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Fundamentals of Microsurgery: A Novel Simulation Curriculum Based on Validated Laparoscopic Education Approaches

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Abstract

Background Microsurgical techniques have a steep learning curve. We adapted validated surgical approaches to develop a novel, competency-based microsurgical simulation curriculum called Fundamentals of Microsurgery (FMS). The purpose of this study is to present our experience with FMS and quantify the effect of the curriculum on resident performance in the operating room.

Methods Trainees underwent the FMS curriculum requiring task progression: (1) rubber band transfer, (2) coupler tine grasping, (3) glove laceration repair, (4) synthetic vessel anastomosis, and (5) vessel anastomosis in a deep cavity. Resident anastomoses were also evaluated in the operative room with the Stanford Microsurgery and Resident Training (SMaRT) tool to evaluate technical performance. The National Aeronautics and Space Administration Task Load Index (NASA-TLX) and Short-Form Spielberger State-Trait Anxiety Inventory (STAI-6) quantified learner anxiety and workload.

Results A total of 62 anastomoses were performed by residents in the operating room during patient care. Higher FMS task completion showed an increased mean SMaRT score ($p = 0.05$), and a lower mean STAI-6 score (performance anxiety) ($p = 0.03$). Regression analysis demonstrated residents with higher SMaRT score had lower NASA-TLX score (mental workload) ($p < 0.01$) and STAI-6 scores ($p < 0.01$).

Conclusion A novel microsurgical simulation program FMS was implemented. We found progression of trainees through the program translated to better technique (higher SMaRT scores) in the operating room and lower performance anxiety on STAI-6 surveys. This suggests that the FMS curriculum improves proficiency in basic microsurgical skills, reduces trainee mental workload, anxiety, and improves intraoperative clinical proficiency.

Keywords
- microsurgery
- surgical education
- reconstructive surgery
- surgical simulation

Microsurgery is a mandatory part of plastic surgery training and an essential component of plastic surgery with over 12,000 free flap breast reconstruction cases performed annually.[1] Teaching microsurgical skills in the operating room is challenging and exhibits a steep learning curve.[2–4] Standard surgical teaching models based on clinically graduated

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Table 1 Fundamentals of Laparoscopic Surgery training protocol and proficiency levels by task[89]

Task	Task name	Proficiency level	Seconds	Allowable errors	Repetitions[b]
1	Peg transfer	Mean	48	No drops outside field of view	2 consecutive + 10 nonconsecutive
2	Precision cutting	Mean + 2 SD	98	All cuts between 2 circles of the training gauze	2 consecutive
3	Ligating loop	Mean + 2 SD	53	Up to 1 mm accuracy error allowed	2 consecutive
4	Suture with extracorporeal knot	Mean + 2 SD	136	Up to 1 mm accuracy error allowed	2 consecutive
5	Suture with intracorporeal knot	Mean + 2 SD	112	Up to 1 mm accuracy error allowed	2 consecutive + 10 nonconsecutive

Abbreviation: SD, standard deviation.
[a]Based on expert-derived performance.[89]
[b]Maximum number of repetitions is 80.[89]

autonomy, subjective evaluation, and apprenticeship are difficult to apply to microsurgical training.[5] Proficiency in microsurgery require acquisition of a variety of skills including dexterity, ambidexterity, depth perception, instrument to target accuracy, hand-eye coordination, and adaptation to a magnified field.[6–8] The fundamental technical skills, such as handling microsurgical instruments and suture, should ideally be taught outside of the operating room in a skills laboratory.

The gold standard for microsurgery skills development has been the live animal model employed in many curricula.[9–13] Live animal laboratories provide a high-fidelity environment; however, they have several disadvantages including ethical concerns, cost, and time required to prepare and care for the animals.[3–5,9–11,14,15] Many microsurgical training courses offer nonbiologic models as useful alternatives to the live animal model. These models can be isolated tasks or incorporated into training curricula using cadaveric models for anastomosis practice.[15–36] Recent developments in microsurgical simulation and education even eliminate the use of a standard operating room microscope and instead incorporate a portable binocular microscope or monocular smartphone technology with video recording and feedback.[35–37] Some curricula rely on progression of skills based on learner postgraduate year (PGY), but reported outcomes are often not related to PGY level.[12]

