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Preclinical Performance of the Combined Application of Two Robotic Systems in Microsurgery: A Two-center Study

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Background: Recent advancements in the development of robotic devices increasingly draw the attention toward the concept of robotic microsurgery, as several systems tailored to open microsurgery are being introduced. This study describes the combined application of a novel microsurgical robot, the Symani, with a novel robotic microscope, the RoboticScope, for the performance of microvascular anastomoses in a two-center preclinical trial.

Methods: Six novices, residents, and experienced microsurgeons (n = 18) performed five anastomoses on 1.0-mm-diameter silicone vessels with a conventional versus combined robotic approach, resulting in 180 anastomoses. Microsurgical performance was evaluated, analyzing surgical time, subjective satisfaction with the anastomosis and robotic setup, anastomosis quality using the anastomosis lapse index score, microsurgical skills using the Structured Assessment of Microsurgery Skills score, and surgical ergonomics using the Rapid Entire Body Assessment score.

Results: All participants significantly improved their performance during the trial and quickly adapted to the novel systems. Surgical time significantly decreased, whereas satisfaction with the anastomosis and setup improved over time. The use of robotic systems was associated with fewer microsurgical errors and enhanced anastomosis quality. Especially novices demonstrated accelerated skill acquisition upon robotic assistance compared with conventional microsurgery. Moreover, upper extremity positioning was significantly improved. Overall, the robotic approach was subjectively preferred by participants.

Conclusions: The concept of robotic microsurgery holds great potential to improve precision and ergonomics in microsurgery. This two-center trial provides promising evidence for a steep learning curve upon introduction of robotic microsurgery systems, suggesting further pursuit of their clinical integration. *(Plast Reconstr Surg Glob Open 2024; 12:e5775; doi: 10.1097/GOX.0000000000005775; Published online 29 April 2024.)*

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INTRODUCTION

Robot-assisted surgery has transformed many surgical specialties over the last decades, driven by the rise of the da Vinci system dedicated to minimally invasive procedures. In the field of plastic and reconstructive surgery, successful application of the da Vinci system has been demonstrated for minimally invasive muscle harvest, robot-assisted breast reconstruction, transoral head and neck reconstruction, and microvascular anastomoses.[1–4] Advancements in the development of surgical strategies for defect coverage and flap design are currently leading to increased application of supermicrosurgical approaches, aiming to further reduce donor site morbidity and optimize the functional and aesthetic outcome.[5,6] Thereby, reconstructive microsurgery more than ever

Disclosure statements are at the end of this article, following the correspondence information.

heavily relies on optimal vision, precision, and dexterity to successfully perform microvascular and supermicrovascular anastomoses.

Lately, the concept of robot-assisted microsurgery is gaining traction through the development of novel robotic systems specifically designed for the needs of open (super-)microsurgery. The Symani surgical system (Medical Microinstruments Inc., Wilmington, Del.) provides motion scaling and tremor reduction to improve the handling and suturing of submillimeter structures. It has been successfully used for lymphovenous anastomoses, lymph node transfers, and free flap reconstructions in initial clinical studies, demonstrating safety and feasibility of the approach.[7–9] Moreover, novel robotic microscopes are aiming to improve microsurgical performance by enhanced vision and more ergonomic working positions. The RoboticScope (BHS Technologies, Innsbruck, Austria) has been successfully applied in the field plastic surgery and head and neck surgery for free flap reconstruction, in otorhinolaryngology for cochlear implantation, and in neurosurgery for brain tumor resection and lumbar spine decompression so far, consistently revealing increased operative comfort and workflow efficacy.[10–14]

This study was set out to further investigate the combined application of a novel robotic microsurgery system with a robotic microscope in a preclinical setting and to provide evidence for the benefits and limitations of robotics in (super-)microsurgery.

Takeaways

Question: What are the benefits and limitations of novel robotic devices for microsurgery, based on different levels of microsurgical experience?

Findings: In this nonrandomized controlled preclinical study, which included 180 microvascular anastomoses on 1.0-mm-diameter artificial silicone vessels, participants showed improved microsurgical skill acquisition, anastomosis quality, and surgical ergonomics upon robotic assistance compared with conventional microsurgery.

Meaning: The introduction of novel robotic devices for microsurgery holds great potential to facilitate microsurgical procedures and potentially improve their outcome.

