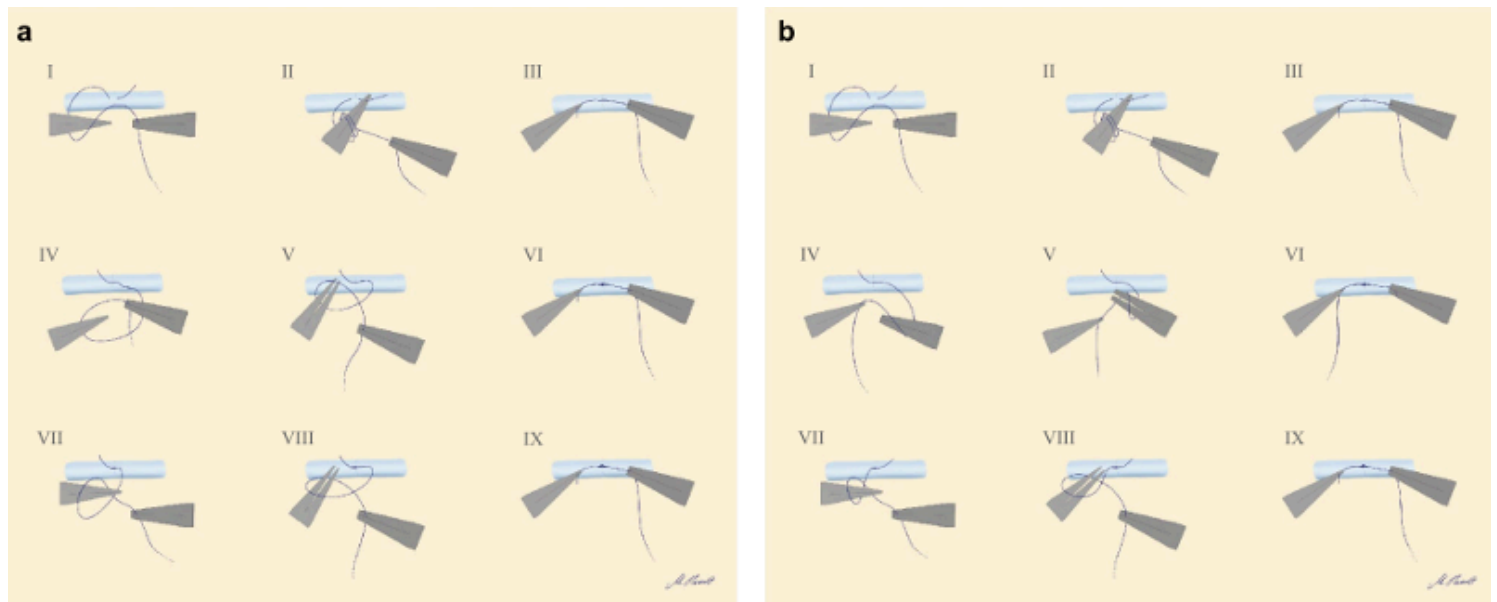


Figure 1

Schematic representation of the steady-thread (a) and switch-thread (b) suturing techniques for robot-assisted microsurgical anastomosis. Reproduced from Wessel et al.[13], under the terms of the Creative Commons Attribution 4.0 International License (CC BY 4.0).

