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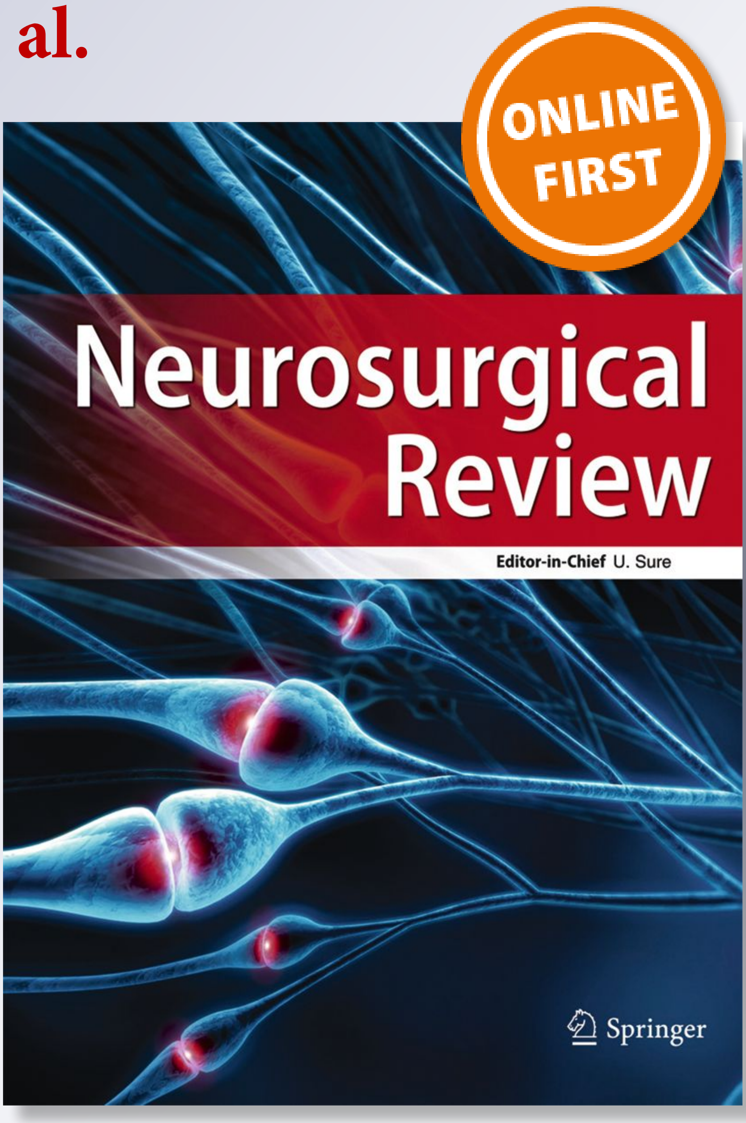

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REVIEW

A review of virtual reality simulators for neuroendoscopy

Britty Baby[1,2] · **Ramandeep Singh**[1] · **Ashish Suri**[1,2] · **Rohan Raju Dhanakshirur**[2] · **Argha Chakraborty**[2] · **Subodh Kumar**[3] · **Prem Kumar Kalra**[3] · **Subhashis Banerjee**[3]

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Abstract

Neurosurgery is a challenging surgical specialty that demands many technical and cognitive skills. The traditional surgical training approach of having a trainee coached in the operating room by the faculty is time-consuming, costly, and involves patient risk factors. Simulation-based training methods are suitable to impart the surgical skills outside the operating room. Virtual simulators allow high-fidelity repeatable environment for surgical training. Neuroendoscopy, a minimally invasive neurosurgical technique, demands additional skills for limited maneuverability and eye-hand coordination. This study provides a review of the existing virtual reality simulators for training neuroendoscopic skills. Based on the screening, the virtual training methods developed for neuroendoscopy surgical skills were classified into endoscopic third ventriculostomy and endonasal transsphenoidal surgery trainers. The study revealed that a variety of virtual reality simulators have been developed by various institutions. Although virtual reality simulators are effective for procedure-based skills training, the simulators need to include anatomical variations and variety of cases for improved fidelity. The review reveals that there should be multi-centric prospective and retrospective cohort studies to establish concurrent and predictive validation for their incorporation in the surgical educational curriculum.

Keywords Neurosurgery · Virtual reality · Simulators · Neuroendoscopy · Skills · Training · Virtual endoscopy

Introduction

Minimally invasive neurosurgical procedures are now widely accepted and practiced by neurosurgery fraternity. Surgeons require a unique skill-set for these procedures that account for bimanual dexterity, fulcrum effect, eye-hand coordination, and adaption of two-dimensional (2D) visualization. The traditional apprenticeship model for training of neurosurgeons shows limited acceptance in the case of minimally invasive procedures. The ever-increasing number of patients, limited available time for teaching in the operating room (OR), ethical concerns, financial burdens, work hour restrictions, and seriously ill patients demanding skilled hands encourage the search for alternative training methods [1].

Even though live animal models are established methods for surgical training, political and social barriers motivate

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developing simulation-based education for skills-training in surgery. Simulators have shown to improve the learning rate and performance of the trainee by providing individual feedback [2, 3]. Simulators offer a safe, patient-detached training environment, by providing activities that mimic OR practices [4, 5]. Web-based learning, automated learning systems, and virtual reality (VR) systems are highly recommended [6]. Along with physical trainers and animal models, the new trend in the simulation is virtual reality systems, because they can facilitate objective criteria for trainee evaluation and quantitative analysis in surgical studies [7].

The advent of computer technology has led to a dramatic surge to VR environments in the field of medical simulation [8–10]. Along with a variety of surgical specialties, the wide spectrum of VR simulators covers autonomous skills training and incorporating anatomy, pathology, and varied surgical environment. Simulation-based training methods should also include appropriate assessment methods that potentially provide benefits like self-assessment, feedback, efficient training, and patient safety, along with accreditation or certification [11–13].

Learning curve can be tracked by pre- and post-evaluation of the trainee on a particular simulator or using repeated iterations on the same simulator at regular intervals. There is also an opportunity to evaluate the trainees by providing them repeated practice sessions under standardized conditions. The institution generally evaluates the trainees by their locally standardized methods based on national accreditation guidelines [13]. There are no globally accepted standardized performance measures to evaluate the trainees in neurosurgery. In neurosurgery curriculum, the final stage of training is imparted using the high-fidelity simulators like cadavers or VR simulators. The performance evaluation by expert neurosurgeons can provide an idea whether the trainee is ready for actual surgery, but this is debatable.

An ideal simulator should provide training for psychomotor skills, cognition, and decision-making skills to the trainees. It must provide timely feedback on the performance with objective assessment scales or metrics and should provide holistic training environment with both engineering and psychological fidelity. The main objective of this paper was to review the available virtual training systems in neuroendoscopy based on design, tasks, evaluation methods, and validation.

Methodology

Our study aimed to describe the various virtual training systems available for neuroendoscopy. The related articles were searched using PubMed, Scopus, Google Scholar, IEEE Xplore, and dblp search engines. The keywords used were "neurosurgery", "virtual endoscopy", "neuroendocopy", "training", "virtual reality", and "skills evaluation". We found results in 40 PubMed articles, 265 Google Scholar articles, 13 IEEE Xplore articles, 25 Scopus articles, and 36 dblp articles. To be eligible for the review, the paper had to

- Be published in the English language,
- Describe a virtual simulation developed for neuroendoscopy.
- Be relevant for training in endoscopic third ventriculostomy (ETV) and endoscopic endonasal transsphenoidal surgery (EETS) procedures.

