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Applying objective metrics to neurosurgical skill development with simulation and spaced repetition learning

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OBJECTIVE Surgical skills laboratories augment educational training by deepening one's understanding of anatomy and allowing the safe practice of technical skills. Novel, high-fidelity, cadaver-free simulators provide an opportunity to increase access to skills laboratory training. The neurosurgical field has historically evaluated skill by subjective assessment or outcome measures, as opposed to process measures with objective, quantitative indicators of technical skill and progression. The authors conducted a pilot training module with spaced repetition learning concepts to evaluate its feasibility and impact on proficiency.

METHODS The 6-week module used a simulator of a pterional approach representing skull, dura mater, cranial nerves, and arteries (UpSurgeOn S.r.l.). Neurosurgery residents at an academic tertiary hospital completed a video-recorded baseline examination, performing supraorbital and pterional craniotomies, dural opening, suturing, and anatomical identification under a microscope. Participation in the full 6-week module was voluntary, which precluded randomizing by class year. The intervention group participated in four additional faculty-guided trainings. In the 6th week, all residents (intervention and control) repeated the initial examination with video recording. Videos were evaluated by three neurosurgical attendings who were not affiliated with the institution and who were blinded to participant grouping and year. Scores were assigned via Global Rating Scales (GRSs) and Task-based Specific Checklists (TSCs) previously built for craniotomy (cGRS, cTSC) and microsurgical exploration (mGRS, mTSC).

RESULTS Fifteen residents participated (8 intervention, 7 control). The intervention group included a greater number of junior residents (postgraduate years 1–3; 7/8) compared to the control group (1/7). External evaluators had internal consistency within 0.5% (kappa probability > Z of 0.00001). The total average time improved by 5:42 minutes ($p < 0.003$; intervention, 6:05, $p = 0.07$; control, 5:15, $p = 0.001$). The intervention group began with lower scores in all categories and surpassed the comparison group in cGRS (10.93 to 13.6/16) and cTSC (4.0 to 7.4/10). Percent improvements for the intervention group were cGRS 25% ($p = 0.02$), cTSC 84% ($p = 0.002$), mGRS 18% ($p = 0.003$), and mTSC 52% ($p = 0.037$). For controls, improvements were cGRS 4% ($p = 0.19$), cTSC 0.0% ($p > 0.99$), mGRS 6% ($p = 0.07$), and mTSC 31% ($p = 0.029$).

CONCLUSIONS Participants who underwent a 6-week simulation course showed significant objective improvement in technical indicators, particularly individuals who were early in their training. Small, nonrandomized grouping limits generalizability regarding degree of impact; however, introducing objective performance metrics during spaced repetition simulation would undoubtedly improve training. A larger multiinstitutional randomized controlled study will help elucidate the value of this educational method.

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KEYWORDS education; neurosurgery; simulation; spaced repetition; surgical training; technical skills

ABBREVIATIONS cGRS = craniotomy GRS; cTSC = craniotomy TSC; GRS = Global Rating Scale; mGRS = microsurgical exploration GRS; mTSC = microsurgical exploration TSC; TSC = Task-based Specific Checklist; VR = virtual reality.

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SURGICAL education has traditionally been accomplished through a combination of apprenticeship, graduated responsibility, and didactics, supplemented with skills workshops predominantly using cadaveric specimens. There is an abundance of neurosurgical literature that emphasizes the immense time and practice required for ascending the technical skills learning curve, and all reports underscore the importance of repetition.¹⁻⁴ Research on mastery in other technical fields suggests that learning occurs in stages: observing, imitating action based on instruction, taking action without assistance, and repetition of actions.^{5,6} The repetition stage is integral for the automatization of skill; ultimately it leads to the trainee being able to perform a skill without any instruction or assistance.⁷ A step further than repetition alone is spaced repetition. Spaced repetition is an educational technique for efficient memorization that uses repeated review of content following a schedule to improve long-term retention.⁸

