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Advancing Surgical Education: The Use of Artificial Intelligence in Surgical Training

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Abstract

The technology of artificial intelligence (AI) has made significant in-roads into the field of medicine over the last decade. With surgery being a discipline where repetition is the key to mastery, the scope of AI presents enormous potential for resident education through the analysis of technique and delivery of structured feedback for performance improvement. In an era marred by a raging pandemic that has decreased exposure and opportunity, AI offers an attractive solution towards improving operating room efficiency, safe patient care in the hands of supervised residents and can ultimately culminate in reduced health care costs. Through this article, we elucidate the current adoption of the artificial intelligence technology and its prospects for advancing surgical education.

Keywords

artificial intelligence, surgical education, machine learning, virtual reality, simulation

Introduction

With the increasing complexity of surgical procedures over the last decade, optimal education and training have gained magnified importance. The novel concept of artificial intelligence (AI) is starting to transform the way surgery is practiced and taught. As new technology becomes more accessible, educators and training programs are striving for structural changes in surgical education to incorporate AI to improve the quality of graduating residents.[1-3]

Surgical residency is an area where AI has massive potential to complement training experience. Traditional methods of surgical training have tended to focus on in-person tasks and learning by repetition, but restrictions imposed by duty hours and pending administrative tasks impact the time that trainees spend in the operating room with seasoned mentors.[4-6] The reduction of in-person training opportunity has been further impacted by the COVID-19 pandemic.[7] Surgery residents are being exposed to a significantly narrower range of operations over the last 20 years, which has raised concerns regarding the competency for independent practice.[8-10] The integration of AI with other newly emerging technologies promises to deliver a multimodal solution to help address these challenges. The aim of this paper is to provide an overview of the ways that AI is currently being leveraged to advance surgical education.

AI in Surgical Education

To better understand what AI in surgical education means, the following definition has been suggested and adopted for this review: "An intelligent system/program that acts to fulfill or support the fulfillment of educational tasks traditionally performed exclusively by surgical educators, through making decisions in a manner similar to educators, and providing customized adaptation, including performance assessment and feedback to surgical trainees."[11] In regards to the surgical specialty in particular, there are 4 major subsets of AI that are being incorporated into training most frequently: machine learning, natural language processing, artificial neural networks, and computer vision.[12]

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The Use of AI in Robotic Surgical Training

Robotic surgery has been around for almost 4 decades.[13] One of the most well-known robotic instruments is the da Vinci Surgical System (Intuitive Surgical Inc. Sunnyvale, CA) which was approved by the FDA in 2000 for general robotic surgery. Since that time, over 10 million minimally invasive procedures have been performed using this system. Over the years, it has evolved and become more sophisticated by the introduction of new features, including a greater number of operating arms that have better range of motion, higher definition imaging systems, and a second console for surgical training.[14] New curricula have been developed with the aim to improve and standardize robotic surgical training.[15,16]

Surgical robot capabilities are continuously advancing, but the same progress has not been seen in assessing surgeon skills in using such technology. The customary methods have been based on proctor-based direct observation in the operating room followed by analysis of procedure recordings. Assessment based on reliable, objective data has long been in demand but remains elusive.[17] Many educational programs incorporating robotic tools still rely on the trainee operating in a real-world environment and offer limited virtual reality simulator options for practice.[18] This has provided the rationale for researchers to develop methods that remove the subjectivity dictum for surgical skill evaluation.

Through machine learning and computer vision, AI is now being incorporated into robotic surgical systems to gather data and provide objective feedback on surgical performance. This method of assessment has been shown to accurately distinguish between a seasoned and novice surgeon. In a study conducted by Fard et al, 8 global movement features were collected from surgeons with varying robotic experience while performing 2 minimally invasive surgical tasks using the da Vinci robot. Kinematic data from both hands during surgical knot tying and suturing was analyzed, and global rating scores were created to group the surgeons into 2 skill levels: novice and expert. Kinematic analysis theory was utilized to transform the data into quantitative metrics, such as turning angle, curvature, tortuosity, and task completion time. Three different machine learning techniques for classification (k-nearest neighbor, logistic regression, and support vector machine) were applied to automatically predict robotic surgical skill level. The quantitative metrics were found to be the most relevant for correct classification and the predictive model was able to correctly classify surgeons with 82.3% and 89.9% accuracy for knot tying and suturing, respectively.[19]