METHODS

Technical Setup

The performance of microvascular anastomoses was compared between a combined robot-assisted approach and a conventional approach, further distinguishing by the level of microsurgical experience. During the robotic approach, the Symani surgical system was used in combination with the RoboticScope. The Symani is a CE-certified robotic device, specifically designed for the needs of microsurgical procedures. It is a nonautonomous master slave system, which is fully controlled by the surgeon, offering the world's smallest wristed microsurgical and supermicrosurgical instruments with motion scaling from 7× to 20×, tremor elimination, and additional distal motion axes with seven degrees of freedom. Dedicated to open microsurgery, the robotic arms of the Symani can be positioned at any anatomical region and are intuitively controlled via two forceps-like manipulators.

The RoboticScope is a CE-certified robotic microscope with two extended full HD/HDR+ camera systems, merged 4K resolution (4928 × 2056 pixels) and 2.7–30.1× magnification. The image of the surgical site is captured by a microscopic camera unit and transferred to a head-mounted display, which further detects and interprets head movements of the surgeon. Thereby, the system is operated completely freehand, using only head gestures to modify the setup, such as zoom, focus, and working distance. The unique advantage of the combined application of both systems is the potential to perform microsurgical procedures fully telemetrically by uncoupling the surgeon from the surgical site (Fig. 1).

For manual microanastomoses, a conventional surgical microscope (Leica Microsystems, Germany)

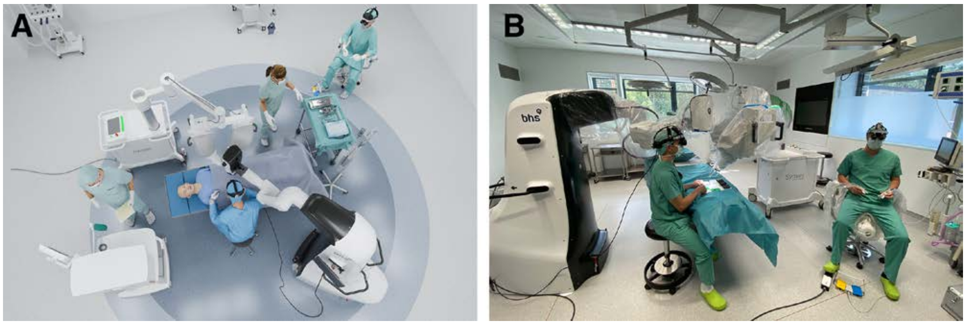

Fig. 1. Surgical setup. A, Illustration of the surgical setup in the operating room. The Symani (top left) is used in combination with the RoboticScope (bottom right), leaving enough space for an assistant, nurse and anesthesiologist. Different working distances of the two systems (Symani arms working directly at the vessel, RoboticScope arm positioned 300 mm above the operative field) enabled unrestricted and collision-free robotic movements. The surgeon (top right) is operating remotely. B, Photograph of the surgical setup under study conditions (left: RoboticScope and assistant, right: Symani and surgeon).

and conventional microsurgical instruments (S&T, Switzerland) were used.

Study Population

The study was performed at two specialized centers for plastic and reconstructive surgery, contributing equal numbers of participants to the cohort. Six participants with 5 years of experience or more in reconstructive microsurgery (attending physicians), six participants with 2–4 years of experience (senior residents), and six being complete novices in microsurgery (medical students) were included. None of the participants had previous working experience with the Symani or RoboticScope. Therefore, a systematic introduction into the use of the robotic devices and standardized skill tasks were performed before the start of the study. Novices further received a general microsurgery introduction.

Microvascular anastomoses were performed in an end-to-end fashion using 1.0-mm-diameter artificial silicone vessels (WetLab, Japan) with six stitches of 10-0 sutures (Ethilon, Ethicon, USA), three on the front wall and back wall, respectively. Microvessels were stabilized using approximators. In an alternating order, each participant performed five full robotic anastomoses using the Symani and RoboticScope and five full conventional anastomoses using a conventional microscope and conventional micro-instruments, resulting in 180 anastomoses in total (90 per approach). Robot-assisted anastomoses were performed with 10× motion scaling, 4× zoom, 300-mm working distance, 5% brightness, and 50% contrast.

Data Collection and Processing

The time to complete anastomoses was recorded. After finishing each anastomosis, participants had to fill out a questionnaire evaluating their subjective satisfaction with the anastomosis and satisfaction with the Symani system performance, RoboticScope performance, and combined performance of both systems on a numeric rating scale from 1 (minimum) to 10 (maximum). Moreover, participants evaluated the robotic approach relative to the conventional approach using a questionnaire described by Will et al[15] regarding the following aspects: team interaction and communication, freedom of movement, back and neck tenderness, intraoperative tremor, muscle fatigue, optical detail, microsurgical handling, depth and 3D structure visualization, operative comfort, and overall satisfaction (1 = significantly worse, 2 = worse, 3 = equal, 4 = better, 5 = significantly better).

