Title: Continuous Instrument Tracking in a Cerebral Corticectomy Ex Vivo Calf Brain Simulation Model: Face and Content Validation

Abdulrahman Almansouri, MB.BCh

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Abstract

Introduction

Subpial corticectomy involving complete lesion resection while preserving pial membranes and avoiding injury to adjacent normal tissues is an essential bimanual task necessary for neurosurgical trainees to master. We sought to develop an ex vivo calf brain corticectomy simulation model that enables assessment of continuous surgical instrument movement during the simulation, carried out a case series study of skilled participants to assess face and content validity to gain insights on the utility of this training platform, along with determining if skilled and less skilled participants had statistical differences in validity assessment.

Hypothesis

The ex vivo calf brain simulation model will reach face and content validity.

Objective

To assess the face, content validity and comparing the assessment of face and content validation between two groups: A-skilled and B-less skilled.

Methods

An ex vivo calf brain simulation model was developed in which participants performed a subpial corticectomy of three defined areas. Surgical movements were continuously captured via optical cameras that track fiducial markers attached to surgical instruments. A case-series study assessed face and content validity of the model using 7-point Likert scale questionnaires.

Results

Twelve skilled and eleven less skilled participants were included in this study. Overall median score of 6.0 (range 4.0-6.0) was determined for face validity and median score of 6.0 (range 3.5-7.0) for content validity on 7-point Likert scale, with no statistical differences between skilled

and less skilled groups were identified. The simulation model created captures continuous instrument movement and allowed the generation of several single and bimanual instrument movement metrics focused on safety, efficiency, and bimanual dexterity.

Conclusion

A novel ex vivo calf brain simulator was developed to replicate the subpial resection procedure. The model demonstrates face and content validity and may have utility in neurosurgical education involving brain operative procedures.

Le Résumé

Introduction

La corticectomie sous-piale impliquant une résection complète de la lésion tout en préservant les membranes piales et en évitant de blesser les tissus normaux adjacents est une tâche bimanuelle essentielle que les stagiaires en neurochirurgie doivent maîtriser. Nous avons cherché à développer un modèle de simulation de corticectomie du cerveau du veau ex vivo qui permet l'évaluation du mouvement continu des instruments chirurgicaux pendant la simulation, réalisé une étude de série de cas de participants qualifiés pour évaluer la validité du visage et du contenu afin de mieux comprendre l'utilité de cette plate-forme de formation, en plus de déterminer si les participants qualifiés et moins qualifiés présentaient des différences statistiques dans l'évaluation de la validité.

Hypothèse

Le modèle de simulation de cerveau de veau ex vivo atteindra la validité apparente et de contenu.

Objectif

Évaluer le visage, la validité du contenu et comparer l'évaluation du visage et du contenu entre deux groupes : A-qualifiés et B-moins qualifiés.

Méthodes

Un modèle de simulation de cerveau de veau ex vivo a été développé dans lequel les participants ont effectué une corticectomie sous-piale de trois zones définies. Les mouvements chirurgicaux ont été capturés en continu via des caméras optiques qui suivent les marqueurs repères attachés aux instruments chirurgicaux. Une étude de séries de cas a évalué la validité apparente et de contenu du modèle à l'aide de questionnaires à l'échelle de Likert en 7 points.

Résultats

Douze participants qualifiés et onze moins qualifiés ont été inclus dans cette étude. Un score médian global de 6,0 (intervalle de 4,0 à 6,0) a été déterminé pour la validité apparente et un score médian de 6,0 (intervalle de 3,5 à 7,0) pour la validité du contenu sur l'échelle de Likert à 7 points, sans aucune différence statistique entre les groupes qualifiés et moins qualifiés. Le modèle de simulation créé capture le mouvement continu des instruments et a permis la génération de plusieurs mesures de mouvement d'instruments simples et bimanuels axées sur la sécurité, l'efficacité et la dextérité bimanuelle.

Conclusion

Un nouveau simulateur de cerveau de veau ex vivo a été développé pour reproduire la procédure de résection sous-piale. Le modèle démontre une validité apparente et de contenu et peut avoir une utilité dans l'éducation neurochirurgicale impliquant des procédures chirurgicales cérébrales.

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Preface and Author Contributions

This thesis is an original work by the candidate, and it is structured in a manuscript-based format. The manuscript of the study has been submitted to the journal Operative Neurosurgery for review.

All authors provided significant contributions to this work. The following is a description of each author's contribution:

Abdulrahman Almansouri: Led this study and contributed to all aspects of this project. This includes conceptualization, methodology, formal analysis, investigation, and writing. Also, recruiting participants and creating the simulated scenarios.

Nour Abou Hamdan: Contributed to conceptualization and methodology. This included participant recruitment, creating simulated scenarios, data collection, formal analysis, and resources.

Dr.Recai Yilmaz: Conceptualization, methodology, validation, formal analysis, data Curation, writing - original draft, writing – review & editing, visualization, funding acquisition.

Puja Pachchigar, Mohammadreza Eskandari, and Joshua Bierbrier contributed to instrument calibration, software management and data recording, writing – review & editing.

Trisha Tee, Chinyelum Agu, Bianca Giglio and Neevya Balasubramaniam contributed to project creation, methodology, resources, and manuscript review.

Dr.Houssem-Eddine Gueziri: Contributed to building the instrument tracking system, software design and management. Also, project methodology, investigation, resources, writing – review & editing.

Dr.Louis Collins: Contributed to supervision and management of instrument tracking system. Project methodology, implementation, writing – review & editing.

Dr.Rolando F. Del Maestro: Contributed to project creation, conceptualization, methodology, resources, and investigation. Also, project funding, guidance, and supervision of this research, interpreting results, writing - original draft and writing – review & editing.

Abbreviations

2D: Two-Dimensional

3D: Three-Dimensional

AI: Artificial Intelligence

AR: Augmented Reality

CBME: Competency Based Medical Education

EVBMASE: “Ex Vivo Brain Model to Assess Surgical Expertise”

FLS: Fundamentals of Laparoscopic Surgery

ICEMS: Intelligent Continuous Expertise Monitoring System

OR: Operating Room

PGY: Post-graduate Year

PLA: Polylactic Acid

SD: Standard Deviation

VOA: Virtual Operative Assistant

VR: Virtual Reality

Thesis Introduction

Surgical education takes place at the post-graduate level following formal medical certification. This is an evolving field that aims at teaching the craft of surgery and delivering the best possible outcome to patients.[1] Healthcare is an ever-evolving field that continues to advance as progress in made in research discoveries. Surgical training has traditionally been an apprenticeship where technical skill acquisition was opportunistic rather than formal.[2] The bulk of learning this craft occurs in the operating room on real patients, this has been the learning paradigm that all surgical trainees are exposed to during their residency.[1] Mitigation of error depends on individual trainee's awareness of their own knowledge and skill level as well as supervision by the surgeon educator. Certification in surgery relies heavily on a qualitative knowledge construct rather than quantitative technical skill assessments. Recent changes in healthcare such as work hour restriction, improved standards of care and litigation in healthcare resulted in restructuring post-graduate training into a competency-based framework.[2–4] Adapting to this shift, simulation has been introduced in healthcare and deemed effective in improving skill level.[2,5,6] Simulation is a broad term that includes both technical and non-technical skill education on various platforms: cadaveric, animal, mannequin, ex vivo, virtual reality (VR), and augmented reality (AR).[7,8] Surgical simulators focus on creating high fidelity tasks that recreate real surgical scenarios.[2] This thesis describes an ex vivo simulation model that aims to replicate an important technical skill in neurosurgery.