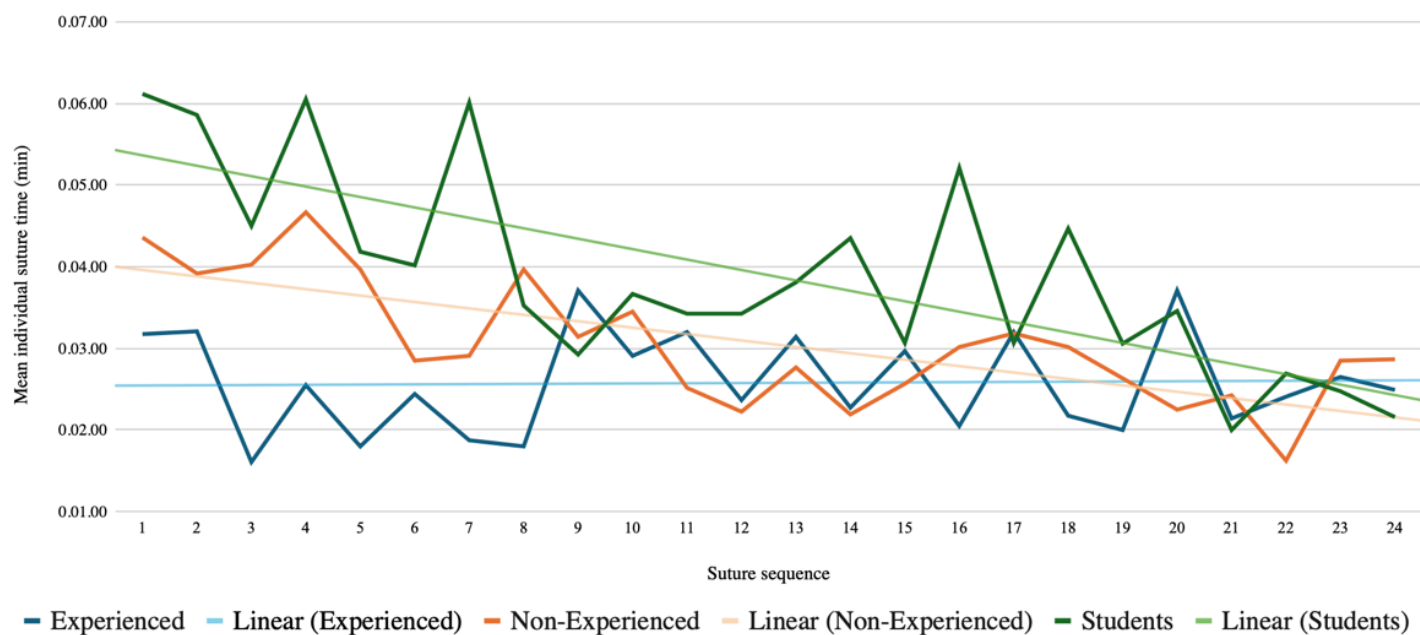


Figure 2

Individual suture time during 2-mm vessel anastomosis.

Mean individual suture completion time is plotted according to suture sequence for experienced surgeons, non-experienced surgeons, and medical students. Each data point represents the mean completion time for the corresponding suture across the two participants within each group. Sutures 1–8, 9–16, and 17–24 correspond to the first (T1), second (T2), and third (T3) anastomosis, respectively, performed at 7-day intervals.