The International Microsurgery Simulation Society consensus statement in 2020 emphasized the importance of nonbiologic models for instruction and need for objective assessment of trainees.[38] Despite the lower fidelity of nonbiologic models in contrast to operating room anastomoses, we believe nonbiologic models are more adaptive to a competency and proficiency-based training model to ensure mastery of skills. Competency-based learning emphasizes that each learner will have a different learning curve, and some learners will need more practice to achieve outcomes.[39] The transition to competency-based education requires measurable goals and assessment tools.[40–44] The standardization of nonbiologic models can sustain competency and promote proficiency in fundamental microsurgical skills development while potentially reducing the need for the rat model.[45]

Nonbiologic models in surgical simulation have successfully been implemented outside of plastic surgery.[16–33,46–53] The Fundamentals of Laparoscopic Surgery (FLS) is a validated program introduced in 2004 by the Society of American Gastrointestinal and Endoscopic Surgeons that trains individuals on the basic cognitive and technical skills required in laparoscopic surgery.[50] It aims to establish competency and develop proficiency in fundamental skills required to successfully perform laparoscopic surgery in the operating room in a stepwise fashion using nonbiologic materials. General surgery trainees are required to demonstrate laparoscopic proficiency by passing the FLS skills exam for board certification. Many laparoscopic technical principles, such as intracorporeal knot tying, overlap with microsurgical techniques (►**Table 1**).

The desire to implement a competency-based curriculum led our program to switch from an intermittent live-animal microsurgical course to a nonbiologic curriculum and develop a novel microsurgery curriculum adapted from FLS principles. This course integrates validated principles from laparoscopic simulation training models applicable to microsurgery and seeks to quantify learner mental workload and anxiety during microsurgical anastomosis using the National Aeronautics and Space Administration Task Load Index (NASA-TLX) and Spielberger State-Trait Anxiety Inventory (STAI-6)[54,55] (►**Tables 2** and **3**). The curriculum is designed to teach fundamental microsurgical skills with competency-based skill progression regardless of training year. Residents are provided 24-hour access to the skills laboratory. The development of an on-campus facility with 24-hour access allows learners the opportunity to repeat tasks as needed until proficiency is reached.[43] Our goal is to show that advancing skill level will decrease perceived mental workload and anxiety during microsurgical anastomosis. We also sought to quantify the effect of curriculum on resident performance in the operating room. The purpose of this study is to (1) introduce the Fundamentals of Microsurgery (FMS) for microsurgical simulation and (2) assess the translation of learner skill acquisition into the operating room.

Table 2 National Aeronautics and Space Administration Task Load Index (NASA-TLX) questionnaire, scale, and scoring used to evaluate overall perceived workload associated with a task[55]

National Aeronautics and Space Administration Task Load Index (NASA-TLX)
Questions
• How mentally demanding was the task?
• How physically demanding was the task?
• How hurried or rushed was the pace of the task?
• How successful were you in accomplishing what you were asked to do?
• How hard did you have to work to accomplish your level of performance?
• How insecure, discouraged, irritated, stressed, and annoyed were you?

Note: Scale/Task Load Index: 0 = very low to 100 = very high. Lower index value is associated with less perceived workload, higher index value is associated with higher perceived workload.

Methods

Participation in the FMS curriculum is mandatory for each resident in our program and consists of reading requirements, skills laboratory participation, and operative performance assessment of microsurgical arterial anastomosis. The FMS skills laboratory, like the FLS, is comprised of five tasks as described below. Each task is performed with a surgical microscope in a simulation laboratory. Trainees have 24-hour access to the laboratory and can participate in self-guided practice as needed for each task. The residents are evaluated by the senior author in person quarterly and must display a level of competency before progressing to the next task. Requirements for passing each task are listed in the description below and similar to the FLS. Residents must participate in the skills laboratory to perform intraoperative arterial anastomoses. The learners who did not complete the course served as our control as our program was implemented in phases.

The intraoperative portion of the FMS curriculum evaluates arterial microsurgical anastomoses performed by the residents during their normal rotations on several different services within plastic surgery. Operative performance evaluations are completed on the day of surgery by the individual trainee and attending. Resident progress of task completion and intraoperative evaluations were recorded through REDCap surveys.