In another study, Lavanchy et al developed a multistage machine learning algorithm to automate surgical skill assessment using video footage of laparoscopic cholecystectomy procedures. The first stage utilized a Convolutional Neural Network (CNN) to identify and localize surgical instruments. Convolutional Neural Network is a deep learning algorithm which can receive an image, assign importance to certain aspects of the image, and then differentiates accordingly. The subsequent stages tracked movement patterns of the surgical instruments over time and applied a linear regression model to the motion features to predict surgical skills. Good surgical performance was determined by narrow and focused instrument handling within the operating field and poor surgical performance was indicated by frequent changes of instrument direction within a larger field. With an 87% accuracy, this novel method was able to identify and analyze the movement pattern of surgical tools to distinguish good and poor surgical performance.[20] These studies are some of the first to leverage AI to collect and analyze data to grade surgical performance during robotic surgery and provide an objective measurement of skill level to the operator.

Artificial intelligence is also being used to develop Intelligent Tutoring Systems (ITS) that can teach surgery techniques. In 2019, Julian et al discussed the development of a computer based ITS that extracts critical data from recorded virtual reality suturing tasks using simulation on the da Vinci surgical system. Systems like this provide automated feedback based on proficiency standards. They can assess a trainee's performance and adjust the multimedia-based instructional material presented to focus on areas where the surgeon is not meeting the required benchmarks. With the help of the ITS, trainees can identify and perfect areas needing improvement outside the operating room. This is beneficial in shortening overall operative times and reduces healthcare costs. An ITS can benefit new surgeons just starting their robotics training or experienced surgeons seeking to refresh their robotic surgical skills.[21]

The Use of AI in Virtual Reality Simulator Surgical Training

Virtual reality (VR) uses a computer-generated, three-dimensional artificial setting to provide users with simulated experiences where they can interact with the environment. The technology first emerged in the early 1990s but is now commonly used in surgical education to give trainees the opportunity to practice new procedures before entering the operating room. Virtual reality was first used in surgical training to simulate tendon transfer in lower extremity orthopedic procedures.[22] Since then, it has become an important surgical training tool because it allows trainees to develop their techniques and skills in a fully-immersive environment. It has become such an integral part of surgical education that reputable healthcare institutions have begun partnering with VR companies to develop VR haptic simulators to train surgeons.[23]

Utilizing VR during surgical training has been shown to have a number of benefits, including improvements in efficiency, knowledge, and tissue handling, as well as reduced error rates when compared to the traditional apprenticeship-style of training.[24] As an example, the Osso VR surgical platform was used to train medical students with no prior procedural experience on how to perform an intramedullary nailing of the tibia. The VR training module provided written instructions and prompts for each step in the procedure. After training, the participants performed a simulated tibia intramedullary nailing of the tibia procedure using SawBones medical training model. On average, these procedures were completed 20% faster with a significantly higher percentage of steps completed correctly when compared to those that were trained through standard guides. In fact, the Osso VR training led to significantly higher ratings in all categories measured by the Physician Global Assessment 5-point scoring scale.[25]

The incorporation of AI into VR surgical simulators has helped add objective feedback to practice sessions, a unique positive that may occasionally be inadequate in the apprenticeship model of surgical teaching.[26] One of the most noted achievements in this area is the use of machine learning algorithms to identify, classify, and interpret patterns of surgeon performance, and then distinguish between skill levels (novice vs experienced).[27-29] Such algorithms have been shown to classify surgical expertise with 90% accuracy during VR simulation surgeries.[30] AI collects extensive data throughout the entirety of the VR simulation and processes it in real time. This can include kinematic data which analyzes instrument placement, as well as trajectory and performance data such as the amount of bleeding and completeness of resections during a surgical task. In addition, it can analyze crucial metrics that cannot be traditionally evaluated because they cannot be assessed visually, such as the amount of force applied during a task in the procedure.[24] The data is processed to define metrics which can be used to determine whether a surgery was performed well and to identify areas where improvement is needed. Such trainee assessment during a VR simulation correlates with visual rating scales such as the Objective Structured Assessment of Technical Skills.[27] This accurate, objective, and efficient way of assessing the performance of surgical trainees addresses a long-standing issue regarding the subjectivity of surgical assessment.