Background

Evolution of Neurological Surgery

Neurosurgery is an ever-growing field that witnessed revolutionary discoveries over the years.[9,10] Introduction of the operative microscope allowed neurosurgeons to push boundaries and expanding capabilities while operating on wide range of pathologies.[11,12] This visual enhancement allowed improved precision to reach delicate structures and deep-seated pathologies within the brain. Endoscopic, exoscopic, and endovascular procedures each with its unique learning curve are commonplace in neurosurgical practice.[12] Moreover, the field of spinal neurosurgery underwent tremendous advancements in surgical techniques over the last decade.[13] Improvements in open surgical techniques, introduction of microscopic and endoscopic surgical decompression and fixation opened wide avenues in minimally invasive spine neurosurgery.[13,14] Such complexity is not only associated with an advanced skill level but also thorough enhanced understanding of surgical anatomy when working through small surgical corridors.[15] This raised the type and complexity of the technical skills required in preforming complex operations as well as improved focus on meticulous planning required prior to each surgery. Improved patient outcomes including a decrease in surgical morbidity and mortality are a byproduct of this revolutionary change.[16] Advancing each neurosurgical subspeciality with the aid of complex technology is not without impact on the learning curve during neurosurgical residency training. Achieving competencies in all aspects of training may not be possible given the opportunistic nature of surgical cases and limited opportunities to grasp and practice bimanual skills during real life scenarios.[17] In fact, dissatisfaction among neurosurgical residents has been reported related to mastering operative skills during structured clinical training.[18,19] Objective assessment of technical skills rather than heavily relying on written assessments towards the end of training are currently implemented through competency-based medical education (CBME).[3,4,20] Simulation based training is another avenue that is currently being explored to assess its efficacy in training neurosurgical residents.[21–27]

The Subpial Resection Technique

Topographically, human brains consist of gyri and sulci. Underlying the skull bone are three membranes that protect the brain: dura, arachnoid and pia.[28] The pial membrane is most fragile and is the only covering that is completely attached to the brain and follows this topographical arrangement to the limits. Blood vessels responsible for delivering oxygen and removing waste from the brain travel in the subarachnoid space; above the pia and below the arachnoid membrane.[28] One of the bimanual skills that requires mastering in neurosurgery, is subpial resection "resecting cortex under the pia". Described first in the field of epilepsy surgery, Dr. Wilder Penfield performed operations focusing on resecting epileptogenic foci while preventing vascular injury and damage to normal brain through pial preservation.[28–30] This operative procedure resulted in increased freedom from seizures.[28] Performing this technique is common in epilepsy and brain tumor operative procedures. This approach aids in maximal resection while minimizing injury through preservation of adjacent brain tissue and blood vessels. The most common instruments used in performing this technique are the bipolar cautery forceps and an aspirating instrument.[28] These corticectomy resections continue in a stepwise fashion until reaching the pial boundary.[28] Incomplete or suboptimal tissue left on the pial boundary, pose the risk of future seizures as this scarred tissue can irritate the brain resulting in abnormal electrical activity.[28] Moreover, inadvertently damaging the vessels running in the sulci above the pia can result in bleeding or vessel thrombosis that subsequently induces an infarction in the respective parenchyma supplied by these vessels. In brain tumor surgery, extent of resection has been shown to offer a survival benefit [31], especially when no new neurological deficits are induced after the surgery. This is often referred to as supramarginal or supratotal resection, where normal anatomical boundaries define the limit of surgical resection. Neurological deficits induced after surgery can be transient or permanent.[32] Deficits from tissue swelling rather than vascular injury can be fully or partially reversible with appropriate rehabilitation.[32]

Simulation in Surgical Education

Simulation in healthcare has been proven to benefit skill acquisition as well as to reduce surgical adverse events.[8,33–35] With the evolving educational models and better understanding of learning curves, simulation continues to receive wide acceptance among different surgical disciplines.[36] In general surgery for example, fundamental laparoscopic skills can be practiced on the Fundamentals of Laparoscopic Surgery (FLS) box. In the United States, this simulator has been officially introduced to assess residents' performance.[33] One of the main advantages of simulation, is having the luxury of unlimited task repetition in a patient free risk environment.[34] Traditionally, human cadavers and animals were the only available models to study anatomy and practice surgical procedures.[8] With advancements in technology, VR and AR models have been developed.[37] Computer based simulators can recreate surgical fields with accurate anatomy, offer unlimited task repetition, improve hand-eye coordination and offer the ability of having a built-in instructor. As well as they can generate performance metrics which can improve the understanding of manual dexterity.[35] However, these models can lack the overall real operative environment, utilization of real surgical instruments and more importantly have low tissue fidelity. Simulation based training can allow for the creation of a structured curriculum that teaches technical skills and this can progress from simple tasks such as surgical exposure and closure to performing critical parts of the operation. During real life scenarios case complexity cannot always be anticipated and the learning process depends on case complexity. This may limit the gradual development of technical skills that relates to an appropriate level of expertise needed to perform complex operative procedures. Much time can be spent in the operating room to learn how to use surgical instruments and equipment familiarization and this aspect can be accelerated through simulation.[6] This form of rehearsal is not limited to technical skills only but applies to non-technical skills as well. Simulation can improve teamwork dynamic and ability to perform coherently under stressful situations.[5] While simulation has revolutionized surgical education, it is essential to recognize that it complements rather than replaces traditional clinical training.

Simulation in Neurosurgery and Ex Vivo Models

In recent years numerous simulators have been proposed to replicate essential neurosurgical skills.[24,38–45] Various platforms have been utilized including, VR, AR, Ex vivo, Cadaver and 3D printed models. One of the earliest high fidelity VR simulators developed is the NeuroTouch[46], a computer-based platform with the potential of creating a wide variety of surgical scenarios. This simulator used real brain tumor density tissue parameters and accurate anatomy to replicate a brain tumor resection task.[46–48] One of the advantages of this system was development and quantitative assessment of novel instrument movement metrics which improved understanding and the granularity of expertise classification.[49] Furthermore, utilizing Artificial Intelligence (AI) algorithms allowed the continuous objective skill assessment and training by this simulator.[21,50] Virtual reality simulators in spinal neurosurgical procedures have been validated.[43] These simulated tasks included anterior cervical discectomy and fusion procedures, where the model was found to possess face, content, and construct validity.[43] However, limitations of VR simulators include the lack of realistic operative environment, lack of real surgical instruments and visual realism does not completely create an immersive operative experience.[51,52]