To evaluate the quality of microvascular anastomoses, the anastomosis lapse index (ALI) was applied. Anastomoses were everted, captured, and analyzed by a single reviewer to identify the total number and specific types of errors that were previously described by Ghanem et al[16]: anastomosis line disruption, backwall or sidewall catch, oblique stitch causing distortion, bite leading to tissue infoldment, partial thickness stitch, unequal distancing of sutures, visible tear in vessel wall, strangulation of tissue edges, thread in lumen, and large edge overlap.

The development of microsurgical skills was further analyzed using the Structured Assessment of Microsurgery Skills (SAMS) by Chan et al,[17] later modified by van Mulken et al[18] for robotic microsurgery, evaluating dexterity (steadiness, instrument handling, tissue handling), visuospatial ability (suture placement, knot technique), and operative flow (steps, motion, speed) on a numeric rating scale from 1 (minimum) to 5 (maximum). Deidentified and blinded videos of each procedure were rated by a single experienced reviewer.

Posture analysis was performed using the Rapid Entire Body Assessment (REBA) approach.[19] Therefore, participants were captured during each anastomosis from a right-angled sideview perspective. Neck, trunk, leg, upper arm, lower arm, and wrist position were analyzed, also assessing the load/force score, coupling score and activity score. Total REBA scores and indicative levels of musculoskeletal disorder (MSD) risk were calculated.

Statistical Analysis

Statistical analysis was performed using GraphPad Prism software version 6.0 (GraphPad Software Inc., USA). In all plots and bar charts, dots represent individual values with arithmetic mean and SD or standard error of the mean (SEM), as indicated. Statistical significance was assessed for anastomosis time, subjective satisfaction, ALI scores, SAMS scores, and REBA scores using a two-way ANOVA when comparing multiple groups (corrected for multiple comparisons with Tukey and Sidak test, 95% confidence interval) and Student t test when comparing the means of two groups (unpaired, two-tailed, 95% confidence interval). P values of less than 0.05 were considered statistically significant.

RESULTS

Surgical Time and Subjective Performance

Throughout the training, all participants showed a steep learning curve, significantly reducing their surgical time. In the group of novices, the mean time for conventional anastomoses decreased from 54 minutes in the first attempt to 24 minutes in the fifth attempt, and the mean time for robot-assisted anastomoses significantly decreased from 74 minutes to 27 minutes (Fig. 2A). The surgical time of residents decreased from 29 minutes to 18 minutes for conventional anastomoses and from 35 minutes to 24 minutes for robot-assisted anastomoses (Fig. 2B). Experienced microsurgeons started at a lower baseline with 15 minutes during the conventional approach, finishing with 12 minutes. Upon robotic assistance, their mean surgical time decreased significantly from 29 minutes to 19 minutes (Fig. 2C). At the end of the training, the difference between surgical times of the two approaches was not statistically significant in all groups. Along with a reduction of surgical time, participant's subjective satisfaction with conventional anastomoses increased from 5.3 to 7.2 mean points, whereas their subjective satisfaction with robot-assisted anastomoses significantly increased from 4.8 to 7.4 points (Fig. 2D).

Evaluation of the Surgical Setup

After completion of each robot-assisted anastomosis, all participants evaluated their subjective satisfaction