The Virtual Operative Assistant (VOA) is another example of a surgical system incorporating AI and machine learning to provide automated educational feedback to users. In one study involving a subpial brain tumor resection using the NeuroVR virtual reality platform, the tool used 4 metrics to classify skilled versus novice surgical performance based on proficiency benchmarks. The skilled group consisted of staff neurosurgeons (n = 14), fellows (n = 4), and PGY4-6 residents (n = 10) while the novice group consisted of PGY1-3 residents (n = 10) and medical students (n = 12). The study showed that the VOA successfully classified the participants with 82% specificity, 92% accuracy, and 100% sensitivity.[31] Users were able to get immediate, objective feedback on their performance in 2 stages. The machine learning algorithm first classified each user as "novice" or "skilled." This was followed by individualized metric performance feedback related to safety and movements of the simulated instruments. A randomized clinical trial testing the efficacy of VOA compared with conventional approaches in surgical training found that students who received VOA instruction and feedback had skill acquisition 2.6 times faster and achieved a 36% higher performance on a simulated brain tumor removal surgery compared to those who received remote expert instruction and feedback.[32] Systems like the VOA are extremely useful during surgical training because they can determine the different components of surgical tasks that are correctly performed and assess what areas need improvement. Audio and video-based feedback facilitates and reinforces learning of the technical skills needed to achieve competency. Trainees can guide themselves through a surgical procedure in a standardized manner and receive objective assessment at the end of each module. This advancement provides surgical trainees with an educational tool that guides them through complex surgical procedures, which in turn translates into better operating room performance and patient safety.[33]

The Use of AI in Augmented Reality Surgical Training

Augmented reality (AR) is defined as the technology in which virtual objects are blended and can interact with the real world.[34] It does not replace the operator's vision as occurs with VR, but rather uses a transparent visual device to add layers of virtual objects to the user's real-world environment. Augmented reality allows medical professionals to view clinical notes and text or superimpose preoperative images in a clinical setting without having to feel separated from their surroundings.

Telementoring is one of the most promising applications of AR in surgical education. It allows an expert surgeon (mentor) to provide real-time virtual assistance to a surgical trainee (mentee) during an operation from a remote location.[35] Telementoring has proven to be an effective teaching tool that offers several advantages without an increase in operative time.[36] However, it typically still requires human intervention and feedback. Many of the newest AR technologies on the market do not yet leverage AI to provide objective, real-time performance assessment and feedback to users. This is in part due to the lack of existing video feed data sets needed to provide insights. As the use of video becomes more of an industry standard and data becomes more extensive, the incorporation of AI features in AR is expected to grow.

A notable advancement where AI has been incorporated into AR is the development of a surgical navigation guidance platform that combines 3D visualization of a patient's anatomy and data analytics in real-time during surgery. In 2020, Siemionow et al created an augmented reality and artificial intelligence (ARAI)-assisted surgical navigation system and investigated its accuracy and feasibility using cadavers. The system was used to generate an anatomically accurate 3D picture of the spine from preoperative imaging and overlay it in precise alignment on the cadavers using data analytics and machine learning algorithms. The image was used for guiding the percutaneous placement of metal probes into the pedicles and its navigation to the cortex of the L3, L4, L5 lumbar vertebrae in four cadaveric thoracolumbar spines. Intraoperative CT scans and postoperative examination of the probes were performed to determine the accuracy of the navigation system. The study found that the ARAI-assisted navigation system correctly and accurately identified the starting points at all attempted levels and all probes were placed in excellent position.[37] This study illustrated an innovative surgical planning method and has the potential to be used as an educational tool for spine surgery trainees to learn appropriate insertion points and positioning during percutaneous pedicle screw placement.

