Surgical Endoscopy (2024) 38:3004–3026
https://doi.org/10.1007/s00464-024-10830-x

REVIEW ARTICLE

Using neuroimaging to assess brain activity and areas associated with surgical skills: a systematic review

Annarita Ghosh Andersen[1,2] · Agnes Cordelia Riparbelli[1] · Hartwig Roman Siebner[3,4,5] · Lars Konge[1,3] · Flemming Bjerrum[1,3,6]

Received: 2 January 2024 / Accepted: 24 March 2024 / Published online: 23 April 2024

Abstract

Background Surgical skills acquisition is under continuous development due to the emergence of new technologies, and there is a need for assessment tools to develop along with these. A range of neuroimaging modalities has been used to map the functional activation of brain networks while surgeons acquire novel surgical skills. These have been proposed as a method to provide a deeper understanding of surgical expertise and offer new possibilities for the personalized training of future surgeons. With studies differing in modalities, outcomes, and surgical skills there is a need for a systematic review of the evidence. This systematic review aims to summarize the current knowledge on the topic and evaluate the potential use of neuroimaging in surgical education.

Methods We conducted a systematic review of neuroimaging studies that mapped functional brain activation while surgeons with different levels of expertise learned and performed technical and non-technical surgical tasks. We included all studies published before July 1st, 2023, in MEDLINE, EMBASE and WEB OF SCIENCE.

Results 38 task-based brain mapping studies were identified, consisting of randomized controlled trials, case–control studies, and observational cohort or cross-sectional studies. The studies employed a wide range of brain mapping modalities, including electroencephalography, functional magnetic resonance imaging, positron emission tomography, and functional near-infrared spectroscopy, activating brain areas involved in the execution and sensorimotor or cognitive control of surgical skills, especially the prefrontal cortex, supplementary motor area, and primary motor area, showing significant changes between novices and experts.

Conclusion Functional neuroimaging can reveal how task-related brain activity reflects technical and non-technical surgical skills. The existing body of work highlights the potential of neuroimaging to link task-related brain activity patterns with the individual level of competency or improvement in performance after training surgical skills. More research is needed to establish its validity and usefulness as an assessment tool.

Keywords Functional neuroimaging · Robotic-assisted surgery · Laparoscopic surgery · Technical skills · Non-technical skills · Competency assessment

✉ Annarita Ghosh Andersen
annarita.ghosh@gmail.com

1 Copenhagen Academy for Medical Education and Simulation (CAMES), Center for Human Resources and Education, The Capital Region of Denmark, Ryesgade 53B, 2100 Copenhagen, Denmark

2 Department of Cardiothoracic Surgery, Copenhagen University Hospital - Rigshospitalet, Copenhagen, Denmark

3 Department of Clinical Medicine, Faculty of Health and Medical Sciences, University of Copenhagen, Copenhagen, Denmark

4 Danish Research Centre for Magnetic Resonance, Centre for Functional and Diagnostic Imaging and Research, Copenhagen University Hospital - Amager and Hvidovre, Hvidovre, Denmark

5 Department of Neurology, Copenhagen University Hospital - Bispebjerg and Frederiksberg, Copenhagen, Denmark

6 Gastrounit, Surgical Section, Copenhagen University Hospital - Amager and Hvidovre, Hvidovre, Denmark

Abbreviations

BOLD	Blood Oxygen Level-Dependent Signal Changes
CCN	Convolutional Neural Network
DM	Decision Making (DM)
DLPFC	Dorsolateral Prefrontal Cortex
EEG	Electroencephalography
FLS	Fundamentals of Laparoscopic Surgery
fMRI	Functional Magnetic Resonance Imaging
fNIRS	Functional Near-Infrared Spectroscopy
IPL	Inferior Parietal Lobe
LMM1	Left Medial Primary Motor Area
LG	Lingual Gyrus
M1	Primary Motor Area
MiOG	Middle Occipital Gyrus
PFC	Prefrontal Cortex
PET-CT	Positron Emission Tomography/Computed Tomography
PM	Premotor Cortex
PMd	Dorsal Premotor Cortex
PMv	Left Premotor Cortex
PC	Posterior cingulate gyrus
RAS	Robotic-assisted surgeries
RCT	Randomized controlled trial
SMA	Supplementary motor area
SPL	Superior parietal lobe
SP	Self-paced
SSA	Primary somatosensory area
STS	Left posterior superior temporal sulcus
Tdcs	Transcranial direct-current stimulation
TP	Time pressure
VA	Occipital visual areas
VBLaST	Virtual Basic Laparoscopic Skills Trainer
VLPFC	Ventrolateral prefrontal cortex
WCO	Wavelet coherence

Surgery, especially minimally invasive surgery, requires specific psychomotor skills like visuospatial perception, fine motor skills, and bimanual coordination. Furthermore, surgeons need knowledge about different procedures, anatomy, physiology, and cognitive skills for surgical planning, error prevention and recognition to deal with perioperative complications [1].

Additionally, surgeons must possess non-technical skills for clinical decisionmaking, communication, and interpersonal skills when treating and communicating with patients and other healthcare professionals.

With the introduction of more technically advanced procedures such as laparoscopy and robotic-assisted surgery (RAS) and more work-time restrictions, methods for assessing surgical competency are needed to ensure surgeons possess the necessary skills and improve patient safety [2–4]. Neuroimaging can provide valuable insights into neural changes associated with motor learning [5], and it has been proposed that neuroimaging can be a helpful tool to advance the understanding of the cognitive processes needed to acquire a surgical skill. Furthermore, it has been suggested that neuroimaging can aid in identifying and providing a deeper understanding of possible differences between novice and expert surgeons regarding non-technical skills, such as decisionmaking or situational awareness, among others [6].

It has been suggested that in some types of operations, such as RAS, cognitive assessment of surgeons may aid in defining the levels of expertise when performing complex surgical tasks and could be an adjunct to the traditional ways of assessing surgical competency [2] such as procedural logs, written and oral examinations and objective assessments such as task-specific checklists, global rating scales, and simulator metrics. These traditional measures have been criticized for offering only insight into some aspects of surgical competency [3, 7–9].

Simulation-based training provides an alternative to the traditional learning method in the operating theatre as it allows trainees to train without direct consequences to the patient. Additionally, simulation training, such as virtual reality simulation training, can provide immediate feedback and monitor and assess the progression of the trainees' surgical skills limited to temporal, motion-based, and outcome-based measurements [10–12]. These types of assessments are useful but not representative of all underlying aspects of a "skilled performance". Features that distinguish an expert surgeon from a novice surgeon have not yet been fully identified, and the identification of reliable measures of surgical expertise and its development have yet to be fully understood [13].

In this systematic review, we aimed to examine whether neuroimaging could be used to assess changes in cortical activation when surgeons use technical and non-technical surgical skills. We wanted to identify brain areas of interest and evaluate possible uses of neuroimaging, e.g., for assessing competency or the effect of training and potential gaps in the current knowledge.

Materials and methods

Eligibility criteria

We followed the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines [14] in completing this systematic review. The protocol was registered in PROSPERO (Record ID: 293025).

We included studies examining surgical technical and non-technical skills while using a brain imaging technique to investigate directly or indirectly brain function associated with surgical performance. Technical skills were surgical procedural skills, e.g., laparoscopic instrument handling or knot-tying and suturing, and non-technical skills were cognitive skills, e.g., situational awareness or decisionmaking.

The search concluded on July 1st, 2023. There were no restrictions based on the publication date of publications released before the conclusion. Randomized controlled trials (RCTs), case–control studies, and observational cohort or cross-sectional studies were included. Studies were excluded if they were not available in English or full text.

Search strategy

A systematic search of MEDLINE/PubMed, EMBASE and Web of Science was conducted by reformulating the research questions into a searchable query using the PICO principles and Boolean operators. A research librarian at the University of Copenhagen assisted in the creation of the search string. The search string was tailored to PubMed and modified to work in the other databases.

First, we searched using only MeSH terms in PubMed, followed by a MeSH-term and free-text search (Table 1). In EMBASE, a similar search strategy was conducted, while the search in Web of Science only consisted of a free-text search. Lastly, we manually searched for additional studies in the references of included studies and studies citing the included studies.

Study selection

The relevant studies were added to Covidence (www.covidence.org, Melbourne, Australia) and duplicates were removed. First, two reviewers (AGA, ACR) independently assessed the title and abstract of articles for eligibility based on inclusion criteria. After the initial screening, a secondary screening was conducted. In the secondary screening, the full text was read, and data were extracted by the same two reviewers (AGA, ACR). If any disagreement occurred during this process between the two reviewers, the final decision was made by a third reviewer (FB).

Data extraction, synthesis, and analysis

Both reviewers extracted the following data: general information (authors, publication year, title), aim, study design, brain imaging modality (fMRI, fNIRS, EEG etc.), number of participants, participants' characteristics/surgical experience (if mentioned), inclusion criteria, exclusion criteria, type of technical or non-technical surgical skill, environment

Table 1 Search string used in PubMed

	Population	Competences	Modality
MeSH	Physicians [MeSH] Students, medical [MeSH]	Surgical procedures, operative [MeSH] Psychomotor performance [MeSH] Professionalism [MeSH] Clinical competence [MeSH] Neuronal plasticity [MeSH] Cognition [MeSH] Education, medical [MeSH]	Neuroimaging [MeSH] Electroencephalography [MeSH] Spectroscopy, near-infrared [MeSH]
FREE-TEXT	Medical student Surgeon	motor learning surgical skill bimanual motor skill manual dexterity skill assessment skill level Cognitive load surgical training surgeons' performance Psychomotor performance Surgery [subheading] Laparotomy Endoscopy Medical education	Brain imaging Neuroimaging fMRI fNIRS PET EEG Brain mapping Brain electrical activity mapping Functional cerebral localization

(if mentioned), primary outcomes, brain activation patterns and brain activation localizations.