Although surgical trainees will perform many repetitions of a procedure throughout the course of a 7-year training program, there are limitations in relying on intraoperative training for the most efficient knowledge growth and skill acquisition. This is partially due to the variability in exposure to cases and approaches within and between residency programs due to differences in rotations, case volume, and resident autonomy. Furthermore, increased pressures on healthcare systems to be more efficient may also contribute to variability in trainee surgical autonomy.⁹ Hence, there is a growing interest in integrating new avenues of skill development. As recently emphasized in a perspective article from general surgery, there is a call to action to increase spaced repetition learning within surgical training.¹⁰

Ideally, a spaced repetition learning approach would not have high cost or resource barriers. Although cadaveric skills laboratories remain instrumental in education, they are limited due to their expense and the logistics around specimen preservation and biohazard safety.^{11,12} With the advent of rapidly progressive technologies, surgical simulation with virtual reality (VR), augmented reality, and high-fidelity synthetic models may fill that void. Not only do these tools have the potential of providing high-frequency repetition for trainees, but also their uniformity can potentiate objective evaluation of technical skill improvement. Importantly, the neurosurgical field has historically evaluated skill by subjective assessment or outcome measures, as opposed to process measures with integrated objective and quantitative indicators of technical skill and progression during training. Having a reproducible model enables easier application of quantifiable and trackable metrics.

We developed a pilot surgical training module using a simulator of the pterional approach with disposable skulls and dura mater (UpSurgeOn S.r.l.) for a 6-week guided training program to teach and objectively evaluate residents' understanding and improvement of anatomy and surgical skills using predefined metrics. The objective was to evaluate the impact and feasibility of incorporating model simulation into neurosurgical residency to improve knowledge and technical skills.

Methods

Educational and Simulation Model

The study was articulated in three phases, as follows: a preliminary evaluation, a training phase, and a final evaluation. For the preliminary evaluation, all participants received a link to a 10-minute introductory video explaining the technical objectives, initial session, and evaluation criteria. Residents were also instructed to download the UpSurgeOn phone app, which included stepwise teaching modules for the pterional craniotomy. The simulation model used was the UpSurgeOn PterionalBox (Fig. 1), which consists of a reusable 3D-printed skull, brain, dura, and underlying vascular and nerve structures. The skull's design provided a portion of the skull that corresponded to the approach (pterional, supraorbital, etc.), with the accompanying bony features—superior temporal line, key-hole, sphenoid wing, and clivus.

Trainees were assigned individual skull models and performed craniotomies at surgical stations. They were given printed instructions (Supplement 1) for the approach, which began with a supraorbital craniotomy, followed by extension of the craniotomy to include a pterional craniotomy. The residents were instructed to drill the sphenoid wing, insert three dural tacking sutures, and open the dura. Participants were asked to do this without instructor help and were timed. The procedure was video recorded for subsequent evaluation, and the disposable parts of the skulls and dura were saved for review. Trainees then rotated to a separate station focused on microsurgical identification of anatomy. Using the microscope, a retractor, and bayoneted forceps, the resident was asked by the proctor to identify anatomical structures (Fig. 2, checklist available in Supplement 2). Their microscope's video feed was visible on a screen and was recorded, and they were asked to identify a standardized list of structures for 3 minutes. At the end of the session, each participant completed a survey evaluating the course, their experience, and the models (Supplement 3).

For the training phase, participants in the intervention group received detailed feedback from an external reviewer regarding their first video. Written feedback was given identifying their technique, approach, and timing. In addition, residents attended a total of 4 laboratory sessions with faculty who would provide teaching demonstrations, followed by the residents practicing the supraorbital and pterional craniotomy with feedback from faculty. Sessions also included microscope identification of anatomy structures. During the final 2 sessions, participants were encouraged to time themselves on their procedures to prepare for the final evaluation.

For the final evaluation, all residents (those with and without participation in the focused skills laboratories) performed the same tasks as the initial evaluation, including video recordings of the craniotomies and microscope identification. A postcourse survey was completed.