Surgical education modalities that feature automated feedback to learners offer promise for reducing training costs at academic medical centers. It has been well reported that surgical procedures involving residents are more expensive due to the longer times spent in the operating room and greater frequency of errors which increases cost related to complications.[38,39] In a randomized clinical trial, Lohre et al illustrated that resident training through an immersive virtual reality simulator was up to 34 times more cost-effective than training through an instructional video due to a reduction in learning time. In the study, senior orthopedic surgery residents (PGY 4 and 5) were trained to perform reverse shoulder arthroplasty (RSA) on cadavers either by watching an instructional video or by using an immersive virtual reality platform that provided real-time guided learning. The surgical residents who received virtual reality training not only completed it significantly faster but also had significantly higher Objective Structured Assessment of Technical Skills (OSATS) scores.[40] The results of this study help to illustrate the cost benefit that AI-assisted surgical tools offer to residency programs when adopted and used efficiently. Additionally, AI based feedback may reduce time spent by surgeon educators in teaching some of the more basic tasks and thereby improve healthcare efficiency. Simulation-based performance evaluations assisted by AI technology may be used as a guide by staff surgeons to trust trainees with different portions of complex operations—thereby fostering earlier and greater operative autonomy.

Limitations and The Future of AI in Surgical Training

AI in surgical education is not without limitations. Firstly, and perhaps most importantly, the use of AI in surgery is itself in its early stages. New AI-assisted surgical applications are being developed but widespread adoption continues to lag. There is a paucity of experience with limited literature, especially peer-reviewed randomized controlled studies, investigating the use of AI in surgical education. The AI that has been incorporated into surgical education tools is presently not standardized. Machine learning algorithms require large data sets to provide high level feedback and the output is only as good as the input into the system. Lack of data limits the extrapolations that AI can make. To fully leverage AI in surgical training, the performance of the trainee must be measured based on proficiency benchmarks, and there is no industry consensus on parameters most important for assessing surgeon skill and optimal objective rating scales. While these concerns represent the bare surface challenges, the present utilization of AI reflects only the tip of the iceberg, and it is just a matter of time before future work elucidates how AI is going to revolutionize surgical training across the world.

Conclusion

As medicine advances and procedures become increasingly complex and novel, opportunities for repetitious training as a resident are limited. AI offers a technology-focused solution that gives surgeons an opportunity to test their abilities in performing new techniques while receiving real-time, objective feedback, in a controlled and accessible environment. However, the incorporation of AI into the existing training modalities is still a new endeavor and we have limited published data and limited curricula to date. Increasing the use of AI will provide more exposure for surgical trainees to practice and receive guidance on how to improve their procedural skills which will ultimately prepare them better for independent surgical practice.

Author Contributions

DTG – Draft of preliminary manuscript, approval of final version
MA, AR – manuscript revision, critical review of manuscript with revision for incorporating intellectual content, approval of final version

AH – critical review of manuscript with revision for incorporating intellectual content, approval of final version
CEB – senior author, critical review of manuscript with revision for incorporating intellectual content, approval of final version

Declaration of Conflicting Interests

The author(s) declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: Dr. Butler is a consultant for Allergan Inc. The remaining authors do not have any conflicts of interest to report in regards to the contents of this article.