Studies were categorized by the type of brain imaging used.

Quality assessment was done by AGA and ACR independently. Methodological quality was assessed using the MERSQI and NOS-E checklists [15], as a standardized quality assessment for studies using neuroimaging in medical education has not been developed. The checklist was not used to determine whether a study was to be included or not, as the studies were very heterogeneous, and the scores varied depending on the study design itself.

We used Microsoft Excel for Mac 2022 (Microsoft Corp, Redmond, WA) to manage the extracted data. We did not conduct a meta-analysis due to the heterogeneity of the included studies but performed a qualitative data synthesis.

Results

Study selection and characteristics

A total of 5406 studies were imported for screening in Covidence. Of these, 5273 came from the database search, and 133 came from studies citing included studies and reference cross-searching. We removed 75 duplicate references. 5260 studies were excluded by the title and abstract screening due to either not using neuroimaging as a skill assessment or not assessing surgical or non-surgical skills. We evaluated 71 studies for full text assessability, and 38 studies were included in the final synthesis. See Fig. 1 for the PRISMA diagram and exclusion reasons.

Neuroimaging modalities utilized in the included articles were EEG ($n=14$), fNIRS ($n=16$), fMRI ($n=6$), and PET-CT ($n=1$), see Tables 2, 3, and 4. Of the 16 articles using fNIRS, two by Leff et al. Used the same population but with different outcome measures, and one used a study group b for comparison. The study population was only counted once. One article by Walia et al. Incorporated both EEG and fNIRS.

A total of 782 participants were described in the studies, and Table 5 shows the participant characteristics and the skills examined.

NOS-E scores ranged from 1 to 6 with a mean NOS-E of 3.9 (SD = 1.7), see Table 6, while MERSQI scores ranged from 10 to 14 with a mean score of 12 (SD = 1.1), see Table 7. Inter-rater reliability showed a strong agreement with a Cohens $\kappa=0.80$ [16].

Technical skill assessment

Neuroimaging has the possibility of being an objective assessment tool, with a range of different studies finding the same areas of interest and further exploring models such as neural networks explicitly for assessing surgical skills. Twenty-eight studies investigated neuroimaging for technical skill assessment. In all modalities, EEG, fNIRS, fMRI and PET-CT, the Prefrontal Cortex (PFC) [4, 17–33], Supplementary Motor Area (SMA) [4, 19, 20, 23–25, 30, 33–37], and the Primary Motor Area (M1) [4, 19, 20, 23, 25, 27, 34–36, 38, 39] were the predominantly investigated areas of interest. Some studies investigated a broader part of the brain, such as the frontal cortex, which includes the PFC, SMA, and M1 [36, 40], while EEG studies tended to focus on frequency over specific locations [2, 32, 34, 41–43] and fMRI tended to distinguish the areas in greater detail [24–28, 39].

Thiretten studies across neuroimaging modalities compared novices with experts [2, 19–21, 31, 33, 35, 37, 39, 40, 44–46], with 8 studies found significant higher or increased activation in the prefrontal cortex in novices [19–21, 31, 33, 40, 44, 45], one study found non-significant increase in activation in novices [2] and another study found higher activation across the frontal lobe [46].

Non-technical skill assessment

Sixteen studies investigated the use of neuroimaging for the assessment of non-technical skills. EEG was the most used neuroimaging modality in non-technical skill assessment, identifying engagement [2, 47], stress [31, 46], distractibility [41, 42], and identifying surgical complexity [2, 31, 32, 36, 43, 48]. One study showed a significant difference between audio and audio-visual conditions in utilizing auditory display when training image-guided neurosurgery, where EEG could be viewed as a marker for greater cognitive load [49].

Other neuroimaging modalities also investigated non-technical performance. Decisionmaking in surgeons and trainees was examined using fNIRS, which showed that ventromedial activation trends were observed solely among novices and not in experts [50], and the same modality was used to establish correlations between the subjective experience of cognitive load and perceived workload and prefrontal activation [44, 51]. This correlation was further used to investigate the impact of time pressure on prefrontal activation and technical performance [22]. The effect of the operative platform and the complexity of surgery was investigated for surgeons using fNIRS, finding a greater prefrontal change in oxy-Hb in robotic-assisted compared to conventional laparoscopic surgery [30] and EEG with a significant increase in interhemispheric coherence in the range of beta activity (and in upper alpha band but less robust), for surgeons using the robotic device compared both with resting condition and laparoscopic modality [36]. Likewise, both primary surgeons and assistants had significantly higher prefrontalww