Placenta models have been utilized in recreating brain tumor resections, aneurysm clipping and vascular anastomosis.[53–55] However, placentas are not readily available and pose a supply challenge when needed for everyday training. In cerebrovascular neurosurgery, with the improved ability of minimally invasive endovascular techniques, open surgical clipping is not as common, however, continuity in training such skills is imperative, as a subset of cases still require open surgical interventions. This has resulted in the need to develop realistic models for aneurysm clipping, Belygh et al[44] described a novel simulator for clipping anterior, middle, and basilar artery aneurysms models utilizing turkey arteries. This model lacked the ability of replicating microdissection and controlling hemostasis.[44] Ex vivo calf brain simulation models were described in simulating brain tumor resection scenarios with or without 3D printed human skull replicas and AR technology.[41,42,56,57] Injected alginate or gelatin-based materials into the brain was feasible in simulating a mass lesion that is distinguishable from normal parenchyma.[57] However, the challenge with such scenarios was the lack of realistic brain-tumor interface.[45] Low cost and availability of calf brains make them attractive to be used in neurosurgical simulation.[57] These brains have been shown to share similarity with the overall human brain, in terms of sulci and gyri as well the presence of intact pial membrane.[56,58]

Surgical Instruments Tracking

Virtual reality simulations demonstrated the ability of instrument tracking and recording operative performance.[49,59] This improved our understanding of surgical expertise based on quantifiable performance metrics.[48,49] Furthermore, certain metrics such as instrument tip separation distance and bipolar cautery force application were shown to be superior than other performance metrics.[60] With the aid of artificial intelligence, computer based tutoring systems that monitor performance, mitigate error and provide feedback during an operation have been developed.[21,50] Translating this technology to real operative environments utilizing surgical instruments used in clinical practice has been demonstrated.[57]

Simulator Validation

When simulators are developed, they must undergo a series of validation steps to assess their utility.[52] This is a critical step ensuring accuracy and functional capacity in simulating the intended task. Also, it contributes to the simulator's credibility and reliability in generating valid results. Three main validation metrics used in the initial process are: face, content, and construct validation.[43,44,51–53,55] Each metric tests the simulator's ability in representing what the tool was intended to simulate. Face validation is a qualitative assessment by experts to determine whether the simulator shares visual and tactile realism with real-world operations it aims to recreate. However, it is not known if expert validation differs significantly from that of senior residents and fellows who are learning the techniques on ex vivo models. During face validation, the simulator is assessed based on visual and sensory realism, overall simulated environment, tools, and user interface. Content validation assesses simulator ability to train and reproduce tasks meeting the educational objectives. This involves comprehensive evaluation of training components, such as ability to train bimanual skills, hand-eye coordination, appropriateness with respect to level of training and utilization of surgical equipment. Both face and content validation steps are imperative in determining whether a simulator can move forward and utilize resources to further develop the system. Data for face and content validation can be gathered in the form of questionnaires, direct feedback, or formal interviews. The 7-point Likert scale has been commonly used for this validation process.[43,61] Given the heterogeneity in reporting, currently no current consensus exists, however, median score of 4 or more on 7-point Likert scale has been accepted previously to satisfy face and content validations.[43,51] Other aspects of validation, such as construct validation which involves assessing the simulator's ability to differentiate between different levels of performance, can be carried out once face and content validity are satisfied. Finally, predicative validity is the ability to determine future performance accurately based on simulation metrics. This type of validation requires prolonged assessment following implementation of this education tool.[52,61]

Thesis Rationale, Hypotheses and Objectives

Rationale

Developing a hybrid high fidelity model that can replicate subpial resections would be an important addition to task specific neurosurgery simulators. Ex vivo simulators are valuable with respect to visual appearance and tactile feedback in representing real tissues compared with VR simulators. Furthermore, ex vivo simulations can take place in a simulated operating room (OR) environment utilizing real surgical instruments. This model can potentially serve as bridge between VR, AR simulators and real surgical operations. Gathering performance metrics from VR simulators showed significant difference in performance across different levels of expertise.[48,49] This knowledge was further used to establish expert benchmarks and create VR intelligent tutor platforms powered by AI technology including the Virtual Operative Assistant (VOA) and the Intelligent continuous Expertise Monitoring System (ICEMS) that continuously assess and guide performance, predict, and mitigate error.[21,50] These educational and training components of surgical performance do not exist during real operations, as surgical instruments do not gather any form of performance data. Transitioning this technology to a simulated operating room and testing performance data on real surgical instruments would be an important step towards having intelligent surgical instruments that detect performance and mitigate error. The first step of this project is to create a simulated ex vivo operative environment and test its resemblance to real-world systems through face and content validation.

Hypotheses

The ex vivo calf brain simulation model will have face and content validity in simulating the subpial resection technique. There will be no significant statistical difference in these two validation steps when comparing two participant groups: A. Expert neurosurgeons and neurosurgical fellows in subspecialities focusing on mastering this skill and B. Neurosurgical fellows in other neurosurgical subspecialities and senior neurosurgical residents.

Objectives

1) To assess face and content validity for the ex vivo calf brain subpial resection model.

2) To outline quantitative methodology to assess instrument movement during performance of the subpial resection in a realistic operative environment.

3) To demonstrate if significant differences in face and content validity between skilled and less skilled participants are present.

Manuscript

Title: Continuous Instrument Tracking in a Cerebral Corticectomy Ex Vivo Calf Brain Simulation Model: Face and Content Validation

Abdulrahman Almansouri, MB.BCh[1,2*], Nour Abou Hamdan, MSc[1*], Recai Yilmaz, MD[1], Trisha Tee, BSc[1], Puja Pachchigar, MSc[1], Mohammadreza Eskandari, MEng[3], Chinyelum Agu, MEng[1], Bianca Giglio, BSc[1], Neevya Balasubramaniam[1], Joshua Bierbrier, MEng[3], D.Louis Collins, PhD[2,3], Houssem-Eddine Gueziri, PhD[2,3], Rolando F. Del Maestro, MD, PhD[1,2]

Affiliations

[1] Neurosurgical Simulation and Artificial Intelligence Learning Centre, Department of Neurology & Neurosurgery, Montreal Neurological Institute, McGill University, 300 Rue Léo Pariseau, Suite 2210, Montreal, Quebec, Canada, H2X 4B3.

[2] Department of Neurology and Neurosurgery, Montreal Neurological Institute and Hospital, McGill University, 3801 Rue University, Montreal, Quebec, Canada, H3A 2B4.

[3] Neuro Imaging and Surgical Technologies Laboratory, Department of Biomedical Engineering, McConnell Brain Imaging Centre, Montreal Neurological Institute, McGill University, 3801 Rue University, Montreal, Quebec, Canada, H3A 2B4.

*Abdulrahman Almansouri, MB,BCh and Nour Abou Hamdan, MSc are co-first authors.

*** Corresponding Author**

Abdulrahman Almansouri, MB,BCh

Neurosurgical Simulation and Artificial Intelligence Learning Centre,

Department of Neurology and Neurosurgery,

Montreal Neurological Institute and Hospital,

300 Rue Léo Pariseau, Suite 2210, Montreal, Quebec, Canada, H2X 4B3.

E-mail: abdulrahman.almansouri@mail.mcgill.ca

Data availability statement. The dataset collected during the study is available on a reasonable request from the corresponding author.

