OPEN

PRS GLOBAL OPEN

ORIGINAL ARTICLE
Education

Developing Microsurgery Skills Outside of the Operating Room

Tessa E. Muss, MD
Elizabeth Malphrus, MD, MPP
Nicholas Albano, MD
Suhail Kanchwala, MD

Background: The complex skills required to perform microsurgery are primarily taught in the high-stakes environment of the operating room. However, learners would benefit from developing these abilities in lower-stakes environments beforehand, allowing them to focus on higher-level tasks intraoperatively. This article outlines available resources for developing microsurgical skills outside the operating room and evaluates their alignment with best practices for performance enhancement, thereby identifying ways to improve microsurgical education.

Methods: A systematic review and web search were performed in April 2024 to identify available microsurgical skills courses. Descriptive data were extracted from these resources, including course objectives, unique features, model used, and curriculum.

Results: Literature and web search revealed 7 online video courses addressing microsurgical skill development. These had freely available multimedia content and used low-fidelity models with widely accessible materials. Six offered a curriculum. By contrast, 14 in-person flap and microsurgery courses in the United States were identified. These occurred over 2–5 days, cost thousands of dollars, and used high-fidelity models with guidance from experts. Finally, there were many simulation platforms ranging from low-fidelity synthetic models to cadaveric tissue to high-fidelity live animal models. These also encompassed technology-based practices such as virtual reality.

Conclusions: Compared with high-fidelity training, low-fidelity models are more affordable, are reusable, and allow for dedicated educational opportunities that are better aligned with best practices for knowledge and skill acquisition. Consequently, they have the potential to reach a broader range of trainees and accelerate the learning curve, and therefore should be integrated into every microsurgery training program. *(Plast Reconstr Surg Glob Open 2024; 12:e6342; doi: 10.1097/GOX.0000000000006342; Published online 6 December 2024.)*

INTRODUCTION

Microsurgery requires a unique set of physical skills to enable proper tissue handling and suturing at a microscopic level. Today, these complex skills are primarily taught in the operating room (OR), where stakes are high and tolerance for error is low. Ideally, trainees would maximize microsurgical skill development outside of the OR—in a low-stakes environment focused on learning—before their first intraoperative experiences. By deliberately practicing these procedural skills before entering the OR, they can open up mental space to focus their attention to the nuances of the case, such as decision-making, rather than having to concentrate on each step of basic tasks such as instrument handling and suturing.[1] Moreover, with a finite number of microsurgical cases available to learners during their training, this type of self-regulated and self-directed education is an invaluable tool in augmenting their microsurgical abilities.[2] In this article, we review and evaluate how currently available resources for microsurgical skill development outside of the OR align with best practices for skill acquisition and performance improvement, so that we may identify opportunities to enhance microsurgical education.

METHODS

A systematic review was conducted in PubMed in compliance with the Preferred Reporting Items for Systematic

From the Division of Plastic Surgery, Department of Surgery, University of Pennsylvania, Philadelphia, PA.

Received for publication May 30, 2024; accepted September 16, 2024.

DOI: 10.1097/GOX.0000000000006342

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

Reviews and Meta-Analyses guidelines to identify articles describing online microsurgical skills courses (Fig. 1). The database was queried on April 3, 2024, using the terms ("virtual" OR "online" OR "remote" OR "tele-" OR "tele") AND ("microsurgery" OR "microsurgical") AND ("training" OR "curriculum" OR "education" OR "course"). Articles that described digitally available microsurgical skills courses and were published in English were included. Articles that only reported on simulation models or in-person microsurgical courses did not address physical microsurgical hand skills, or were published in a non-English language were excluded.

A complementary web search was conducted through Google and YouTube to capture online resources that may not have been reported in the published literature. Google was queried on April 3, 2024, using the terms "online microsurgery course," "online microsurgery training," "online microsurgery curriculum," "virtual microsurgery course," "virtual microsurgery training," and "virtual microsurgery curriculum." The top 100 results of each query were screened. YouTube was queried on April 3, 2024, using the term "microsurgery training course." The top 100 results were screened. Resources containing microsurgical skill courses that addressed physical hand skills in the context of an educational program were included.

Two independent authors (T.E.M. and E.M.) conducted the search and screening to determine the full list of included studies and digital resources. Controversies were resolved through discussion. Descriptive information was extracted, including course name, institutional affiliation, cost, materials, course objectives, unique features, models used, and inclusion of curriculum.