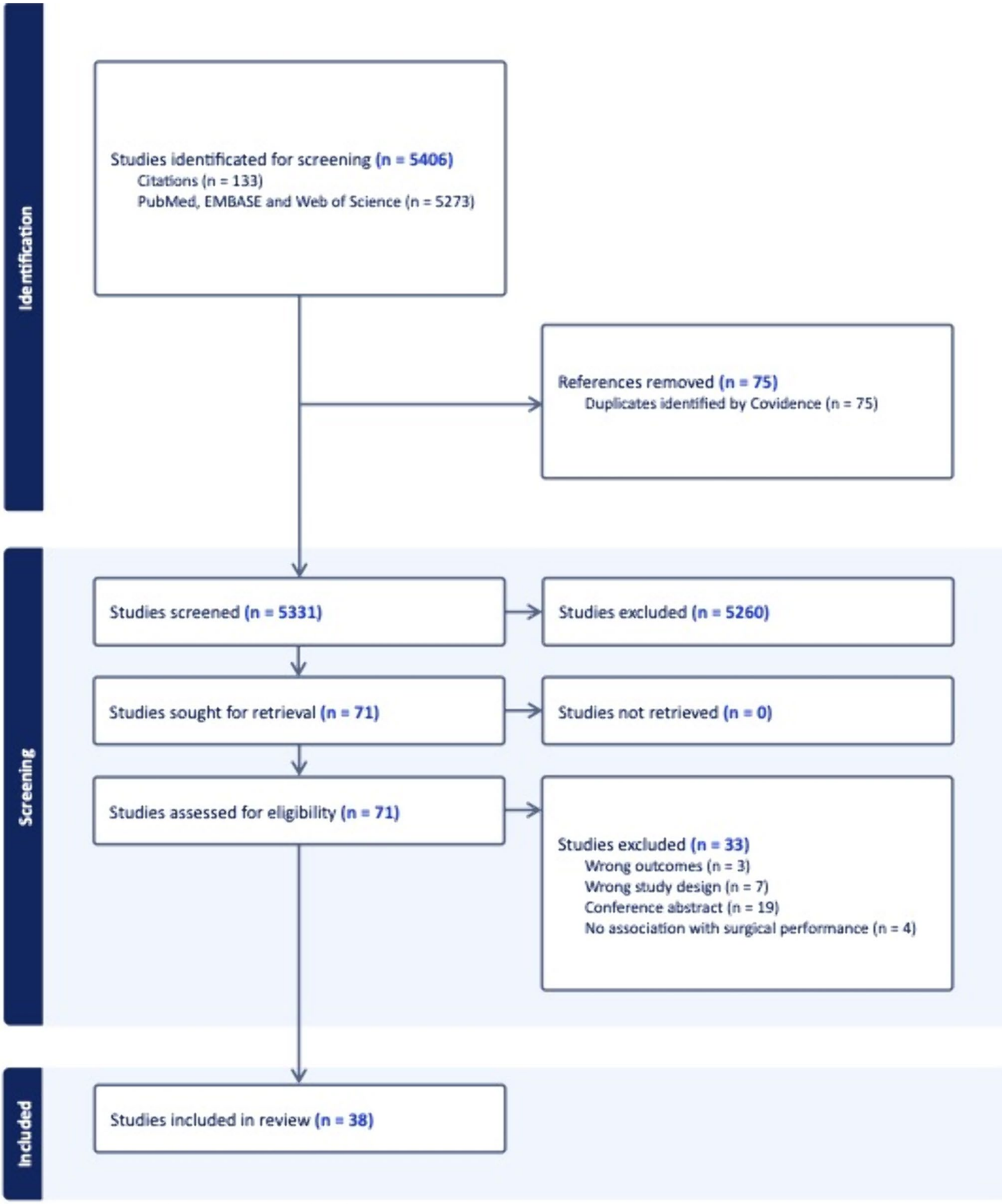

Fig. 1 PRISMA 2020 flow diagram for new systematic reviews

Table 2 Main findings of included EEG articles

Study ID	Bocci 2013 [36]	Ciechanski 2019 [43]	Guru 2015 [2]
Aim	Randomized cross-over study to investigate the influence of RAS on brain dynamics of the operator by measuring intra-hemispheric and inter-hemispheric coherence with EEG, and coorelation between coherence data and surgical performance	Randomized controlled study using EEG to investigate if and how transcranial direct-current stimulation (tDCS) and complex surgical training alters electrical activity in the sensorimotor network to enhance complex surgical skill acquisition and to pinpoint neural markers of that can be targeted by neuromodulation to optimize complex surgical training, by measuring FLS performance, tDCS safety and tolerability and beta and gamma frequency bands during performance	Observational study to investigate the utility of cognitive assessment during robot-assisted surgery (RAS) to define skills in terms of cognitive engagement, mental workload, and mental state; while objectively differentiating between novice and expert surgeons
Number of participants	16 trained surgeons	22 medical and veterinary students	2 beginner (BG), 5 competent (CPG) and 3 expert (EG) surgeons
Type of technical or non-technical surgical skill	Conventional, laparoscopic (Karl Sorz cart and Ethicon Endosurgery pelvic trainer) and robotic (da Vinci® Surgical System (Intuitive Surgical Inc., Sunnyvale, CA)) placement of three stitches in three different black targets on a gel case	Fundamentals of Laparoscopic Surgery (FLS) pattern cutting and peg transfer tasks	Robot assisted surgery (da Vinci® Surgical System (Intuitive Surgical Inc., Sunnyvale, CA))
Brain activation patterns and/or localizations	In surgeons using conventional laparoscopic approach there was a significant increase in intra-hemispheric coherence (M1 vs. SMA, SSA vs. SMA, SSA vs. pre-SMA and M1 vs. SSA; $p < 0.001$) in the range of theta activity (and the lower alpha band but less robust), compared both with resting condition and robotic surgery. Meanwhile for surgeons using the robotic device there was a significant increase in inter-hemispheric coherence (right vs. left M1, right vs. left SSA, right pre-SMA vs. left M1, left pre-SMA vs. right M1; $p < 0.001$) in the range of beta activity (and in upper alpha band but less robust), compared both with resting condition and laparoscopy modality	Surgical training modulated delta frequency band activity in sensorimotor regions. The performance of unimanual and bimanual skills evoked unique EEG profiles, primarily within the beta frequency band in parietal regions. Anodal tDCS enhanced the acquisition of unimanual surgical skill and tDCS-paired surgical training independently modulated delta and alpha frequency bands in sensorimotor regions, compared with sham-controlled surgical training	The expert group had lower high-level engagement and/or lower mental state compared with the competent and proficient group and the beginner group, measured over the frontal, central, parietal and occipital regions with a head-band EEG. There were no significant differences between the CPG and EG for both basic and intermediate skills using tool-based metrics. There were significant differences between the BG and alle other groups with tool-based metrics in basic skills. Using tool-based metrics there were no significant differences between the CPG and the EG except time. Using cognitive metrics, there were significant differences between all groups for the basic and intermediate skills. For cognitive metrics in advanced skills there were significant differences between both groups

Table 2 (continued)

Kwon 2021 [45]	Maddox 2015 [31]	Morales 2019 [46]	Plazak 2019 [47]
Observational cohort study to evaluate the real-time intraoperative stress analysis using wearable 2-channel EEG and heart rate variability detecting devices worn by orthopedic surgeons while performing surgery	Observational cohort study to measure gamma and alpha brain wave activity as a measurement of concentration and stress levels during surgical simulator performance of laparoscopic tasks to determine if expert surgeons have different brain activity patterns compared with intermediate and novice surgeons	Observational cohort study to assess the sensitivity of an electroencephalographic (EEG)-based index, the prefrontal beta power, to quantify the mental workload in surgeons in real scenarios, meauring the effects of the surgical complexity on beta activity and effectiveness of the surgical complexity manipulation	Randomized cross-over study to examine if adding audio information to visual displays within image-guided neurosurgery would improve performance within a 3D navigation task, be associated with reduced cognitive load, and be rated as subjectively less demanding than visual trials alone. Cognitive load was measured with MUSE EEG headband over the frontoparietal and temporoparietal areas
3 novice (less than 5 years experience, 3 associate professors (5–15 years exp.), 2 senior surgeons (+ 15 years experience)	6 medical students, 9 urology residents, and 4 attending urologists	8 surgeons, in 4 pairs of 2 (primary and secondary surgeon)	13 non-expert participants
Orthopedic real-life surgeries	Peg transfer and laparoscopic suturing in EDGE laparoscopic simulator (SimuLab; Seattle, WA)	Porcine models in the Advanced Multi-Purpose Simulation and Technological Innovation Complex situated at IAVANTE (Granada, Spain)	To navigate a tracked surgical tool to randomly placed 3D virtual locations while being aided by visual, aural, or both visual and aural feedback
The beta waves, measured over Fp1 and Fp2 to reflect the brains' frontal lobe cortical activity, were higher among novice surgeons than experienced surgeons, indicating that the psychological stress decreases with surgical experience. Especially during the first and second stage of surgery the novices maintained a relatively high beta 3 waves, indicating that the initial stress of might be high when anticipating the course of surgical treatment and planning the process. Other factors such as Prolonged operation time or excessive intraoperative blood loss appeared to be contributing factors that increased stress, by having a greater the proportion of beta waves in the total EEG frequencies of surgeons	EEG brain activity, measured over the prefrontal cortex, in more experienced surgeons showed a significant increase in concentration levels during both peg-pointing and suture tasks ($p=0.036$, $p=0.0039$), with a significant decrease in stress during laparoscopic suturing and trended toward a significant decrease in the peg transfer task ($p=0.0003$, $p=0.06$) compared with novices	For both the primary and assistant surgeon there was higher beta-activity over the prefrontal cortex when participants performed either suture (interrupted or continuous) using the more complex surgical procedure ($p<0.05$). Within the same surgical exercises (interrupted or continuous suturing employing employing low and high complex procedure), beta activity did not differentiate between surgical roles	There was a significant difference in cognitive load, measured by a higher relative alpha band EEG activity, between the audio and audio-visual condition ($p=0.01$), whereas the difference between the visual and audio-visual condition was not significant ($p=0.18$). Thus, the results were not consistent with the hypothesis that audio-visual feedback resulted in lower deduced working cognitive loads relative to visual-only feedback

Table 2 (continued)

Shafiei 2018 [34]	Shafiei 2021a [41]	Shafiei 2021b [42]	Suárez 2022 [53]
Observational cohort study to investigate cognitive and functional connectivity changes during acquisition of Fundamental Skills Robotic Surgery curriculum	Observational case series to investigate the utilization of brain network metrics extracted from EEG data, representing communication and information transformation between brain areas, and extract relationships between those metrics and surgical performance and distraction by collecting EEG data from 142 surgeries and select EEG features that have a significant relationship with surgeon performance and distraction while carrying out a RAS surgical task in the OR	Observational cross-sectional study to develop and validate an algorithm for objective evaluation of distraction of surgeons during RAS. To evaluate the performance of the model of the proposed approach using input EEG sequences with varying lengths	Observational cohort study to evaluate changes in brain activity, as cognitive assessment, of trainees during laparoscopic surgical training from EEG signals in realistic scenarios with few restrictions for the user
27 medical students	3 (doing in all 142 surgeries)	22 medical students	16 first-year surgical residents
Robot assisted surgery (da Vinci® Surgical System (Intuitive Surgical Inc., Sunnyvale, CA))	Robot assisted bladder drop, dissection, urethro-vesical anastomosis, and suturing in real-life surgeries	Robot assisted surgery (da Vinci® Surgical System (Intuitive Surgical Inc., Sunnyvale, CA))	4-week training program with the VR simulator, one session per week, where residents performed three consecutive tasks in LapSim® (Surgical Science Ltd., Göteburg, Sweden)
Channels in motor area (Frontal and Central channels) were consistently assigned to the same community (recruited). The same thing happened to channels in cognitive (Prefrontal and Parietal channels) and visual areas (Occipital channels). There was a significant correlation between performance level and motor-cognitive integration during the β frequency band. A higher practice gap was associated with lower recruitment of motor (α and β), and visual (β) modules and the study detected significant negative correlations between network features (strength and communication) and FSRS metrics	The flexibility of perceptual process-related areas, and strength and recruitment of the cognitive process-related areas were significantly associated with the performance score, where a 0.1 unit increase in the flexibility of perceptual process-related areas lead to an approximate increase of 2.2 for the performance score. Every 10 unit increase in strength for the cognitive process-related areas resulted in an increase of performance of nearly 1 point. A 0.1 unit increase for recruitment of cognitive process-related areas led to a 5-point increase in performance. Distraction during surgery affected surgeon's performance score (Pearson correlation coefficient = 0.37, $p < 0.0001$). Sensors were placed over frontal, temporal, parietal, central, and occipital cortices	The developed model (with sliding window ($L = 10$) was capable of classifying low, intermediate, and high distraction with the accuracy of 94%, 89%, and 95%, respectively. Only 4% of high distractions were mis-classified as low. There was a significant negative correlation between performance and Surg-TLX scores ($r = -0.021$, $p = 0.003$). Sensors were placed over frontal, temporal, parietal, central, and occipital cortices	There was statistically significant positive correlations between improvements in task performance for coordination and peg transfer tasks and changes in neuronal activity in frontal midline theta activity ($p = 0.041$, $p = 0.048$), but not in the grasping task. For the coordination task there was a significant negative correlation from the central parietal alpha cluster ($p = 0.023$). There was no statistically significant difference in NASA-TLX score as a measurement of percieved workload. There was however a significant difference in temporal demand and perceived performance of the NASA-TLX score ($p = 0.017$, $p = 0.015$)

Table 2 (continued)