Assessment Tools and Performance Tracking

Intraoperative assessment tools include the Stanford Microsurgery and Resident Training (SMaRT) score, NASA-TLX, and the STAI-6 score.[54–56] Data was managed using Research Electronic Data Capture (REDCap, Nashville, TN) tools hosted at Indiana University.[57,58] Anastomosis time and intraoperative technical issues (e.g., thrombosis, need for repair sutures) were also collected. The SMaRT scale is a global rating scale to evaluate performance of arterial anastomosis.[56] It is based on the Operative Performance Rating System used by the American Board of Surgery. Nine areas of technique assessment are scored on a Likert scale (1 to 5) and averaged, with a higher score corresponding to better performance. These areas of evaluation include instrument handling, respect for tissue, efficiency, suture handling, suturing technique, quality of knot, final product, operation flow, and overall performance.

Table 3 Six-Item Short Form of the Spielberger State-Trait Anxiety Inventory (STAI-6) questionnaire, scale, and scoring

Six-Item Short Form of the Spielberger State-Trait Anxiety Inventory (STAI-6)	
Question	Scale
• I feel calm • I am relaxed • I feel content	1 = very much, 2 = moderately, 3 = somewhat, 4 = not at all
• I am worried • I am tense • I feel upset	1 = not at all, 2 = somewhat, 3 = moderately, 4 = very much

Note: Score: 6 = less anxiety, 16 = most anxiety. Less anxiety per task is associated with a lower score.54

Workload and anxiety were evaluated using the NASA-TLX and STAI-6.[54,55] The NASA-TLX assessment tool is a validated multidimensional rating procedure that evaluates overall perceived mental workload[55] (►**Table 2**). A weighted score is based on six subscales including mental demands, physical demands, temporal demands, own performance, effort, and frustration. On a scale of 0 to 100 (0 = very low, 100 = very high) trainees rate their performance task load after completion of each intraoperative arterial anastomosis. The Short-Form STAI-6 is a questionnaire that evaluates level of anxiety associated with a task[54] (►**Table 3**). Trainees evaluate their degree of anxiety based on six questions and are given a STAI-6 score per intraoperative anastomosis completed. Scores can range from 6 to 16 with higher STAI-6 score corresponding to greater anxiety associated with the activity. Both the NASA-TLX and STAI-6 instruments are readily used as measurement tools in a variety of settings including surgical education and simulation.[59–67]

REDCap (Research Electronic Data Capture) is a secure, Web-based software platform designed to support data capture for research studies. REDCap provides (1) an intuitive interface for validated data capture; (2) audit trails for tracking data manipulation and export procedures; (3) automated export procedures for seamless data downloads to common statistical packages; and (4) procedures for data integration and interoperability with external sources.[55,57,58] REDCap surveys were used to collect microsurgery skills laboratory and intraoperative data.

Pilot Study

Integrated plastic surgery residents at Indiana University in their PGY 4 to 6 and independent residents in years 1 to 3 in the 2020 to 2021 academic year were evaluated. Resident participation in the FMS curriculum in the microsurgery

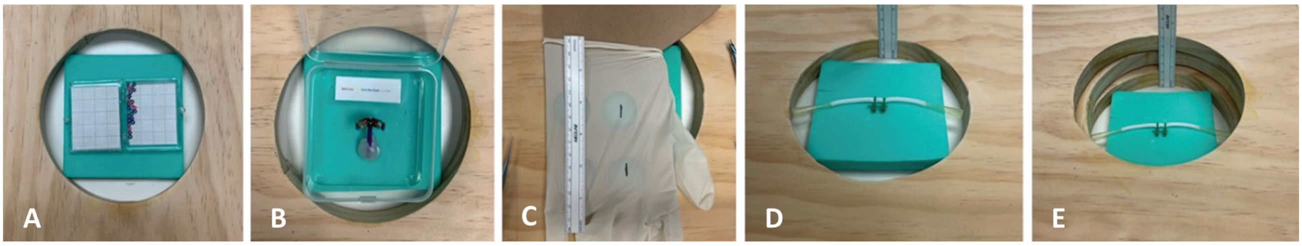

Fig. 1 (A) Task one, rubber band transfer. (B) Task two, coupler tine grasping. (C) Task three, glove laceration repair. (D) Task four, synthetic vessel anastomosis. (E) Task five, synthetic vessel anastomosis in a deep cavity.

skills laboratory and performance intraoperatively was tracked concurrently. Primary outcomes of intraoperative performance were SMaRT score, NASA-TLX score, and STAI-6 score. Secondary outcomes included number of technical issues and anastomosis time. The resident self-evaluation of intraoperative performance included anastomosis time, technical outcomes (e.g., additional repair sutures needed, need for redo anastomosis, thrombosis, etc.), SMaRT score, NASA-TLX, and the STAI-6. Statistical analysis was completed using SPSS Statistics 28 (IBM). Statistical analysis included analysis of variance, Student's *t*-test, and linear regression with statistical significance set at *p*-value of 0.05.