An adjunct search was performed to identify other microsurgical resources, including in-person microsurgery and flap courses and simulation models. Google was queried on April 3, 2024, using the term "in person microsurgery and flap courses." The top 100 results were screened. Resources containing in-person flap and microsurgery courses in the United States relevant to plastic surgery were included. Descriptive information was extracted, including institutional affiliation, cost, learning principles, and models used. Both PubMed and Google were queried on April 3, 2024, using the term "microsurgical simulation models." At least 3 articles were selected from various categories (synthetic models, cadaveric models, live animal models, microsurgical magnification, and virtual reality [VR]/augmented reality [AR]) to represent the diversity of simulation models available.

Takeaways

Question: What resources exist outside of the operating room for surgeons interested in developing microsurgical skills?

Findings: A systematic review was performed to find microsurgical skill development resources outside the operating room. All identified online resources were free, had flexible pacing, and used low-fidelity models. Most had longitudinal curricula. By contrast, in-person courses used high-fidelity models but were expensive and episodic. Finally, many simulation platforms were available for varying levels of expertise and technological experience.

Meaning: Low-fidelity training should be a staple in microsurgical curricula because these models are affordable, accessible, and allow a wide range of learners the opportunity to practice more frequently and accelerate their microsurgical learning.

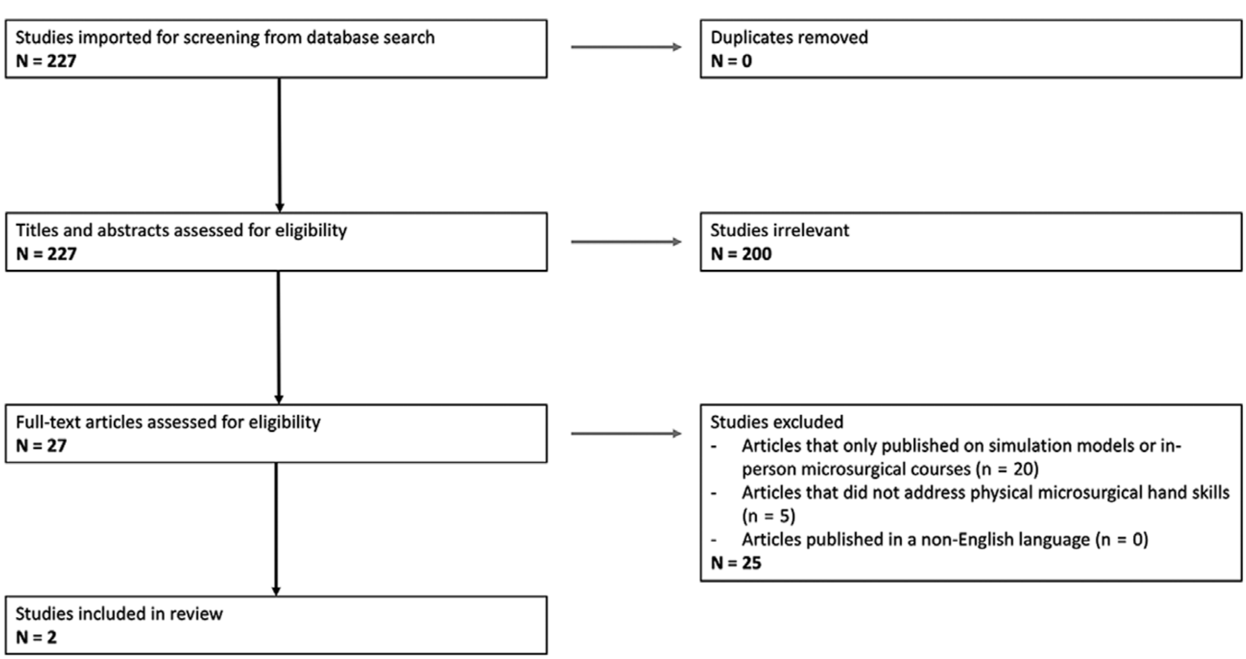

Fig. 1. PRISMA flow diagram of search for online video microsurgical resources. PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses.