Our review is focused on neurosurgery and more particularly to neuroendoscopy techniques. We included review papers relevant for endoscopic third ventriculostomy (ETV) and endoscopic endonasal transsphenoidal surgery (EETS) procedures because these are the most common neuroendoscopic procedures. The virtual simulations of endoscopic procedures involve rendering of structures on a 2D screen and 3D visualization or displays are not involved. The main hypothesis for this selection is based on the fact that neuroendoscopy can be a relevant subset for identifying the advancements in virtual simulators in neurosurgery and determine the spread and depth of assessment and validation studies involved. We included the research papers, their cross-references as well as book chapters and reports. We also considered the papers that do not perform validation studies. We also included the simulation studies by the related non-neurosurgical specialties like ENT or head and neck surgery.

We performed an initial title screen followed by an independent review of abstracts and full article. The articles with ambiguity were reviewed together and disagreement was resolved by consensus. We focused the review on the surgical skills training papers that mentioned neuroendoscopy, endoscopy, and objective skills evaluation.

Results

The existing virtual reality simulators were compared based on their fidelity, user-evaluation methods, and validation measures. Fidelity measure can be defined by the level of realism, contextual parameters (environment, situation, resources), functional parameters (accountability, responsibility, causality), and interfacing (person, data, team members, communication). Virtual reality simulations are considered to be of high fidelity and they include virtual models of the anatomical structures involved in the surgery. The causality and accountability are high and they provide interfacing opportunity for team performance training. Virtual simulation of endoscopic surgery is commonly mentioned as virtual endoscopy (VE). VE deals with the reconstruction of the three-dimensional (3D) model and navigation with a virtual camera. It has many applications ranging from pre-planning, intra-operative assistance, and resident training. We have divided the short-listed papers into two categories: ETV and EETS trainers (Fig. 1).

Virtual simulations for endoscopic third ventriculostomy

Virtual ventricle endoscopy (VIVENDI) by Bartz et al. of the Center for Visual Computing State University of New York in 1997 was adapted from virtual colonoscopy [14]. The main purpose was to provide planning of complicated interventions for ventricular endoscopy. The segmentation of structures was performed on multi-modal data which included magnetic resonance imaging (MRI) and magnetic resonance angiography (MRA). The segmentation was performed through a 3D volume growing algorithm. The fly-through animation of the camera was created using guided navigation. They also included multiple camera paths, to reach different locations from the start point. The virtual endoscopy was simulated on 10 patients prior to neuroendoscopic intervention. The navigation was interactively performed by using mouse movements. They recommend the presented system for planning and training neuroendoscopic procedures. No validation studies were reported for training [15, 16].

Endoscopic third ventriculostomy simulator by Cakmak et al. of Karlsruhe Research Center, Institute of Applied Computer Science, Karlsruhe, Germany in 2000 was a new iteration over the VR platform of KISMET with extended 3D models and animation methods. KISMET featured evaluation and assessment factors for activities like grasping, setting of clips, cutting, cautery, irrigation, suction, and suturing (KISMET-endoscope). The 3D anatomical models were created using KisMo (KISMET modeler) exploiting modeling methods like meta-balls, splines, and subdivision surfaces. Kismet Force Feedback (KFF) controlled the haptic input and output by registering the position of endoscope and instrument and calculating the collision and resultant forces and torques. KisGrid was used for collaborative haptic training by connecting the simulators in a network which helped in transferring haptic data, images and audio using a grid applet ViaCoM. They provided soft tissue modeling using a hybrid deformation algorithm combining the mass-spring network and linear elastostatic finite element method (FEM). They also modeled cerebrospinal fluid, blood, and irrigation fluid. The training includes blunt perforation of the floor of third ventricle using a bipolar electrode and dilatation by using a Fogarty balloon catheter. The validation studies were not reported in the paper [17–19].

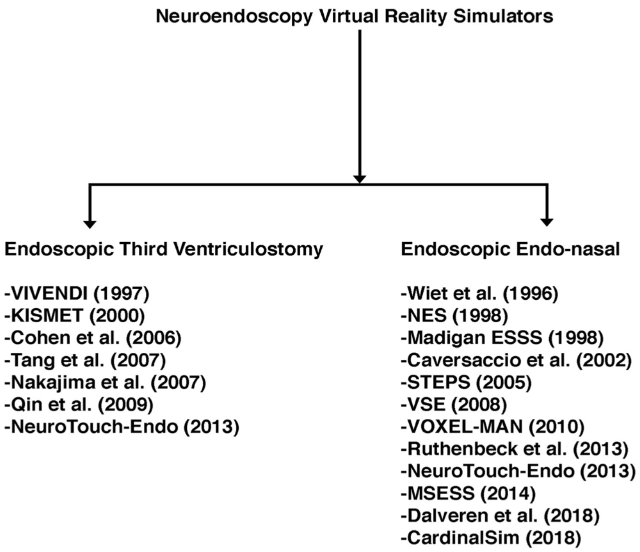

Fig. 1 Classification of neuroendoscopic virtual simulators for endoscopic third ventriculostomy and endoscopic endonasal surgeries

Cohen et al. of the Department of Neurosurgery, Boston Children's Hospital, Boston, MA, USA, in 2006 developed the virtual endoscopy simulation for third ventriculostomy training. They discuss the steps involved in virtual simulation development like graphics, volume rendering, model behavior, tissue deformation, and haptic feedback. They used GiPSi framework which is an open source platform for organ-level surgical simulation [20]. This framework helped in shared model development, simulation at organ level processes, and use of heterogeneous models of computation. It also provided interfacing with heterogeneous physical processes and input/output interface with haptic and visual feedback for real-time interactive applications. They employed a multi-rate simulation approach for improved stability of haptic interaction [21]. Lorensen and Cline's Marching Cubes algorithm was used to reconstruct the 3D model of third ventricular surfaces. The phantom haptic interface was used along with a separate portal for Fogarty catheter placement. No validation studies were reported [22, 23].

Tang et al. of The Chinese University of Hong Kong, Hong Kong, China, in 2007 explained the development of a virtual reality-based surgical simulation system for virtual neuroendoscopy or third ventriculostomy. The details of system architecture to implementation were described. The segmentation of the object of interest was done using Photoshop, and the segments were reconstructed to one palette volume and stored in Lattice format. This lattice format was converted to the stereolithography (STL) mesh format, and post-processing of the mesh was performed in Visualization Toolkit (VTK) including decimation and removal of unwanted vertices. Visualization Virtual Reality Simulation (VVRS) library was developed for 3D visualization and VR simulation. Isosurface rendering was performed from the volume data; the endoscopic view was simulated by radial distortion and using the stencil buffer. Three visualizations were provided: endoscopic, volume rendered, and surface rendered. The input was mouse pointer and trackball and no sensory feedback was provided. The utility of the simulator in a training setup was not described [24].