Fundamentals of Microsurgery Curriculum

Task 1: Rubber Band Transfer (►Fig. 1A) ►Video 1
Twenty-five rubber bands are transferred sequentially between the right and left in a tray. Individuals must successfully grasp, transfer from one hand to the next, and arrange each rubber band in a 1-cm square by color on the contralateral side. Microsurgical forceps are used to complete this task. Task completion requirements include completion within 2 minutes, no bands can be dropped outside the field of view, and rubber bands must be grasped with the correct hand and placed neatly within the square.

Task 2: Coupler Tine Grasping (►Fig. 1B) ►Video 1
Trainees grasp venous coupler tines in a predetermined order using an angled forceps. Task two begins with the left hand. The base of tines is grasped on both sides of the coupler in the following order: Red, Orange, Yellow, Green, Blue, Purple, Silver, and Gold. The learner repeats this with the right hand. Task completion requirements include completion within 1 minute, the base of the tine must be grasped, and tines must be grasped in the correct order.

Task 3: Glove Laceration Repair (►Fig. 1C, ►Video 1)
Learners will successfully suture a 1-cm laceration in a latex glove in an allotted time. A latex glove is placed taut over a clipboard with small cutouts. A 1-cm laceration is created in the glove using microsurgical scissors and forceps. The laceration is repaired with four 6–0 Prolene sutures, each with three knots. The suture must be loaded on the forceps under the microscope and each suture is to be placed and tied prior to proceeding to the next suture. In addition, the nondominant hand forceps should be placed within the glove laceration to mimic intubation of the vessel. Time starts when the needle is loaded and ends when the fourth suture is cut. Task completion requirements include completion within 3 minutes, no lifting the glove off the background, must follow the curve of the needle, must not allow nondominant hand forceps to spring open (to prevent vessel trauma by tearing adjacent sutures during vessel intubation), sutures must be evenly spaced, and knots must be uniform.

Task 4: Synthetic Vessel Anastomosis (►Fig. 1D, ►Video 1)
Task four evaluates the learner's ability to perform an anastomosis using a synthetic vessel. The learner uses microsurgical instruments and 9–0 nylon suture for the task. Anastomosis time is measured from time of placement to removal of double Acland clamps and requires eight sutures for uniformity. Task completion requirements include completion within 12 minutes, no lifting the vessel off the background, must follow the curve of the needle, must not allow forceps to spring open, no back wall sutures, sutures must be evenly spaced, knots must be uniform, and anastomosis must be patent.

Task 5: Synthetic Vessel Anastomosis in a Deep Cavity (►Fig. 1E, ►Video 1)
Task five evaluates the learner on performing an anastomosis at a depth. Synthetic vessels are utilized with depth blocks (5 cm). Microsurgical instruments and 9–0 nylon are used for anastomosis. Anastomosis time is measured from time of placement to removal of double Acland clamps and requires eight sutures for uniformity. Task completion requirements include completion within 12 minutes, no lifting the vessel off the background, must follow the curve of the needle, must not allow forceps to spring open, no back wall sutures, sutures must be evenly spaced, knots must be uniform, and anastomosis must be patent.

Results

A total of 62 intraoperative anastomoses during clinical care were self-reported and 32 evaluated by supervising attendings for five integrated residents and two independent residents. Results were correlated with FMS simulation task completion at time of intraoperative anastomosis performance. Learners were not tracked according to PGY level but by proficiency in the skills laboratory they completed tasks through task five. Resident- and attending-reported outcomes were analyzed.