Table 1. In-person Flap and Microsurgery Skills Courses in the United States

Course Name or Institutional Affiliation	Cost for Nonaffiliated Trainee	General Description/Learning Principles	Hi-fi Model Used
Baylor College of Medicine[3]	Not listed	4-d course Microvascular skill development	Live animal
Cleveland Clinic[4]	\$2000–\$3000	5-d course Microvascular skill development	Live rodent
Columbia University Irving Medical Center[5]	\$3699–\$3899	5-d course Microvascular skill development	Live rodent
Corewell Health (formerly Beaumont)[6]	\$2000–\$2500	5-d course Microvascular skill development	Live rodent
Duke Flap Course[7]	\$1500	2-d course Flap dissection	Human cadaver
Duke University School of Medicine[8]	\$2300	5-d course Microvascular skill development	Live rodent
Mayo Clinic[9]	\$1750–\$1875	5-d course Microvascular skill development	Live rodent
MOET Institute[10]	\$1375–\$2750	5- or 10-d course Microvascular skill development	Not specified
Penn Flap Course[11]	\$1800	2-d course Flap dissection	Human cadaver
University of Illinois College of Medicine[12]	\$2000	5-d course Microvascular skill development	Live rodent
University of Kentucky College of Medicine[13]	\$2000	5-d course Microvascular skill development	Live rodent
University of Louisville[14]	\$2000	5-d course Microvascular skill development	Live rodent
Wake Forest University School of Medicine[15]	\$2000	5-d course Microvascular skill development	Live animal
Weill Cornell Medicine[16]	Not listed	40 h Microvascular skill development	Live rodent

MOET, microsurgery and operative endoscopy training.

All resources were then categorized into 1 of 3 groups: in-person flap and microsurgery courses, online video courses, and simulation platforms.

RESULTS

Fourteen in-person flap and microsurgery courses in the United States were found (Table 1).[3–16] The duration of these events was 2–5 days. Two courses used human cadavers, and the remaining 12 used live or cadaveric animal models. The cost ranged from \$1500 to \$3899. All necessary models and materials were included.

By contrast, the literature and online search revealed 7 online microsurgical skill courses that fit the inclusion criteria.[2,17–24] Each course addressed and included tasks designed to improve microsurgical hand skills. All except 1 course had an established curriculum that trainees could follow. Three courses used low-fidelity (lo-fi) models, and 4 used a combination of lo-fi and high-fidelity (hi-fi) models. Lo-fi models used basic office and OR supplies, whereas hi-fi models were typically cadaveric chicken tissue (Table 2). Every course included freely available learning content, but materials for the practice models were not included.

Finally, a diverse array of simulation platforms and advancing simulation technologies were identified. These existed on a spectrum of fidelity, with synthetic models being the lowest, followed by cadaveric tissue, and then live animals demonstrating the highest fidelity (Fig. 2).

DISCUSSION

Best Practices for Skill Acquisition

The science of procedural learning and best practices for rapid acquisition of new skills have been thoroughly explored in the literature across the fields of psychology, behavioral economics, sociology, neuroscience, education, and business. Although a thorough review of this literature, as it applies to surgery, is beyond the scope of this study, here we highlight a few key principles from this body of work to guide our assessment of current microsurgery resources and training programs.

First, true mastery of a skill requires deliberate practice. Fitts and Posner developed a classic model in the 1960s that describes procedural learning as a process with 3 phases: The first phase, the cognitive phase, is the most mentally taxing and involves slow and deliberate rehearsal of steps. In this phase, every aspect of a task requires conscious awareness, leaving little remaining capacity to consider novel stimuli, which makes the learner vulnerable to distraction and error. Over time, the learner enters the second phase, the associative phase, in which tasks begin to become more fluid but still require cognitive processing for key portions. In the final stage, the autonomous phase, the learner has fully incorporated the movements involved in a task such that it no longer requires conscious awareness, freeing their cognitive capacity to focus on novel challenges.[2]