Nakajima et al. of Department of Radiology, Brigham and Women's Hospital, Boston, MA, USA, in 2007 used virtual endoscopy to compare the performance of surface rendered-virtual endoscopy (SR-VE) to volume rendered-virtual endoscopy (VR-VE). The endoscopic cases of 14 patients who underwent intraventricular surgery were used. SR-VE was developed using open source 3D slicer and VR-VE using commercially available software (Real INTAGE, KGT Inc., Tokyo, Japan). Three neurosurgeons scored the visibility of the substructures of the lateral ventricles, third ventricle, cranial nerves, arteries, and other lesions. There was no significant difference in visualizing the lateral and third ventricle using the two rendering techniques. But for cranial nerves, arteries, and other lesions, SR-VE was marked significantly better than VR-VE for visualization. They also mentioned that the SR-VE took longer time due to manual intervention for the segmentation of the related structures. The virtual endoscopy is suggested to be a good anatomy training tool with the method of surface rendering [25].

Qin et al. of Centre for Smart Health, School of Nursing, HongKong, in 2009 developed an endoscopic third ventriculostomy simulator using physics processing unit (PPU). They extended the PPU-accelerated linear mass-spring system to model a bi-modular stress-strain relation that can describe the elastic behavior of soft tissues. PPU also provided built-in support for fluid modeling using smoothed particle hydrodynamics (SPH). The third ventricular floor was modeled as PPU built-in cloth model. Endoscope and surgical tools were modeled as static shapes and soft tissue as dynamic meshes. When force applied was large enough on the floor of the third ventricle, the cloth model was torn to simulate the cutting of the membrane. The visualization was possible as a 3D anatomic navigation view, endoscopic view, and MRI view. There was no validation study mentioned [26].

Choudhury et al. of Simulation of Deformable Materials, Industrial Materials Institute, National Research Council Canada, in 2013, provides a conceptual framework named the Fundamentals of Neurosurgery, which is an attempt to provide standardized training modules for skills acquisition in neurosurgery. They provide five tasks as the representative of basic and advanced neurosurgery skill and the first task is ventriculostomy. This is integrated into the NeuroTouch platform developed by the National Research Council of Canada. The simulation uses haptic device to track the entry site and angle of insertion. The trajectory is then projected to the virtual model for providing feedback on the performance [27]. No specific validation study of effectiveness of ventriculostomy training on the simulator is reported.

Breimer et al. at the Hospital for Sick Children, Toronto, Ontario, Canada, in 2016 compared the utility of physical and virtual simulators for endoscopic third ventriculostomy training. Twenty-three neurosurgery residents and three fellows performed the ETV on both physical simulator (developed in-house) and virtual simulator (Neuro-Touch) and the trainees rated these on a 5-point Likert scale. For anatomy and decision making, the virtual model was found useful whereas for manual dexterity and technical skills, physical model was found to be better [28].

Virtual simulations for endonasal surgery

Wiet et al. of Department of Otolaryngology, The Ohio State University Hospitals and The Ohio Supercomputer Center, Columbus, in 1997 developed a fundamental endoscopic sinus surgery (FESS) training simulator by using the volumetric model of the anatomical structures from cryosections of Visible Human Project. This setup consisted of forceps simulator, endoscope tracking unit, control computer, interface card, and the host computer. The forceps simulator consisted of a mounting platform, head assembly, calibration fixture, and a modified 3-degree haptic device (Impulse Engine 3-GM) with a 3-gimbal assembly and the forceps. The endoscope was tracked using MicroScribe 3DX, which is a 6 degrees of freedom (DOF) spatial tracking mechanism. It was equipped with a special stylus roll sensor to track the endoscope rotation along its axis. The volume rendering techniques used were splatting and slicing and volume deformation was applied to the rendering agents rather than the objects. The virtual interaction was performed with the help of a physical interface to provide the external landmarks to the trainees. The system faced challenges in volume splatter when the endoscope was moved closer to the target for viewing [29].

Rudman et al. of Department of Otolaryngology, College of Medicine and Public Health, The Ohio State University, USA, in 1998 studied the efficacy of the haptic device of simulator developed by Wiet et al. and compared the iso-surface and volumetric models of the FESS simulator. Objective trials evaluated the ability of the haptic device to perceive 3D shapes without any visual feedback and were found to be 77% effective. Ethmoidectomy was performed using iso-surface and volumetric models. The simulator was found to expedite the understanding of the 3D anatomy of paranasal sinuses and provide a safe environment to learn FESS techniques [30].

Bockholt et al. developed nasal endoscopy simulator (NES) at the Fraunhofer Institute for Computer Graphics in cooperation with the Mainz University Hospital, Germany in 1998. They used computed tomography (CT) slices to reconstruct the anatomical structures and used a magnetic tracking device (Polhemus Fastrak) to track the motion. Three sensors were used: one fixed to the endoscope to simulate the camera, optics, and light source; the second sensor was fixed to the biopsy forceps (gator); and the third sensor was located at the head of the synthetic patient model. A small potentiometer was added to identify the angle of opening of the gator. They simulated tissue deformation of pulling with scissors or pushing with a probe. In the initial approach, smooth interpolation functions were used to show deformation and other approaches were simulated by mass-spring systems. The simulator checks the collision between the endoscope, surgical instrument, and the anatomical structures. A visual and acoustic response on the collision was implemented and they suggested that the collision statistics can be used to measure the trainee progress. No validation study was reported [31, 32].

Madigan endoscopic sinus surgery simulator (ESS or ES3) was developed by US Army Medical Research and Materiel Command Fort Detrick, USA, in 1998, with virtual reality technology using 3D anatomical models created from the photographic cryo-sections of visible human database for the training of ear nose throat (ENT) surgeons. Stochastically generated textures were added to improve the experience. A pair of six-degree-of-freedom input devices interacted with the anatomical model: one for manipulation of the endoscope and other for the instrument. The system was capable of tracking the opening and closing of the instruments like forceps handle adding to the tracked degree of freedom. The user manipulates a mannequin head that was mechanically coupled with the system, and it provides feedback. It also provided a simulated endoscopic view along with training aids like anatomical landmarks, targets, and endoscope trajectory. The training system consisted of three subtasks: navigation, injection, and dissection. The time taken for the procedure and accuracy based on path lengths were the evaluation parameters and were incorporated in the simulation itself. Various geometric models varied the level of training for the novice, intermediate, and expert [33, 34].

There were validation studies reported for construct validity and predictive validity for the above simulator. The different models were able to differentiate the novices and intermediates significantly [35]. The scores obtained on the ES3 correlated with the previously validated measures of perceptual, visuospatial, and psychomotor performance calculated using minimally invasive surgical trainer virtual reality (MISTVR), three visuospatial tests (cube comparison, card rotation, and map planning), and pictorial surface orientation (PicSOr), respectively [36]. The ES3-trained residents showed significant improvement in a real surgical scenario in comparison with the control group [37].

Caversaccio et al. used Dextroscope (Dextroscope; Volume Interactions, Singapore, a company of Bracco S.p.A., Milan, Italy) at University of Bern, Switzerland, in 2002 and studied the effect of the simulator for endonasal surgery. The simulator had stereoscopic glasses, magnetic tracking stylus, a joystick, and mirrored display for the virtual interaction. There was no force feedback or bleeding or blanching simulation. The simulator was used to recognize and mark the landmarks and to reach the surgical site. The CT images of the patient were segmented by the trainees for visualization, and the process was time-consuming. The simulator was used by two third-year residents who had no experience in endoscopic surgery to perform ten sinus surgeries on the simulator followed by the real setting. The residents answered a subjective questionnaire on the experience of working with the simulator. The performance of the trainees to recognize the anatomic landmarks during the simulation and real-time endoscopy was checked and evaluated by a proctor. The results show that the simulator allows the trainees to understand the anatomy but it did not make any significant impact on operating room performance [38].