Intraoperative mean STAI-6 scores decreased ($p = 0.03$) and SMaRT score increased ($p = 0.05$) incrementally as FMS

Table 4 NASA-TLX, STAI-6, and SMaRT scores of intraoperative anastomosis performed by task completed

NASA-TLX, STAI-6, and SMaRT scores for intra-operative anastomoses performed by task completed				
Task completed	**Anastomoses, *n***	**NASA-TLX, mean (SD)**	**STAI-6, mean (SD)**	**SMaRT, mean (SD)**
One and Two	15	50.9 (14.6)	14.3 (3.24)	3.98 (0.64)
Three	19	41.4 (11.6)	11.9 (3.91)	3.91 (0.51)
Four	9	46.7 (19.0)	12.2 (3.15)	3.95 (0.76)
Five	19	48.2 (15.9)	10.1 (4.78)	4.46 (0.76)
Total	62	46.5 (15.0)	12.0 (4.18)	4.10 (0.69)

Abbreviations: FMS, Fundamentals of Microsurgery; NASA-TLX, National Aeronautics and Space Administration Task Load Index; SD, standard deviation; SMaRT, Stanford Microsurgery and Resident Training; STAI-6, Spielberger State-Trait Anxiety Inventory.
Note: Anxiety ($p = 0.03$) and proficiency ($p = 0.05$) improved with completion of tasks. Perceived workload via NASA-TLX score ($p = 0.16$) did not change with completion of FMS tasks.

tasks were completed in succession (►**Table 4**). Residents performing anastomoses who completed the FMS curriculum showed less anxiety with lower STAI-6 scores and higher technical ability via SMaRT score with completion of tasks. The perceived workload, expressed by NASA-TLX scores trended down with task completion at time of intraoperative anastomosis (►**Table 4**). Regression analysis showed that a higher SMaRT score was associated with a lower workload via lower NASA-TLX score ($p < 0.01$) and lower anxiety with lower STAI-6 score ($p < 0.01$) (►**Figs. 2** and **3**). Intraoperative technical issues (e.g., vessel thrombosis requiring revision or repair sutures placed by attendings) ($p = 0.50$) and anastomosis times ($p = 0.40$) were not different regardless of task completion at the time of anastomosis. Residents achieved patency of their intraoperative anastomosis at every encounter.

Discussion

The foundations of microsurgical skills include dexterity, ambidexterity, depth perception, instrument to target accuracy, hand-eye coordination, tactile feedback, and adaptation to a magnified, two-dimensional field.[6] Additionally, learner stress and cognitive workload within and outside the operating room can affect trainee's intraoperative performance, technical performance, economy of motion, and capacity for sustained learning.[59,65,67–69] When a surgical task such as microsurgical arterial anastomosis requires a high level of attention, the trainee will be left with a small amount of mental workload with which to manage secondary tasks or instructions from attending staff.[70–74] Reduction in perceived workload, as measured by NASA-TLX, can improve acquisition of surgical dexterity.[75] As trainees perceived mental workload decreases, the amount of available cognitive attention and working memory will increase and allow them to obtain additional skills[76,77] Repeated exposure to a task or procedure not only improves technical proficiency but can also decrease cognitive workload and learner anxiety in the clinical setting.[67,78,79] Managing learner anxiety in the operating room, an important aspect of surgical education, can improve operative outcomes.[80,81]