Abstract

Background and Objectives

Subpial corticectomy involving complete lesion resection while preserving pial membranes and avoiding injury to adjacent normal tissues is an essential bimanual task necessary for neurosurgical trainees to master. We sought to develop an ex vivo calf brain corticectomy simulation model with continuous assessment of surgical instrument movement during the simulation. A case-series study of skilled participants was carried out to assess face and content validity to gain insights on the utility of this training platform, along with determining if skilled and less skilled participants had statistical differences in validity assessment.

Methods

An ex vivo calf brain simulation model was developed in which trainees performed a subpial corticectomy of three defined areas. Surgical movements were continuously captured via optical cameras that track fiducial markers attached to surgical instruments. A case-series study assessed face and content validity of the model using 7-point Likert scale questionnaires.

Results

Twelve skilled and eleven less skilled participants were included in this investigation. Overall median scores of 6.0 (range 4.0-6.0) were determined for face validity, 6.0 (range 3.5-7.0) for content validity on 7-point Likert scale, with no statistical differences between skilled and less skilled groups identified. The simulation model created captures continuous instrument movement

and allows the generation of several single and bimanual instrument movement metrics focused on safety, efficiency, and bimanual dexterity.

Conclusion

A novel ex vivo calf brain simulator was developed to replicate the subpial resection procedure and demonstrated face and content validity. Continuous tracking of real surgical instruments and the generation of performance metrics has been outlined which may have utility in neurosurgical training involving brain operative procedures.

Running Title: Ex Vivo Subpial Resection Validation.

Keywords: Continuous Instrument Tracking, Corticectomy, Ex Vivo Models, Neurosurgical Simulation Training, Subpial Resection, Surgical Education, Validation Studies.

Abbreviations

3D: 3-Dimensional

2D: 2-Dimensional

AI: Artificial Intelligence

EVBMASE: "Ex Vivo Brain Model to Assess Surgical Expertise"

PGY: Post-Graduate Year

PLA: Polylactic Acid

VR: Virtual Reality

VOA: Virtual Operative Assistant

ICEMS: Intelligent Continuous Expertise Monitoring System

Introduction

In neurosurgery, a corticectomy technique called subpial resection is a critical bimanual skill for trainees to learn. This procedure involves the resection of a pathological lesion while preserving the pia and minimizing damage to surrounding tissue.[28,62,63] Neurosurgical simulation training is not presently an educational component of core curricula which limits the training opportunities for residents to acquire subpial resection technical skills. Surgical training is evolving from an apprenticeship model to more competency-based educational frameworks.[3,8] These frameworks must have assessment capacity based on quantifiable objective metrics and be transparent to both the educator and the trainee.[21,50] To create safe learning and training environments, surgical simulators are being used to simulate complex patient operative pathologies in risk-free environments.[22] Data from virtual reality (VR) simulator platforms have demonstrated improved trainee surgical performance and intelligent tutors powered by artificial intelligence (AI) have been validated. These systems can continuously assess surgical skills by tracking instrument movement, deliver tailored feedback to improve skills, and mitigate errors in simulated complex procedures.[21,50,64,65] One limitation in using VR simulators is the lack of realistic haptic feedback since these platforms do not utilize the actual surgical instruments employed during human operative procedures. Prior research at our centre has outlined the creation of ex vivo calf brain simulation models and demonstrated the ability to continuously track surgical instruments.[57] Our group has also developed best practices for the utilization of ex vivo simulation models for neurosurgical training called the “ex vivo brain model to assess surgical expertise” (EVBMASE) checklist.[51] To address the challenges in training neurosurgical residents for corticectomy procedures, we sought to develop a simulation model that combines the advantages of the realism of ex vivo models while integrating innovative continuous movement tracking technologies. The objectives of this study were to: 1) assess face and content validity for the ex vivo calf brain subpial resection model, 2) outline quantitative methodology to assess instrument movement during performance of the subpial resection in a realistic operative environment, and 3) investigate if significant differences in face and content validity between skilled and less skilled participants are present.

Methods

Study Design

A case-series study was carried out to assess the ex vivo calf brain model's face and content validity. Participants were divided into two groups: Group A "skilled" and Group B "less skilled". Skilled participants were board-certified neurosurgeons, and epilepsy, neurosurgical oncology, and pediatric neurosurgery fellows. Less skilled participants were senior neurosurgery residents and fellows in other neurosurgical subspecialties. This study was approved by the McGill University Health Centre Research Ethics Board, Neurosciences-Psychiatry. All participants signed an informed consent form before trial participation. Participants outlined their subpial technique experience before the trial and assessed the utility of the ex vivo calf brain simulated surgery model through a questionnaire administered upon trial completion. They were asked to rate their satisfaction with the model using a 7-point Likert scale, with 1 being completely unrealistic and 7 being completely realistic. As no previous consensus on a median score for face and content validity has been reached,[7] a median score ≥ 4.0 on a 7-point Likert scale was deemed sufficient validity.[43,51]

Ex Vivo Animal Brain

Calf brains were employed in this study because of their morphological similarity to the human pediatric brain, availability, low cost,[51,57,58] and utility for training microsurgical techniques.[41,42,56]

Fresh calf brains of similar weight, structure, and well-defined gyri were obtained from a local butcher (Figure 1, 1A). Calf brains were positioned in a human skull model (Walter Products, Plymouth, Michigan, USA) within a craniotomy window created off midline (Figure 1, 1B). Our studies utilized the EVBMASE checklist[51] for ex vivo brain simulation development and assessment.

Subpial Resections

Participants received standardized verbal and written instructions on instrument use and function and presented with a 2D microscopic image outlining the location of the 3 subpial resections to be performed (Figure 2, 2A and 2C). In a realistic operative room environment, the subpial cortical resections were performed using a pair of micro-scissors to make an initial incision in the pia mater, a bipolar forceps to lift the pia, and a SONOPET ultrasonic aspirator (Stryker, Kalamazoo, Michigan, USA) to remove the assigned cortical area (Figure 1, 1C and 1D). Neurosurgical operations were performed using an OPMI Pico surgical microscope (Carl Zeiss Co., Oberkochen, Germany).

Capturing Continuous Instrument Movement

Research from our group illustrated the value of VR continuously tracked instrument movement data in quantifying important metrics and objectively classifying skill level.[21,48–50,64] We sought to develop a similar quantitative real surgical instrument tracking platform.[21,48,50,57] Each surgical instrument was attached to a customized 3D-printed polylactic acid (PLA) mount,[57] with attached fiducial markers (Northern Digital Inc., Waterloo, Ontario, Canada). The three instruments were tracked via two optical tracking cameras [FusionTrack 500, Atracsys LLC, Puidoux, Switzerland] and two backup cameras [Polaris, Northern Digital Inc., Waterloo, Ontario, Canada] (Figure 1, 1E). Tracking is achieved through infrared light reflecting on the instrument fiducial markers allowing three-dimensional localization. Instrument calibration is required for each participant prior to surgical resection to ensure accurate tracking. Data output from the tracking was recorded in the 3D Slicer environment[66] (version 5.0.3, https://www.slicer.org/). Raw instrument data included (1) 3D instrument tip position data (X, Y, Z), (2) angulation of the instrument (W_x, W_y, W_z), (3) rotation of the instruments, and (4) timestamp (T). This allows the generation of single-instrument and bimanual instrument metrics. Procedures were recorded through the operating microscope and a facing camera, allowing a broader instrument view for evaluation of tracking data and post-operative performance. Instruments tracking results are beyond the scope of this paper and analysis is underway to assess the tracking data utility. Microscopic video is provided to help appreciate the subpial resection in the calf brain model (Video 1 and Figure 2, 2B).