STEPS, the virtual endoscopic system, was designed by Neubauer et al. of Department of Neurosurgery, Medical University Vienna, General Hospital, Vienna, Austria, in 2005 for training and planning of endonasal transsphenoidal surgery. The anatomical models were created by the registration of CT and MRI data using adaptive simulated annealing. Segmentation of the region of interest was done using manual segmentation and watershed algorithm from markers. Two different first-ray hit algorithms optimized the visualization for foreground and background. The simulator features both endoscopic view and sectional view. The three modes of the simulator were

- Free-flight mode: for preoperative planning and intraoperative investigation.
- Surgical simulation mode: for training of the endonasal procedure.
- Guided navigation mode: for training the movements towards the target point or tumor.

Force feedback for endoscope interaction with the tissue was absent. The components of the simulator included a force-feedback joystick and the handle was reserved for the endoscope rotations. The endoscope was advanced and pulled back using buttons. The visualization of the anatomical landmarks was also extensively studied and reported. It was also implemented as a plugin with Impax EE PACS integration. There was no evaluation metric involved with the system, and no validation studies were reported for training. The usefulness of the system for pre-operative planning and intraoperative guidance was studied using clinical cases [39–41].

Parikh et al. developed 3D interactive pre-operative planner Stanford Virtual Surgical Environment (VSE) at Stanford University, Stanford, California, in 2008 for rhinologic procedures. It included the basic elements for data acquisition and reconstruction, a haptic interface, and a rendering engine. The 3D models were automatically generated from the CT scans. The real-time rendering of the data was based on hybrid isosurface and volume rendering. A mannequin model was used, and the endoscope was inserted through its nostril to limit motion as expected during the surgery. Virtual endoscopic views were created using the CT scans of the patient and compared with the operative videos subjectively. The tool was only for visualization and did not provide any deformation simulation. It provided a patient-specific visualization tool to prepare for endonasal procedures and offered training to the residents [42].

VOXEL-MAN SinuSurg was developed for endoscopic sinus surgery simulation in 2010 by Department of Oto-Rhino-Laryngology, Helios Hospital Krefeld, Krefeld (R.L.), Germany, and was adapted from their VOXEL-MAN TempoSurg simulator (temporal bone surgery). They used high-resolution CT data for human skull segmentation and manually modeled nerves, arteries, veins, periorbita, and the mucosa. The surfaces were visualized using a ray casting algorithm which renders the iso-surfaces. They had customized algorithms for tissue removal, haptic rendering, and subvoxel visualization. The visualization was possible for both microscopic and endoscopic view along with the spatial planes. Angled endoscopes were also modeled for visualization. They proposed their simulator as a tool to learn surgical anatomy and navigation. The evaluation criteria were not quantified and no validation studies were reported [43].

Ruthenbeck et al. of School of Science, Engineering and Mathematics, Flinders University, Australia, in 2013 developed virtual endoscopic sinus surgery simulator as a training tool for Otorhinolaryngology-Head & Neck Surgery (OHNS). CT scans were processed using Simpleware ScanIP software (Synopsys International Limited, Dublin, Ireland) to create 3D triangular mesh models and UV unwrapped for texture using 3DX Max software. The simulator was written in C++ using developed algorithms and software libraries like Microsoft DirectX. User interaction was modeled using a spring-damper system, and dual haptic handpiece devices were used to simulate endoscope and surgical instruments. Bling-Phong lighting model was used with bump maps and specular highlights. Vasoconstriction for bleeding was added for realism. Cut-volumes modeled instrument collision detection along with haptic feedback. The validation study was reported in the subsequent research papers. The participants were final-year medical students, interns, resident medical officers (RMOs), OHNS registrars, and consultants. They assessed face and content validity of the simulator by asking a 5-point online questionnaire after performing four separate simulation tasks. Face and content validity measures show that the simulator needs further development for effective registrar-level training. However, it was indicated as a useful tool for learning OHNS-related anatomy. The construct validity evidence was shown by study among 10 experienced sinus surgeons (five consultants and five registrars) and 14 novices (seven resident medical officers and seven interns/medical students) who completed three simulation tasks. The Flinders sinus surgery was able to differentiate between experts and novices with respect to procedure time, instrument distance traveled, and number of cutting motions to complete the task [44–46].

NeuroTouch-Endo developed by the National Research Council of Canada in collaboration with surgeons at teaching hospitals in Canada simulates the third ventriculostomy and endonasal transsphenoidal surgery (Fig. 2). Rosseau et al. of Department of Neurosurgery, NorthShore University Health System, Evanston, Illinois, in 2013, described the application of Neuro-Touch Endo for endoscopic endonasal transsphenoidal surgical procedures. The group identified the core technical skills required for the surgery and performed a cognitive task analysis. They described the use of the simulator for technical skills assessment for EETS. The simulator included reconstruction of the virtual models of the elements involved in the transsphenoidal surgery including the endoscope, neurosurgical tools, anatomy, tissues, and fluids. The haptic device was modified to accommodate the visual appearance of the endoscope, drill, and microdebrider. Each training module was expanded to include the learning objectives, the level of difficulty, and performance metrics. The metrics of evaluation include efficiency and error identification. Efficiency was studied with the distance traveled and time. The errors were considered by measuring excessive force, tool-tip in the center of focus, and removal of constrained tissues. The authors report that the simulator provides opportunity for beta testing, validation, and evaluation of performance metrics in neurosurgery training [47].

McGill simulator for endoscopic sinus surgery (MSESS) was developed by Varshney et al. in 2014 at McGill University, Montreal, Canada, on the NeuroTouch platform previously developed by National Research Council of Canada (NRC). NRC's software simulation engine, Blade consists of three asynchronous processes for computing tissue mechanics, graphics, and haptic feedback. Tissue deformation was modeled using finite-element methods. The modeling of the structures was performed by a multi-stage method including 3D slicer (www.slicer.org) for manual segmentation and 3D model generation. Blender (Blender Foundation, Amsterdam, Netherlands) was used to correct the artifacts. Five tasks were simulated based on the step-wise approach and increasing the level of difficulty. MSESS allows measurement of bimanual dexterity and incorporate tools like endonasal wash [48]. Varshney et al. also conducted studies on the validation of MSESS in 2014 among 10 medical students, otolaryngology residents (10 junior and 10 senior), and faculty (3 experts). They presented evidence of construct validity by being able to differentiate users based on their level of training using the performance metrics. They also used a post-simulation questionnaire on 10-point rating scale for assessment of perceived realism (face validity) of the simulator getting a score of 7.97 ± 0.29 and content validity for the usefulness of the simulator getting a score of 8.57 ± 0.69. The study demonstrated a significant difference between novices and experts in the metrics related to quality ($p < 0.05$), efficiency ($p < 0.01$), and safety ($p < 0.05$) [49].