Evaluation Metrics

Data were analyzed with a pre- and posttest methodology including de-identified video and surveys. Three neurosurgical attendings not affiliated with the institution

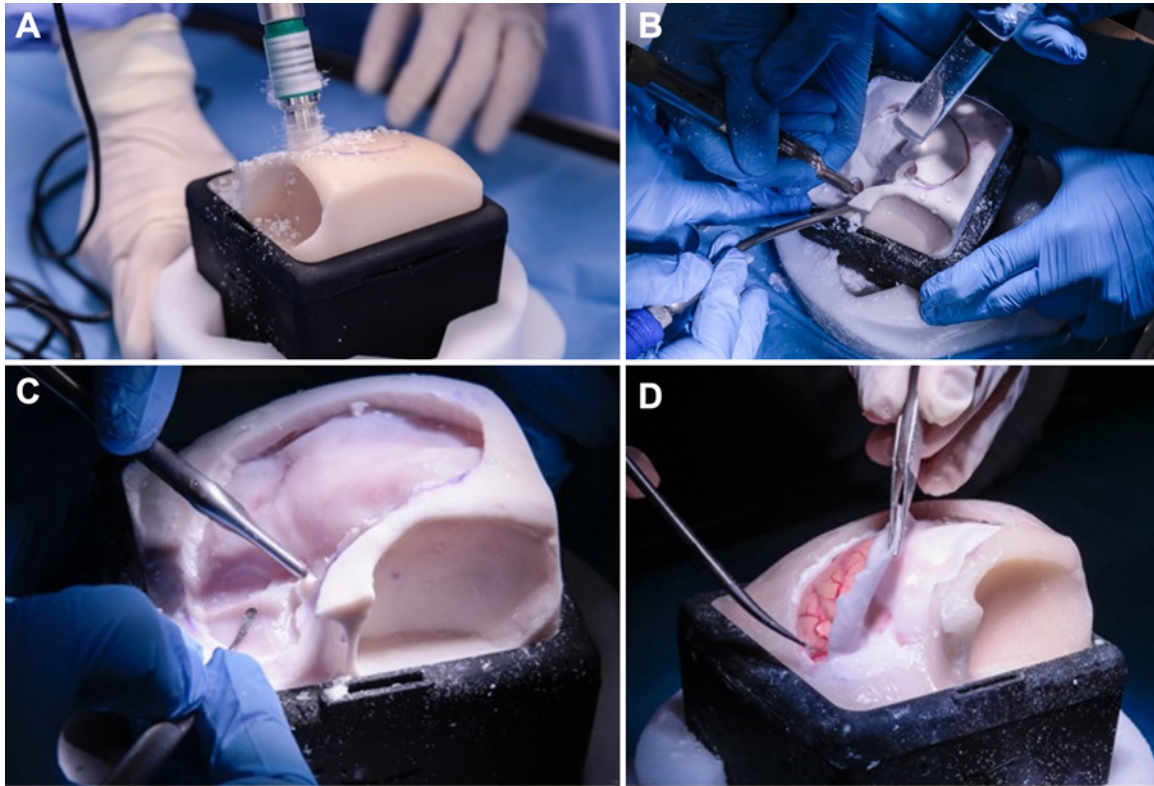


FIG. 1. Performing craniotomies on the simulator. **A–C:** Participants using various drills to perform a pterional craniotomy are pictured. **D:** Example of dural opening. © UpSurgeOn S.r.l., published with permission. Figure is available in color online only.

involved in the study were asked to evaluate the video based on the criteria established (technique-based checklists, identification of anatomy, and timing). These independent evaluators were blinded to the resident groupings and training levels. Dr. Nicolosi (inventor of the simulator model) was not involved in the evaluation process. Interrater reliability was evaluated with a kappa test. During the course, the tasks of Craniotomy, Dural Opening, and Microsurgical Exploration were scored using the Objective Structured Assessment of Technical Skills,¹³ which was adequately modified to our study. These specific Global Rating Scales (GRSs) and precise Task-based Specific Checklists (TSCs) have been built for craniotomy (cGRS, cTSC) and microsurgical exploration (mGRS, mTSC) tasks (Supplement 4).^{14,15} The study design was cocreated by F.C.R., F.N., and F.G. Scores were analyzed with a paired t-test, with significance measures at $p < 0.05$. Data analysis was performed using Microsoft Excel and Stata software.