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References

1. Wartman SA, Combs CD. Medical education must move from the information age to the age of artificial intelligence. *Acad Med*. 2018;93:1107-1109.
2. Wartman SA, Combs CD. Reimagining medical education in the age of AI. *AMA J Ethics*. 2019;21:E146-E152.
3. Rogers MP, DeSantis AJ, Janjua H, Barry TM, Kuo PC. The future surgical training paradigm: Virtual reality and machine learning in surgical education. *Surgery*. 2021;169:1250-1252.
4. Eskander MF, Neuwirth MG, Kuy S, Keshava HB, Meizoso JP. Technology for teaching: New tools for 21st century surgeons. *Bull Am Coll Surg*. 2016;101:36-42.
5. Ahmed N, Devitt KS, Keshet I, et al. A systematic review of the effects of resident duty hour restrictions in surgery: Impact on resident wellness, training, and patient outcomes. *Ann Surg*. 2014;259:1041-1053.
6. Bolster L, Rourke L. The effect of restricting residents' duty hours on patient safety, resident well-being, and resident education: An updated systematic review. *J Grad Med Educ*. 2015;7:349-363.
7. Clements JM, Burke J, Nally D, et al. COVID-19 impact on surgical training and recovery planning (COVID-STAR) - a cross-sectional observational study. *Int J Surg*. 2021;88:105903.
8. Bohnen JD, Chang DC, George BC. Operating room times for teaching and nonteaching cases are converging: Less time for learning? *J Surg Educ*. 2021 Jan-Feb;78:148-159.
9. George BC, Bohnen JD, Williams RG, et al. Readiness of US general surgery residents for independent practice. *Ann Surg*. 2017;266:582-594.
10. Kearse LE, Zeineddin A, Schmiederer IS, Korndorffer JR, Lau JN. A 20-year review of surgical training case logs: Is general surgery still general? *Surgery*. 2021;170:1347-1352.
11. Bilgic E, Gorgy A, Young M, Abbasgholizadeh-Rahimi S, Harley JM. Artificial intelligence in surgical education: Considerations for interdisciplinary collaborations. *Surg Innovat*. 2022;29:137-138.
12. Hashimoto DA, Rosman G, Rus D, Meireles OR. Artificial intelligence in surgery: Promises and perils. *Ann Surg*. 2018;268:70-76.
13. Kwoh YS, Hou J, Jonckheere EA, Hayati S. A robot with improved absolute positioning accuracy for CT guided stereotactic brain surgery. *IEEE Trans Biomed Eng*. 1988;35:153-160.
14. Shah J, Vyas A, Vyas D. The history of robotics in surgical specialties. *Am J Robot Surg*. 2014;1:12-20.
15. Green CA, Chern H, Rogers SJ, Reilly LM, O'Sullivan P. Transforming surgical education through a resident robotic curriculum. *Annals of Surgery Open*. 2021;2:e076.
16. Moit H, Dwyer A, De Sutter M, Heinzel S, Crawford D. A standardized robotic training curriculum in a general surgery program. *J Soc Laparoendosc Surg*. 2019;23:e201900045.
17. Aggarwal R, Grantcharov T, Moorthy K, Milland T, Darzi A. Toward feasible, valid, and reliable video-based assessments of technical surgical skills in the operating room. *Ann Surg*. 2008;247:372-379.
18. Chen R, Rodrigues Armijo P, Krause C, Siu KC, Siu KC, Oleynikov D. A comprehensive review of robotic surgery curriculum and training for residents, fellows, and postgraduate surgical education. *Surg Endosc*. 2020;34:361-367.
19. Fard MJ, Ameri S, Darin Ellis R, Chinnam RB, Pandya AK, Klein MD. Automated robot-assisted surgical skill evaluation: Predictive analytics approach. *Int J Med Robot*. 2018;14:e1850.
20. Lavanchy JL, Zindel J, Kirtac K, et al. Automation of surgical skill assessment using a three-stage machine learning algorithm. *Sci Rep*. 2021;11:5197.
21. Julian D, Smith R. Developing an intelligent tutoring system for robotic-assisted surgery instruction. *Int J Med Robot*. 2019;15:e2037.
22. Delp SL, Loan JP, Hoy MG, Zajac FE, Topp EL, Rosen JM. An interactive graphics-based model of the lower extremity to study orthopaedic surgical procedures. *IEEE Trans Biomed Eng*. 1990;37:757-767.
23. Mayo clinic becomes first U.S. institution to train surgeons with fundamental Surgery VR haptic simulations. Hea! thcare Innovation, 2018. https://www.hcinnovationgroup.com/home/article/13011124/mayo-clinic-becomes-first-us-institution-to-train-surgeons-with-fundamental-surgery-vr-haptic-simulations. Accessed January 24, 2022.
24. Portelli M, Bianco SF, Bezzina T, Abela JE. Virtual reality training compared with apprenticeship training in laparoscopic surgery: A meta-analysis. *Ann R Coll Surg Engl*. 2020;102:672-684.
25. Blumstein G, Zukotynski B, Cevallos N, et al. Randomized trial of a virtual reality tool to teach surgical technique for tibial shaft fracture intramedullary nailing. *J Surg Educ*. 2020;77:969-977.