Sun 2016 [38]	Walia 2022 [37]	Wu 2021 [44]	Zhu 2011 [32]
Observational cohort study to find out if it is possible to obtain quantitative information about the degree of the learning process throughout the training period by analyzing neuro-physiological signals, such as the electroencephalogram, the electrocardiogram and the electrooculogram	Observational study to investigate whether human error processing is proposed to be different in experts and novices due to their differences in the error-related mental processes measured in this study with simultaneously acquired EEG and fNIRS signals	Observational cohort study to measure changes in trainees' cognitive and behavioral states over a 3 month robotic surgeon training curriculum, by measuring task performance in the da Vinci Surgical Simulator, mental workload by pupil diameter and engagement quantified by Engagement Index (EI = beta/(alpha + theta)) from EEG	RCT to examine implicit and explicit motor learning in laparoscopic training, by comparing implicit and explicit training interventions. To examine if they result in in improved movement accuracy and to determine whether implicit and explicit training resulted in different levels of neural coactivation between the verbal-analytic (T3) and motor planning (Fz) regions and between the visuospatial (T4) and motor planning (Fz) regions
10 students, not specified course	13 medical students, 9 expert surgeons (> 1y)	7 surgical trainees	18 students, not specified course
NASA Multi Attribute Task Battery and Task Difficulty Modulation for five consecutive days for a total training period of 30 min per day, with EEG, ECG and EOG on T1, T3 and T5 in a controlled lab environment	Fundamentals of Laparoscopic Surgery (FLS) "suturing and intracorporeal knot-tying" task	45 min training sessions in robot assisted surgery (da Vinci® Surgical System (Intuitive Surgical Inc., Sunnyvale, CA)). In total, 26 training sessions were scheduled over 3 months	Laparoscopic graspers inserted through a trocar in a simulated skin pad. The graspers were used bimanually to maneuver a tracker across an Intuos3 tablet (Wacom, JP, Saitama, Japan)
Across the training sessions there was a significant decrease of EEG theta power spectral density (PSD) in the frontal area ($p \leq 0.00001$). Repeated measure ANOVA showed significant ($p = 0.001$) increase across the training sessions in the alpha band over parietal scalp EEG channels, especially the highest desynchronization happened on the central session of the training (T3), in correspondence of the highest increment of the frontal theta PSD	The proportion of the total time spent in different microstates was significantly affected by the skill level ($p < 0.01$), the microstate type ($p < 0.01$), and the interaction between the skill level and the microstate type ($p < 0.01$). The HbO signal from the overlying the left inferior frontal gyrus—opercular part, left superior frontal gyrus—medial orbital, left postcentral gyrus, left superior temporal gyrus, right superior frontal gyrus—medial orbital cortical areas showed significant ($p < 0.05$) difference between experts and novices	Changes in performance were correlated with changes in engagement index measured over the posterior parietal channels ($p \leq 0.001$) and gaze entropy ($p < 0.001$). Changes in cognitive and behavioral states were able to predict training outcomes with 72.5% accuracy. Findings suggest that cognitive and behavioral metrics correlate with changes in performance between sessions	T3-Fz coherence was lower for the participants in the implicit condition than for the participants in the explicit condition ($p = 0.0027$), suggesting that verbal-analytic involvement in performance of the repeated movement pattern was reduced by implicit motor learning. There was no apparent difference for the T4-Fz regions ($p = 0.882$) and no significant difference in movement accuracy in the retention test ($p = 0.231$) between the two groups

Number in brackets refers to the reference list

EEG Electroencephalogram, *FLS* Fundamentals of Laparoscopic Surgery, *fNIRS* functional Near-Infrared Spectroscopy, *M1* Primary Motor Area, *PSD* Power Spectral Density, *RAS* Robot-Assisted Surgery, *SMA* Supplemental Motor Area, *SSA* Primary Somatosensory Area, *tDCS* transcranial Direct-Current Stimulation

Table 3 Main findings of included fNIRS articles

fNIRS	Andreu-Perez 2016 [19]	Gao 2021a [22]	Gao 2021b [29]
Study design and aim	Observational cohort study investigating whether differences in technical skill level during laparoscopic (keyhole) surgical maneuvers may be reflected in differences in functional brain connectivity within associative and/or sensorimotor brain networks derived from evoked optical imaging responses (fNIRS)	RCT to investigate the effect of transcranial Electrical Stimulation (tDCS) on the learning procedure of a complex surgical motor task by measuring brain connectivity using fNIRS	Validation study to explore the potential of a convolutional neural network (CNN) model in processing fNIRS data to predict the surgical performance level and the ability to use this data in predicting the FLS scores as subjects perform the FLS Precision Cutting task and to investigate the performance of the Brain-NET model in comparison with fNIRS biomarkers
Participants Characteristics	32 (12 novices, 11 trainees, 9 expert consultants)	12 medical students (5 tDCS trained, 7 sham-controlled)	13 medical students
Type of technical or non-technical surgical skill	Laparoscopic needle insertion, double-throw knot tying and single-throw knot tying on a laparoscopic box trainer	Laparoscopic pattern cutting task on a laparoscopic box trainer	Laparoscopic precision cutting on a laparoscopic box trainer
Brain activation patterns and/or localizations	Correlations between PFC and M1 seed regions and other frontal motor cortical regions were observed to be lower in trainees and experts than novices, and was improved when local (i.e., within-region) rather than interregional (i.e., between-region) frontal connectivity was considered ($p=0.002$). SMA-M1 connectivity strength was more stable and skill level-related differences were less apparent. The results demonstrated discrimination of operator skill level with accuracy ≥ 0.82	In the early learning stage there was a similar brain activation pattern between the Sham and the tDCS group, for day 7–12 the tDCS group showed higher activation level in SMA ($p=0.001$) and lower activation level in right PFC and right lateral M1 region ($p=0.001$). There was significant difference between the stimulation type over time ($F=1.799$; $p=0.048$) and the time points ($F=114.367$; $p=0.001$), but not the stimulation ($F=0.024$; $p=0.879$). The performance error showed significant negative correlation to middle PFC and SMA region activation.The left PFC, middle PFC, and left lateral M1 region brain activation and the performance time were also significantly correlated	In comparison to other models, with 600 or more observations the mean performance of the proposed neural network was significantly higher than the other three approaches ($p<0.05$), however below 550 observations the accuracy of the CNN model proposed was significantly lower. Removing any of the proposed prefrontal (rightmost, second right, medial right, leftmost, second left or medial left) leads to a reduction in accuracy. HbR slope and the left PFC region showed the biggest contribution to the motor skill level. The proposed CNN was the most accurate in predicting pass/fail scores with the area under the curve value of 0.91

Table 3 (continued)

Izzetoglu 2021 [16]	Keles 2021 [49]	Khoe 2020 [17]	Leff 2008a [20]
Observational cohort study to investigate brain activation through measures of the changes in hemodynamic responses, with fNIRS, from the cortical regions associated with attention and working memory while trainees are engaged with robot-assisted surgery training	Observational cross-sectional cohort study to investigate whether there is sufficient information available in the optical signals (fNIRS) to make accurate predictions about the surgeons' subjective experiences by comparing prefrontal activation with NASA-TLX scores as well as discriminate skill levels (student vs attending)	Prospective RCT pilot study to examine the neuro-physiological basis underlying the learning processes in laparoscopic surgical training, by measuring the difference in HbOμm between post- and pre-intervention readings (ΔHbOμm = (Post-intervention HbOμm) − (Pre-intervention HbOμm)) for each of four laparoscopic tasks using fNIRS on medical students before and after a training workshop	Observational cohort study to investigate variations in cortical activations patterns during acquisition of a surgical task by measuring technical performance and task-related changes of cortical haemodynamics with fNIRS across five knot-tying trials
24 surgical residents (OB&Gyn or general surgery)	33 (17 medical students, 5 surgical residents, 11 attending surgeons)	32 medical students (16 trained and 16 untrained)	62 (22 medical students, 21 surgical registrars, 19 consultants)
Robot assisted sponge suturing tasks in two blocks, starting with the easiest task (da Vinci® Surgical System (Intuitive Surgical Inc., Sunnyvale, CA))	Two laparoscopic tasks (Peg transfer and String pass) on a laparoscopic box trainer	Laparoscopic peg transfer, precision cutting, suture insertion and intracorporeal knotting on a laparoscopic simulator (Endo Trainer)	Hand-tied surgical reef knotting on a bench top knot-tying trainer (Ethicon Ltd, New Jersey, USA)
Post hoc testing of the same difficulty levels across blocks indicated significantly lower oxygenation in the secon training session (Block 2) than in Block 1 for the easy level (HbO: $p<0.001$, $d=1.65$; Oxy: $p<0.001$, $d=1.93$), showing that realtive relative oxygenation changes in the prefrontal cortex were significantly lower during the second training session compared to the first session while the trainees were performing the tasks with varying difficulty levels as well	Students who experienced higher task load also had higher PFC activations. The response was greater in the left PFC of students particularly near the dorso- and ventrolateral areas. Attendings who reported higher task load generally had lower PFC activations. Lack of prior laparoscopy experience correlated with higher PFC activation. The results showed the classification of skill level and subjective task load could be predicted based on PFC activation, however the number of surgery residents was not enough for statistical analysis	During the precision cutting task, trained individuals demonstrated an attenuation in left PFC activation ($p=0.007$) compared to the untrained group, and in the subgroup analysis there was statistically significant differences between trained and untrained females in both peg transfer ($p=0.005$) and precision cutting ($p=0.003$). Untrained females had a greater increase in left PFC activation while performing the same tasks. There was no statistically significant difference between trained and untrained males, nor any observed difference during other FLS tasks	Cortical haemodynamic change varied considerably across trials in medical students, while there were comparatively minimal fluctuations in haemodynamic change were observed across trials in trained surgeons. Statistically significant increase in ΔHbO2 coupled to decreases ΔHHb were commonly observed between the first and second trials ($p\leq0.01$), and decreases in ΔHbO2 and increases in ΔHHb between the third and fourth, and fourth and fifth trial ($p\leq0.01$). No consistent patterns of haemoglobin change were identified in trained surgeons

Table 3 (continued)