Setting and Participants

The study was conducted within the neurosurgery residency training program at Massachusetts General Hospital, where there are 21 trainees in the program (although junior residents rotate at an outside hospital, and research residents may be based out of town). The workshops were conducted in the anatomy laboratory of the Massachusetts Eye and Ear Institute, where there is access to 11 procedure stations. Each station was equipped with high-speed

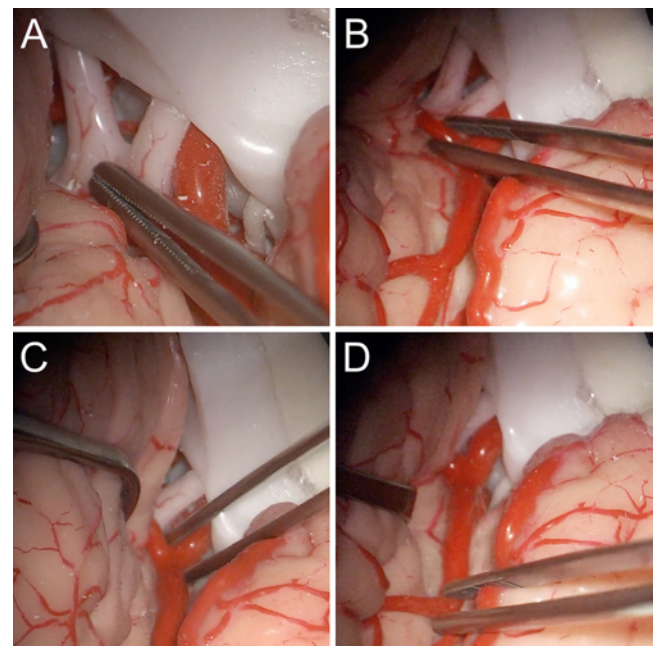


FIG. 2. Microscope identification. Examples of anatomy that participants examined during the microscope identification portion as screenshots from the video recording. **A:** Optic chiasm. **B:** Anterior cerebral artery. **C:** Internal carotid artery. **D:** Middle cerebral artery bifurcation. Figure is available in color online only.

drills, suction, handheld irrigation, a microscope, and pertinent surgical instruments. Residents rotated through the stations so that there would only be one resident at each station during the examination.

Neurosurgical trainees were asked to voluntarily participate in the educational pilot study, with a group of the residents assigned to complete an educational course (an initial evaluation, 4 sessions of simulation across 2 months, and a final evaluation), whereas the other group would only complete the initial and final phases, without the focused curriculum. Because of the volunteer and nonmandatory nature of the training, residents were not able to be perfectly randomized by class year. There was a separate consent form to authorize video and photographs during the session, and their use by UpSurgeOn S.r.l.

Results

Fifteen residents participated (8 in the intervention and 7 in the comparison group). Some residents were unable to participate due to rotations at external hospitals. Given that the trainees were not randomized and were permitted to choose their group, the intervention group included fewer senior residents (3 in year 1; 2 in year 2; 2 in year 3; and 1 in year 6) compared to those who only did the pretest and final (1 in year 2; 1 in year 4; 1 in year 5; 1 in year 6; and 3 in year 7).

The three evaluators had an internal consistency within 0.5%, posting identical scores for approximately 70% of the evaluations. A kappa test for interrater agreement had a kappa of 0.5546, a Z-score of 33.08, and a probability $> Z$ of 0.00001. Therefore, we can confidently reject the hypothesis that the evaluators were making their determinations randomly. The average results for the different scales are reported in Table 1. All participants improved; however, the intervention group had greater percentages of improvement. The average time for the two openings improved by 5:42 minutes ($p < 0.003$; intervention, 6:05, $p = 0.07$; comparison, 5:15, $p = 0.001$). While the intervention group began with lower scores in all categories, they surpassed the comparison group in cGRS (10.93 to 13.6/16) and cTSC (4.0 to 7.4/10; Fig. 3). Percent improvements for the intervention group were cGRS 25% ($p = 0.02$), cTSC 84% ($p = 0.002$), mGRS 18% ($p = 0.003$), and mTSC 52% ($p = 0.037$). For controls, improvements were cGRS 4% ($p = 0.19$), cTSC 0.0% ($p > 0.99$), mGRS 6% ($p = 0.07$), and mTSC 31% ($p = 0.029$). Given that the control group was composed mostly of more senior residents, it is notable that the final score of the study group exceeded the pretest scores of the senior residents in three of the four categories.