Table 2. Online Video Microsurgical Skills Courses

Reference, Course Name, or Institutional Affiliation	Cost	Materials	General Description/Learning Principles	Unique Features	Curriculum	Model Fidelity
Bagli et al[17]	Free	• Home/office supplies • Rice	Platform with 6 lo-fi exercises to enhance instrument handling	Exercises targeted at different, specific facets of microsurgical dexterity and instrument handling	Yes	L
Microsurgery Institute 4[18]	Free	• Home/office supplies • Basic OR supplies • Grape • Cadaveric chicken thigh with leg	Multiple lo-fi exercises to improve dexterity	Organizes microsurgical learning into 4 main graduated steps	Yes	H/L
			Advance to hi-fi exercises once basics are mastered	Timed tasks with target goals for dexterity and efficiency		
PennMicro[19]	Free	• Home/office supplies • Basic OR supplies	Microvascular skill development	Highlights methods to improve fundamental movements and skills	Yes	L
			Focus on fundamental movements	Emphasizes daily practice and high repetition		
			Practice exercise videos on lo-fi models			
Rajaratnam et al[2]	Free	Basic OR supplies	Emphasizes motor imagery and mental practice	Incorporates multimedia learning theories to enhance learning	Yes	L
			Focuses specifically on microsuturing on lo-fi model	Provides mental script and encourages its use in the frequent mental practice of microsuturing		
SHARE Microsurgery Workshop[20,21]	Free preparation materials	• Home/office supplies • Basic OR supplies • Cadaveric chicken thigh	Preparation materials and outline for 2-session curriculum	Practices technique in a macromodel to understand basics before graduating to micromodel	Yes	H/L
			First session focused on lo-fi practice and second on hi-fi practice			
Stanford Microsurgery Essentials[22,23]	Free	• Office supplies • Basic OR supplies • Cadaveric chicken feet	Step-by-step instructions in multimedia format for microsurgical preparation, practice models, and suturing	Provides description and utility of typical microsurgical instruments and materials	No	H/L
			Simulation videos on lo-fi and hi-fi models	Organizes practice tasks and concepts into easy-to-follow steps		
University of Wisconsin Microsurgery Education[24]	Free	• Home/office supplies • Basic OR supplies • Silicone tube/fake vessel • Blue-blood chicken and porcine model • Live rat	Lessons advance from lo-fi to hi-fi gradually	Thorough curriculum with relevant topics, milestones, and assessment criteria	Yes	H/L
			Includes multiple different approaches to microvascular anastomosis	Several training videos demonstrating preparation and use of blue-blood models		
			5 publications and training videos on augmented animal models			

H, hi-fi; L, lo-fi.

The only way to advance through these stages is to practice. Typically, learners make significant gains early in the cognitive phase in terms of speed and competence, but studies show that even experts continue to improve their performance with additional practice over time. An interesting effect of this process, and one that is unique to procedural learning, is that over time, experts lose access to the information that they used to develop their skills when they were in the early stages of learning, as this information is no longer required to maintain their skills. This can make teaching a novice challenging, as it can be difficult for an expert to verbalize what they are doing with precision and accuracy.[1]

Another common theme in the procedural learning literature is that working memory is the bottleneck of all learning. Although the amount of knowledge and skill that we can gain is essentially infinite, learning any new information or skill relies on our working memory, which has an innately limited capacity for only 7 ± 2 items at any 1 time. Optimizing learning requires making the most of this "magic number," so that new skills can be both understood and stored to be built upon in the future. The environment and circumstances surrounding a learning experience matter significantly for how efficiently learners can move new information through this working memory bottleneck.[1]

An ideal learning environment is free of distractions and hosts learners that are mentally and physically prepared. After learning a new task, learners should have the opportunity to practice and reflect to optimize how the

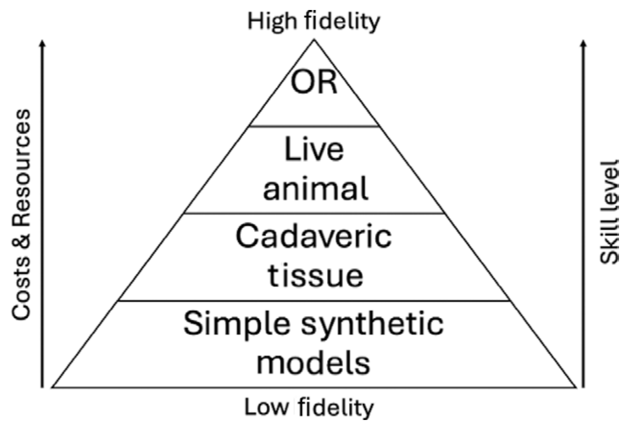

Fig. 2. Lower fidelity models are useful to a larger number of learners and also require fewer resources to implement. These models represent an opportunity for accelerating the learning curve for microsurgery in resource-limited settings.

new information is stored, reviewed, and retrieved. The typical environment for surgical training—the OR—is not, from this perspective, the ideal venue for learning. For residents, who are often managing consults and phone calls while they operate, maintaining the mental bandwidth to learn can be challenging, and this limited cognitive capacity can slow the overall process of learning.

Third, learning requires feedback. Studies across numerous fields have shown that high-quality feedback leads to faster skill acquisition and potentially superior skill development overall. A randomized controlled trial conducted at a Canadian general surgery program found that implementing a coaching regimen led to significantly greater skill acquisition compared with traditional surgical training.[25] Applying these principles to microsurgical training has the potential to accelerate trainees' learning curves, enabling residents to achieve competency in microsurgery earlier in the course of their training.