Leff 2008b [51]	Leff 2017 [48]	Modi 2018 [50]	Modi 2020 [21]
Observational cohort study investigate prefrontal cortex activity in relationship with technical expertice, by using fNIRS and dexterity analysis to compare expert and novice surgeons performing a surgical knot-tying task in a block design. Furthermore to investigate the PFC response in novices pre- and post training	Observational cohort study investigating the differences in the quality, confidence, consistency of intraoperative surgical decision making (DM), and using fNIRS to explore the cortical decision systems that operators use	Cross-over study investigating the impact of time pressure on prefrontal activation and technical performance by using fNIRS on surgical resident while performing a laparoscopic suturing task under self-paced (SP) and time pressure (TP) conditions in a randomized block design	Observational cohort study comparing surgeons' PFC responses during a laparoscopic suturing exercise performed under a temporal demand, a cognitive demand, and both temporal and cognitive demands concurrently, using fNIRS
Study A: 62 (22 medical students, 21 surgical registrars, 19 consultants). Study B: 19 medical students	22 (10 medical students, 7 residents, 5 attendings)	33 surgical residents (Postgraduate Year (PGY)1–2 = 15, PGY3-4 = 8, and PGY5 = 10)	29 surgical residents
Hand-tied surgical reef knotting on a bench top knot-tying trainer (Ethicon Ltd, New Jersey, USA)	Intraoperative decision making (DM) while watching simulated laparoscopic cholecystectomy videos	Laparoscopic intracorporeal suturing on a laparoscopic box trainer (iSim2, iSurgicals, Chorley, UK)	Laparoscopic intracorporeal suturing on a laparoscopic box trainer (iSim2, iSurgicals, Chorley, UK)
Expert surgeons' data points clustered more tightly than novices', though after a week of practicing the arrangement of data appeared less dispersed. There was a statistically significant decrease in relative ΔHbT ($p < 0.001$), in ΔHbO2 ($p < 0.001$) and a significant increase in ΔHHb ($p < 0.01$) across training	Attendings and residents were more certain ($p < 0.001$), had a superior decision quality (script concordance: attendings = 90%, residents = 78.3%, and novices = 53.3%) and had superior decision consistency (experts: $p < 0.001$, residents: $p < 0.05$, novices: $p = 0.183$). During the unprimed decision making trials novices had significant activation of DLPFC channels, this activation pattern was not observed among residents and attending. During primed DM trials no significant activation patterns were observed. Ventromedial activation trends were observed solely among novices during DM trials	In all residents TP led to greater perceived workload, while it led to deterioration in task progression, error scores, knot tensile strength ($p < 0.05$), and diminished PFC activation in both junior and intermediate residents. Experts had worse task progression and error scores ($p < 0.05$) but less attenuation of PFC activation under TP. The areas in which channel activation was evident in SP but absent under TP were located predominantly in the bilateral VLPFC and DLPFC. Senior residents demonstrated significantly greater ΔHbO2 in the right dorsomedial PFC during SP conditions and in the bilateral PFC in the TP condition compared to junior or intermediate residents ($p < 0.05$)	Dorsolateral prefrontal cortex (DLPFC), ventrolateral prefrontal cortex (VLPFC). In the absence of any additional demands, laparoscopic suturing was associated with significant activation of the DLPFC ($p < 0.05$), meanwhile in the presence of temporal stress deactivation responses were observed in the VLPFC along with performance deterioration. Suturing while engaging with a decision-making task (dual-tasking) led to deactivation in both the DLPFC and VLPFC and greater decline in technical performance. Random effects regression analysis confirmed decision-making predicts VLPFC and DLPFC deactivation

Table 3 (continued)

Nemani 2018 [18]	Nemani 2019 [23]	Nemani 2021 [33]	Ohuchida 2009 [40]	Singh 2018 [30]
Observational cohort study comparing a fNIRS-based approach with currently used metrics in surgical certification by assessing bimanual motor tasks that are a part of surgical training accreditation, during training and classification of subjects with varying surgical expertise levels	RCT investigating if fNIRS can accurately assess motor skill transfer from simulation to ex-vivo environments for trained and untrained subjects as they perform a laparoscopic pattern cutting task on either a FLS-certified box trainer or the Virtual Basic Laparoscopic Skills Trainer (VBLaST) system	Observational cohort study investigating if fNIRS can objectively assess the correspondence between brain activation with surgical motor skills differences between expert and novice surgeons on physical (FLS) or virtual (VBLaST) simulators	Observational cohort study investigating cortical activation using fNIRS during endoscopic surgical tasks, measuring changes in oxy-Hb, deoxy-Hb or total-Hb levels during repeated suturing and knot-tying tasks	Randomized cross-over study assessing the effect of the operative platform (robotic surgery or conventional laparoscopy) on prefrontal cortical activation, measured with fNIRS, during a suturing task performed under temporal demand
12 medical students (3 skilled, 4 unskilled, 5 controls), 17 surgeons (9 novices (pgY 1–3), 8 experts (pgY 4–5 or attendings))	18 medical students (5 untrained controls, 7 FLS trained, 6 VBLaST trained)	22 medical students (5 untrained controls, 9 FLS trained, 8 VBLaST trained), 17 surgeons (9 novices (pgY 1–3), 8 experts (pgY 4–5 or attendings))	21 (13 novices, 4 trainees, 4 surgical experts)	8 surgeons
Laparoscopic bimanual pattern cutting task on a FLS-certified box trainer	Laparoscopic pattern cutting task performed on cadaveric abdominal tissue on either a FLS-certified box trainer or the Virtual Basic Laparoscopic Skills Trainer (VBLaST) system	Laparoscopic pattern cutting task on either a FLS-certified box trainer or the Virtual Basic Laparoscopic Skills Trainer (VBLaST) system	Endoscopic suturing and knot-tying on a standard closed-box endoscopic trainer (K26348; Storz, Tuttlingen, Germany)	Intracorporeal suturing task
Novice surgeons had, compared to expert surgeons, significantly higher functional activation in the PFC regions ($p<0.05$) and significantly lower functional activation in the LMM1 and SMA regions. There was no significant differences between medical students (control, unskilled and skilled) at the onset of the training program ($p>0.05$). However, at the completion of the training and after a 2-week break period, both skilled and unskilled trainees exhibited a significantly lower functional activation in the left lateral and right lateral PFC compared to the untrained control students ($p<0.05$) and trained FLS students had significantly higher LMM1 and SMA activation than untrained control students during the posttest ($p<0.05$)	The misclassification errors based on traditional metrics between simulator trained and untrained subjects ranged from 20 to 41%, while fNIRS could successfully classify untrained subjects from physical or virtual simulator trained subjects with misclassification errors of 2.7% and 9.1%, respectively. Regarding activation patterns both FLS and VBLaST simulator trained subjects had significantly higher functional activation in the left medial M1 compared to untrained control subjects ($p=0.018$ and $p=0.004$, respectively) and significant increases in functional activation in the SMA when compared to untrained control subjects ($p=0.048$ and $p=0.009$, respectively)	There was as statistically significant difference in the interregional WCO metrics for physical (FLS) simulator task for expert versus novice surgeons ($p<0.01$). The interregional WCO metric was found to have the highest effect size for the central PFC and SMA. Furthermore, a statistically significant ($p<0.001$) difference in the central PFC-SMA WPCO metric was found for the physical (FLS) simulator training group when compared to the untrained control group following baseline equivalence and then training for 10 consecutive days (in addition to the pretest and posttest days). Functional connectivity between the Central PFC and the SMA was lower for subjects that exhibit expert surgical motor skills than untrained subjects in laparoscopic physical simulators	There were no changes in oxy-Hb, deoxy-Hb or total-Hb levels in any of the frontal channels in surgical experts nor novices with no experience, however in surgical trainees and one novice with experience of endoscopic surgical training there was found significant increases in oxy-Hb and total-Hb levels in most of the frontal channels. There were significant differences between surgical experts and trainees in oxy-Hb and total-Hb levels ($p=0.02$ for both), and between surgical experts and novices ($p=0.008$ for both). Oxy-Hb levels during the task and subsequent rest periods were increased after training compared with those before training	Compared to laparoscopic suturing, greater prefrontal activation was identified in seven channels located primarily in lateral prefrontal regions during robotic suturing. Greater prefrontal change in HbO2 was observed during robotic compared to laparoscopic suturing in seven channels, particularly those located in the right VLPFC, when under a 2 min time restriction

Number in brackets refers to the reference list

CNN Convolutional Neural Network, *DLPFC* Dorsolateral Prefrontal Cortex, *DM* Decision Making, *FLS* Fundamentals of Laparoscopic Surgery, *fNIRS* Functional Near-Infrared Spectroscopy, *LMM1* Left Medial Primary Motor Area, *M1* Primary Motor Area, *PFC* Prefrontal Cortex, *SMA* Supplementary Motor Area, *SP* Self-Paced, *tDCS* Transcranial Direct-Current Stimulation, *TP* Time Pressure, *VBLaST* Virtual Basic Laparoscopic Skills Trainer, *VLPFC* Ventrolateral Prefrontal Cortex, *WCO* Wavelet Coherence

