Neurosurgical simulation

Neurosurgical simulation refers to the use of advanced computational models and technologies to replicate the conditions of neurosurgery, offering a safe and controlled environment for training, planning, and innovation. With the increasing complexity of neurosurgical procedures and the demand for precision, simulation has emerged as a critical tool in modern neurosurgery.

Key Components

1. **Anatomical Modeling:**

   1. Accurate representation of the brain, skull, and spinal cord, including tissue properties and vascular structures.
   2. Integration of patient-specific data from imaging modalities like MRI and CT.

2. **Tissue Interaction Models:**

see Soft tissue simulation

3. **Haptic Feedback:**

   1. Real-time tactile response to simulate the sensation of operating on different tissues.
   2. Essential for training surgeons in delicate tasks like tumor resection or aneurysm clipping.

4. **Real-Time Imaging Integration:**

   1. Incorporation of intraoperative imaging techniques such as neuronavigation and intraoperative MRI.
   2. Real-time updates to the simulation environment based on ongoing surgical actions.

5. **Surgical Instrument Modeling:**

   1. Simulation of tools like scalpels, drills, and endoscopes.
   2. Replication of tool-tissue interactions to provide realistic practice scenarios.

6. **Performance Metrics:**

   1. Objective evaluation of surgical skills, including precision, timing, and adherence to anatomical constraints.
   2. Feedback systems to guide skill improvement.

—

Applications of Neurosurgical Simulations

1. **Surgical Training:**

   1. Safe practice for residents and neurosurgeons to develop and refine skills without risks to patients.
   2. Opportunities to simulate rare or complex cases.

2. **Preoperative Planning:**

   1. Visualization and rehearsal of surgical approaches using patient-specific models.
   2. Assessment of potential risks and optimal strategies.

3. **Intraoperative Assistance:**

   1. Real-time simulations integrated with navigation systems to guide surgeons.
   2. Adaptation to intraoperative findings, enhancing decision-making.

4. **Innovation and Device Testing:**

   1. Development and validation of new surgical techniques and devices.
   2. Testing of novel materials or robotics in a simulated environment.

5. **Research and Development:**

   1. Investigation of biomechanical behavior of brain and spinal tissues.
   2. Testing hypotheses on disease progression or treatment efficacy.

—

Challenges in Neurosurgical Simulation

1. **Computational Complexity:**

   1. Achieving real-time feedback while maintaining high anatomical and physical accuracy.

2. **Validation:**

   1. Ensuring that simulations accurately reflect the behavior of real tissues and surgical outcomes.

3. **Cost and Accessibility:**

   1. High development costs may limit widespread adoption in smaller or resource-limited institutions.

4. **Haptic and Visual Fidelity:**

   1. Bridging the gap between simulated and real-world sensations and visuals.

5. **Surgeon Acceptance:**

   1. Ensuring that simulations are intuitive and provide value to experienced neurosurgeons.

—

Future Directions

1. **Artificial Intelligence Integration:**

   1. Use of AI for predictive modeling and real-time adaptation of simulations.
   2. Enhanced feedback systems for personalized training.

2. **Virtual Reality (VR) and Augmented Reality (AR):**

1. Immersive environments for enhanced surgical planning and intraoperative guidance.
2. Collaboration in remote or distributed surgical training programs.

3. **Cloud-Based Platforms:**

1. Making simulations more accessible through online platforms, reducing costs and expanding reach.

4. **Biomechanical Advances:**

1. Improved modeling of tissue behavior under various surgical conditions.
2. Incorporation of patient-specific pathological changes.

5. **Regulatory and Ethical Considerations:**

1. Development of standards and protocols for the validation and certification of neurosurgical simulation systems.

—

Conclusion

Neurosurgical simulation is revolutionizing the field by providing safer, more precise, and innovative ways to train surgeons and plan surgeries. With ongoing advancements in computational modeling, AI, and immersive technologies, these tools will become indispensable in improving neurosurgical outcomes and patient safety.

Neurosurgical training has been traditionally based on an apprenticeship model. However, restrictions on clinical exposure reduce trainees' operative experience. Simulation models may allow for a more efficient, feasible, and time-effective acquisition of skills. Our objectives were to use face, content, and construct validity to review the use of simulation models in neurosurgical education.