Hi-fi Versus Lo-fi Training

A large portion of the learning opportunities for microsurgery revolve around hi-fi training. These include in-person flap courses and microsurgery skills courses, which rely on live animal models or cadaveric tissue from humans or animals to enable close simulation of the intraoperative experience. They are especially useful for individuals with prior microsurgical experience. However, the tradeoff for hi-fi training is the high cost, number of resources, and ethical concerns for the tissue provided. This then makes frequent practice with these models somewhat impractical. Consequently, learners would benefit from a teaching modality that can be practiced on a more regular basis.

Lo-fi models and training offer a means of practicing microsurgical tasks on synthetic or homemade models. These may include latex gloves, office supplies, or more formal, commercially available platforms. Because these are portable, budget-friendly, and can be done without additional staff, lo-fi training enables learners to have flexibility in their training and theoretically practice more frequently. Although they do not give the same complexity of experience as hi-fi training, lo-fi training has demonstrated efficacy for novice surgeons in refining their technical skills.[26–28]

Each type of training modality provides its own unique set of advantages and disadvantages for mastering microsurgery. Later, we discuss three main categories of resources that can aid trainees in the deliberate practice of these skills: in-person flap and microsurgery courses, online video courses, and simulation platforms.

In-person Flap and Microsurgery Courses

In-person flap and microsurgery courses are classic methods of learning for trainees interested in microsurgery. A typical course offers an intensive, multiple-day experience working with and learning from fellow trainees and attending on hi-fi models. This allows for specific and diligent training of these skills for an extended period and fosters a collaborative learning environment. Importantly, these courses enable trainees to gain real-time guidance and feedback from experts.[29] However, 2 disadvantages of these courses are the price and logistics, as they can be prohibitively expensive and difficult to attend as a trainee, given they often occur over multiple days and are located at a distance from their home institution. In addition, although participants undoubtedly gain valuable lessons from these courses, they do not offer longitudinal curricula to practice skills regularly. Rather, these are episodic events that are attended at most once or twice per year.

Online Video Courses

Online video microsurgery courses are a growing body of resources that provide an approach to learning at a customizable pace with easily accessible content. Rather than episodic learning through in-person courses or surgical cases, online video courses provide users with the flexibility to engage with the material at their convenience and the ability to revisit the material as necessary. For example, the University of Wisconsin's program includes a multilesson curriculum that can be followed according to the user's schedule, and PennMicro includes a curriculum with several videos organized by topic so that users may easily navigate to the subject they desire.[19,24] Moreover, these curricula are valuable tools in giving direction and making the overall learning experience more efficient. In addition, these resources use mixed media, offering multiple ways to engage with the material. This is especially exemplified by the course created by Rajaratnam et al,[2] which was developed in line with Mayer's multimedia theory guidelines. Importantly, these resources are also free to the public and do not require a subscription or specialized equipment, with all courses using office or basic OR supplies as part of their models. Despite these advantages, 1 of the main downsides is little opportunity for feedback.

Of note, YouTube offers several videos that show intraoperative footage of surgeons performing microsurgical techniques on hi-fi models or real patients, often accompanied by descriptive audio or text. This content is not typically created within the context of an established educational program and therefore does not necessarily provide guidance by which trainees can practice these skills, but may provide educational value by offering more observational exposure to microsurgery. However, users should carefully appraise these resources, as a recent systematic review of microsurgery-related videos on YouTube showed that these videos, on average, scored medium to low on 3 different educational assessment scales and overall had large variability in educational quality.[30]

In addition, digital flap atlases can be a helpful complement to online courses and give trainees extra resources to better understand the anatomy of various flaps. A commonly used, publicly available atlas is microsurgeon.org, which provides descriptions and images of several flaps, as well as access to lectures on microsurgical topics.[31]

Simulation Platforms

Simulation platforms are helpful adjuncts in acquiring microsurgical skills, as they provide a means to actively engage and practice tangible skills. Synthetic or homemade models such as gauze or beads are useful for novices in acquiring the basic hand dexterity required for microsurgical movements.[27,32–34] Although these do not accurately simulate human physiology, they are low-cost, portable, reusable, and easy to assemble. This enables users to iterate over these exercises frequently. By contrast, cadaveric tissue from animals or humans provides a model with anatomical context and the ability to practice real-tissue handling. A wide variety of models have been shown to be effective in microsurgical training, but there is variability in the cost and resources required.[35–39] Finally, live animals are great training tools for experienced individuals because they more closely mimic clinical scenarios. They offer the distinct advantage of providing actively perfused tissue and the ability to practice complex microsurgical tasks.[40–43] However, using these models is often limited by the cost, high number of resources, and ethical concerns. Overall, the utility of these models depends on the available time and stage of the learner.