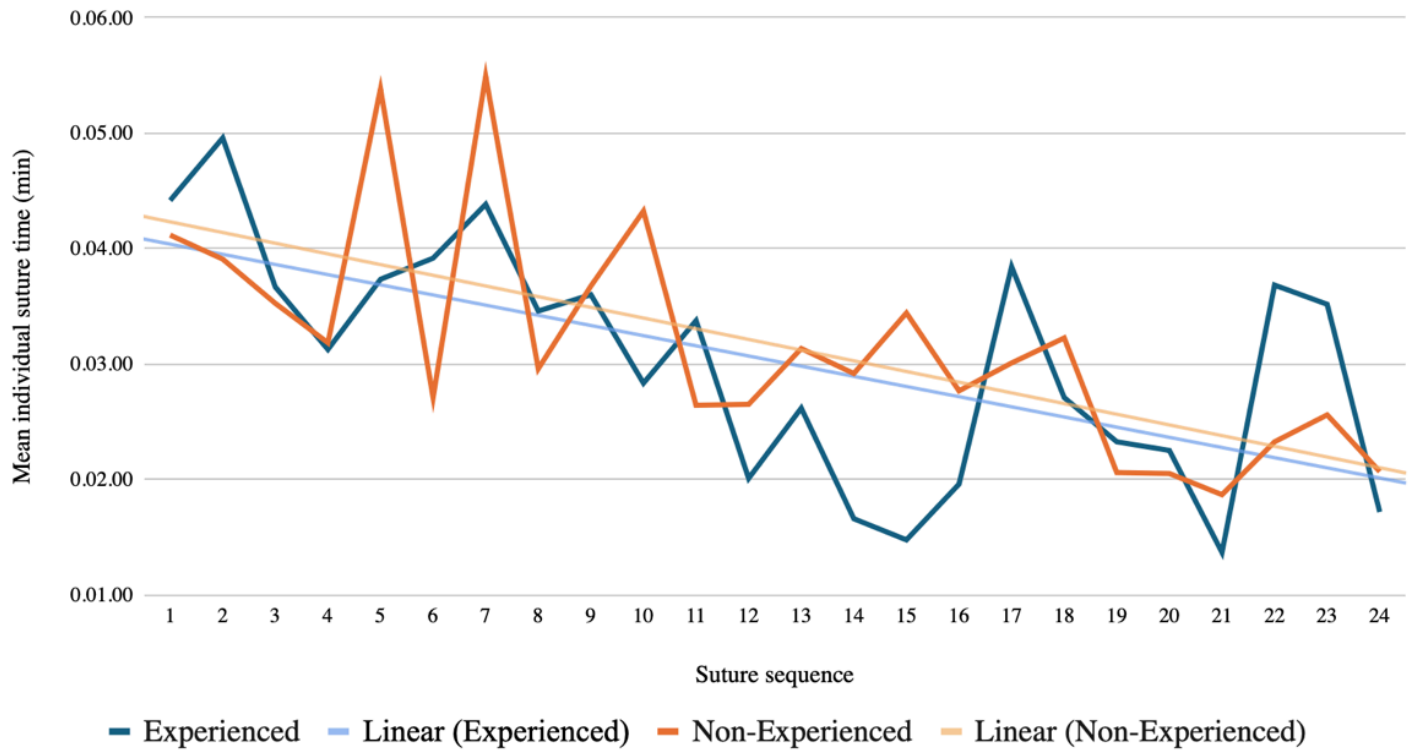


Figure 3

Individual suture time during 1-mm vessel anastomosis.

Mean individual suture completion time is plotted according to suture sequence for experienced surgeons and non-experienced surgeons. Each data point represents the mean completion time for the corresponding suture across the two participants within each group. Sutures 1–8, 9–16, and 17–24 correspond to the first (T1), second (T2), and third (T3) anastomosis, respectively, performed at 7-day intervals.

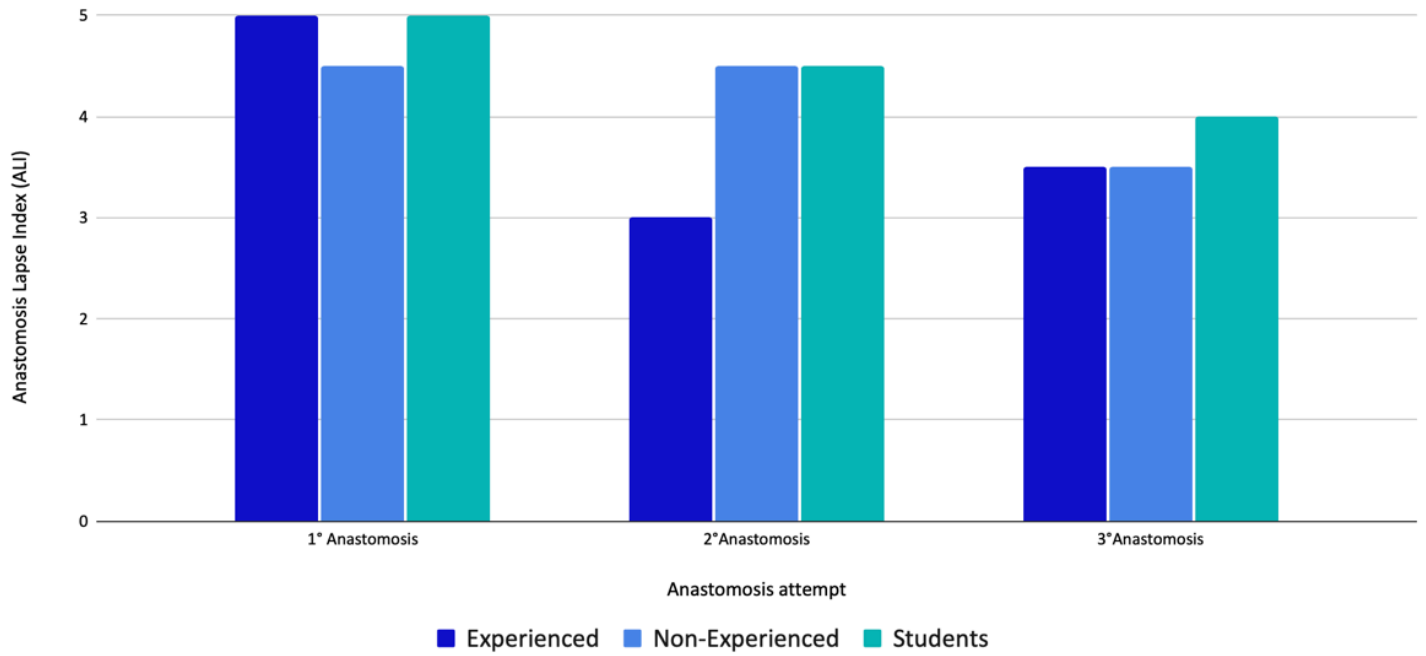


Figure 4

Anastomosis Lapse Index during 2-mm vessel anastomosis.

