

Editorial

Neurosurgical Training with Agentic AI & Robotics

Prof. Dr. Saman Shahid

National University of Computer & Emerging Sciences (NUCES)-
FAST Lahore Campus, Pakistan (Email: drshahidsaman@gmail.com)

DOI: 10.36552/pjns.v30i3.1300

1. Introduction

Neurosurgical training is undergoing a paradigm shift as artificial intelligence (AI) and surgical robotics mature from experimental technologies to integral components of education for residents and early-career neurosurgeons. Agentic AI systems—AI tools capable of autonomously assessing performance, personalizing curricula, and orchestrating multimodal feedback—can augment existing simulation, virtual reality (VR), and robotic platforms to accelerate skill acquisition while improving patient safety. High-fidelity neurosurgical simulators and VR environments have already demonstrated benefits for technical skills, visuospatial understanding, and the safe rehearsal of complex cranial and spinal procedures, yet many programs still lack objective, scalable assessment methods.¹ Recent AI-powered simulators use machine-learning models to classify expertise level, extract motion metrics, and generate automated, explainable feedback, enabling continuous, competency-based training outside the operating room.² Concurrently, structured curricula for robotic-assisted neurosurgery translate Accreditation Council for Graduate Medical Education (ACGME) milestones into progressive modules that integrate didactics, simulation, and supervised console time, providing a template for standardized robotic education.³

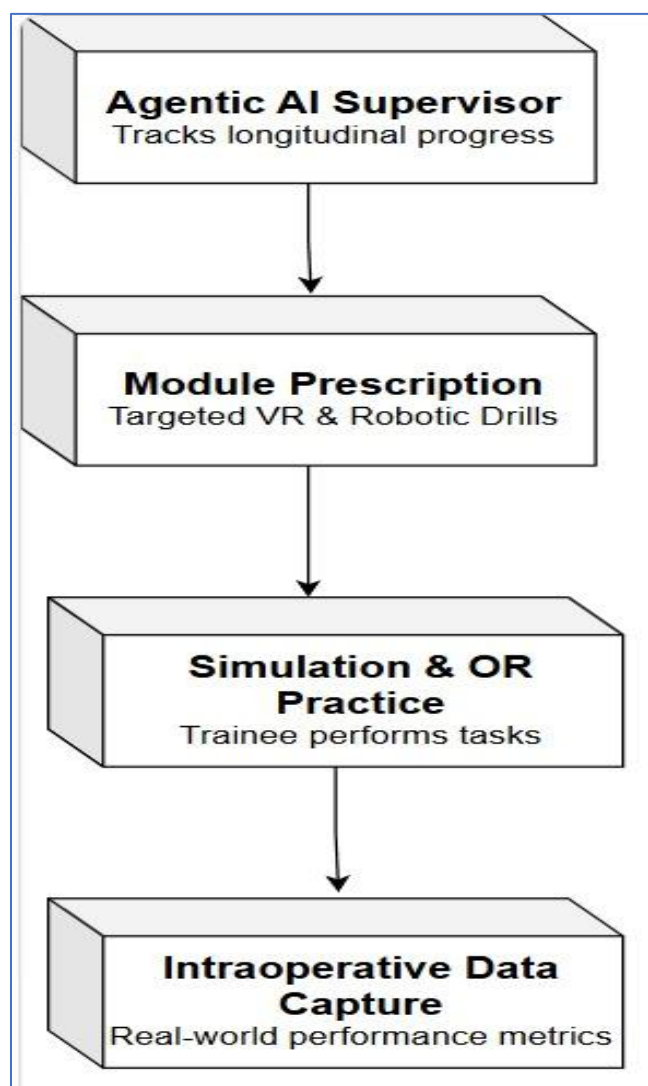


Figure 1: The agentic AI closed-loop training ecosystem.

Sangwon et al, (2026)⁴ created and test a multi-artificial intelligence (AI) agent conversation framework for neurosurgical case assessment, allowing for the creation of realistic clinical conversations with simulated patients and the provision of structured access to objective clinical information. The multi-AI agent framework offers a more difficult assessment approach for LLMs, as well as a captivating neurosurgical training tool. Agentic AI is revolutionizing neurosurgical training by shifting from passive software tools to autonomous, goal-driven digital assistants. The discipline of neurological surgery has been robust and dedicated to advancing the technologies employed to achieve maximally safe resection of brain lesions, resulting in a significant burden on the healthcare systems, from the standpoint of mortality, disability, and impact on quality of life. While the cost of these technologies is high, the cost of the care of patients with high-grade gliomas is much higher.⁵