For the surveys, which were all on a 4-point scale, the study group had an average 0.42-point (10.7%) increase in subjective proficiency in both craniotomy practice and microsurgical dexterity (final averages 1.71 and 1.86, respectively). There was also an average 0.42-point (10.7%) increase in subjective confidence in the use of neurosurgical instruments (final average 3.43), and a 1-point increase (25%) in confidence with the microscope (final average 2.29). When asked if this method of training should be part of a standard training curriculum, pre- and post-

course scores were unchanged, with an average of 3.43. For the comparison group, there was a 1-point increase in subjective confidence in the use of neurosurgical instruments, a 0.33-point increase in confidence with the microscope, and a 0.33-point increase in favor of including this in the residency curriculum, with all members rating a 4 (strongly agree).

Discussion

This 6-week pilot study aimed to evaluate the impact and feasibility of incorporating model simulation and spaced repetition learning into neurosurgical residency programs to improve anatomical knowledge and technical skills by using objective criteria that could be tracked over time. There appeared to be key significant differences seen for participants undergoing iterative training in the study group in scores from the craniotomy and microscope anatomy GRSs and TSCs. The study group improved an average of 3 points per evaluation, versus 0.57 points in the comparison group. Given that the sample size was small, there were not enough data to better ascertain which exact skills improved most with the training (e.g., if improvements were more related to use of the craniotome vs drilling the sphenoid ridge). Both cadres had improvements in the time taken to perform the craniotomy tasks, with greater improvements in the study group. However, in both analyses the higher initial score of the more senior residents makes it more difficult to have a comparable increase, because there is likely to be a plateau in the learning curve. Nonetheless, this study is unique because it demonstrated that a set curriculum with synthetic models could have benefits for technical skill development through repetition over a relatively short time span. This concept of spaced repetition is clearly defined in the literature for fact or word memorization, such as with the use of flashcards or digital apps.⁸ As this understanding has become more prevalent, there has been a call to action to try to integrate this for surgical technical skills as well.¹⁰ This pilot demonstration is important for three key reasons: high-fidelity simulators with ease of use, objective evaluation, and feasibility to incorporate into formal neurosurgical education.

The search for high-fidelity simulation with increased levels of complexity has been a priority for neurosurgical programs in the past decade, because the field recognizes the benefit of providing a reproducible risk-free practice to further motor acquisition and automate psychomotor skills.^{16,17} In a 2013 national survey of US neurosurgical program directors, 45% thought that residents should achieve predefined levels of proficiency on simulators before working on patients, and 74% indicated that they would make simulator practice mandatory if available.¹⁸ Only 17% of program directors expressed a desire for more use of cadaveric models, whereas 84% believed that physical models and virtual simulation were more advantageous. The Society of Neurological Surgeons has historically orchestrated a national course (i.e., “Intern Boot Camp”) to teach first-year residents with simulation for basic procedures such as placement of external ventricular drains, lumbar puncture, central lines, and craniotomy

TABLE 1. Scores for participants in a surgical skills simulation course

Participant	cGRS					mGRS				
	Pretest		Posttest		% Improvement	Pretest		Posttest		% Improvement
	Average	SD	Average	SD		Average	SD	Average	SD	
Control										
1	14.7	0.6	15.0	1.0	2%	10.0	0.0	11.0	0.0	10%
2	13.3	0.6	14.0	1.0	5%	11.0	0.0	10.7	0.6	−3%
3	7.0	0.0	7.0	0.0	0%	9.3	0.6	10.7	0.6	14%
4	13.3	0.6	15.3	0.6	15%	9.0	0.0	9.0	0.0	0%
5	9.0	0.0	10.0	1.0	11%	9.3	0.6	9.3	0.6	0%
6	16.0	0.0	16.0	0.0	0%	9.7	0.6	11.0	1.0	14%
7	12.7	0.6	12.0	0.0	−5%	10.3	0.6	11.0	0.0	6%
Combined	12.3	3.0	12.8	3.2	4%	9.8	0.7	10.4	0.9	6%
Paired t-test	0.19					0.07				
Intervention										
1	9.3	0.6	14.0	0.0	50%	8.0	0.0	8.7	0.6	8%
2	7.3	0.6	12.3	0.6	68%	6.0	0.0	8.0	0.0	33%
3	10.0	0.0	14.0	0.0	40%	7.0	0.0	8.7	0.6	24%
4	11.0	0.0	10.0	0.0	−9%	7.7	0.6	8.0	0.0	4%
5	11.3	0.6	14.7	0.6	29%	7.3	0.6	7.7	0.6	5%
6	14.0	0.0	15.7	0.6	12%	8.0	1.0	10.3	0.6	29%
7	15.0	0.0	15.7	0.6	4%	7.7	1.2	9.7	0.6	26%
8	9.3	0.6	12.7	0.6	36%	8.7	0.6	10.3	0.6	19%
Combined	10.9	2.4	13.6	1.9	25%	7.5	0.9	8.9	1.1	18%
Paired t-test	0.02					0.003				