Mean Anastomosis Lapse Index (ALI) values are shown for experienced surgeons, non-experienced surgeons, and medical students across three consecutive anastomosis attempts (T1–T3), performed at 7-day intervals. Each bar represents the mean ALI of the two participants within each group at the corresponding attempt.

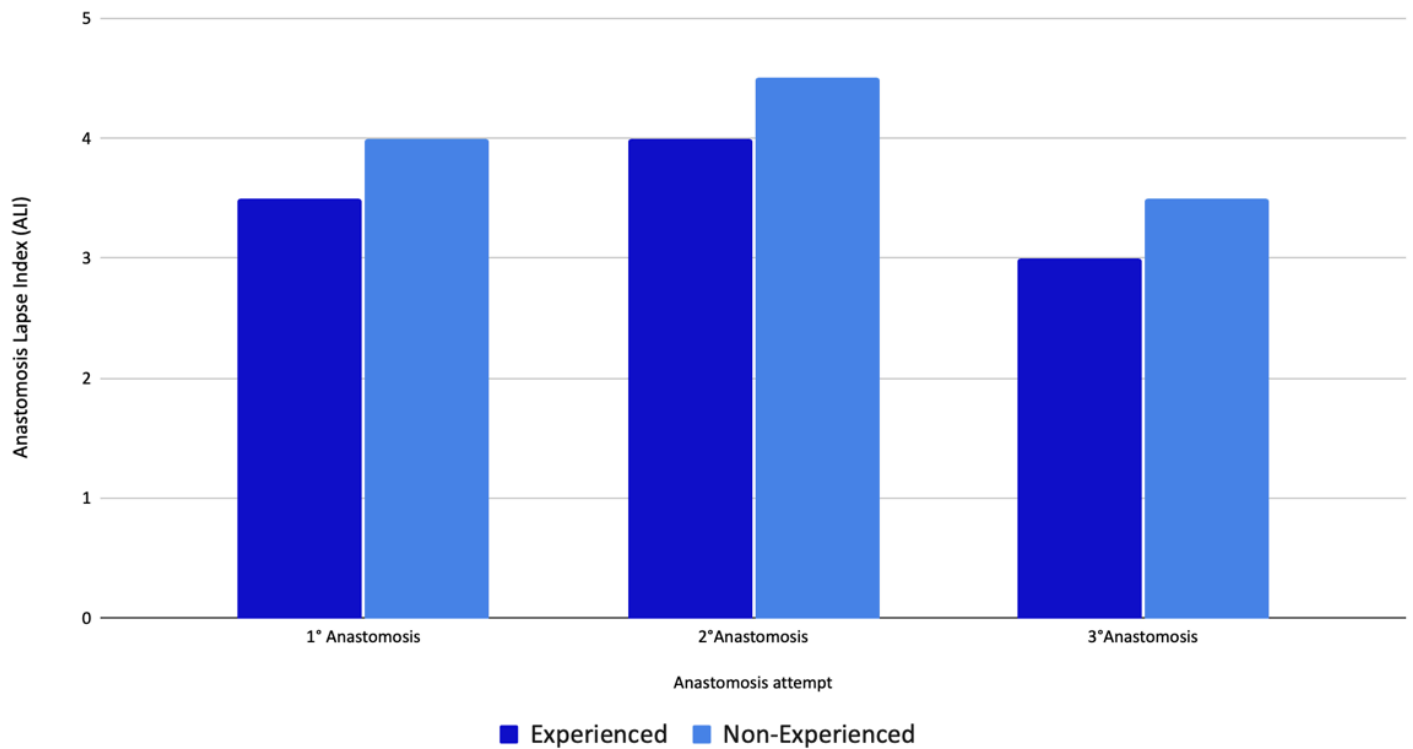


Figure 5

Anastomosis Lapse Index during 1-mm vessel anastomosis.

Mean Anastomosis Lapse Index (ALI) values are shown for experienced and non-experienced surgeons across three consecutive anastomosis attempts (T1–T3), performed at 7-day intervals. Each bar represents the mean ALI of the two participants within each group at the corresponding attempt.