2. Large Language Models in Health Care

The application of large language models (LLMs) in healthcare is rapidly changing, but their impact on pediatric neurosurgery is understudied. This narrative review presents an interpretation of the evolution of LLM from a neuroscientific viewpoint that is familiar to pediatric neurosurgeons. We find that LLM's development mirrors that of the human brain, from sequential processing to the introduction of attention mechanisms similar to the maturation of the prefrontal cortex; from training to the equivalent of synaptic exuberance, adolescent pruning, and socialization; and from reasoning using chain-of-thought prompting and reinforcement learning to deliberate cognitive processes. We then consider what features current LLM models do not possess but would enable AI systems to attain artificial general intelligence (AGI): continual learning; multimodal perception; self-awareness; world models; and physical

embodiment, assigning each of these capabilities to a neural function. We show the impact of these technologies by using a representative case of pediatric medulloblastoma.⁶

3. Multi-Agent Clinical Classrooms (Cognitive Training)

Traditional board exam prep utilizes text-based multiple-choice vignettes. Researchers have developed multi-AI agent frameworks—inspired by CRAFT-MD (Conversational Reasoning Assessment Framework for Testing in Medicine)—that transform flat clinical questions into realistic, shifting patient interactions. Traditional neurosurgical apprenticeship faces growing constraints from duty-hour restrictions, variable case exposure, and subjective assessment methods. AI-driven platforms and robotic-assisted systems are emerging as scalable, objective complements that offer personalized feedback and standardized skill acquisition for trainees⁷⁻⁸

- **Patient AI:** Acts autonomously as the patient, volunteering subjective complaints, updating symptoms dynamically, and exhibiting realistic conversational variance.
- **System AI:** Manages access to objective clinical data, forcing the trainee to explicitly

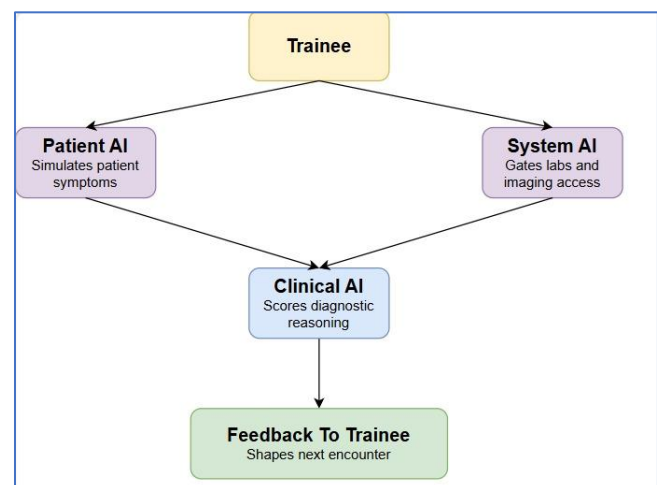


Figure 2: Multi-agent clinical classroom architecture for cognitive training.

Table 1: *Comparative Advantage: Traditional vs. Agentic Training.*

Feature	Traditional Training	Agentic AI-Driven Training
Primary Arena	Operating Room (Real Patients)	VR Simulations & In Silico Labs
Feedback Style	Subjective, retrospective by seniors	Objective, real-time, data-backed metrics
Error Handling	Caught by attending; can carry risks	Intercepted by AI agents in risk-free sandboxes
Case Exposure	Dependent on hospital volume & rotation	Unlimited, rare, or complex custom cases

request specific laboratory or pre-operative imaging findings.

- **Clinical AI:** Analyzes the young neurosurgeon's diagnostic reasoning and provides targeted post-encounter feedback.

4. Intelligent Tutoring Systems (Psychomotor Training)

Agentic AI integrates deeply with advanced Virtual Reality (VR) platforms like NeuroVR. Instead of analyzing a surgery after it is over, these AI agents continuously track hand-movement metrics up to every 20 milliseconds.

- **Real-time Interventions:** The AI agent acts as a co-pilot, issuing immediate verbal instructions if a trainee applies excessive force, operates too quickly, or separates instruments improperly.
- **Surgical Force Fingerprints:** The agent measures a unique "fingerprint" composed of thousands of metrics—such as instrument acceleration, deceleration, and the exact physical force applied to remove virtual tumor tissue.

5. Crucial Safeguard: The Hybrid Approach

While autonomous AI tutors provide standardized, data-driven assessments, recent peer-reviewed studies indicate that AI-only tutoring can cause unintended drawbacks. Trainees guided strictly by rigid AI constraints often exhibit significantly lower instrument velocity and reduced efficiency.