Single-instrument Metrics

The isolated assessment of each single instrument performance can be measured. Eight metrics can be generated and below is a description of each:

1. Instrument Location (IL): For a point in time t, the instrument tip coordinates were recorded in millimeters (mm) in three dimensions: X_t, Y_t, and Z_t.
2. Instrument Velocity (IV): Instrument 3D velocity between two successive time points t and t+1 (mm/s)

$$IV_t = \frac{\sqrt{\left(X_t - X_{(t-1)}\right)^2 + \left(Y_t - Y_{(t-1)}\right)^2 + \left(Z_t - Z_{(t-1)}\right)^2}}{\left(T_t - T_{(t-1)}\right)^2}$$

3. Instrument Acceleration (IA): This metric stems from velocity. Measured in mm/s^2 between time t and t+2 was obtained as:

$$IA_t = \frac{IV_t - IV_{(t-1)}}{T_t - T_{(t-1)}}$$

4. Instrument Total Tip Path Length (ITTPL): The total length of the path traversed by the tip of the instrument tool measured in millimeters (mm). This metric can allow the measurement of efficiency in tool usage during the resection. Instrument total tip path length is the summation of changes in position in time (velocity) during the entire procedure:

$$ITTPL = \sum_t \sqrt{\left(X_t - X_{(t-1)}\right)^2 + \left(Y_t - Y_{(t-1)}\right)^2 + \left(Z_t - Z_{(t-1)}\right)^2}$$

5. Total Time of Instrument Use (TTIU): The time of instruments usage throughout the procedure labeled on video recordings.

$$TTIU = \sum_{t \in \{labels\}} \left(T_t - T_{(t-1)}\right)$$

6. Pedal Activation Frequency (PAF): This is calculated from the audio recordings during the procedure. This metric allows the assessment of efficiency in aspirator use.
7. Pedal Activation Time (PAT): This metric is calculated from the audio recordings during the procedure.
8. Efficiency Index (EI): Defined as the amount of time ultrasonic aspirator was actively used for the resection (TTIU) divided by total time of the task.

Bimanual Metrics

Bimanual metrics can be developed after analyzing individual instrument metrics. These metrics were designed to evaluate complex psychomotor and cognitive bimanual neurosurgical skills:

1. Instrument Tip Average Separation Distance (ITASD): Defined as the average distance (in millimeters) between the tip of the ultrasonic aspirator used in the dominant hand and the tip of the bipolar used in the non-dominant hand. This allows assessment of bimanual

movement during the procedure. ITASD is calculated based on the difference of X, Y, Z coordinates between instrument A (ultrasonic aspirator) and instrument B (bipolar):

$$ITASD = \sqrt{(X_A - X_B)^2 + (Y_A - Y_B)^2 + (Z_A - Z_B)^2}$$

2. Coordination Index (CI): Defined as the amount of time ultrasonic aspirator and bipolar are used simultaneously divided by the time ultrasonic aspirator was used during the procedure. This metric measures the quality of bimanual interaction during the subpial resection where a high score indicates supporting of the aspirator with bipolar in the non-dominant hand more efficiently. For a total time of both instrument use T_{AB} and total time of only aspirator use T_A, the coordination index is calculated by the equation: $CI = T_{AB}/T_A$.

Statistical Analysis

IBM SPSS statistical software was used for data analysis (IBM Corp. Released 2021. IBM SPSS Statistics for Macintosh, Version 28.0. Armonk, NY: IBM Corp). Non-parametric Mann-Whitney U tests ware used for comparisons between groups.

Results

Twenty-three participants were enrolled, 12 Group A "skilled" along with 11 Group B "less skilled". Participant demographic and subpial resection data can been seen in Table 1. Sixty-nine simulated subpial resection scenarios were created, where each participant performed three different resections.

Model Validation

Face Validity

Face validation was based on eleven items as outlined in Table 2. These included:

<u>Overall simulated task:</u>

Participants in both groups found the overall operative setup realistic ((skilled: median 6.0, (range 3.0 – 7.0); less skilled: median 5.0 (range 1.0 – 7.0)) (P=0.83). Appearance and tactile feedback of the simulated tissue was realistic (skilled: median 6.0, (range 3.0 – 7.0); less skilled: median 6.0, (range 2.0 – 7.0)) (P=0.52).

<u>Visual and sensory realism:</u>

Sensory realism of simulated pia rated median 6.0 (range 3.0-7.0) and median 6.0 (range 1.0-7.0) among skilled and less skilled respectively (P=0.78). The visual realism of simulated pia also was found to be realistic (skilled: median 6.0 (range 4.0-7.0); less skilled: median 6.0 (range 3.0-7.0)) (P=1.0).

<u>Surgical Instruments:</u>

Related to the use of surgical instruments, ultrasound aspirator achieved the highest median score of 6.0 in both groups (range 4.0-7.0) (P=0.74).

Content Validity

Content validation was based on ten items as outlined in Table 3. These included:

<u>Coordination and bimanual training:</u>

Skilled participants assigned a median score of 6.0 (range 3.0-7.0) in task's ability to train hand-eye coordination as well as bimanual training versus median 6.0 (range 1.0-7.0) in less skilled group (P=0.88).

<u>Surgical Instruments:</u>

With respect to surgical instruments, in both groups, content validity was achieved for micro-scissors (skilled; median 4.0 (range 2.0-6.0), less skilled; median 6.0 (range 1.0-7.0)) (P=0.09) and ultrasonic aspirator (skilled; median 6.0 (range 4.0-7.0), less skilled; median 7.0 (range 2.0-7.0)) (P=0.69). Bipolar forceps did not reach content validity in skilled group (median 3.5 (range 2.0-

6.0)) versus less skilled; median 5.0 (range 1.0-7.0)) (P=0.19). This may have been due to inability to use the bipolar for coagulating tissues as the simulator lacked perfusion and the bipolar was not connected to the electrosurgical unit.

Subpial resection training and utility for trainees:

This simulated task was seen as highly appropriate in replicating and practicing subpial resections (skilled; median 6.0 (range 1.0-7.0), less skilled; median 7.0 (range 2.0-7.0)) (P=0.69). Both groups approved the overall task usefulness in training residents (skilled; median 7.0 (range 2.0-7.0), less skilled; median 7.0 (range 2.0-7.0)) (P=0.83). This was considered most useful during junior years of residency training (PGY1-3) (skilled; median 7.0 (range 4.0-7.0), less skilled; median 7.0 (range 1.0-7.0)) (P=0.69).

Overall Task Difficulty and Satisfaction

The task had a low difficulty level (median 3.0, range 1.0-6.0) among both groups. Eighteen participants (78.3%, median ≥ 4) would use this simulator to practice subpial resections (skilled; median 6.0, range 1.0-7.0, less skilled; median 7.0, range 1.0-7.0). Overall satisfaction with the simulator had a median score of 6.0 (range 2.0-7.0). Seventy-five percent (9/12) of the skilled along with 90% (10/11) of less skilled responded 'yes' to recommending the integration of simulation training into the curriculum during the neurosurgery training program as a mandatory block.