26. Su Yin M, Haddawy P, Suebnukarn S, et al. Formative feedback generation in a VR-based dental surgical skill training simulator. *J Biomed Inf*. 2021;114:103659.
27. Winkler-Schwartz A, Marwa I, Bajunaid K, et al. A comparison of visual rating scales and simulated virtual reality metrics in neurosurgical training: A generalizability theory study. *World Neurosurg*. 2019;127:e230-e235.
28. Mirchi N, Bissonnette V, Ledwos N, et al. Artificial neural networks to assess virtual reality anterior cervical discectomy performance. *Oper Neurosurg (Hagerstown)*. 2019;19:65-75.
29. Winkler-Schwartz A, Bissonnette V, Mirchi N, et al. Artificial intelligence in medical education: Best practices using machine learning to assess surgical expertise in virtual reality simulation. *J Surg Educ*. 2019;76:1681-1690.
30. Winkler-Schwartz A, Yilmaz R, Mirchi N, et al. Machine learning identification of surgical and operative factors associated with surgical expertise in virtual reality imulation. *JAMA Netw Open*. 2019;2:e198363.
31. Mirchi N, Bissonnette V, Yilmaz R, Ledwos N, Winkler-Schwartz A, Del Maestro RF. The virtual operative assistant: An explainable artificial intelligence tool for simulation-based training in surgery and medicine. *PLoS One*. 2020;15:e0229596.
32. Fazlollahi AM, Bakhaidar M, Alsayegh A, et al. Effect of artificial intelligence tutoring vs expert instruction on learning simulated surgical skills among medical students: A randomized clinical trial. *JAMA Netw Open*. 2022;5:e2149008.
33. Seymour NE, Gallagher AG, Roman SA, et al. Virtual reality training improves operating room performance: results of a randomized, double-blinded study. *Ann Surg*. 2002;236:458-464.
34. Yildiz E. *Augmented Reality Research and Applications in Education*. IntechOpen, London; 2021.
35. Butt K, Augestad KM. Educational value of surgical telementoring. *J Surg Oncol*. 2021;124:231-240.
36. Ponce BA, Jennings JK, Clay TB, May MB, Huisingh C, Sheppard ED. Telementoring: Use of augmented reality in orthopaedic education: AAOS exhibit selection. *J Bone Joint Surg Am*. 2014;96:e84.
37. Siemionow KB, Katchko KM, Lewicki P, Luciano CJ. Augmented reality and artificial intelligence-assisted surgical navigation: Technique and cadaveric feasibility study. *J Craniovertebral Junction Spine*. 2020;11:81-85.
38. Babineau TJ, Becker J, Gibbons G, et al. The “cost” of operative training for surgical residents. *Arch Surg*. 2004;139:366-370.
39. Malloy SM, Sanchez K, Cho J, Mulcahy SE, Labow BI. Hidden costs in resident training: Financial cohort analysis of first assistants in reduction mammaplasty. *Plast Reconstr Surg Glob Open*. 2021;9:e3333.
40. Lohre R, Bois AJ, Pollock JW, et al. Effectiveness of immersive virtual reality on orthopedic surgical skills and knowledge acquisition among senior surgical residents: A randomized clinical trial. *JAMA Netw Open*. 2020;3:e2031217.