Consequently, modern neurosurgical curricula utilize a hybrid instruction model. Expert human mentors use the data harvested by agentic AI to provide nuanced, contextual, and adaptive feedback. This combination yields the highest mastery rates, particularly in critical risk-management skills like managing unexpected bleeding and protecting microscopic tissues.

6. Telesurgery:

Telesurgery with the use of robotic arms with artificial intelligence is one of the sources. Innovative direction in the field of neurosurgery, which could enhance the accuracy and precision of the surgery. Effectiveness of interventions to the brain. The aim of this present research is to study the benefits and Problems with this technology, along with potential future directions. The methodology employed includes a systematic study of the last 5 years literature. The results suggest that neurosurgery can be performed with the use of the artificial intelligence and robotic technologies in a way that is comparable to telesurgery. if treating the patient's disease could be facilitated more precisely and less invasively, but there are difficulties concerned with: The integration of technology and clinical acceptance. Further, the viability of implementing telesurgery in neurosurgical interventions is analyzed and discussed. The telesurgery using robotic arm with artificial intelligence can be used for. Nevertheless, they have the potential to revolutionize surgical practice and need further research to overcome the challenges that exist today.⁹

Table 2: Comparison of AI tutoring modalities validated in neurosurgical simulation trials.

AI Tutoring Modality	Key Outcome	Evidence Strength
VOA automated feedback (vs. expert)	+0.66 Expertise Score, equivalent OSATS*	Multi-site RCT, n=70 (Fazlollahi et al., 2022) 10-11
Real-time multifaceted AI (vs. in-person)	Composite score +0.332, p=.005	RCT, n=97 (Yilmaz et al., 2024) 12
AI-augmented human instruction	Fewer errors, less frequent feedback	Cohort, n=87 (Davidovic et al., 2025) 13
AI-derived learning curves	Expertise-sensitive skill tracking	Mixed-model ANOVA, n=50 (Ledwos et al., 2022)

* Objective Structured Assessment of Technical Skills

7. AI-Driven Simulation and Intelligent Tutoring:

The Virtual Operative Assistant (VOA), an explainable AI platform built on the NeuroVR simulator, classifies skilled and novice neurosurgical participants using four performance metrics with 92% accuracy, 82% specificity, and 100% sensitivity (Mirchi et al., 2020). In a multi-institutional randomized controlled trial of 70 medical students, VOA feedback improved practice Expertise Scores by 0.66 points over remote expert instruction, with equivalent OSATS ratings and no differences in cognitive load or emotional response.¹⁰⁻¹¹ A separate crossover randomized trial of 25 trainees confirmed that real-time intelligent instruction significantly improved composite scores across both training sessions, while in-person human instruction alone produced no significant improvement.¹² AI-augmented personalized instruction—where a human instructor receives AI error data to guide feedback—reduced feedback frequency by the third repetition, indicating fewer trainee errors, and improved all performance metrics from baseline.¹³ AI-derived metrics also generate expertise-sensitive learning curves across neurosurgeons, fellows, residents, and medical students, enabling educators to design more focused formative paradigms.

8. Robotic-Assisted Training Curricula

Robotic systems in neurosurgery span master-

slave, semi-active, and fully active configurations, with the NeuroMate being the first FDA-approved device for neurosurgical use¹⁴. A structured curriculum for robot-assisted SEEG and DBS electrode implantation, aligned with ACGME milestones, has been implemented across more than 100 patients since 2019, with residents participating in all aspects of surgical planning and execution. Survey data from this program revealed that residents receive most training intraoperatively but desire more cadaveric simulation sessions.³ In robotic-assisted spine surgery, a trained neurosurgery resident achieved 96.99% clinical acceptance across 166 screw insertions, with time per screw decreasing significantly as experience accumulated. Despite high resident interest, survey results indicated limited actual surgical participation during training and a deficiency in structured robotic curricula.¹⁵