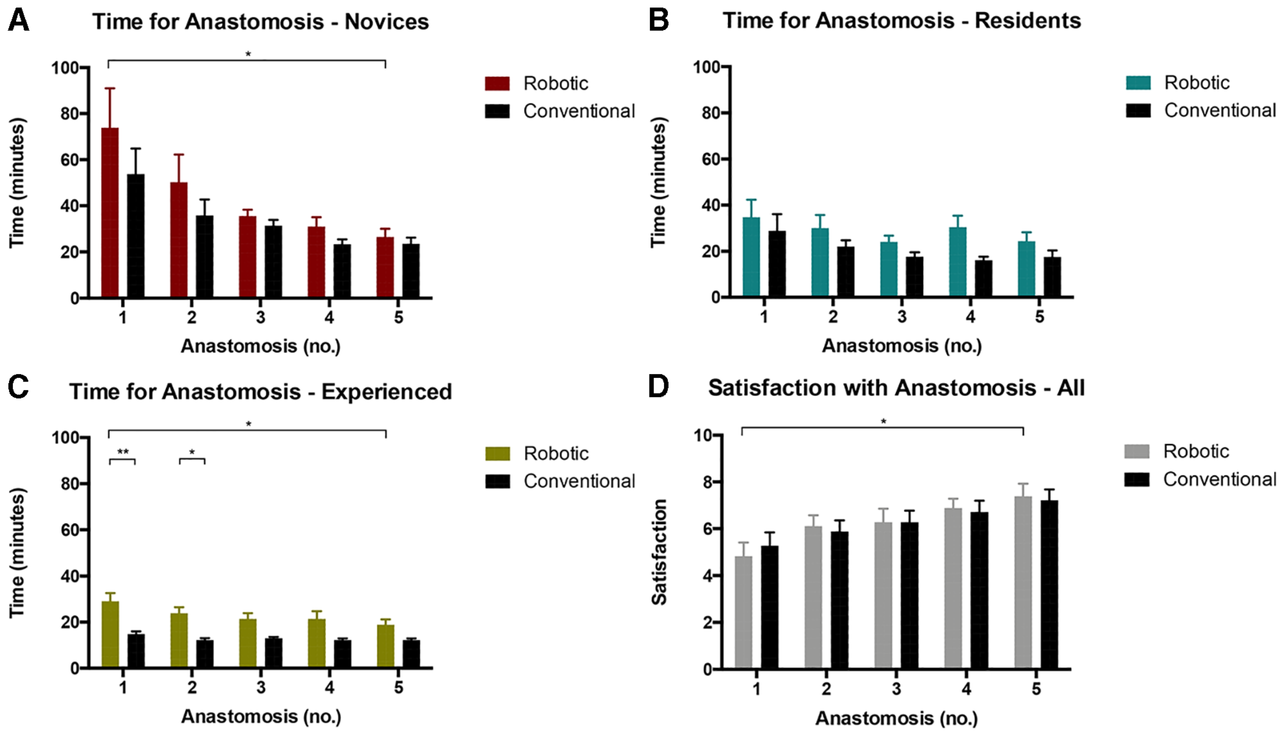

Fig. 2. Time for anastomosis and satisfaction with anastomosis. Participants performed five microsurgical anastomoses with the conventional technique and five anastomoses with the robot-assisted technique on artificial blood vessels with 1 mm diameter. Bar charts indicate the mean time in minutes with SEM that (A) novices (n = 6), (B) residents (n = 6), and (C) experienced microsurgeons (n = 6) needed to complete each anastomosis. D, Participants further evaluated their subjective satisfaction with the anastomosis on a scale from 1 (minimum) to 10 (maximum). The bar chart indicates the mean satisfaction with each anastomosis of all participants (n = 18; $*P < 0.05$, $**P < 0.01$).

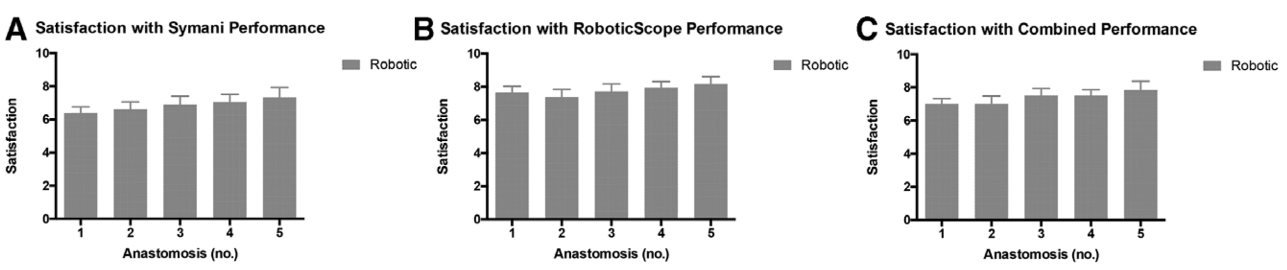

Fig. 3. Evaluation of the robotic systems. After each robot-assisted anastomosis, all participants (n = 18) separately evaluated the performance of (A) the Symani surgical system and (B) the RoboticScope, as well as (C) the combined application of the Symani system with the RoboticScope. Bar charts indicate mean satisfaction on a scale from 1 (minimum) to 10 (maximum) with SEM.

with the Symani system and RoboticScope performance separately, as well as the synergistic performance of both systems combined. Throughout all three groups, subjective satisfaction with the Symani system performance increased from 6.4 to 7.4 mean points after the first and last robotic anastomosis (Fig. 3A), whereas subjective satisfaction with the RoboticScope performance increased from 7.7 to 8.2 mean points (Fig. 3B). Subjective satisfaction with the combined performance of both systems was rated with 7.0 mean points at the beginning of the trial and 7.8 mean points at the end of the trial (Fig. 3C).