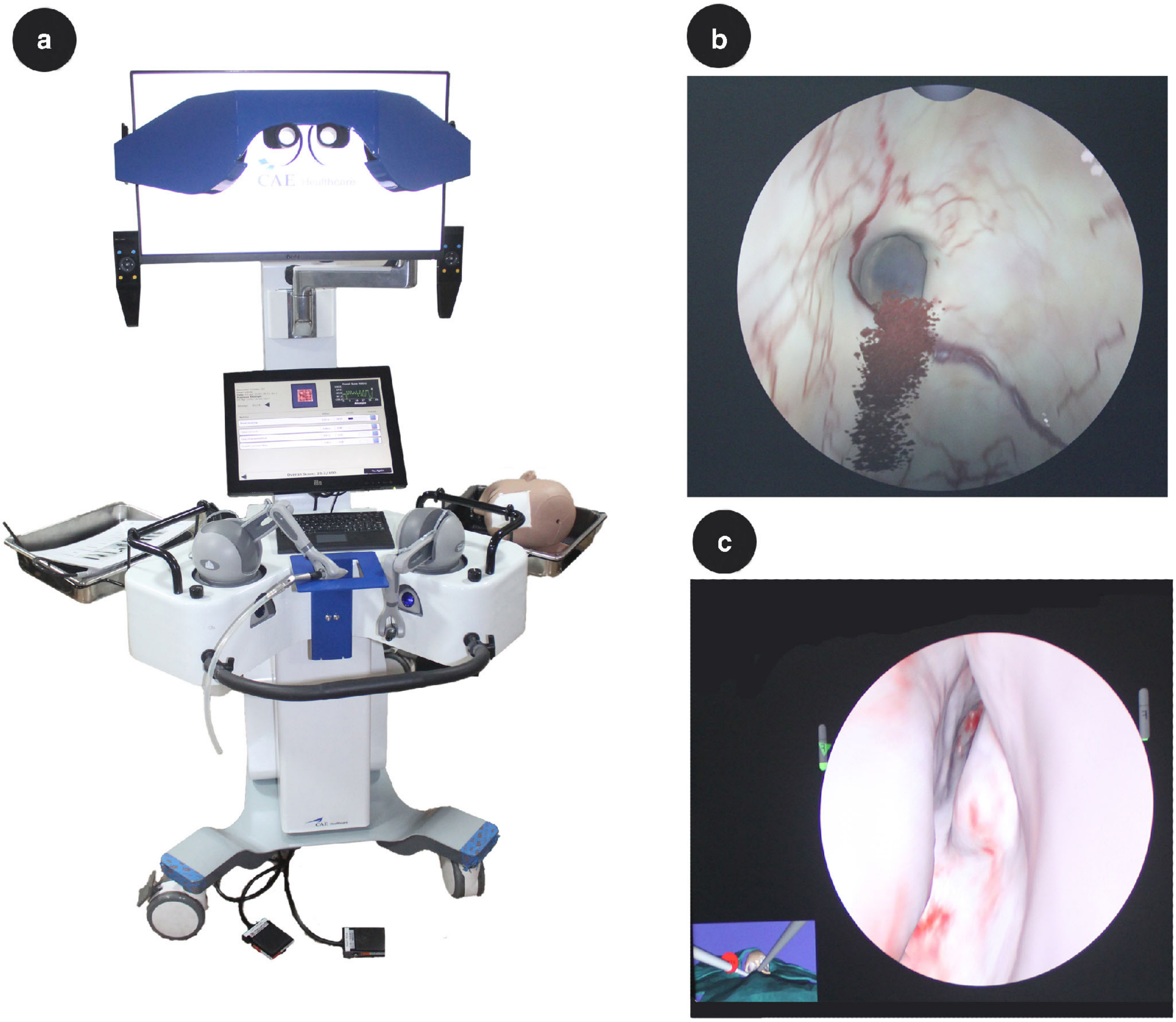

Fig. 2 Neuro-Touch virtual reality simulator: **a** complete training setup, **b** ETV surgery view on simulator, and **c** EETS surgery view on simulator

Thawani et al. of Department of Neurosurgery, Hospital of the University of Pennsylvania, Philadelphia, in 2016, used NeuroTouch-Endo haptic simulation platform to analyze if the simulation practice improved resident performance in endoscopic endonasal surgery in the operating room. Three first year and three second year residents were assessed using a visual analog scale on the simulator as well as intra-operatively. During session 1 on the simulator, the residents were assessed and subjects with lower scores were made as study participants for simulation training and the rest as control participants without training. An alternate simulation task was provided for task-learning to avoid bias. These residents were then evaluated in the operating room over 6 months by one of the authors who was blinded to trained/untrained subjects. The performance score averaged over all measures obtained from the operating room of those who underwent simulation training was found statistically significant ($p = 0.0045$) [50].

Dalveren et al. developed the Educational Computer-based-simulation Environment (ECE) for endonasal surgery training at Atilim University, Ankara, Turkey in 2018. They developed four different scenarios of training on this simulator in which the third scenario was a virtual nose model to provide high fidelity. Twenty-three participants of neurosurgery and ENT surgery departments participated in the study. They collected the eye movement data using Eye Tribe Eye Tracker to obtain fixation number and fixation duration events. GeomagicTouch (3D Systems, North Carolina, USA) mid-range professional haptic device was used for interaction. The study was conducted to understand the effect of eye movements for hand condition, gender differences, and surgical scenario difficulty. According to the study, these factors were found to make changes on the mental workload of surgical residents [51].

CardinalSim was a rhinologic VSE developed by Won et al. of Department of Otorhinolaryngology–Head and Neck Surgery, Seoul National University Hospital, Seoul, Korea, in 2018 that featured patient-specific virtual rhinologic surgical simulation platform along with the simulation of tissue deformation. The force feedback was provided based on the forces applied using the haptic device and the interaction between bone and soft tissues. The simulator also provided audio feedback for realism. Critical landmarks were demarcated on the axial scans for easy 3D reconstruction. Amira Software and Image Processing ToolKit (ITK)-snap were used for the same. The virtual endoscopy images and operative images of ten cases were compared by three trained rhinologic surgeons using a 4-point Likert scale. They found a good correlation for the surgical exposure, pathology locations, and anatomical features [52].

Discussion

The currently available commercial virtual simulators for neurosurgery training are Neuro-Touch (Cranio and Endo, CAE Inc., Montreal, Canada) and Immersive-Touch (ImmersiveTouch Inc., Chicago, USA). Immersive touch simulator includes ventriculostomy simulation and shunt placement and endonasal module (Fig. 3), but was not included as a part of the current study as we could not find indexed papers on endoscopic modules, even though there are literature available for craniotomy and pre-operative planning [53].

Satava of US army hospital, in 1993, identified the challenges of the virtual reality simulators, as the need for improved technical fidelity, standardization of the performance metrics for skills evaluation, validation of the simulators developed, the inclusion of the simulators into an educational curriculum, and intuitive simulators that do not demand a separate learning curve [54]. The challenges remain the same even in the current scenario. The development of virtual endoscopy simulators is technology intensive, and there are various computer graphics techniques reported for 3D modeling, visualization, and interaction with the virtual world. The detailed description of the various technologies used in each of the virtual reality platforms is shown in Table 1.

The virtual endoscopy simulators are classified into ETV and EETS. The classification of neuroendoscopic virtual skills training simulators, their assessment methods, and validation results are shown in Table 2.