In addition, the need for microsurgical magnification to use these models previously presented a challenge, but fortunately, a magnified surgical field can now be achieved without a microscope. Although most microsurgical trainees use loupes in their training, for those without loupes or for learners interested in a simulated experience that is more similar to operating with a microscope, many platforms have shown success using already-owned or low-cost technology such as smartphones, tablets, and laptops in place of expensive microscopes.[44–47] These technologies can be powerful tools to elevate the experience of working with lo-fi models and can help reduce the overall cost of simulation-based training.

Notably, VR or AR simulations are becoming more used in microsurgery to closely simulate the experience of a real procedure in a low-stakes environment. These portable devices are versatile and enable users to simulate complex tasks under a surgical microscope, as exemplified by Huang et al,[48] who showed users performing microsurgical techniques on a chicken wing model with a VR system. Even basic tasks may be simulated through a VR environment, such as in work done by Kazemi et al,[49] who evaluated suturing performance in a VR platform and demonstrated an association between skills shown in the simulation and reality. Moreover, these platforms are now being investigated to better visualize the microsurgical field. Falola et al[50] developed an AR headset to enhance microsurgical field visualization of a chicken thigh model and found that users appreciated the head-tracking technology and ability to use the system in an ergonomically appropriate position. However, 1 drawback to these platforms is the initial cost, but as the technology progresses in the future, VR and AR are likely to become more accessible. The other disadvantages to these models are similar to online platforms in that there are limited opportunities for feedback, and they do not provide the experience of working on real tissue.

CONCLUSIONS

Microsurgical training models can be categorized on a continuum from lo-fi to hi-fi, with lower fidelity models tending to be the least costly and resource-intensive, as well as the most reusable or repeatable. Lower fidelity models also tend to be useful and appropriate for the largest range of potential learners, with higher fidelity models providing benefits to learners with existing microsurgical experience.

Lo-fi models and courses represent an opportunity to accelerate the learning curve for microsurgery with minimal outlay of resources. The literature shows that effective and efficient skill acquisition requires frequent repetition to make novel motor functions automatic. Although trainees typically have hundreds of opportunities to practice other basic surgical skills such as tying under tension, tissue handling, and layered closures through routine intraoperative experiences, microsurgical opportunities tend to be more limited, both because total case numbers are smaller and because these high-stakes tasks have limited margins for error.

Although VR and artificial intelligence–driven simulations may, in the future, provide hi-fi learning opportunities for trainees that could essentially replicate a real intraoperative microsurgical experience, these types of training models in their current forms tend to be expensive, require specialized equipment, and still differ significantly from a real intraoperative experience. Although flap courses, live animal dissections, and cadaver laboratories are effective approaches to learning, these activities are quite resource-intensive, and typically only offered for trainees a few times per year.

Further development of lo-fi microsurgical training programs has the potential to make teaching and learning microsurgery both more efficient and more effective without increasing costs or resource needs for training programs. As these resources expand and potentially become more integrated into formal surgical education, future studies should investigate their effectiveness for learners at varying levels of microsurgical experience. This will improve our understanding of their impact on surgeons as they progress through their training and help identify opportunities for developing new modules tailored toward certain learners. Overall, given the range of resources already available, and the low cost and resource demands for implementation, these types of programs should be a standard component of the curriculum at every microsurgery training program.

Tessa E. Muss, MD
Division of Plastic Surgery
University of Pennsylvania
3400 Civic Center Blvd
Philadelphia, PA
E-mail: Tessa.muss@pennmedicine.upenn.edu

DISCLOSURES

Dr. Suhail Kanchwala is a consultant for RTI and Integra. The other authors have no financial interest to declare in relation to the content of this article.