Furthermore, participants evaluated the combined robotic approach relative to the conventional approach, using a multidimensional questionnaire. Remarkably, none of the 10 items was evaluated worse or significantly worse upon robotic assistance compared with the conventional approach throughout all groups. Mean evaluations of "team interaction and communication," "freedom of movement," "back or neck tenderness," and "microsurgical handling" lay between equal and better upon robotic assistance, whereas "intraoperative tremor," "muscle fatigue," "optical detail," "depth and 3D structure visualization," and "operative comfort" were rated between better and significantly better with the robotic approach (Fig. 4). Overall, the robot-assisted approach was preferred over the conventional approach by participants from all groups.

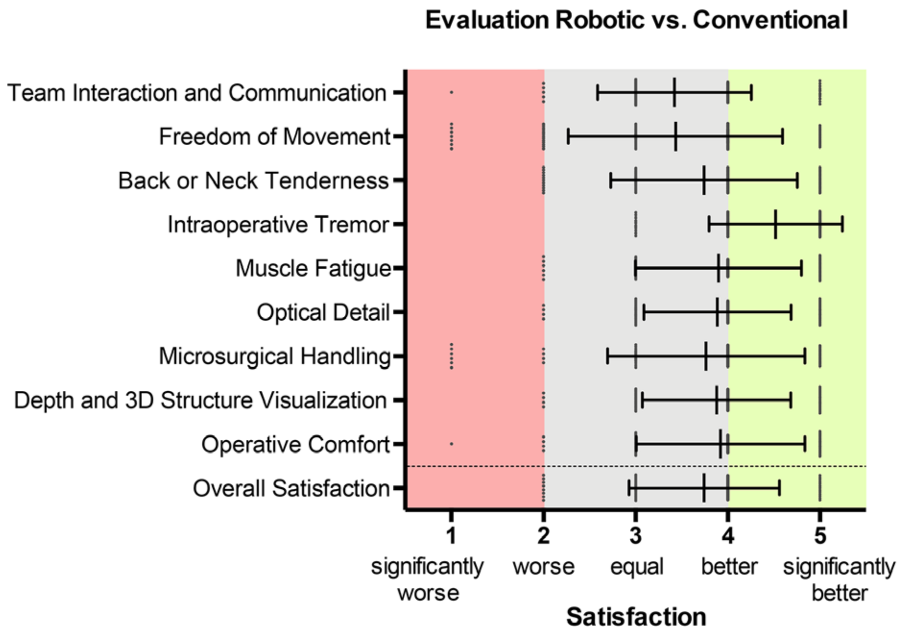

Fig. 4. Multidimensional comparison of the robotic and conventional approach. After the performance of each robot-assisted anastomosis (n = 90), novices, residents, and experienced microsurgeons evaluated the robotic approach relative to the conventional approach, according to an established multidimensional questionnaire. Black bars and whiskers indicate mean evaluations with SD, whereas gray dots represent individual values.

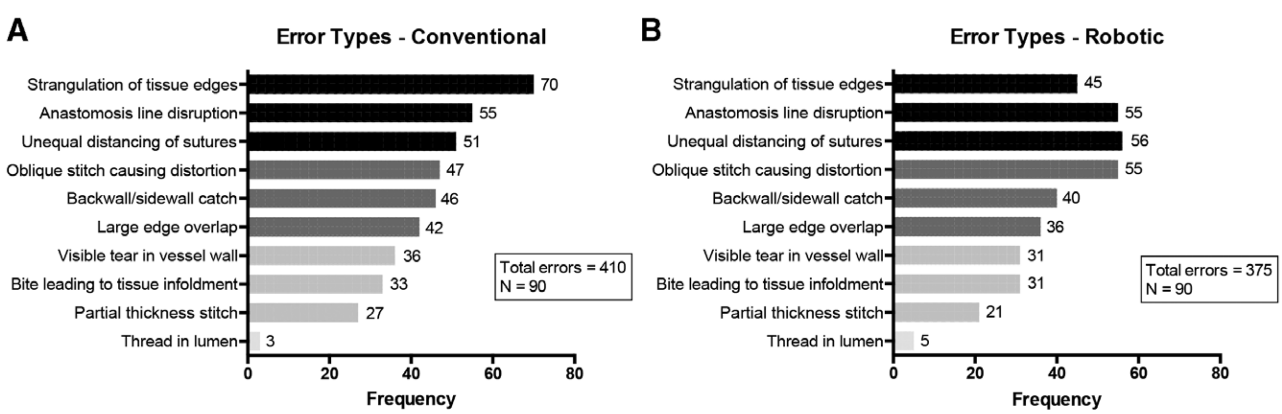

Fig. 5. Quantification of error types. Anastomosis quality was assessed using the established ALI, classifying 10 distinct error types for each stitch. The total number of errors and the different error types were quantified for (A) all conventional anastomoses (n = 90) and (B) all robot-assisted anastomoses (n = 90), as indicated by the bar charts.