Validity types for surgical simulators or surgical training platforms include face, content, construct, concurrent, and predictive validity [55]. Even though the design and development of the virtual endoscopy simulators were available, the studies on the objective evaluation of skills and validation of the simulators were limited. The validation studies were not found for any of the third ventriculostomy simulators except Neuro-Touch Endo. Neuro-Touch Endo is a commercially available simulator that simulates both endoscopic third ventriculostomy and endonasal approaches. There are studies that show face, content, construct, and predictive validity for endonasal module and comparative study for endoscopic third ventriculostomy with physical simulators. In the case of endonasal simulators, most of them used a questionnaire-based assessment for face and content validity. Madigan endoscopic sinus surgery simulator was found to have wide acceptance in the ENT society, and studies for validation including construct, concurrent, and predictive validity were reported.

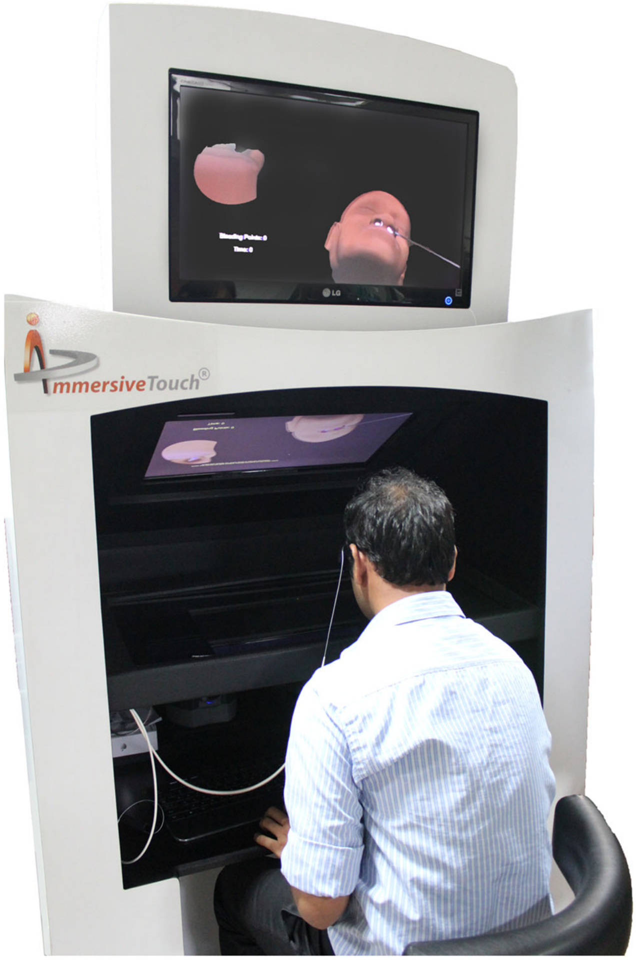

Fig. 3 Immersive touch virtual reality simulator showing the user console and display

Choudhury et al. opine that the validation studies are limited in neurosurgery due to lack of objective assessment tools and they propose to develop a global rating scale to measure neurosurgical performance in the operating room called the Global Assessment of Intraoperative Neurosurgical Skills (GAINS) [27]. The NEVAT scale developed by Breimer et al. showed content validation

Table 1 Virtual reality simulators for neuroendoscopy skills training

S.No	Name of simulator	Application	Hardware/software information	3D model creation	Soft tissue deformation	Collision detection	Visualization	Haptic feedback
1	VIVENDI (1999)	Endoscopic third ventriculostomy	(PA-8500/440 MHz CPU, fx6-pro graphics card, 4GB RAM (only 256 MB are necessary), HP-UX 10.20) Magneto'm, Vision, Siemens, Germany	Magnetic resonance imaging (MRI) and magnetic resonance angiography (MRA) using volume growing	–	Combining distance fields and kinematic rules for collision avoidance for camera	Octree based parallel implementation of Marching Cubes algorithm. an intuitive scheme for navigating and Dijkstra's minimum path algorithm, view frustum culling algorithm	Mouse click based submarine model
2	KISMET (2000)	Endoscopic Third ventriculostomy simulator	SGI UNIX-workstations and Windows-NT KisMo (Kismet modeler), KISMET, Kismet Force Feedback (KFF), KisGrid for collaborative training, ViaCoM applet	Metaballs, splines and subdivision surfaces from MRI	Hybrid deformation algorithm combining the mass-spring network and linear elastostatic finite element method (FFEM), cerebrospinal fluid modeling with calculation and visualization of blood and irrigation fluid	Hierarchical collision handling algorithms	Volume rendered with movable slices, volume rendered as blocks.	IOMaster3D, Collaborative haptic training algorithms
3	Cohen et al. (2006)	Endoscopic third ventriculostomy	GiPSi /GiPSiNet open source framework using OpenGL shading language	MRI images	Nonlinear plastic lumped element model		Lorensen and Cline's Marching Cubes algorithm Endoscopic View	PHANTOM® Omni™ Haptic Device, Multirate simulation approach based on local linear approximations
4	Tang.et al. (2007)	Endoscopic third ventriculostomy	Visualization Toolkit (VTK), Visualization Virtual Reality Simulation (VVRS) library	Segmentation from MRI using Photoshop and stored in Lattice format and then converted to STL format	–	Ray-cast based collision detection from mouse	Normal alpha-blended rendering and maximum intensity projection (MIP) for volume rendering, Iso-surface rendering, endoscopic view by radial distortion and stencil buffer.	Mouse and trackball
5	Nakajima et al. (2007)	Endoscopic third ventriculostomy visualization comparison study	Real INTAGE, KGT Inc., Tokyo, Japan 3D Slicer Dell Precision 470, Dell Inc., Round Rock, TX Magnetom Symphony or Avanto; Siemens AG, Erlangen, Germany	MRI images	–	–	Ray casting for volume rendering, Marching cubes for surface rendering	
6	Qin et al. Simulator (2009)		Windows and UNIX platform using Visual	Surface or volumetric models from CT, MRI.	Bi-modular stress-strain model, fluid modeling	Continuous Collision	GPU-based Marching cube rendering.	Six degrees-of-freedom (DOF) force model

Table 1 (continued)

S.No	Name of simulator	Application	Hardware/software information	3D model creation	Soft tissue deformation	Collision detection	Visualization	Haptic feedback
		Endoscopic third ventriculostomy	Studio 2005 (C++) and Eclipse SDK 3.1.0 (Java), OpenGL for rendering, Pentium(R) 4 CPU 3.20GHz, 1024 M RAM and NVIDIA GeForce 6800 display adapter		using smoothed particle hydrodynamics, PPU-cloth model and mass-spring damper system	Detection (CCD)	External 3D navigation, endoscopic view, MRI view	for haptic rendering, 3-DOF haptic device
7	NeuroTouch-Endo (2013)	Endoscopic third ventriculostomy	2 Xeon Quad-Core X5570 processors running at 2.93 GHz (Intel, Santa Clara, California), and 1 GeForce GTX 285 graphics card (NVidia, Santa Clara, California)	MRI images using 3D slicer and Blender	The tissue mechanics processes use finite elements with explicit time-integration, viscoelastic solids using the quasilinear viscoelastic constitutive model, elastic part is modeled as generalized Rivlin constitutive model, tissue removal volume-sculpting technique	Collision detection on shaft and on the tip	Endoscopic view	Phantom Omni, Freedom 6S haptic systems, Instantaneous reaction forces for penalty and forces obtained from the haptic device position and deformation of tissue
8	Wiet et al. (1996)	Endoscopic sinus surgery	Impulse Engine 3GM, MicroScribe 3DX, Silicon Graphics workstation	Volumetric model of the anatomical structures from cryosections of Visible Human Project	Volume deformation is applied to the rendering agents and is called deflector	–	Volume rendering using splatting and slicing	Impulse Engine 3GM haptic device
9	NES (1998)	Endoscopic sinus surgery	Electro-magnetic tracking system (POLHEMUS FASTRAK) and sensors on endoscope, instruments and mannequin head	–	- smooth interpolation function to show the motion between the deformed and undeformed tissues - mass-spring systems.	The simulator checks the collision between the endoscope, surgical instrument and the anatomical structures. - A visual and acoustic response for collision	–	–
10	Madigan Endoscopic Sinus Surgery Simulator (1998)	Endo-nasal sinus surgery	6 - DOF input devices by Immersion Corporation	3D anatomical models created from the photographic cryosections of Visible Human database	–	–	–	Haptic system emulator