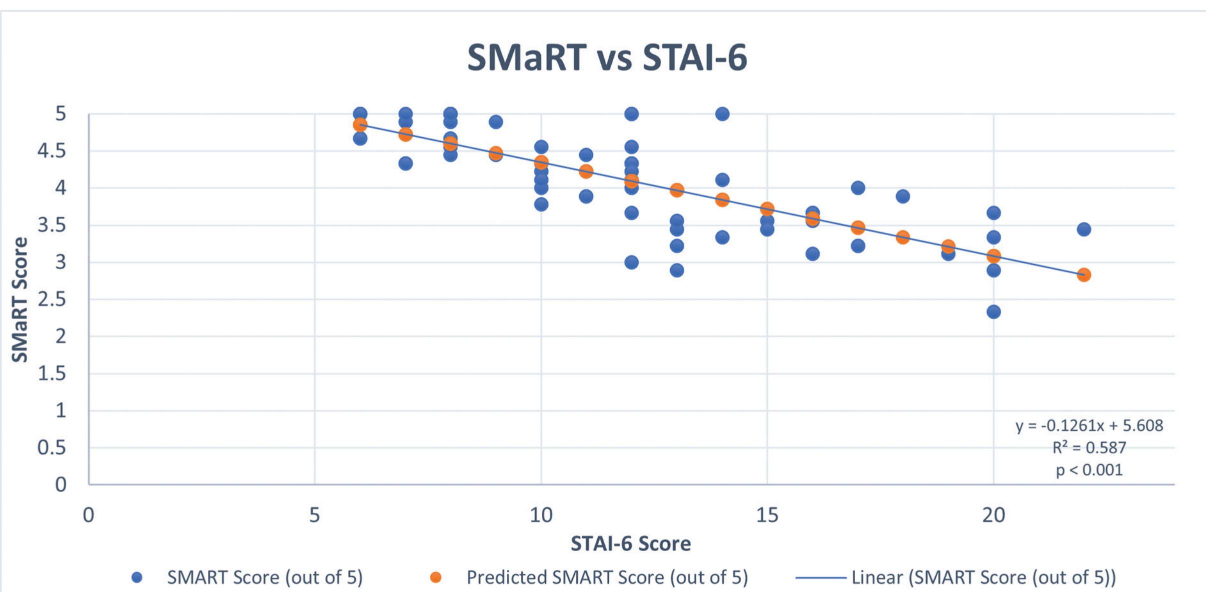

Fig. 2 Stanford Microsurgery and Resident Training (SMaRT) score versus Spielberger State-Trait Anxiety Inventory (STAI-6) for intraoperative anastomoses completed by residents completing the Fundamentals of Microsurgery (FMS). Lower anxiety scores were associated with increased proficiency in intraoperative anastomoses.

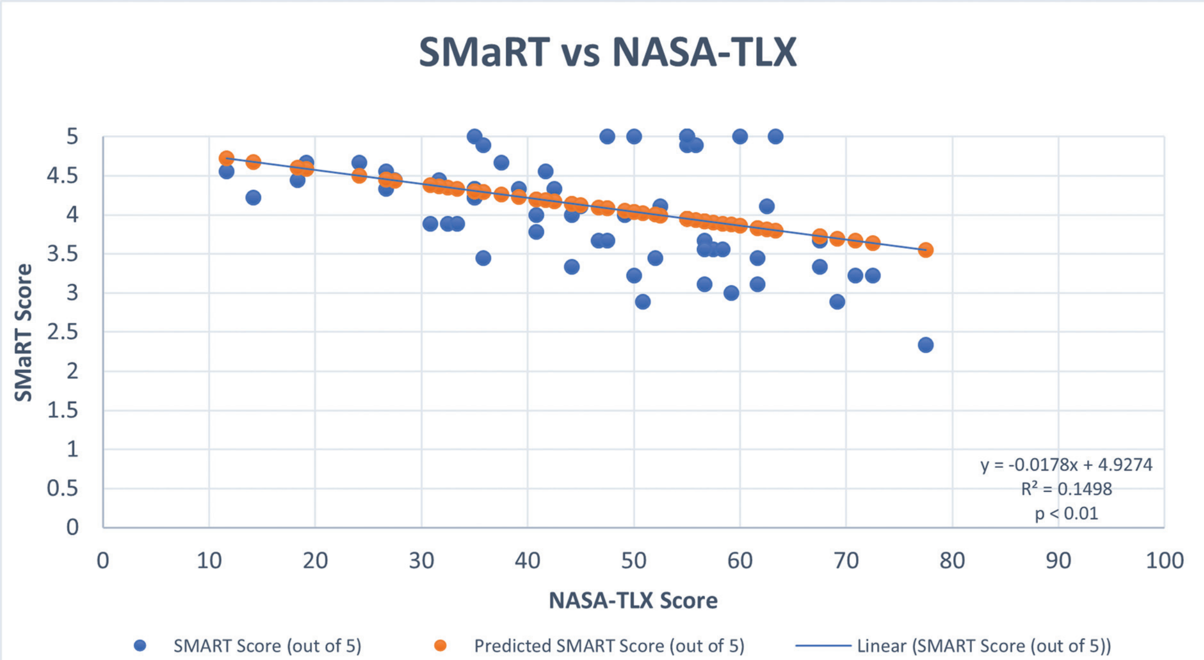

Fig. 3 Stanford Microsurgery and Resident Training (SMaRT) score versus National Aeronautics and Space Administration Task Load Index (NASA-TLX) score for intraoperative anastomoses completed by residents completing the Fundamentals of Microsurgery (FMS). Lower workload was associated with increased proficiency in intra-operative anastomoses.

Residents who underwent evaluation of intraoperative anastomosis with task level completion in the FMS curriculum demonstrated less anxiety and greater proficiency as shown with lower and decreasing STAI-6 scores ($p = 0.03$) and higher SMaRT scores ($p = 0.05$). In addition, as residents achieved improvement in technical skills (higher SMaRT scores), they demonstrated less anxiety (lower STAI-6) and perceived workload (lower NASA-TLX). This suggests that the FMS curriculum improves proficiency in microsurgical skills while also reducing intraoperative anxiety.