Anastomosis Quality and Microsurgical Skills

To analyze the quality of microsurgical anastomoses, the ALI score was applied, classifying ten distinct error types of each stitch. In total, 410 errors were detected in all conventional anastomoses (n = 90; Fig. 5A), whereas only 375 errors were detected in all robot-assisted anastomoses (n = 90; Fig. 5B), not distinguishing by the level of microsurgical experience. Moreover, the "hitlist" of error types showed a different order comparing the two approaches. "Strangulation of tissue edges," "backwall/sidewall catch," "large edge overlap," "visible tear in vessel wall," "bite leading to tissue infoldment," and "partial thickness stitch" occurred more often with the conventional technique, whereas "anastomosis line disruption" occurred with equal frequency and "unequal distancing of sutures," "oblique stitch causing distortion," and "thread in lumen" occurred more often with the robotic technique.

Total ALI scores (sum of errors per anastomosis) were analyzed based on the level of microsurgical experience. Novices' ALI scores decreased from 6.5 to 4.0 mean errors per anastomosis between the first and fifth attempt with the conventional approach. On the other hand, novices' ALI scores upon robotic assistance decreased highly significantly from 7.7 to 2.7 mean errors per anastomosis (Fig. 6A). Residents' mean ALI scores decreased from 6.5 to 3.5 with the conventional approach and from 5.2 to 3.0

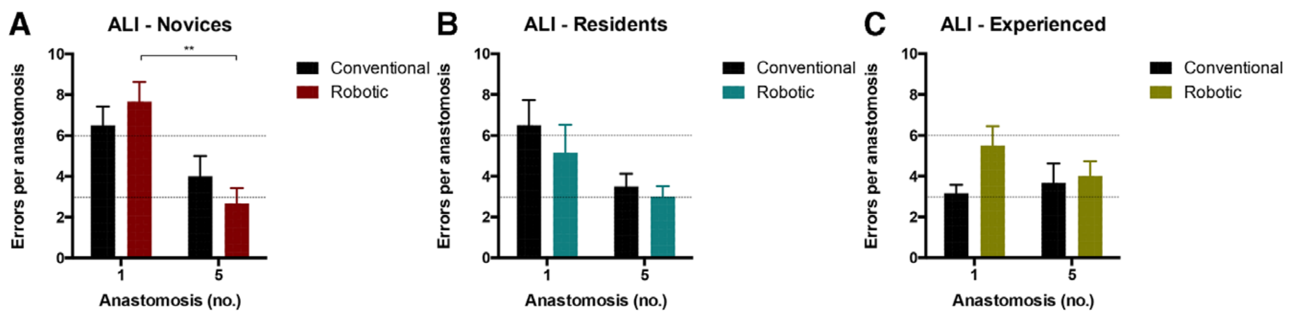

Fig. 6. ALI scores. ALI was determined for each conventional and robot-assisted anastomosis as an objective measure of anastomosis quality, by summing up the number of errors per anastomosis. Mean ALI scores were compared between the first and fifth anastomosis of (A) novices (n = 6), (B) residents (n = 6), and (C) experienced microsurgeons (n = 6) with the conventional and robotic approach. Bar charts indicate mean scores with SEM, dashed lines indicate the thresholds for different skill levels (*P < 0.05, **P < 0.01).

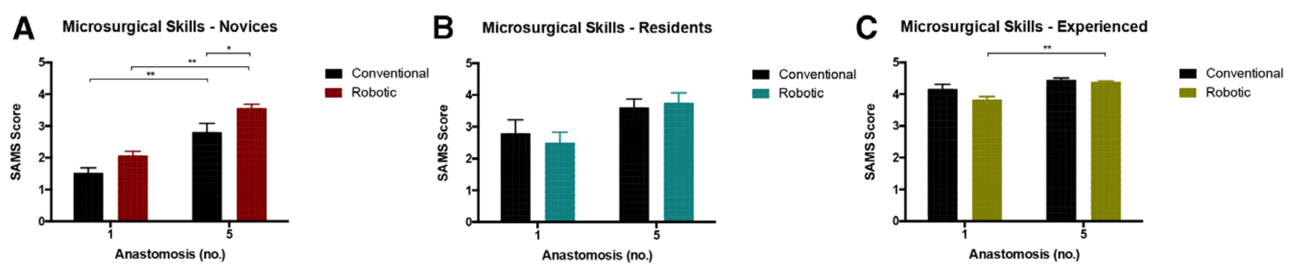

Fig. 7. SAMS scores. All anastomoses were video-recorded, and microsurgical skills were assessed in a blinded fashion according to a modified version of the SAMS score. Mean SAMS scores were determined for the first and fifth anastomosis of (A) novices (n = 6), (B) residents (n = 6), and (C) experienced microsurgeons (n = 6) with both surgical techniques (1 = minimum, 5 = maximum). Bar charts indicate mean scores with SEM (*P < 0.05, **P < 0.01).