Table 1 (continued)

S.No	Name of simulator	Application	Hardware/software information	3D model creation	Soft tissue deformation	Collision detection	Visualization	Haptic feedback
11	Caversaccio et al. (2002)	Endo-nasal	Workstation, Mirrored display, stereoscopic glasses, stylus and joystick VizDexter 1.2 software	The CT images of the patient was downloaded and segmented by the trainees	–	–	Volume visualization software that combines VR technology and volume rendering.	
12	STEPS (2005)	Endo-nasal transphenoid-al approach	Java-based medical workstation J-Vision (Tiani Medgraph, Vienna, Austria).	Registration of MRI, CT, MRA images by optimizing a similarity criterion (based on mutual information) using adaptive simulated Annealing, Segmentation by manual segmentation and watershed algorithm from markers	Soft tissue deformation in implicit way, manifests itself only in relieved constraints of movement and in force-feedback	Collision detection is only performed for the center axis of the virtual endoscope	Optimized image-order (pixel by pixel) ray casting technique for foreground, optimized object-order algorithm cell-based first-hit ray casting for background	Force-feedback joystick (WingMan Force 3D, Logitech Force feedback using tension relief vector
13	VSE (2008)	Endo-nasal	Intel Core2 Q6600 Quad-CoreX, 4 GB RAM, 768 MB NVIDIA GeForce 8800 GTX graphics board, Dell, Inc., Round Rock, TX) desktop computer	Three experienced surgeons performed endoscopy on the virtual representation of the patient to produce rendered images to match the intraoperative views	–	–	Hybrid iso-surface and volume rendering	Sensable Omni
14	VOXEL-MAN SinuSurg (2010)	Endo-nasal	Standard PC hardware		Customized algorithms for tissue removal	Multipoint collision detection of the tool	Customized algorithms haptic rendering and subvoxel visualization	6-DOF haptic device
15	Ruthenbeck et al. (2013)	Virtual endoscopic sinus surgery	ScanIP software, 3DX max software, C++, DirectX	CT scans	Spring-damper system	Modeled by cut-volumes	Bling-Phong lighting, bump-maps, specular lighting	Novint Falcon haptic device and a Phantom Omni haptic device
16	NeuroTouch-Endo, (2013)	Endo-nasal transphenoid-al	2 Xeon Quad-Core X5570 processors running at 2.93 GHz (Intel, Santa Clara, California), and 1 GeForce GTX 285 graphics card (NVidia, Santa Clara, California)	MRI images using 3D slicer and Blender	The tissue mechanics processes use finite elements with explicit time-integration, viscoelastic solids using the quasilinear viscoelastic constitutive model, elastic part is modeled as generalized Rivlin constitutive model, tissue removal volume-sculpting technique	Collision detection on shaft and on the tip	Endoscopic view	Phantom Omni, Freedom 6S haptic systems, Instantaneous reaction forces for penalty and forces obtained from the haptic device position and deformation of tissue

Table 1 (continued)

S.No	Name of simulator	Application	Hardware/software information	3D model creation	Soft tissue deformation	Collision detection	Visualization	Haptic feedback
17	MSESS (2014)	Endo-nasal transphenoidal	Same as Neuro-Touch platform	MRI images using 3D slicer and Blender	Upgraded the NRC's simulation engine Blade with thin layer of finite elements, realistic feeling tissue properties, tissue deformability and mobility of turbines	Same as Neuro-Touch platform	Endoscopic view, Touch screen for user interface	Bimanual system; one haptic device for endoscope and other for the microdebrider
18	Dalveren et al. (2018)	Used endo-nasal simulation to evaluate workload	64-bit Windows, Intel(R) Xeon(R) CPU E5–2620 2.00 GHZ processor and 32.0 GB RAM, Eye Tribe Eye Tracker					Geomagic Touch mid-range professional haptic device
19	CardinalSim (2018)	Endo-nasal	Intel Core i7-CPU, 8 GB RAM, Graphics 620, Passive stereoscopic display, Amira Software and ITK-snap	3D models were automatically generated from the CT scans	Soft tissue deformation simulation is present	Realtime collision detection present	Volume rendering using a technique known as graphics processing unit (GPU)-accelerated ray casting	Geomagic Touch haptic device

Table 2 Detailed classification of neuro-endoscopic virtual skills training simulators, their assessment methods, and validation results

Type of simulator	Sub-type	Examples	Assessment	Validation
Virtual endoscopy	Endoscopic Third ventriculostomy	VIVENDI (1999) [14–16]	Visualization of structures	–
		KISMET (2000) [17–19]	–	–
		Cohen et.al (2006) [20–23]	–	–
		Tang.et.al (2007) [24]	–	–
		Nakajima et.al (2007) [25]	Compare Surface rendered-ETV to Volume-Rendered-ETV	–
		Qin.et.al (2009) [26]	–	–
		NeuroTouch-Endo [27, 28]	5-point Likert scale	Face, content
	Endonasal transphenoidal	Wiet.et.al (1996) [29, 30]	Effect of haptic and visual feedback	
		NES (1998) [31, 32]	–	–
		Madigan Endoscopic Sinus Surgery Simulator (ESS) (1998) [33–37]	Time taken Accuracy Path analysis	Construct, Concurrent, Predictive
		Caversaccio et al. (2002) [38]	Subjective questionnaire	Face
		STEPS (2005) [39–41]	–	–
		VSE (2008) [42]	Subjective comparison	Face
		VOXEL-MAN (2010) [43]	–	–
		Ruthenbeck et.al (2013) [44–46]	5-point online questionnaire	Face, Content
			Internal metric	Construct
		NeuroTouch-Endo (2013) [47, 50]	Visual analog scale	Predictive
		MSESS on NeuroTouch platform (2014) [48, 49]	10-point questionnaire	Face, Content
			Internal metric	Construct
		Dalveren et al. (2018) [42]	Eye Tribe Eye Tracker for tracking eye-movements	–
		CardinalSim (2018) [43]	4-point Likert scale	Face

evidence on a physical neuroendoscopy simulator (SIMONT) for endoscopic third ventriculostomy by examining the inter-rater reliability and internal consistency of the scores generated. It provided insights to the importance of validation of an evaluation metric [56].