REFERENCES

1. Sullivan ME. Applying the science of learning to the teaching and learning of surgical skills: the basics of surgical education. *J Surg Oncol.* 2020;122:5–10.
2. Rajaratnam V, Ng HJH, Rahman NA, et al. Online training module for micro suturing incorporating motor imagery and mental practice: a design and development research study. *ANZ J Surg.* 2022;92:2072–2081.
3. Baylor College of Medicine. Simulation-based surgical education. Available at https://www.bcm.edu/departments/surgery/education/simulation-based-surgical-education. Accessed April 29, 2024.
4. Cleveland Clinic. Microsurgery training courses. Available at https://my.clevelandclinic.org/departments/dermatology-plastic-surgery/medical-professionals/microsurgery-training-courses. Accessed April 29, 2024.
5. Columbia Orthopedic Surgery. Courses. 2019. Available at https://www.columbiaortho.org/education/professional-education/microsurgery-lab/courses/. Accessed April 29, 2024.
6. Corewell Health. Microsurgery Workshop 2024—Beaumont Health—Continuing Education (CE). 2024. Available at https://beaumont.cloud-cme.com/course/courseoverview?P=0&EID=73037. Accessed April 29, 2024.
7. Duke Department of Surgery. Fresh cadaver flap dissection course. 2024. Available at https://surgery.duke.edu/education-and-training/continuing-medical-education/courses/plastic-surgery/fresh-cadaver-flap-dissection-course. Accessed April 29, 2024.
8. Duke Department of Surgery. Microsurgical techniques and skills training course. Available at https://surgery.duke.edu/education-and-training/continuing-medical-education/courses/plastic-surgery/microsurgical-techniques-and-skills-training-course. Accessed April 29, 2024.
9. Mayo Clinic School of Continuous Professional Development. Microvascular surgery skills training course 2024. CME course conference. 2024. Available at https://ce.mayo.edu/surgical-specialties/content/microvascular-surgery-skills-training-course-2024#group-tabs-node-course-default4. Accessed April 29, 2024.
10. MOET Institute. Microsurgery and laparoscopic surgery training. Available at https://moetinstitute.com/courses/microsurgery/. Accessed April 29, 2024.
11. Penn Medicine. Penn flap course. 2024. Available at https://pennflapcourse.com/. Accessed April 29, 2024.
12. Department of Orthopaedics, University of Illinois College of Medicine. Medical students. Available at https://chicago.medicine.uic.edu/orthopaedics/education/medical-students/. Accessed April 29, 2024.
13. Research and Microsurgery Training Laboratory, University of Kentucky College of Medicine. Surgery. Available at https://medicine.uky.edu/departments/surgery/research-and-microsurgery-training-laboratory. Accessed April 29, 2024.
14. Price Institute of Surgical Research. Microsurgery teaching laboratory. Available at https://louisville.edu/priceinstitute/microsurgery-teaching-laboratory. Accessed April 29, 2024.
15. Wake Forest University School of Medicine. Core microsurgery skills course. Wake Forest Institute for Regenerative Medicine. Available at https://school.wakehealth.edu/research/institutes-and-centers/wake-forest-institute-for-regenerative-medicine/education-and-training/core-microsurgery-skills-course. Accessed April 29, 2024.
16. Center for Male Reproductive Medicine & Microsurgery. Courses & registration. Available at https://maleinfertility.org/research/cornell-microsurgery-training-and-research-program/courses. Accessed April 29, 2024.
17. Bagli D, Odeh R, Penna F, et al. A practice platform for systematic development of microsurgical instrument technique. *Cureus.* 2017;9:e1253.
18. Masud D, Haram N, Mohanna P, et al. MI4 (Microsurgery Institute 4): programme. Available at http://www.microsurgeryeducation.com/p/stage-1.html. Accessed April 29, 2024.
19. Kanchwala S, Malphrus E. PennMicro Home. Penn Microsurgery. Perelman School of Medicine at the University of Pennsylvania. Available at https://www.med.upenn.edu/microsurgery/. Accessed April 29, 2024.
20. The Plastic Surgery Foundation. SHARE Microsurgery Workshop Prep Materials. 2022. Available at https://www.thepsf.org/programs/surgeons-in-humanitarian-alliance-for-reconstruction-research-and-education/microsurgery-workshop-1. Accessed April 29, 2024.
21. Davis GL, Abebe MW, Vyas RM, et al. Results of a pilot virtual microsurgery course for plastic surgeons in LMICs. *Plast Reconstr Surg Glob Open.* 2024;12:e5582.
22. Satterwhite T, Lee GK, Paro J, et al. Microsurgery essentials. Division of Plastic & Reconstructive Surgery, Stanford Medicine. 2024. Available at https://plasticsurgery.stanford.edu/education/microsurgery.html. Accessed April 29, 2024.
23. Satterwhite T, Son J, Carey J, et al. Microsurgery education in residency training: validating an online curriculum. *Ann Plast Surg.* 2012;68:410–414.
24. Poore SO, Zeng W. Microsurgery education. Available at https://microsurgeryeducation.org/. Accessed April 29, 2024.
25. Soucisse ML, Boulva K, Sideris L, et al. Video coaching as an efficient teaching method for surgical residents: a randomized controlled trial. *J Surg Educ.* 2017;74:365–371.
26. Grober ED, Hamstra SJ, Wanzel KR, et al. The educational impact of bench model fidelity on the acquisition of technical skill. *Ann Surg.* 2004;240:374–381.
27. Prunières GJC, Taleb C, Hendriks S, et al. Use of the Konnyaku Shirataki noodle as a low fidelity simulation training model for microvascular surgery in the operating theatre. *Chir Main.* 2014;33:106–111.
28. Chan WY, Figus A, Ekwobi C, et al. The “round-the-clock” training model for assessment and warm up of microsurgical skills: a validation study. *J Plast Reconstr Aesthet Surg.* 2010;63:1323–1328.
29. Park KH, Romero G, Paladino J, et al. Microsurgical education in the USA: past, present and future. *Issu Reconstr Plast Surg.* 2021;24:9–18.
30. Fernandez-Diaz OF, Navia A, Berner JE, et al. Watch one, do one? A systematic review and educational analysis of YouTube microsurgery videos, and a proposal for a quality assurance checklist. *Arch Plast Surg.* 2022;49:668–675.
31. Buntic R. Microsurgeon.Org. 2001. Available at https://www.microsurgeon.org/. Accessed April 29, 2024.