Table 4 Main findings of included fMRI and PET-CT articles

Other (fMRI and PET-CT)	Bahrami 2014 [24]	Duty 2012 [39]	Garbens 2020 [25]
Study design and aim	Observational cohort study to provide characterization of the brain regions involved in FLS-based laparoscopic surgery training tasks in the fMRI environment	Observational cohort study to correlate functional brain activation with the degree of laparoscopic experience by measuring changes in regional cerebral blood flow and metabolism using positron emission tomography (PET) with oxygen 15 (15O)–labeled water	Prospective cohort study explore brain function between high- and low-performing medical trainees using fMRI during laparoscopic tasks and using a computer-based task developed to assess surgeons' ability to infer 3D structure from a 2D object
Participants Characteristics	9 novices	5 novices, 5 expert laparoscopist	18 medical students
Type of technical or non-technical surgical skill	Parts of FLS (pegboard transfers, pattern cutting, placement of a ligating loop, suturing with extracorporeal knot tying, and suturing with intracorporeal knot tying)	Laparoscopic peg transfer task	Parts of FLS (peg-pointing, intracorporeal knot tying), and the Pictorial Surface Orientation (PicSOr) test
Brain activation patterns and/or localizations	Subjects' performance in the last practice sessions improved compared with the first practice sessions, over all tasks. Performance, measured in points in the modified FLS tasks, declined as the level of task complexity increased. The regional extent of brain activation increased with increasing task complexity. In task 1 the contralateral PM, the SMA (BA 6), S1 including BA 1, BA 2, and BA 3 was activated. Activation of the IPL and BA 5 and 7 was observed for tasks 2 and 5. PC and SMA both activated in task 5 (bimanual task), as well as greater activation in the medial frontal gyrus. Activation of the primary SSC was observed for all five tasks	Novice subjects had increased blood flow to the brain compared to expert laparoscopists during surgery-related motor and visual association tasks. The novice group had a significantly ($p=0.001$) higher activation (with deactivation in the expert group) in the left precentral gyrus and insula and the right precuneus and inferior occipital gyrus. The second analysis compared the 2 video scans and the rest scan. In contrast to the expert group, the novices had significantly ($p=0.001$) higher activation in the right precuneus and cuneus but deactivation in the bilateral posterior cerebellum	Subjects from the high performing group completed intracorporeal knot-tying faster and made more successful knot ties than low performers. In the peg-pointing task regions activated in both groups included the PM, SMA, precentral gyrus, and the S1 including, with more bilateral activation in the MiOG, thalamus, LG, and the insula. Subjects from the low-performing group showed more activation in the SMA compared to the high performers ($q=0.02$). All other brain regions had no significant differences in activation. All subjects showed activation in the PM and SMA, M1, S1, SPL and the precuneus, fusiform, LG and the insula during intracorporeal knot-tying. The high performers showed activation of the anterior and posterior cingulate cortex during knot-tying tasks, this was not observed in low performers

Table 4 (continued)

Irmen 2020 [26]	Karabanov 2019 [27]	Pelizzo 2020 [28]	Ridgway 2015 [35]
RCT to investigate parallel structural and functional plasticity following sensorimotor training (full-routine group, three sessions of in-scanner endoscopy performance and an additional 5-days of training on a VR-simulator) compared to a control group (brief routine group, three sessions of in-scanner endoscopy performance), using fMRI	RCT to investigate functional plasticity within tool-use relevant ventral frontoparietal network during acquisition of a complex bimanual skill. Second, to identify neural markers of training success within these networks	RCT to analyze the involvement of visual systems and other brain areas while performing and observing different types of surgery (robotic, laparoscopic, and open surgery) and the role of surgical training in modulating brain activation and to study the relationship between brain activation patterns and performance during training	Observational cohort study to assess the feasibility of utilizing a novel assessment method by measuring blood oxygen level–dependent signal changes (BOLD) in specific brain regions via fMRI during a surgical skills task
39 Medical students	48 medical students	23 Medical students	3 Novices, 3 intermediates, 3 experts
Endoscopic pointing and transfer task	Endoscopic pointing and transfer task	Stitching and guiding the surgical needle through a series of rings	Knot tying
Microstructural white-matter plasticity mirrored the spatiotemporal profile of task-dependent plasticity. There were significant changes in a left-hemispheric subcortical cluster underlying the ventral premotor region and the spatiotemporal expression of microstructural plasticity during early bimanual skill learning paralleled task-related functional plasticity induced by endoscopic exercises. In the time domain, functional and structural plasticity showed the greatest changes after the initial training session. In the spatial domain, functional and structural plasticity converged in the left PMv and adjacent subcortical white matter. Early bimanual skill learning also led to a training-depended upregulation of rs-connectivity in the left PMv and the magnitude of change in rs-connectivity correlated with the decrease in activation for participants that completed the full training routine	Functional impact of the left PMv onto the right PMv significantly decreased over time in the training group. A bilateral dorsal frontoparietal network associated with visual guidance of actions including the SPL and PMd was activated in all participants throughout all fMRI sessions. Transient task-exposure related activity increased in the left anterior putamen and the right PMd. In both groups, activity in these regions transiently increased during the second exposure to in-scanner laparoscopy, but had returned to baseline levels at the time of the third fMRI session. The ventrolateral grasping-network consisted of the PMv, aIPS, and primary motor hand area	All subjects had a strong activation of the dorsodorsal stream before and after training, involving the parietal-occipital junction and parietal regions including the medial IPL and SPL, and the PMd. There was a strong activation after training for the execution of tasks in the robotic group, this was not present in any of the other groups. Training also affected activation in the open group. At T0 there was activation of the dorsodorsal stream, together with prefrontal activation. After training, the involvement of the ventrodorsal stream was observed. The laparoscopic group showed similar activation of the dorsodorsal stream before and after training and seemed to be less affected by the training	Specific regions of interest identified included the left supramarginal, left rolandic operculum, and left postcentral regions. The BOLD activity during fingertapping was equal in all categories, indicating that this was an accurate control event. There was less BOLD activity in experts than in novices during knot tying compared with during finger tapping. With regard to the abstract thought process "imagine," an increase in BOLD activity was found in experts compared with novices at the temporal parietal junction and posterior STS. The activity difference for contrast for tying vs tapping was smaller, however not significantly, in experts than in novices. Regarding the "imagine" task, significantly increased activity was seen in the primary visual cortex in experts

Number in brackets refers to the reference list

BOLD Blood Oxygen Level–Dependent Signal Changes, *FLS* Fundamentals of Laparoscopic Surgery, *fMRI* Functional Magnetic Resonance Imaging, *IPL* Inferior Parietal Lobe, *LG* Lingual Gyrus, *MiOG* Middle Occipital Gyrus, *PET-CT* Positron Emission Tomography-Computed Tomography, *PC* Posterior Cingulate Gyrus, *PM* Premotor Cortex, *PMv* Left Premotor Cortex, *PMd* Dorsal Premotor Cortex, *aIPS* Anterior Intraparietal Sulcus, *SMA* Supplementary Motor Area, *S1* Primary Somatosensory Cortex, *SPL* Superior Parietal Lobe, *STS* Left Posterior Superior Temporal Sulcus

Table 5 Study, participant, and skill characteristics

	EEG	FMRI AND PET-CT	FNIRS	Total
No. of articles	14[a]	8	16[b]	38
No. of participants	221[a]	156	427[b]	804
Non-medical novices or unspecified	41	9		50
Medical students	90	136	203	429
Surgical trainees	42	3	142	187
Surgical experts	48	8	82	138
Advanced open surgery	1			
Basic surgical skills		1	1	
Laporascopic surgery	7	6	12	
Robot assisted surgery	4		2	
Non-technical skill			1	
Bimanual non-surgical skill	2			

EEG Electroencephalogram, *fMRI* functional Magnetic Resonance Imaging, *fNIRS* Functional Near-Infrared Spectroscopy, *PET-CT* Positron Emission Tomography/Computed Tomography

[a]One study investigated both EEG and fNIRS is in this counted in EEG as EEG was the primary outcome measure (Walia 2022)

[b]Two articles included with the same study population, but different aims (Leff 2021a, b). The study population was only counted once

activity in the beta band performing more complex surgical procedures, in this case, multiport laparoscopic surgery versus laparo-endoscopic single-site surgery. However, within the same surgical procedure, beta activity did not differentiate between surgical roles.

Discussion

In this systematic review, we found that the use of neuroimaging for surgical skill assessment is quickly evolving. As seen in Fig. 2, there has been a surge in publications after 2018. The studies are characterized by different methods, finding the same brain areas of interest and patterns in differentiating novices from experts. Neuroimaging is a promising area of interest as it has the possibility of in the future being used for objectively assessing surgical competence [2, 4, 19, 20, 23, 29, 32, 34, 35, 39, 41, 42, 42, 45], investigate the difference in brain activation patterns in novices and experts [2, 19–21, 31, 33, 35, 39, 40, 44–46, 50], identify the early learning phases and help individualize training programs [17–19, 21, 23, 24, 26–28, 34, 38, 39, 43, 52, 53], and explore non-technical aspects of surgical education such as cognitive load [22, 30, 36, 44, 47–49, 51, 53], intraoperative stress [31, 46], distractability [41, 42], and decision making [50].

Brain areas of interest in assessment

Studies investigating brain areas involved in investigating surgical skills used different methods and subsequently the distinction between the functional areas was poorly defined across all studies. However certain areas of interest were predominantly investigated and found important for surgeons and surgeons-to-be (Fig. 3). Across studies these were the PFC, which is responsible for consolidation of motor learning, motor planning and decision making, the SMA, which is responsible for controlling movement functions, the M1 which are responsible for motor function functions and SSA and VA which are responsible for somatosensory input and coordination and visual input and sensory integration.

Studies using fNIRS examined brain activity by measuring hemodynamical cortical activity, measuring oxy- and deoxy hemoglobin levels. Some studies that investigated hemodynamic patterns in novices compared with experts before and after training showed greater activation in PFC for novices at the beginning of the surgical training process compared to later [17–19] or compared to experts [19–21, 44, 45] and lower activation in the primary motor areas and SMA [19, 20]. Others found increased oxy-Hb levels in the frontal cortex after training in novices with no endoscopic surgical experience, with one study showing no change in surgical experts after training [40], while two other studies showed that senior residents demonstrated a significantly greater change in oxy-Hb in the right dorsomedial PFC during self-paced conditions [22] and in the bilateral PFC in a time-paced condition [51] compared to junior or intermediate residents.