Discussion

A high-fidelity ex vivo corticectomy model replicating the subpial resection technique has been developed and this investigation has outlined face and content validity of this platform. This justifies investment in assessing construct validity, the incorporation of AI-powered tutor platforms, and studies to demonstrate the utility of ex vivo models into residency training curriculums. Calf brains have consistent anatomy including intact pia, presence of cortical grey and subcortical white matter fibers and provide an excellent model to assess and train subpial resection bimanual skills.

The subpial resection technique, initially described in epilepsy surgery,[29] follows normal anatomical boundaries,[67] allowing safe maximal resection of an epilepsy focus. In brain tumor surgery, the extent of surgical resection is associated with a survival benefit, and subpial techniques are employed when performing wide tumor resections beyond the visible tumor boundary.[31,67] As of 2019, neurosurgery residency programs in Canada incorporated a competency based educational framework. Assessment of specific technical and non-technical skills is carried out by supervising neurosurgeons through entrustable professional activity (EPA) checklists.[4,20] One of the educational platforms available to improve surgical performance and skill level is practicing real life scenarios in simulated settings.[23–25] In one survey of 99 neurosurgery programs, over 70% of program directors stated that simulation could augment traditional training and potentially improve patient outcomes.[68] Simulation platforms include: cadaveric, ex vivo, VR and augmented reality, along with 3D-printed models.[51] Each simulator faces challenges related to reproducibility, realism, cost and availability of objective performance data. Cadaveric simulations possess high fidelity and realistic anatomical representation, yet availability and cost make these models challenging to provide for resident training.[37,69] Printed 3D models lacked the ability to replicate high fidelity neurosurgical dissections.[39,40,70,71] VR and augmented reality simulators are costly and lack realism. However, quantitative data from virtual reality instrument movement can assess skill level.[26,36,49,50]

Neurosurgical simulation models have demonstrated visual and tactile realism, yet many lack the ability to measure performance metrics through instrument tracking.[38,41,51,56,72] The second objective of this study was to outline quantitative methodology to assess instrument movement during performance of the subpial resection in a realistic operative environment. Developing the ex vivo calf brain simulator involved 3D-printed mounts on surgical instruments used. The employment of these modified instruments did not significantly detract from face or content validity. These results demonstrate the feasibility in continuous tracking of real surgical instruments and the possibility of generating further performance metrics that may differentiate levels of expertise utilizing various ex vivo model simulation platforms (construct validity). This study describes a series of quantitative metrics which can be utilized in other ex vivo calf brain studies including neurosurgical procedures like temporal, frontal and occipital lobectomy, corpus callosotomy along with the disconnection procedures involved in hemispherectomy.

The third objective of this study was to outline if statistically significant differences in face and content validity were present between skilled and less skilled participants, and none were identified. These results suggest that when dealing with small expert groups the inclusion of others such as senior residents and fellows in other specialties may provide valuable input.

The ex vivo simulation model developed in this study may be considered a hybrid model since it provides a realistic reconstruction of a surgical operative environment and provides an educational platform derived from VR instrument tracking for surgical training involving the subpial resection technique. The model has the capability of generating large data sets for training and testing machine learning algorithms. Our group has employed instrument tracking data and AI methodology such as: classifying algorithms, artificial neural networks along with deep learning to understand and prioritize specific novel metrics able to improve the granularity of participants classification based on expertise level.[21,50,59,60,73] Quantitative data from instrument movement tracking from ex vivo models has the potential to be used in outlining surgical trainee learning curves[74] and developing and testing of AI-powered tutoring systems to prevent surgical error like the Virtual Operative Assistant (VOA)[21] and the Intelligent Continuous Expertise Monitoring System (ICEMS) .[50,64,75] The use of calf brains providing high tissue fidelity and realism along with quantitative metrics may enhance trainee engagement and learning while AI tutors encourage focus on safety and efficiency in performing neurosurgical procedures.[76]

The ultimate goal of these projects is the development and testing of equivalent AI-powered tutoring systems in the human operating room to develop an "Intelligent Operating Room" capable of continuous learner assessment, training and mitigating surgical errors.

Limitations

Although the calf brain simulation platform used in this study allows detailed and continuous quantitative assessment of bimanual psychomotor skills, it fails to capture the complete set of competencies such as interdisciplinary teamwork required in neurosurgical procedures. Blood vessels are visible in calf brains, but blood flow and bleeding were not simulated in this model. Some studies have described the use of porcine brains with intact vascular structure where intracranial and capillary blood flow were achieved,[77,78] however these models involve extensive preparation.[79]

Conclusion

A novel hybrid ex vivo calf brain simulation model was developed for this study which achieved face and content validity in simulating the subpial resection technique. Continuous tracking of real surgical instruments and the possibility of generating novel performance metrics has been delineated.

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Thesis Discussion

Neurosurgical training continues to evolve as it shifts from an informal apprenticeship model to competence by design model which stems from competency-based medical education (CBME).[4,80] This educational paradigm incorporates a structured curriculum to the traditional 'time-based' training. Continuous assessments, clear learning objectives, direct observation and feedback and learners' taking responsibility and control over their education are rationales behind adapting this new model.[80,81] Improving surgical outcomes are related to the training of knowledgeable and skilled surgeons. Transfer of skills and knowledge from experts to trainees continues to expand as new techniques and treatment modalities are developed. Complex operations and surgical challenges in neurosurgery require expertise rather than competency alone.[82] Traditionally, surgical experience develops thorough practice, beyond residency training.[82] Simulation has been introduced as a tool to aid surgical training in replicating certain tasks. There are many challenges and unanswered questions when one acquires technical skills from simulators. Realistic replications of surgeries are often incomplete, where certain parts of the operation are often missing such as: decision making, teamwork, and choosing the proper instruments. The ultimate utility of simulation has not been defined since it is not known how technical skills in performing real operations are improved by the utilization of simulation-based training. Other limitations include the difference in metrics assessed in different simulators and costs associated with creating and maintaining high fidelity simulators.[82] However, progress has been made in proving the benefit of simulation in other surgical disciplines such as general surgery. Laparoscopic skills training indeed correlates with operative performance and passing simulated sessions is mandatory.[33,35] Furthermore, performance does improve with repetition and tutoring on VR neurosurgical simulators.[64]

In this project we developed a high-fidelity simulator replicating the subpial resection technique. The first objective of this study has been completed which was the demonstration of face and content validity based on a 7-point Likert rating scale. Other modalities to assess validity such as specific narrative comments or interviews may have also been used. In this study only a general comments section was provided in the questionaries, but this was not analyzed as it did not target specific validity domains. Demonstrating face and content validity is imperative and further justifies investment in developing this simulator to incorporate AI-powered tutors as well as studies to demonstrate the utility of ex vivo models integration into residency training curriculums. Calf brains have consistent anatomy including intact pia, presence of cortical grey and subcortical white matter fibers.[83] Brains are also readily available at local butchers with an approximate cost of 10 Canadian dollars. The model has the potential to replicate neurosurgical procedures such as hemispherectomy and temporal lobectomy. Furthermore, implementing certain criteria can allow a uniform reproducibility of this simulator. This includes employing fresh calf brains rather than frozen brains, standardized operative setting and surgical instruments.