with the robotic approach (Fig. 6B). Experienced microsurgeons made 3.2 mean errors per anastomosis during the first anastomosis and 3.7 during the last conventional anastomosis, whereas ALI scores with the robot-assisted approach decreased from 5.5. to 4.0 errors per anastomosis (Fig. 6C).

Furthermore, the development of microsurgical skills was assessed using a modified version of the SAMS score. Novices' skills during conventional anastomoses significantly improved from the first to the fifth anastomosis from 1.5 to 2.8 mean points. However, upon robotic assistance novices' skills significantly improved from 2.1 to 3.6 mean points, thereby performing significantly better upon robotic assistance during the final anastomosis compared with the conventional approach (Fig. 7A). Residents' conventional skills improved from 2.8 to 3.6 mean points, whereas their robotic skills improved from 2.5 to 3.8 mean points (Fig. 7B). Experienced microsurgeons showed proficient skills during the first and last conventional anastomosis with 4.2 and 4.5 mean points. Nevertheless, their robotic skills also significantly improved from 3.8 to 4.4 mean points, thereby reaching comparable skill levels during the final anastomosis (Fig. 7C).

Surgical Ergonomics

Surgical ergonomics of all participants were compared between the two approaches using the REBA score, whereby low scores indicate more ergonomic positioning. Overall, a statistically significant difference between the two approaches was not detectable. However, when differentiating by different body parts, upper arm, lower arm, and wrist positioning was significantly improved upon robotic assistance compared with conventional anastomoses. Nevertheless, neck, trunk and leg positioning, as well as the force/load score, coupling score, and activity score did not show significant differences between the two approaches (Fig. 8).

DISCUSSION

The concept of robot-assisted microsurgery is currently gaining momentum in the field of plastic surgery through the development of novel robotic devices. Furthermore, the trend is progressively moving from microsurgical to supermicrosurgical procedures, addressing anatomical structures within a submillimeter range, aiming to reduce donor site morbidity and surgical invasiveness. Thereby, the physiological limits of human physical abilities and dexterity are gradually being reached, generating a special need for novel surgical approaches. Robotic devices specifically designed for the requirements of open microsurgery provide beneficial features such as tremor elimination, motion scaling, and enhanced vision. However, because clinical and preclinical data are limited due to the high novelty of the systems, this study was set out to further investigate the combined application of the Symani and RoboticScope in a preclinical setting.

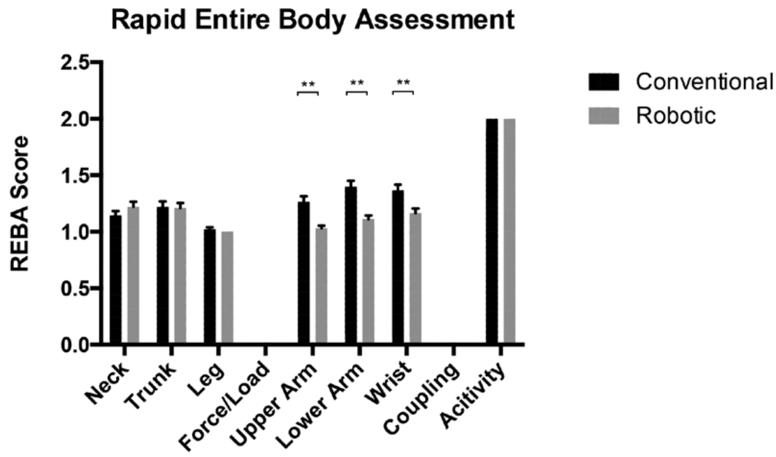

Fig. 8. REBA scores. Body posture of participants was captured at a random time-points during the performance of each anastomosis. Separate categories of the REBA score were determined for all conventional anastomoses (n = 90) and robot-assisted anastomoses (n = 90) of novices, residents, and experienced microsurgeons. Low REBA scores indicate more ergonomic postures. Bar charts indicate mean scores with SEM (*$P < 0.05$, **$P < 0.01$).