Our microsurgery skills laboratory curriculum utilizes several nonbiologic methods to develop, improve, and maintain fundamental skills.[45] Many nonbiologic models show the utility of our presented tasks in improving core microsurgical skills including economy of motion, tissue handling and transfer, ease of microsurgical instrument use, suturing, and knot tying.[23] Published models include the use of bead transfer, latex glove, and synthetic tubing (e.g., polytetrafluoroethylene, GorTex, and silastic tubing) to simulate vessels and peripheral nerves.[15–22,26,28,32,34–36,45,51,52] These are effective models in skill development and retention demonstrating construct and content validity with the addition of synthetic-based models having face validity.[24] These models do not depend on use of live or cadaveric tissue and are cost-effective.[20] Existing training curricula and programs rely on the use of live or cadaveric animals for evaluation of anastomosis.[12,14,15,22,28–30,37,39,47] Reduction in use or even elimination of animals in microsurgical training does not have a negative impact on microsurgical skill acquisition and instead may improve proficiency.[14,15] In turn, we believe a nonbiologic model is ideal for teaching basic microsurgical skills since it allows skill acquisition in a competency- and proficiency-based manner.[9–11]

Most plastic surgery residency programs desire a mandatory curriculum in microsurgery.[82] The FMS curriculum would not be difficult to implement. Our FMS curriculum emphasizes the development of fundamental surgical skills using nonbiologic methods that are reliably transferable to effective intraoperative performance. The materials are easily accessible and cost-effective compared with live animal models.[20] The FMS tasks are reproducible, and the course is self-directed. Residents can record videos and send to the senior author for evaluation, similar to the ►**Video 1**. Direct faculty observation of learners and real-time feedback for those struggling or requiring additional guidance with tasks is valuable and necessary.[13] The FMS optimizes this direct faculty involvement.

Video 1

Compilation of tasks one through five performed in order of completion. Online content including video sequences viewable at: https://www.thieme-connect.com/products/ejournals/html/10.1055/a-2003-7425.

Our pilot study has several limitations. Previously, our residency program had a once-a-year live animal course that was changed to an ongoing nonbiologic course for improved skill retention. We designed our FMS curriculum to begin with fundamentals and to emphasize competency-based progression without the influence of training year. We then implemented our FMS curriculum with reading, skills laboratory, and intraoperative performance feedback. We did not, however, previously evaluate intraoperative performance, mental workload, and anxiety and so we do not have a control group that includes residents without any FMS training. In addition, there is no long-term data to compare resident SMaRT scores after FMS completion to experience, number of intraoperative arterial anastomoses performed, or years of training.

Although multiple studies show that microsurgical skill acquisition outside the operating room is critical, a standardized microsurgery curriculum has not been universally adopted.[2,9–11,16,17,38,45] Many programs provide a spectrum of basic and advanced microsurgical courses for trainees, but despite this a standardized curriculum is not shared among training programs.[48] Uniform curriculums allowing trainees to develop skills in a competency- and proficiency-based manner has been successfully implemented in other surgical fields and should be implemented for microsurgical education.[40,41,83–88] Learners with a broader set of fundamental skills will have an advantage when performing microsurgery in the operating room.

Conclusion

Competency-based learning includes the use of assessment tools and the ability to provide immediate feedback to trainees. Implementation of our FMS curriculum will allow training programs to add a competency-based component to ongoing training with a concurrent reduction in experienced stress and anxiety in the operating room. FMS allows learners at various skill levels to progress at their own pace while simultaneously building and maintaining a strong technical foundation in microsurgery. Trainees who demonstrate early proficiency can progress through the curriculum with little practice needed. Others may require repeated performance of a task with observation to increase efficiency or elicit additional feedback, and FMS levels the playing field for those who demonstrate competency and proficiency at a slower pace or struggle technically.

A competency-based model ensures learners can advance their microsurgical skills based on their real-time skill level and practice needs rather than training year. We believe a nonbiologic curriculum, such as the FMS, is favorable over the rat model for development of fundamental microsurgical skills. Microsurgery is a field that can provide various opportunities and broaden one's practice. Augmenting the number of trainees who are competent and comfortable in microsurgical techniques will increase patient access to the full depth and breadth of reconstructive care.

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Conflict of Interest
None declared.

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