32. Demirseren ME, Tosa Y, Hosaka Y. Microsurgical training with surgical gauze: the first step. *J Reconstr Microsurg*. 2003;19:385–386.
33. Yenidunya MO, Tsukagoshi T, Hosaka Y. Microsurgical training with beads. *J Reconstr Microsurg*. 1998;14:197–198.
34. Lahiri A, Lim AYT, Qifen Z, et al. Microsurgical skills training: a new concept for simulation of vessel-wall suturing. *Microsurgery*. 2005;25:21–24.
35. Zeng W, Gunderson KA, Sanchez RJ, et al. The blue-blood porcine chest wall: a novel microsurgery training simulator for internal mammary vessel dissection and anastomosis. *J Reconstr Microsurg*. 2021;37:353–356.
36. Zeng W, Shulzhenko NO, Feldman CC, et al. "Blue-blood"—infused chicken thigh training model for microsurgery and supermicrosurgery. *Plast Reconstr Surg Glob Open*. 2018;6:e1695.
37. Creighton FX, Feng AL, Goyal N, et al. Chicken thigh microvascular training model improves resident surgical skills. *Laryngoscope Investig Otolaryngol*. 2017;2:471–474.
38. Lausada NR, Escudero E, Lamonega R, et al. Use of cryopreserved rat arteries for microsurgical training. *Microsurgery*. 2005;25:500–501.
39. Achar RAN, Lozano PAM, Achar BN, et al. Experimental model for learning in vascular surgery and microsurgery: esophagus and trachea of chicken. *Acta Cir Bras*. 2011;26:101–106.
40. Bodin F, Diana M, Koutsomanis A, et al. Porcine model for free-flap breast reconstruction training. *J Plast Reconstr Aesthet Surg*. 2015;68:1402–1409.
41. Shurey S, Akelina Y, Legagneux J, et al. The rat model in microsurgery education: classical exercises and new horizons. *Arch Plast Surg*. 2014;41:201–208.
42. Sakrak T, Köse AA, Karabağli Y, et al. Rat tail revascularization model for advanced microsurgery training and research. *J Reconstr Microsurg*. 2011;27:391–396.
43. Rodríguez A, Alvarez A, Aguirrezabalaga J, et al. The anteromedial thigh flap as a training model of a perforator flap in rat. *J Reconstr Microsurg*. 2007;23:251–255.
44. Kim DM, Kang JW, Kim JK, et al. Microsurgery training using a smartphone. *Microsurgery*. 2015;35:500–501.
45. Karakawa R, Yoshimatsu H, Nakatsukasa S, et al. A new method for microsurgery training using a smartphone and a laptop computer. *Microsurgery*. 2018;38:124–125.
46. Sayadi L, Fligor J, Couchois S, et al. A novel application of digital microscope for microsurgery training. *J Reconstr Microsurg Open*. 2020;05:e32–e35.
47. Malik MM, Hachach-Haram N, Tahir M, et al. Acquisition of basic microsurgery skills using home-based simulation training: a randomised control study. *J Plast Reconstr Aesthet Surg*. 2017;70:478–486.
48. Huang TCT, Sabbagh MD, Adabi K, et al. Compact and economical microsurgical training made possible with virtual reality. *Plast Reconstr Surg*. 2018;142:993e–995e.
49. Kazemi H, Rappel JK, Poston T, et al. Assessing suturing techniques using a virtual reality surgical simulator. *Microsurgery*. 2010;30:479–486.
50. Falola RA, Lombana NF, Rodriguez-Unda NA, et al. Augmented reality microsurgery: proof of concept for a novel approach to microsurgical field visualization in plastic surgery. *Plast Reconstr Surg*. 2024;153:650e–655e.