All groups of participants showed a strong reduction of surgical time with the robotic devices, demonstrating a steep learning curve. At the end of the trial, there was no statistically significant difference between the surgical time of the robotic and conventional group on all levels of experience. However, conventional anastomoses were still performed slightly faster than robotic anastomoses, which is consistent with other preliminary preclinical[20,21] and clinical studies[7,8] using the Symani system. Compared with standardized study conditions, further aspects such as the setup and more challenging surgical conditions need to be considered, once the systems are used for clinical cases. Therefore, an improvement of the overall surgical time cannot be expected in the near term. However, improved microsurgical skills may affect flap selection and surgical strategies in general, as less-invasive approaches may become more feasible.

Participant's subjective satisfaction with robotic anastomoses increased significantly throughout the trial. Consistently, the Symani performance, RoboticScope performance, and combined performance were constantly rated at high levels, suggesting a reliable performance of the robots from a technical perspective. Furthermore, subjective evaluations revealed preference of the robotic approach over the conventional approach regarding items assessing surgical ergonomics (freedom of movement, back or neck tenderness, muscle fatigue, operative comfort), visual characteristics (optical detail, depth and 3D structure visualization) and intraoperative performance (microsurgical handling, intraoperative tremor, team interaction and communication).

Because this is the first study, to our knowledge, investigating the combined application of the Symani and RoboticScope, comparable trials using the same approach are not available. However, several clinical studies using the RoboticScope for conventional microsurgery in the field of head and neck surgery, plastic surgery, and neurosurgery have been reported, revealing a consistent trend of improved surgical ergonomics, increased comfort, and quick adaptation to the system, as well as clinical safety and feasibility.[10,11,13,14]

Microanastomosis quality and microsurgical skills were demonstrated to significantly improve upon robotic assistance, especially if microsurgical experience is limited. Thus, novices showed significantly better robotic skills compared with conventional skills at the end of the trial, whereas experienced microsurgeons reached a comparable level of microsurgical skills with both approaches, even though lacking years of experience compared with the conventional technique. Moreover, in total, fewer mistakes occurred throughout all groups upon robotic assistance compared with the conventional approach, suggesting enhanced precision and dexterity with the novel devices. These findings are further supported by consistent results reported by Ballestin et al,[20] demonstrating refined suturing precision in a needle passage test using the Symani and by Savastano et al,[21] using the Symani for suturing of partial corneal transplants in a porcine eye model. It can only be hypothesized which level of microsurgical skills could be achieved throughout several years of experience with the robotic systems. Therefore, it will be interesting to follow up on this study and further investigate their clinical application that is currently emerging at multiple centers worldwide. Nevertheless, conventional microsurgery training should not be neglected, especially by novices, as it still provides the basis for the majority microsurgical procedures, and to avoid becoming reliant on robotics. Because this study was performed on artificial vessels according to the 3R principle of animal research, which we believe mimic the features of biological vessels to an appropriate degree, follow-up studies should confirm our results in vessels of living organisms. Moreover, we recommend collaborative research approaches of multiple specialized centers, to generate significant numbers of participants in this innovative field.

Surgical ergonomics were assessed in this study because work-related musculoskeletal disorders are highly prevalent among surgeons. Moreover, the use of loupes, headlamps and microscopes, which are inherently required for microsurgery, was identified as a specific risk factor for musculoskeletal injuries in open surgery.[22] Previous studies further revealed that robot-assisted laparoscopic surgery is ergonomically superior to open and conventional laparoscopic surgery for surgeons and trainees.[23] This study demonstrated improved upper arm, lower arm, and wrist positioning upon robotic assistance, but total REBA scores were not significantly affected. Subjective evaluations of ergonomics clearly tended toward preference of robotic assistance. Alternative objective scores should be applied in follow-up studies to further investigate potential ergonomic benefits of robotics in open microsurgery.

In conclusion, this preclinical study using artificial vessels provides promising evidence for the great potential of novel robotic systems dedicated to open reconstructive microsurgery, especially revealing benefits for the acquisition of microsurgical skills and the quality of microanastomoses. As preliminary clinical studies recently provided proof of feasibility and safety,[8,9] follow-up investigations should further identify surgical procedures benefitting the most from novel robotic features. Especially supermicrosurgical procedures, such as lymphovenous anastomoses and perforator-to-perforator flaps as well as reconstructive procedures requiring anastomoses in deep anatomical planes, are hypothesized to profit from enhanced precision, dexterity, and distal motion axes provided by robotic assistance. Moreover, cost–benefit analyses should be carried out, to further elucidate the economic significance of robotic microsurgery for hospitals.

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DISCLOSURES

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