Participant	cTSC					mTSC				
	Pretest		Posttest		% Improvement	Pretest		Posttest		% Improvement
	Average	SD	Average	SD		Average	SD	Average	SD	
Control										
1	8.0	0.0	8.0	0.0	0%	10.0	0.0	14.0	0.0	40%
2	4.0	0.0	5.0	0.0	25%	14.0	0.0	12.0	0.0	−14%
3	6.0	0.0	6.0	0.0	0%	9.0	0.0	14.0	0.0	56%
4	8.0	0.0	7.0	0.0	−13%	7.0	0.0	14.0	0.0	100%
5	3.0	0.0	3.0	0.0	0%	8.0	0.0	11.0	0.0	38%
6	8.0	0.0	8.0	0.0	0%	10.0	0.0	14.0	0.0	40%
7	7.0	0.0	7.0	0.0	0%	13.0	0.0	14.0	0.0	8%
Combined	6.3	2.0	6.3	1.7	0%	10.1	2.4	13.3	1.2	31%
Paired t-test	>0.99					0.029				
Intervention										
1	4.0	0.0	8.0	0.0	100%	10.0	0.0	9.0	0.0	−10%
2	2.0	0.0	6.0	0.0	200%	6.0	0.0	11.0	0.0	83%
3	3.0	0.0	8.0	0.0	167%	9.0	0.0	14.0	0.0	56%
4	3.0	0.0	8.0	0.0	167%	7.0	0.0	7.0	0.0	0%
5	3.0	0.0	6.0	0.0	100%	8.0	0.0	5.0	0.0	−38%
6	5.0	0.0	8.0	0.0	60%	5.0	0.0	14.0	0.0	180%
7	8.0	0.0	8.0	0.0	0%	6.0	0.0	14.0	0.0	133%
8	4.0	0.0	7.0	0.0	75%	7.0	0.0	14.0	0.0	100%
Combined	4.0	1.8	7.4	0.9	84%	7.3	1.6	11.0	3.5	52%
Paired t-test	0.002					0.037				

Average scores are displayed for specific GRSs and precise TSCs for craniotomy and microsurgical exploration tasks. Data were compared using a paired t-test, and boldface values are statistically significant ($p < 0.05$).