Reviews

Methods: PubMed, Web of Science, and Scopus were queried for eligible studies. After excluding duplicates, 1204 studies were screened. Eighteen studies were included in the final review.

Results: Neurosurgical skills assessed included aneurysm clipping (n = 6), craniotomy and burr hole drilling (n = 2), tumour resection (n = 4), and vessel suturing (n = 3). All studies assessed face validity, 11 assessed content, and 6 assessed construct validity. Animal models (n = 5), synthetic models (n = 7), and VR models (n = 6) were assessed. In face validation, all studies rated visual realism favourably, but haptic realism was key limitation. The synthetic models ranked a high median tactile realism (4 out of 5) compared to other models. Assessment of content validity showed positive findings for anatomical and procedural education, but the models provided more benefit to the novice than the experienced group. The cadaver models were perceived to be the most anatomically realistic by study participants. Construct validity showed a statistically significant proficiency increase among the junior group compared to the senior group across all modalities.

This review highlights evidence on the feasibility of implementing simulation models in neurosurgical training. Studies should include predictive validity to assess future skill on an individual on whom the same procedure will be administered. This study shows that future neurosurgical training systems call for surgical simulation and objectively validated models [1].

The emphasis on simulation-based training in neurosurgery has led to the development of many simulation models and training courses.

Simulation-based training is increasingly being used for the assessment and training of psychomotor skills involved in medicine. The application of artificial intelligence and machine learning technologies have provided new methodologies to utilize large amounts of data for educational purposes. A significant criticism of the use of artificial intelligence in education has been a lack of transparency in the algorithms' decision-making processes.

A study aimed to 1) introduce a new framework using explainable artificial intelligence for simulation-based training in surgery, and 2) validate the framework by creating the Virtual Operative Assistant, an automated educational feedback platform. Twenty-eight skilled participants (14 staff neurosurgeons, 4 fellows, 10 PGY 4-6 residents) and 22 novice participants (10 PGY 1-3 residents, 12 medical students) took part in this study. Participants performed a virtual reality subpial brain tumor resection task on the NeuroVR simulator using a simulated ultrasonic aspirator and bipolar [2]

Surgical simulation practices have witnessed a rapid expansion as an invaluable approach to resident training in recent years. One emerging way of implementing simulation is the adoption of extended reality (XR) technologies, which enable trainees to hone their skills by allowing interaction with virtual 3D objects placed in either real-world imagery or virtual environments. The goal of the present systematic review is to survey and broach the topic of XR in neurosurgery, with a focus on education. Five databases were investigated, leading to the inclusion of 31 studies after a thorough reviewing process. Focusing on user performance (UP) and user experience (UX), the body of evidence provided by these 31 studies showed that this technology has, in fact, the potential of enhancing neurosurgical education through the use of a wide array of both objective and subjective metrics. Recent research on the topic has so far produced solid results, particularly showing improvements in young residents, compared to other groups and over time. In conclusion, this review not only aids to a better understanding of the use of XR in neurosurgical education but also highlights the areas where further research is entailed while also providing valuable insight into future applications [3].

see Simulation-based training.

see Simulation Center

see Simulation model

1)

Chawla S, Devi S, Calvachi P, Gormley WB, Rueda-Esteban R. Evaluation of simulation models in neurosurgical training according to face, content, and construct validity: a systematic review. Acta Neurochir (Wien). 2022 Feb 4. doi: 10.1007/s00701-021-05003-x. Epub ahead of print. PMID: 35122126.

2)

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 Feb 27;15(2):e0229596. doi: 10.1371/journal.pone.0229596. PMID: 32106247; PMCID: PMC7046231.

[3]

Iop A, El-Hajj VG, Gharios M, de Giorgio A, Monetti FM, Edström E, Elmi-Terander A, Romero M. Extended Reality in Neurosurgical Education: A Systematic Review. Sensors (Basel). 2022 Aug 14;22(16):6067. doi: 10.3390/s22166067. PMID: 36015828; PMCID: PMC9414210.