Performance time and left and middle PFC and left lateral M1 brain region activity were significantly correlated, while performance error showed a significant negative correlation to middle PFC and SMA brain region activation measured with fNIRS.

EEG monitoring showed consistent recruitment of frontal, motor, and prefrontal areas during laparoscopic skills training. There was a significant correlation between performance level and motor-cognitive integration while activity was in the beta frequency band [34]. In concordance with the fNIRS studies, one study showed a significant decrease of theta band activity in the frontal area across training sessions and a significant increase in the alpha band over parietal regions [38].

Functional MRI was able to describe brain areas of interest in detail and activation involved in the training of technical skills [24–28, 39], with especially the left PFC, the SMA, the primary somatosensory area (SSA), and the occipital visual areas (VA) of interest. Novice surgeons, in general had a higher activation in the left precentral gyrus and insula and the right praecuneus and inferior occipital gyrus [39], the Brodmann Area of the SMA [25], and left ventral premotor

Table 6 NOS-E

Source, year	Representativeness of intervention group (0–1)	Selection (0–1)	Comparability (0–2)	Study retention (0–1)	Blinding (0–1)	Total NOS-E
Andreu-perez 2016	1	1	2	1	0	5
Bahrami 2014	1	0	0	0	0	1
Bocci 2013	1	0	0	1	0	2
Ciechanski 2019	1	1	2	1	0	5
Duty 2012	1	0	2	1	0	4
Gao 2021	1	1	2	1	1	6
Gao 2021	1	0	0	1	0	2
Garbens 2020	1	1	2	1	1	6
Guru 2015	1	1	2	1	1	6
Irmen 2020	1	1	2	1	1	6
Izzetoglu 2021	1	0	0	0	1	2
Karabanov 2019	1	1	2	1	1	6
Keles 2021	1	0	2	1	0	4
Khoehch 2020	1	1	2	1	1	6
Kwon 2021	1	1	2	1	1	6
Leff 2008	1	0	2	1	1	5
Leff 2008	1	0	0	1	0	2
Leff 2017	1	1	2	1	0	5
Maddox 2015	1	1	2	1	0	5
Modi 2018	1	0	2	1	0	4
Modi 2020	1	0	0	1	0	2
Morales 2019	1	0	0	1	0	2
Nemani 2018	1	1	2	1	1	6
Nemani 2019	1	1	2	1	0	5
Nemani 2021	1	1	2	1	0	5
Ohuchida 2009	1	0	1	1	0	3
Pelizzo 2020	1	1	2	1	0	5
Plazak 2019	0	0	0	0	1	1
Ridgway 2015	1	0	2	1	1	5
Shafiei 2018	1	0	2	1	1	5
Shafiei 2021	1	0	0	1	0	2
Shafiei 2021	1	0	0	1	0	2
Singh 2018	1	0	0	1	0	2
Suárez 2022	1	0	0	1	1	3
Sun 2016	1	0	0	1	0	2
Walia 2022	1	0	1	1	0	3
Wu 2021	1	0	0	1	0	2
Zhu 2011	1	1	1	0	1	4

cortex [26, 27]. Left PFC showed the biggest contribution to the motor skill level in a convolutional network model for predicting surgical performance level, and removing any prefrontal regions led to reduced accuracy [29]. During robotic suturing tasks, greater prefrontal activation was identified compared with laparoscopic suturing [30].

Duty et al. [35] performed the only study comparing novices and experts using PET-CT. Novice subjects had significantly increased blood flow (with deactivation in the expert group) in the left precentral gyrus and insula and the right precuneus and inferior occipital gyrus, while the experts had deactivation in the same areas.

There was a greater variation in activation in students than in experts, who showed lesser fluctuations in cortical activity [21, 52].

When researching non-technical skills, the PFC again emerged as the most frequently identified brain area, with a higher activation correlating with higher cognitive load [30, 31, 44, 46–49, 53]. However, in two studies, a diminished PFC activation correlated with higher perceived workload

Table 7 MERSQI

Study ID	Study design (0–3)	Sampling (0–3)	Type of data (0–3)	Validity of evaluation instrument score (0–3)	Data analysis (0–3)	Outcomes (0–3)	Total MER-SQI (0–18)
Andreu-Perez 2016	1.5	1.5	3	3	3	1.5	12
Bahrami 2014	1	1	3	2	3	1.5	10
Bocci 2013	1	1	3	2	3	1.5	10
Ciechanski 2019	3	1.5	3	3	3	1.5	13.5
Duty 2012	2	1.5	3	2	3	1.5	11.5
Gao 2021	3	1.5	3	3	3	1.5	13.5
Gao 2021	1.5	1	3	3	3	1.5	11.5
Garbens 2020	2	1.5	3	2	3	1.5	11.5
Guru 2015	2	2	3	3	3	1.5	13
Irmen 2020	3	2	3	3	3	1.5	14
Izzetoglu 2021	1.5	1.5	3	3	3	1.5	12
Karabanov 2019	3	2	3	3	3	1.5	14
Keles 2021	2	2.5	3	3	3	1.5	13.5
Khoehch 2020	3	1	3	2	3	1.5	12
Kwon 2021	2	3	3	2	3	3	13
Leff 2008	2	2	3	3	3	1.5	13
Leff 2008	1.5	1	3	2	3	1.5	10.5
Leff 2017	2	1.5	3	2	3	1.5	11.5
Maddox 2015	2	1	3	2	3	1.5	11
Modi 2018	2	1	3	3	3	1.5	12
Modi 2020	1	1	3	3	3	1.5	11
Morales 2019	1	2	3	3	3	1.5	12
Nemani 2018	2	1.5	3	2	3	1.5	11.5
Nemani 2019	3	1	3	3	3	1.5	13
Nemani 2021	2	1.5	3	2	3	1.5	11.5
Ohuchida 2009	2	3	3	2	3	1.5	13
Pelizzo 2020	3	1.5	3	2	3	1.5	12.5
Plazak 2019	2	1.5	3	2	3	1.5	11.5
Ridgway 2015	2	2.5	3	3	3	1.5	13.5
Shafiei 2018	2	1	3	3	3	1.5	12
Shafiei 2021	1	1	3	2	3	3	10
Shafiei 2021	1	1	3	2	3	1.5	10
Singh 2018	1	2	3	2	3	2	13
Suárez 2022	1.5	1	3	3	3	1.5	11.5
Sun 2016	1.5	1	3	3	3	1.5	11.5
Walia 2022	1	2.5	3	2	3	1.5	11.5
Wu 2021	1	2	3	2	3	1.5	11
Zhu 2011	3	2	3	2	3	1.5	13

[51] and temporal stress [22] using fNIRS. With EEG being the most frequently used modality for assessing non-surgical competencies, some studies even used activation in PFC to measure cognitive load, comparing activity in the different wavelength bands over the prefrontal cortex as a substitute for cognitive load, intraoperative stress, and distraction. The reported findings correlated with both self-observed workload and performance [36, 42, 46, 48, 53]. In one study NASA-TLX did not always correlate with performance [53], EEG showed great promise as an objective and verifiable measurement of workload.

Using neuroimaging for the assessment of technical skills

Six studies investigated the feasibility of using neuroimaging for surgical skill assessment, with two investigating the validity evidence of novel classification systems.