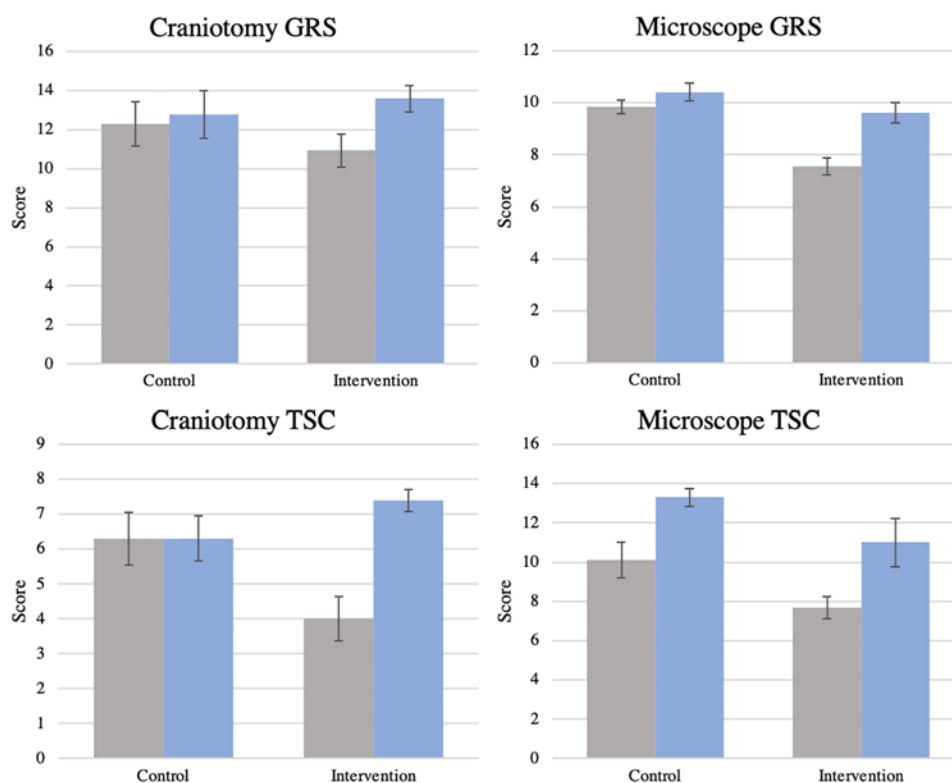


FIG. 3. Pretest and posttest scores for each assessment. GRSs and precise TSCs for craniotomy (cGRS, cTSC) and microsurgical exploration (mGRS, mTSC) tasks. Figure is available in color online only.

and dural suturing.¹⁷ It was instituted in 2009, and by 2011, 100% of US residents in Accreditation Council for Graduate Medical Education (ACGME)–accredited neurosurgical training programs were participating in the program.¹⁹ Although it was a great success, the skull models were single use and the underlying anatomy was limited, leaving much to be desired for training individuals beyond entry-level interns.

In recent years, realistic physical and VR models for surgical training have gained significant popularity as a complement and sometimes an alternative to traditional cadaveric specimens.²⁰ Also, in 2013 the Congress of Neurological Surgeons established a Simulation Committee to explore the use of technology in maximizing neurosurgical education. Their report noted that VR-based models are limited in reproducing the tactile learning of a surgical procedure, leading residents to prefer physical models.²¹ Additionally, they noted that VR models have dedicated hardware 10–100 times more expensive than physical models. The Brainbox simulator used in this study has the benefit of a disposable and exchangeable skull cover that is limited to the area of focus to permit repeated use at a much more affordable cost. The underlying brain specimen incorporates a tremendous level of detail; for example, the pterional box includes the cranial nerves (first and third cranial nerves, optic chiasm) and the internal carotid, anterior cerebral, anterior communicating, middle cerebral, posterior communicating, posterior cerebral, ophthalmic, and perforating arteries. Structures also include the pituitary stalk, lamina terminalis, and surrounding brain. This

level of detail allows the user to appreciate the view obtained by the craniotomy placement, and to acquire more anatomical study and practice navigating deeper structures. Many other physical models have been designed and studied, e.g., for aneurysms^{22–27} including deep anastomoses,^{28,29} cerebral^{30,31} and thalamic³² tumor resections, the skull base approach,^{33,34} the presigmoid approach,³⁵ craniofacial deformities,³⁶ craniosynostosis,^{37,38} foramen ovale puncture,³⁹ pediatric lumbar pathology,⁴⁰ and endoscopic intracranial^{41–43} and paranasal^{31,44} approaches. This study is not stating that the surgical simulator used in this case is the one that should be used in all situations, but merely that the model should have a reusable component, be anatomically accurate, and be affordable.

Returning to the Society of Neurological Surgeons' intern boot camp, the effectiveness of the program was measured by participant surveys about subjective knowledge gained, as well as a 6-month follow-up knowledge test.¹⁹ The authors themselves admitted that "In general, validated assessments are often lacking from surgical simulation models." For simple procedures like a lumbar puncture or external ventricular drain placement, residents can be evaluated for a general sense of hitting the target space, but the detailed planning, dexterity of tool handling, careful drilling, and other more complex skills are rarely assessed. In this pilot, we used craniotomy and microscope anatomy GRSs and TSCs that could be evaluated in detail by external reviewers. This approach permits the reviewer to attend to finer detail than may occur in the operating room and to provide objective feedback. Furthermore, by having

an external reviewer, residents may have less discomfort than if one of their known attendings is scrutinizing their technique. Therefore, it creates a safe space for individuals to practice, and to be aware of areas in which they need to improve. Although the reports were not shared with institutional faculty in this study, the transparency of the reports with the program directors could be decided by the respective programs.