In medical education, simulation has been foundational in clinical skills training. Students learn how to insert intravenous lines, urinary catheters, and simple suturing. The goal is to deliver proper technical skill education in a controlled environment in preparation for the real-life scenario. This also aims at reducing harm to patients.[2] It appears appropriate to further explore methodology and assess this educational modality in post-graduate surgical education. Time constraints and availability of expert surgeons make it challenging to implement formal structured clinical simulations during residency training, one of the obstacles of implementation. However, AI-powered tutor systems that learned from expert benchmarks is one way to address this limitation since this decreases demand on expert surgeons' presence during simulation-based training.[50]

Developing a quantitative approach to assess instrument movement during performance of the subpial resection, in a realistic operative environment, is one methodology to aid in the understanding and teaching of bimanual expertise in neurosurgical procedures. Results from this study outline the feasibility of continuous tracking of real surgical instruments with metric output that detects performance level. The utility of instruments tracking is yet to be determined as construct validity will be an important step in assessing these metrics, but this study outlines a series of quantitative metrics which can be exploited in further studies. Differences in performance metrics at different levels of expertise has been shown when analyzing similar quantitative metrics from VR simulations.[49,50,60] While simulation training is an exciting field that continues to evolve, it does not replace formal learning from skilled surgeons, rather this educational modality is a bridge to practice with intent to refine performance in preparation for real surgical operations. Instrument tacking technology can potentially be applied to all previously described ex vivo simulation models that utilize real surgical instruments.[44,45,53–55] The third objective of this study was to demonstrate if significant differences in face and content validity between skilled and less skilled participants was present during the performance of the ex vivo corticectomy subpial resection model. Assessment of a simulator's face and content validity is traditionally performed by experts, however, we sought to investigate the assessment of individuals who are in their advanced stages of training (senior resident and fellows). No significant differences between the skilled and less skilled participants were identified. These results suggest that when dealing with small expert groups the inclusion of others such as senior residents and fellows in other specialities can also provide valuable input. However, it is currently unknown if these results could change when increasing the sample size.

Limitations

Although the calf brain simulation platform used in this study allows detailed and continuous quantitative assessment of bimanual psychomotor skills, it fails to capture the complete set of competencies, such as interdisciplinary teamwork, required in neurosurgical procedures. One of the other limitations in this model is lack of blood perfusion. Hemostasis is an essential skill all surgeons need to master. However, bleeding is generally not expected during subpial resection, therefore we elected to proceed with model development without brain perfusion. Another limitation is the small sample size. Only twenty-three participants evaluated this model for face and content validity. Ideally a larger sample size would add more power to validation results. Given the relatively smaller number of trainees and neurosurgeons compared to other surgical disciplines, recruiting more participants may be challenging. The simulated task was performed in the standing position, ideally this part of the operation could be performed while sitting on a surgeons' chair with armrests adding more stability to the instruments.

Future Directions

It is well established that capabilities exist in developing various neurosurgical simulators using different modalities. Many of these simulators have been validated including the subpial resection simulated VR scenario on the NeuroVR.[50,84] The next question that needs to be explored is conducting comparisons between simulation-based platforms. For example, it is unclear whether VR or ex vivo models will result in the best performance related to technical skills training in surgical specialties. This can be assessed in randomized controlled trials that assess performance on these different platforms. Randomized controlled trials utilizing medical students have demonstrated the efficacy of the AI-powered virtual reality tutoring systems like the Virtual Operative Assistant (VOA)[21] and Intelligent Continuous Expertise Monitoring System (ICEMS) developed by our group in improving surgical performance.[85] In neurosurgical education, it has not been established whether simulation-based training improves intraoperative skill level. Randomized controlled trials between VR simulator training systems like the ICEMS and simulator training using the ex vivo model outlined in this thesis, utilizing residents, can address this question. These trials are being designed. Ultimately, hybrid operating rooms with intelligent surgical instruments that assess surgical performance will allow the creation of operation specific expert benchmarks and AI-powered training platforms that can continuously monitor performance, tutor, and detect impending surgical errors.

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Appendix

Tables and Figures

Table 1. Demographics of Participants Performing the Simulated Subpial Resection Procedure

	Group A- Skilled	Group B- Less skilled
Number of participants	12	11
Mean age in years (range)	42.7 (32-58)	32.9 (26-39)
Sex		
Female	3 (25%)	3 (27.3%)
Male	9 (75%)	8 (72.7%)
Level of Training		
Neurosurgeons	8	-
Pediatric Neurosurgeon	3	-
Neurosurgical Oncologist	2	-
Skull base/Vascular Neurosurgeon	2	-
Spine Neurosurgeon	1	-
Mean number of years in practice (range)	11.4 (2-27)	-
Mean number of subpial resections performed in practice (median, range)	513 (150, range 20-3000)	-
Neurosurgical Fellows		
Epilepsy	1	-
Oncology	1	-

Pediatrics	2	-
Spine	-	2
Functional	-	1
Mean number of subpial resections performed in fellowship (median, range)	66 (50, range 50-100)	10 (10, range 8-12)
Residents (PGY[a] 4-6)	-	8

[a]PGY: Post graduate year

Table 2. Face Validity

Validity Statement	Group A-skilled Median (Range) Mean ± SD[a]	Group B-less skilled Median (Range) Mean ± SD[a]	P-Value
The preoperative setup was realistically reproduced	5.5 (2.0-7.0) 5.2±1.2	5.0 (1.0-7.0) 4.6±1.9	P=0.44
Overall, the simulated operation setting was realistic	6.0 (3.0-7.0) 5.5±1.1	5.0 (1.0-7.0) 5.2±1.6	P=0.83
The overall appearance of the simulated tissues was realistic	6.0 (5.0-7.0) 6.0±0.7	6.0 (3.0-7.0) 5.6±1.2	P=0.52
The overall tactile feeling was realistic	6.0 (3.0-7.0) 5.3±1.3	6.0 (2.0-7.0) 5.5±1.6	P=0.52
The sensory realism of the 'feel' of the simulated pia was realistically similar to a human pia	6.0 (3.0-7.0) 5.7±1.1	6.0 (1.0-7.0) 5.2±1.9	P=0.78
The sensory realism of the 'feel' of the simulated brain tissue was realistically similar to a human brain tissue	6.0 (3.0-6.0) 5.4±1.1	6.0 (1.0-7.0) 5.1±2.0	P=0.83
The visual realism of the simulated pia was realistically similar to a human brain pia mater	6.0 (4.0-7.0) 6.0±0.9	6.0 (3.0-7.0) 5.8 ±1.5	P=1.0