The virtual simulation has been a vast topic, and we found neuroendoscopic studies not particularly curtailing to training systems. There were studies related to modeling of the anatomical structures [57], modeling of cerebrospinal fluid and blood [58], virtual instruments with surgical environment [59], physical models for the deformation of the structures [60, 61], interaction models with haptic feedback [62], visualization of virtual endoscopy [63], relevance of virtual endoscopy from MRI for visualization of the anatomical structures involved in third ventriculostomy and the related pathology and planning the surgery by its combination with neuronavigation [64–69]. There are various virtual endoscopy systems that mainly focus on applications of surgical planning rather than skills training [70–72]. There are also studies that compared the performance of virtual endoscopy output obtained from a commercially available Navigator software (General Electronics, Boston, Massachusetts, United States) with the real endoscopic images [73, 74]. There is also a study that compared the virtual endoscopy output of open source software 3D slicer (http://www.slicer.org, version 4.4.0) with real endoscopic videos for suprasellar arachnoid cysts [75]. Virtual endoscopy studies are also available that provide intra-operative assistance for the neurosurgeons [76, 77]. There are various studies that demonstrated the use of virtual endoscopy (VE) that helps surgeons in understanding pathologies, demonstrating morphological aspects, and predicting anatomical variations [78].

The augmented reality (AR) systems augment the virtual objects or scenes to the real operative or training scenario. The augmented reality-based training is reported for laparoscopy [79]. AR for neuroendoscopy has been used mainly for surgical navigation and assistance. The endoscopic videos during the surgery are augmented with preoperatively chosen landmarks for effective navigation. The endoscope is tracked with the help of optical trackers. The registration of the CT, MRI-based patient data to the endoscope system is performed by mapping external landmarks. The 3D position or model of the anatomical structure is augmented to the corresponding endoscopic video clip. This can also be used to provide critical structure proximity alert of endoscope [80–83]. Navigation systems are used in endoscopic neurosurgery for preoperative planning of trajectories and intra operative localization of the pathology [84].

The present review on virtual training systems for neuroendoscopy included studies that discuss topics ranging from the development of endoscopic VR simulators for training to their validation and inclusion in the surgical curriculum. The otolaryngology studies on endonasal sinus simulators were also included as they are directly applicable to the neuroendoscopic skills training, even though the study group was not neurosurgeons in particular. Other neurosurgical training systems for microscopic training were not included.

Generally, simulators can be broadly classified as low fidelity and high fidelity. Low fidelity simulator provides less or no resemblance to anatomical structures and is bench models, which are usually low cost and portable. High fidelity simulators provide realistic resemblance to anatomical structures. There is also another perspective of 'engineering fidelity' which means whether the simulation is realistic and 'psychological fidelity' for whether the simulator contains elements that demands specific behavior to complete the task. High fidelity expensive simulations of virtual reality are considered to have good 'engineering fidelity' but reduced 'psychological fidelity'. The psychological fidelity can be increased in the VR simulator by including different examples of confusable categories or training management of complex problems involving different health professionals. Some studies show that the research on VR simulator performance was generally tested on VR simulators in comparison to a control group that did not go through any educational intervention which leads to biased conclusions [85].

The authors feel that high physical resemblance itself does not provide any added advantage to the virtual simulators. The virtual simulators should include holistic training approach including interactive anatomical orientation along with variations, cognitive skills training by including different categories of confusing and challenging case studies, managerial skills training for managing the patient under critical situations by collaborating with other surgical and medical professionals.

The review was including virtual simulators on neuroendoscopy which is a subset of neurosurgery and serves as an illustration for the trend in virtual simulation development and validation. The authors opine that the virtual simulators should include validation studies that provide evidence of superior performance on comparing these simulators with other teaching modalities like animations, 3D video demonstrations, and cadaveric dissection. There are also questions related to simulators, whether it provides the necessary training to improve surgical skills that can be extended to the real surgical scenario, or is it just making the trainees good as simulation users [86]. Authors agree with the Gallagher et al. [86] that success of virtual reality simulators is more probable if they are systematically integrated into a well-designed educational and training program which assess the technical skills objectively along with the learning experience. The performance metric should be validated and relevant to the task and overall skillset required. Virtual reality-based training should be included in the training module on interval basis rather than providing extensive practice for short duration.

Simulation-based training should always be imparted by taking into consideration of the constraints and scenario of actual surgical procedure and instrumentation. Moreover, the training should be imparted in a standardized and staged manner, starting from basic trainers to high fidelity simulations like cadavers or virtual simulators. In this way, learning of bad skills can be prevented. Simulation-based training can be incorporated in the residency program based on the results of the validity studies performed. Multi-centric validation studies on the particular simulation platform should be performed for inclusion in the residency program. More and more training institutes should take up validation of simulators as a research option. Authors feel that simulation-based training provides safe, repeatable environment for developing surgical skills.

There are various factors that hurdle the integration of the virtual simulators into the educational curriculum. The virtual simulators are arcade-sized machines and are locked away in devoted spaces, or laboratories. The investment in the available VR simulators may not be worth considering the cost of the neurosurgical programs and requires huge funding and allotted space [87]. From the user's perspective, the current simulators include standard case studies and do not provide surgical challenges to the trainees as expected by the community. The simulators provide limited haptic feedback in comparison to the real human tissue. From the developer's perspective, neurosurgery includes subjective approach and case-by-case variations which are non-trivial to be included into a general simulation environment. This makes the virtual simulators expensive and there is a trade-off in the installation of virtual simulators in the training laboratories in view of its usefulness, realism, and skillset.

The communication gap between the user and the developer needs to be addressed to develop and validate successful virtual reality simulations. The user of the simulators who are neurosurgeons should dedicate their time for research with technologists and provide well-thought educational curriculum with suitable intervention model for the virtual simulators. Technologists, at the other hand, should visit operation rooms and elaborately understand the skillset required and various challenges that the neurosurgeons face while performing the surgery. Timely intervention, feedback, and collaborative efforts of the medical community and technologists only can be the solution to develop acceptable virtual simulators that can be readily integrated to the curriculum.

There are studies on the effect of non-surgical video games showing improvement in the performance of surgeons [88, 89]. Serious Games is another emerging field that provides a platform for effective learning with an appropriate blend of learning and entertainment [90]. Though serious games are being reported for surgical skills training [53], they are not yet developed for neuroendoscopy applications. We agree with Cobb et al. [87] that there is a possibility of exploring the integration of direct simulation methods like virtual simulators and indirect simulation methods like Web-based surgical games to provide a useful and practical solution to facilitate neurosurgical learning.

Conclusion

The neuroendoscopy is being widely accepted in the neurosurgery community for certain surgical procedures like third ventriculostomy and endonasal transsphenoidal approach. There are various training systems developed for these surgical techniques from various institutes that include physical, virtual, and high-fidelity cadaver simulations. The virtual reality simulators developed provide objective assessment of technical skills with the help of internal metric and provides a safe and repeatable training environment. The study showed that validation studies on endoscopic third ventriculostomy did not include any objective assessment scale and only one case of validation was reported using subjective questionnaire. The validation studies found for endonasal virtual simulators are mostly face, content, and construct validity. Also, even after the validation studies, virtual simulators are not widely used in the curriculum for training neurosurgeons. High fidelity expensive virtual simulators provide physical resemblance to the surgical site but do not provide evidence on hands-on and technical skills improvement in comparison to box-trainers or cadaveric dissections. Medical and technological institutions should actively collaborate to create standardized simulation-based training methods with its proper analysis on appropriate intervention to the educational curriculum and facilitate multi-centric validation for the virtual simulators. With emerging technologies, validation studies should be conducted to establish the usefulness of the virtual reality simulators alongside the gold standard teaching modalities without bias and explore the chances of blending it with indirect simulation applications.

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