Finally, there is the issue of feasibility. Traditionally, skills workshops occur at few and variable time points in a resident's training. There is one during intern boot camp, then there may be a couple led by industry at his or her institution, and then perhaps another 1–3 sessions hosted by programs or meetings where they will spend a few consecutive days working on the craft. These are all valuable, but the repetition required for mastering a skill requires both frequent and spaced repetition. This pilot provided a total of 6 sessions for those in the course. This was held during the weekly education time provided for students, although there were some days when residents were pulled away for clinical duties. Each residency program would have to align an iterative skills curriculum with their education structure and laboratory availability, but the absence of biological material, minimal setup, and fast cleanup required facilitate this process. The 6-week course was also a trial, and more studies will be needed to determine the optimal length of the training and its frequency, and ideally there will be a delayed evaluation to assess for knowledge and skill retention. Additionally, given more enthusiasm from residents in earlier training periods and the relatively simple skills assessed in this study, the pterional module may be best suited for junior residents. More complex simulations with tumor resection or aneurysm clipping may be better suited for more senior residents, although the junior residents would be likely to benefit from those as well.

Limitations

The limitations of this study warrant further discussion. First, this was a pilot study conducted at a single institution, so the small group size limits the power of analysis. Although there did appear to be statistically significant improvements with the intervention, the small number limits the granularity of detail of assessment; e.g., we are unable to discern which specific skills improve most with this approach. Additionally, because the pilot program was voluntary and not randomized, there was a greater number of senior residents in the control group. This was partially reflective of lower interest by senior residents in practicing more basic technical skills, although on the surveys they thought this was a useful tool that should become a permanent part of the curriculum. Thus, inferences from the data on degree of improvement and overall significance should be interpreted with caution, because participants with less experience at baseline are more likely to have larger gains than those already scoring highly on the examination. Future studies, if aiming to isolate the degree of impact more accurately, would be likely to require mandatory participation within the program and randomization by class year, as well as standardized, multiinstitutional participation.

Conclusions

This single-center pilot program demonstrated that a 6-week course in which a high-fidelity cadaver-free simulation model was used improved speed and objective skill scores among neurosurgical residents. This demonstration of objective measurement is key, because one cannot manage what one does not measure, and our field has historically fallen short in objective and quantitative technical skill measurement. Comparable fields such as aviation and sports are much further ahead in the realm of statistical tracking and improvement, and we believe this paper not only emphasizes the gestalt understanding that practice leads to improvement, but also underscores the need for more measurement. Further understanding of which skill components improve most under these conditions, as well as the appropriate time course for an iterative training program, will require a larger, multiinstitutional study. Such an effort is being coordinated, as well as expansion to using other models (spine, complex tumor), with hopes of moving toward simulation becoming a core part of technical skill development for neurosurgical trainees.

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Disclosures

Dr. Nicolosi: inventor of technology used in this study, outside the submitted work; also founder and CEO of UpSurgeOn S.r.l. In addition, Dr. Nicolosi had a patent for 20705104.6 issued. Dr. Spena: cofounder of UpSurgeOn S.r.l.

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Conception and design: Robertson, Stapleton, Coumans, Nicolosi, Guerrini, Spena. Acquisition of data: Robertson, Nicolosi, Zoia, Nahed. Analysis and interpretation of data: Robertson, Nicolosi, Guerrini, Zoia. Drafting the article: Robertson, Nicolosi, Blitz, Nahed. Critically revising the article: Robertson, Stapleton, Coumans, Nicolosi, Vooijs, Blitz, Spena, Giussani, Zoia.

Reviewed submitted version of manuscript: Robertson, Stapleton, Coumans, Nicolosi, Vooijs, Blitz, Giussani, Nahed. Approved the final version of the manuscript on behalf of all authors: Robertson. Statistical analysis: Robertson. Administrative/technical/material support: Robertson, Vooijs. Study supervision: Robertson, Stapleton, Giussani, Nahed.

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