9. Conclusion, Limitations, and Future Directions:

The advent of artificial intelligence (AI) has had an unprecedented impact on neurosurgical care and there are emerging applications in education and training. Traditional apprenticeship-based learning is limited in terms of operative exposure, being subjectively assessed, and the quality of the teaching. AI tools such as machine learning (ML), deep learning (DL), extended-reality simulations and intelligent tutoring systems provide scalable and personalized training opportunities for

neurosurgical trainees that provide data-driven learning. AI offers transformative opportunities for neurosurgical education, such as objective assessment and immersive simulation. However, before large-scale implementation, the models used in AI need to be well validated, be understandable by the users, and be fairly distributed globally. Future studies could involve the implementation of standardized, ethically regulated frameworks for the use of AI in surgical education.⁷ AI-based assessment systems differentiate neurosurgical expertise levels with 83–100% accuracy across diverse simulation platforms and tasks. Deep learning approaches enable continuous monitoring of surgical performance and objective tracking of skill progression over time, aligning with competency-based medical education frameworks.⁸ In microsurgical education more broadly, AI-enhanced training reduced training time improved ergonomics, and accelerated learning.¹⁶ AI applied to surgical video and instrument kinematics generates automated skills assessments and tailored intraoperative feedback for trainees.¹⁷ It has been observed that the cost, maintenance, and sterilization concerns limit robotic system adoption, particularly in lower-income countries.^{14,18} Early exposure in basic training modules and rotatory training at facilities with robots may catalyze adoption.¹⁸ There could be an excessive dependence on technology during training risks neglecting essential manual skills that residents must master.¹⁵ Major barriers to broader integration include small sample sizes, single-center study designs, limited external validation, and methodological heterogeneity that restricts comparability. Ethical concerns surrounding trainee surveillance, algorithmic bias, informed consent for AI-mediated learning, and unequal global access to these technologies require cautious, well-regulated implementation.^{7,17} AI currently performs inferiorly to neurosurgery residents in test-taking, highlighting that cognitive and decision-support applications remain less

mature than technical skills training.^{19,7} Future research should prioritize multi-institutional validation, standardized outcome metrics, explainable AI models, and ethically governed curricular frameworks before widespread adoption.⁷⁻⁸ Agentic AI and robotics offer transformative potential for neurosurgical education, with the strongest evidence supporting AI-driven simulation tutoring and objective technical skill assessment; robotic curriculum development and cognitive AI applications remain earlier-stage and require robust validation before integration into global training standards.

REFERENCES

1. Davids J, Manivannan S, Darzi A, Giannarou S, Ashrafian H, Marcus HJ. Simulation for skills training in neurosurgery: a systematic review, meta-analysis, and analysis of progressive scholarly acceptance. *Neurosurgical review*. 2021;44(4):1853-67. DOI: 10.1007/s10143-020-01378-0
2. Khalifa A, Tahhan O, Al-Bazooni M, Saeed M, Hamdi R, Stanners M, Malik A, Malik A. Automated and artificial intelligence (AI)-derived performance assessment in surgical simulation: A systematic review. *Cureus*. 2025;17(12). DOI: 10.7759/cureus.100477
3. Mallela AN, Beiriger J, Gersey ZC, Shariff RK, Gonzalez SM, Agarwal N, González-Martínez JA, Abou-Al-Shaar H. Targeting the future: developing a training curriculum for robotic assisted neurosurgery. *World neurosurgery*. 2022;167:e770-7. DOI: 10.1016/j.wneu.2022.08.076
4. Sangwon KL, Zhang J, Steele R, Stryker J, Choi JJ, Lee JV, Alber DA, Valliani A, Kannapadi N, Ryoo J, Feng A. A Multi-AI Agent Framework for Interactive Neurosurgical Education and Evaluation: From Vignettes to Virtual Conversations. *Neurosurgery Practice*. 2026;7(2):e000217. DOI: 10.1227/neuprac.0000000000000217
5. Valerio JE, Ramirez-Velandia F, Fernandez-Gomez MP, Rea NS, Alvarez-Pinzon AM. Bridging the global technology gap in neurosurgery: disparities in access to advanced tools for brain tumor resection. *Neurosurgery Practice*. 2024;5(2):e00090. DOI: 10.1227/neuprac.0000000000000090