The visual realism of the simulated brain tissue was realistically similar to a human brain tissue	6.0 (4.0-7.0) 6.2±0.8	5.0 (3.0-7.0) 5.4±1.2	P=0.13
Related to the use of the micro-scissors, the instrument handling was similar to the micro-scissors used in the operating room	4.0 (1.0-7.0) 4.0±1.6	5.0 (2.0-7.0) 5.0±1.8	P=0.26
Related to the use of the bipolar, the instrument handling was similar to the bipolar used in the operating room	5.0 (2.0-6.0) 4.5±1.5	5.0 (2.0-7.0) 4.8±1.7	P=0.83
Related to the use of the ultrasonic aspirator, the instrument handling was similar to the ultrasonic aspirator used in the operating room	6.0 (4.0-7.0) 6.1±0.9	6.0 (5.0-7.0) 6.0±0.8	P=0.74

[a]SD: Standard Deviation

Table 3. Content Validity

Validity Statement	Group A-Skilled Median (range) Mean SD[a]	Group B-Less Skilled Median (range) Mean SD[a]	P-value
This exercise is appropriate to train hand-eye coordination	6.0 (5.0-7.0) 6.1±0.8	6.0 (1.0-7.0) 5.9±1.7	P=0.88
This exercise is appropriate to train the use of both hands	6.0 (3.0-7.0) 5.9±1.2	6.0 (1.0-7.0) 5.8±1.7	P=0.88
This exercise is appropriate to train the use of micro-scissors	4.0 (2.0-6.0) 4.2±1.4	6.0 (1.0-7.0) 5.2±1.8	P=0.09
This exercise is appropriate to train the use of a bipolar	3.5 (2.0-6.0) 3.5±1.3	5.0 (1.0-7.0) 4.5±2.0	P=0.19
This exercise is appropriate to train the use of an ultrasonic aspirator	6.0 (4.0-7.0) 6.2±0.8	7.0 (2.0-7.0) 6.1±1.4	P=0.69

This exercise is appropriate to train the subpial resection technique	6.0 (1.0-7.0) 5.9±1.6	7.0 (2.0-7.0) 6.0±1.6	P=0.69
The simulated task is useful for training residents	7.0 (2.0-7.0) 6.3±1.4	7.0 (2.0-7.0) 6.1±1.5	P=0.83
The simulated task is useful for training junior residents with little to no knowledge of the subpial resection	7.0 (4.0-7.0) 6.3±1.2	7.0 (1.0-7.0) 6.0±1.8	P=0.69
The simulated task is useful for training senior residents who have some knowledge of the subpial resection	6.0 (1.0-7.0) 5.7±1.7	6.0 (1.0-7.0) 5.0±2.0	P=0.41
The simulated task is useful for training fellows	6.0 (1.0-7.0) 5.6±1.6	5.0 (1.0-7.0) 4.5± 2.1	P=0.23

[a]SD: Standard Deviation

Figure 1. Ex vivo calf brain corticectomy model. (A) Fresh calf brain. (B) Calf brains were positioned in a human skull model within a off midline craniotomy window (C) View of the realistic operative environment (D) Surgical instrument used for movement capture. Micro-scissors, bipolar, and ultrasonic aspirator with fiducial markers attached via 3D-printed polylactic acid mounts. (E) Drawing representing the setting of the ex vivo model: (1) the brain model with the references on each side, (2) the operating microscope positioned over the ex vivo brain, (3) four optical cameras positioned around the trainee for instrument movement capture, (4) the three surgical instruments with mounted fiducials, (5) the computer recording instrument tracking data and microscope live video setup.

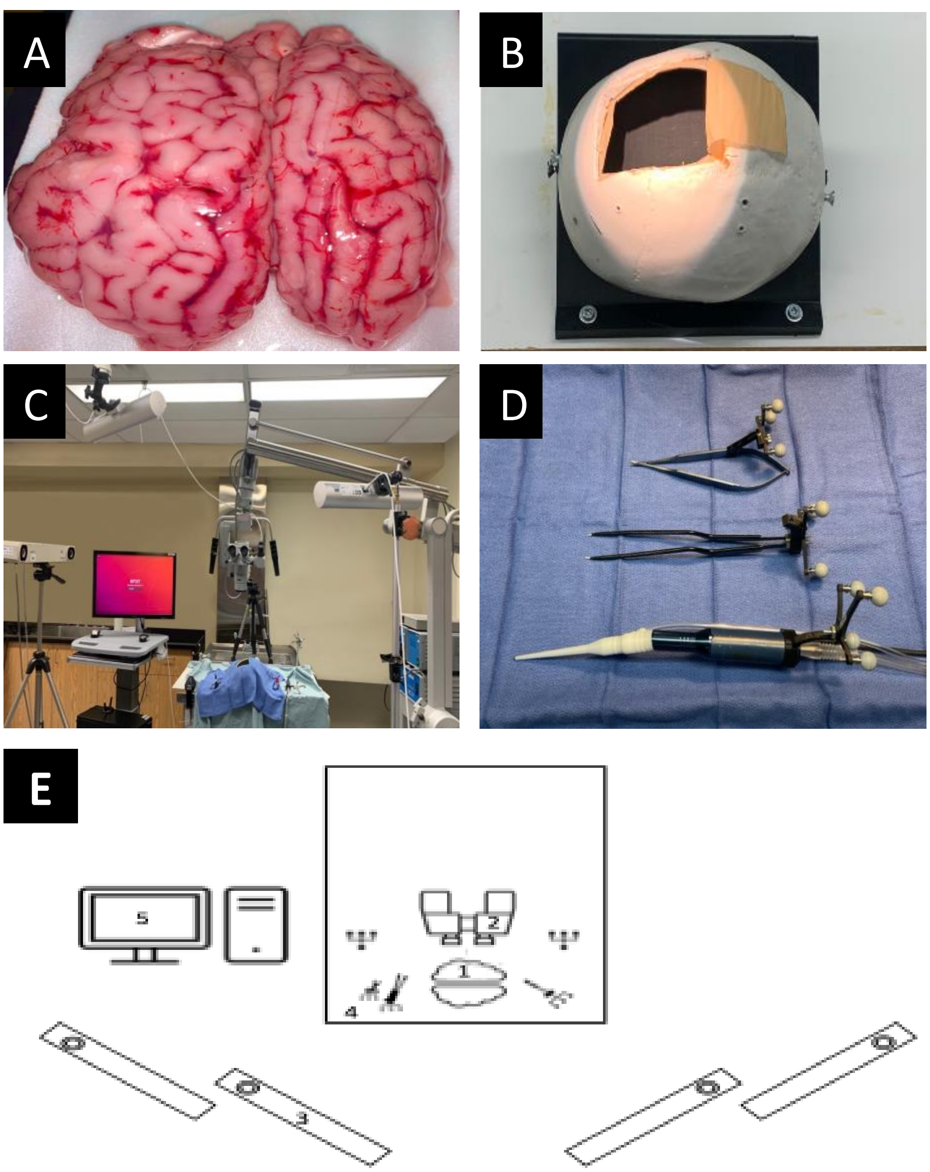

Figure 2. Subpial resection operative procedure: A) A 2D microscopic image outlining the location of the 3 subpial resections to be performed B) View through the operating microscope following completion of the three subpial resections. The white mater and pial membranes can be seen at the depth of the subpial resection cavities C) Participant performing the corticectomy procedure. The fiducials can be visualized attached to the instruments being utilized.