6. Yuh WT, Ryu SJ, Kim TS, Choi I. Large Language Model and Pediatric Neurosurgery-A Neurosurgeon's Perspective on the Artificial Nervous System. *Journal of Korean Neurosurgical Society*. 2026;69(4):496-514.
DOI: <https://doi.org/10.3340/jkns.2026.0029>
7. Sankar S, Rabbi KA, Crosby RF, Al Rajhi Y, Karunaratne V, Rathnayake M, Duhan R, Li J. Artificial Intelligence in Neurosurgical Training: Applications, Challenges, and Future Directions. *Asian Journal of Neurosurgery*. 2026 Jun 30.
DOI: <https://doi.org/10.1055/s-0046-1824448>
8. Şahin ÖS, Dinç S. Artificial Intelligence in Neurosurgical Education: A Systematic Review of Technical Skills Training, Clinical Reasoning, and Surgical Planning. *Lokman Hekim Health Sci* 2026;6(2):303–312. DOI: 10.14744/lhhs.2026.20865
9. Gamazeliuc G, Nechita RM, Ulerich O, Bădiță-Voicu LL, Cristoiu C. Fusion of Ai and robotics for transforming neurosurgery. *International Journal of Mechatronics and Applied Mechanics*. 2024(18):175-83.
10. Fazlollahi AM, Bakhaidar M, Alsayegh A, Yilmaz R, Winkler-Schwartz A, Mirchi N, Langleben I, Ledwos N, Sabbagh AJ, Bajunaid K, Harley JM. Effect of artificial intelligence tutoring vs expert instruction on learning simulated surgical skills among medical students: a randomized clinical trial. *JAMA network open*. 2022;5(2):e2149008.
DOI: <https://doi.org/10.1001/jamanetworkopen.2021.49008>
11. Fazlollahi AM, Bakhaidar M, Alsayegh A, Yilmaz R, Winkler-Schwartz A, Mirchi N, Langleben I, Ledwos N, Sabbagh AJ, Bajunaid K, Harley JM. Effect of artificial intelligence tutoring vs expert instruction on learning simulated surgical skills among medical students: a randomized clinical trial. *JAMA network open*. 2022;5(2):e2149008.
DOI: https://doi.org/10.1227/neu.0000000000001880_510
12. Yilmaz R, Fazlollahi A, Alsayegh A, Bakhaidar M, Del Maestro R. 428 Artificial intelligence training versus in-person expert training in teaching simulated tumor resection skills-a cross-over randomized controlled trial. *Neurosurgery*. 2024 Apr;70(Supplement_1):129-30.
DOI: https://doi.org/10.1227/neu.00000000000002809_428
13. Davidovic V, Giglio B, Al-Beloushi A, Alhaj AK, Al-Hantoobi M, Saeedi R, Deraiche S, Yilmaz R, Tee T, Fazlollahi AM, Ha M. Effect of artificial intelligence-augmented human instruction on feedback frequency and surgical performance during simulation training. *Journal of Surgical Education*. 2025;82(11):103743.
DOI: <https://doi.org/10.1016/j.jsurg.2025.103743>
14. Kazemzadeh K, Akhlaghdoust M, Zali A. Advances in artificial intelligence, robotics, augmented and virtual reality in neurosurgery. *Frontiers in surgery*. 2023 Aug 24;10:1241923.
DOI: <https://doi.org/10.3389/fsurg.2023.1241923>
15. Lee JS, Son DW, Lee SH, Lee JH, Kim YH, Lee SW, Oh BK, Sung SK, Song GS, Yi S. Robotic-assisted spine surgery: role in training the next generation of spine surgeons. *Neurospine*. 2024;21(1):116.
DOI: <https://doi.org/10.14245/ns.2448006.003>
16. Raquipo TM, Tobin M, Puducheri S, Yamin M, Dhillion J, Bridgeman M, Cauley RP. Artificial intelligence in microsurgical education: a systematic review of its role in training surgeons. *Journal of Reconstructive Microsurgery*. 2025 Aug 14.
DOI: <https://doi.org/10.1055/a-2672-0260>
17. Knudsen JE, Ghaffar U, Ma R, Hung AJ. Clinical applications of artificial intelligence in robotic surgery. *Journal of robotic surgery*. 2024;18(1):102.
DOI: <https://doi.org/10.1007/s11701-024-01867-0>
18. Ghimire S, Shrestha S, Shrestha D, Awal S. Robotics in neurosurgery: the past, present and the future. *Egyptian Journal of Neurosurgery*. 2025;40(1):96.
DOI: <https://doi.org/10.1186/s41984-025-00395-9>
19. Windermere SA, Shah S, Hey G, McGrath K, Rahman M. Applications of AI in neurosurgery for improving outcomes through diagnostics, predictive tools, and resident education. *World Neurosurg*. 2025;123809:1016.
DOI: <https://doi.org/10.1016/j.wneu.2025.123809>
20. Escobar-Castillejos D, Barrera-Animas AY, Noguez J, Magana AJ, Benes B. Transforming surgical training with AI techniques for training, assessment, and evaluation: scoping review. *Journal of Medical Internet Research*. 2025 Nov;27:e58966. DOI: <https://doi.org/10.2196/58966>