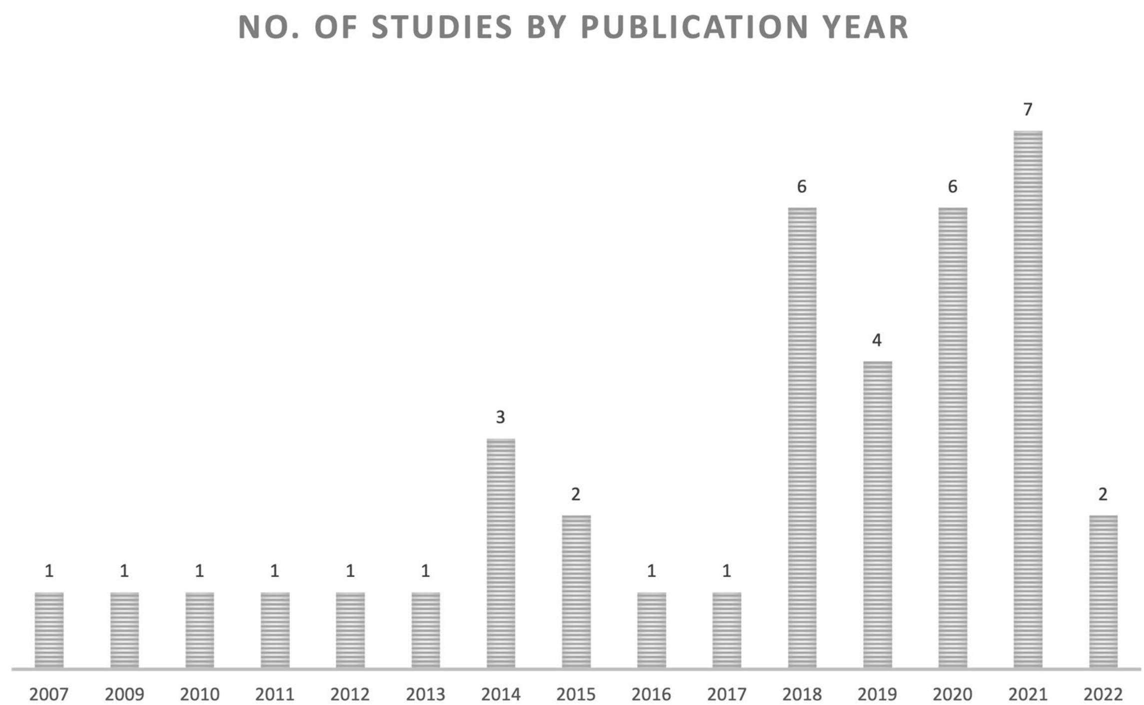

Fig. 2 Number of articles published by year

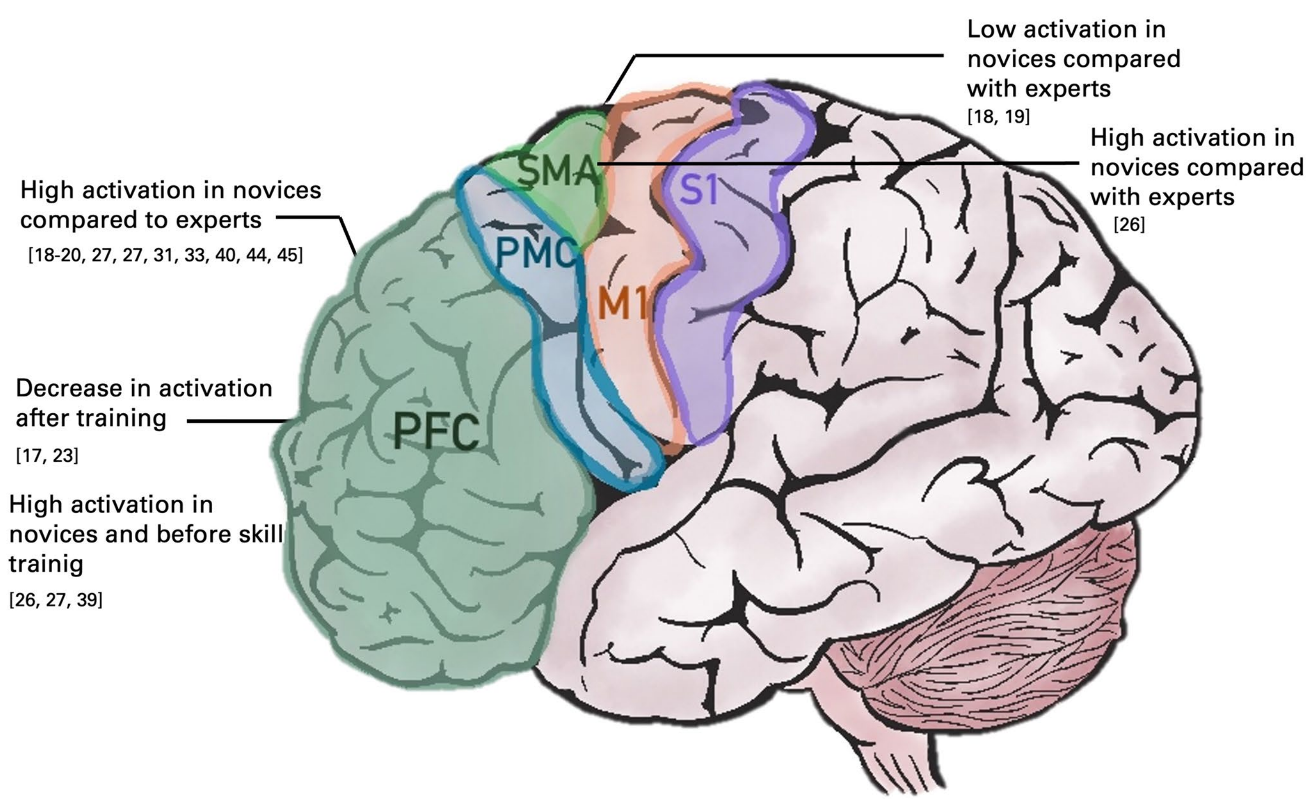

Fig. 3 Brain regions investigated and findings with with references. *M1* Primary Motor Cortex, *S1* Primary Sensory Cortex, *SMA* Supplemental Motor Cortex, *PFC* Prefrontal Cortex, *PMC* Premotor Cortex

Gao et al. [29] investigated a Convolutional Neural Network based on fNIRS, which, with over 550–600 observations could predict pass/fail scores in a pattern cutting task with an AUC of 0.91. Nemani et al. [4] found that fNIRS could successfully classify untrained subjects from physical or virtual simulator trained subjects with misclassification errors of 2.7% and 9.1% compared to traditional metrics that had misclassification errors ranging from 20 to 41%. They also found that functional connectivity changes based on WCO and WPCO metrics corresponded to the surgical motor skill proficiency.

One study by Guru et al. [2] using both EEG and fNIRS showed that the time spent in each activity state was significantly affected by the participant's skill level while also showing a significant difference in HbO signal over the left PFC and SMA in novices and experts. This method was able to both investigate activated brain areas and focus attenuation, concluding that novices had a widespread stimulus-driven hemodynamic activation without the same focusing effect seen in experts [37].

One fMRI study used a novel assessment method in identifying experience level by using blood oxygen level-dependent signal changes [29], and EEG was also used to investigate experience level [2, 31, 46].

As the PFC and SMA emerged as the most researched areas of interest, these were also investigated for assessing skills. The methods mostly consisted of either measuring changes, neural networks or measuring activity states. 8 studies [19–21, 31, 33, 40, 44, 45] found significantly lower activation or a decrease in activation in experts compared to novices in the PFC, and 2 studies found a significant decrease in PFC activation after training compared with untrained controls [4, 18]. The PFC is important in the cognitive recognition and analysis of motor planning, "thinking about doing", while the PMC and SMA are necessary for coordinating bimanual tasks [54]. Experts don't require as much cognitive planning for movements because they have performed them hundreds of times.

Limitations

Most studies were observational or non-randomized, with only six randomized controlled studies, five randomized cross-over studies, and two validity investigation studies. The studies were very heterogeneous in design, control, quality, and surgical skill assessment tools, making it difficult to compare them.

Many studies had small sample sizes with limited statistical power. They were conducted with specific surgical populations such as urology residents or orthopedic surgeons etc. in realistic operation conditions. In contrast, others were conducted with medical students or unspecified untrained individuals in laboratories or scanners.

Most studies did not assess the long-term impact of training on the brain nor the long-term impact of different assessment methods on surgical outcomes, instead focusing on comparing novices and experts or pre- and posttest investigations.

There is a risk of reporting bias as studies with positive results are more likely to be published, and unpublished negative results could skew the consensus towards neuroimaging being more useful.

Future perspectives

The mapping of brain areas during training has great potential in directing surgical training or even assisting in this process, as shown in a study by Galvin et al. using transcranial direct-current stimulation during the acquisition of laparoscopic surgical skills [55].

Increasing our understanding of functional brain networks in learning can aid in developing individualized training programs, as suggested by Shaifei et al., who used specific neural activity measured with EEG and eye gaze tracking to predict performance and learning rate for various laparoscopic surgical tasks [56].

Armstrong et al. [57] did a pilot study that, building on our knowledge of the correlation between neural activity and future motor errors, showed that EEG can predict errors intraoperatively during surgery. The pilot study found that specific neural signatures predicted technical errors in laparoscopic surgery.

In this rapidly evolving field, this knowledge can further other research areas, such as the use of artificial intelligence [58] or have implications for intraoperative feedback [57], for example, by incorporating neuroimaging in a machine learning model to provide objective skill classification models and feedback in surgical training [59].

While there is potential in using neuroimaging, only a few studies touch upon the cost of introducing neuroimaging in surgical skill training. With the introduction of simulation into surgical skill training, studies sought to highlight the cost-effectiveness and the need to regularly assess the feasibility but also found that the implementation cost can be a substantial investment [60, 61].

Future research in this area should address the above-mentioned limitations and focus on developing more standardized and reliable neuroimaging-based assessments of surgical skills both in the learning process and the implications for intraoperative real-time feedback. Research is also needed to investigate the long-term impacts of training on the brain.

Conclusion

Using neuroimaging to assess surgical skills is a quickly evolving research area with the potential for evaluating technical and non-technical surgical competencies. Different neuroimaging modalities have shown similar patterns in brain activations patterns, with the prefrontal cortex, supplementary motor area, and primary motor area being the most frequently investigated areas. There is not yet agreement on which areas and activation patterns are relevant when assessing surgical skills, but the prefrontal cortex shows the greatest potential in novice-expert comparisons and in investigating cognitive load and performance and has significant activation patterns when comparing novices with experts and untrained with trained subjects. Therefore, we recommend that research focus on the PFC when using neuroimaging to assess surgical skills.

Overall, this systematic review highlights the potential of neuroimaging in surgical skill assessment, but further research is needed to establish whether it can be a useful assessment tool in surgical education.

Funding None of the authors received funding for the work in this study. No grant from any funding agency in the public, commercial, or not-for-profit sectors was provided to conduct the systematic review.

Declarations

Disclosures Hartwig Roman Siebner has received honoraria as speaker and consultant from Lundbeck AS, Denmark, and as editor (Neuroimage Clinical) from Elsevier Publishers, Amsterdam, The Netherlands and has received royalties as book editor from Springer Publishers, Stuttgart, Germany, Oxford University Press, Oxford, UK, and from Gyldendal Publishers, Copenhagen, Denmark. Annarita Ghosh Andersen, Agnes Cordelia Riparbelli, Lars Konge and Flemming Bjerrum have no conflicts of interest or financial ties to disclose.

References

1. Shah J, Darzi A (2001) Surgical skills assessment: an ongoing debate. BJU Int 88(7):655–660
2. Guru KA, Esfahani ET, Raza SJ, Bhat R, Wang K, Hammond Y et al (2015) Cognitive skills assessment during robot-assisted surgery: separating the wheat from the chaff. BJU Int 115(1):166–174
3. Vassiliou MC, Feldman LS (2011) Objective assessment, selection, and certification in surgery. Surg Oncol 20(3):140–145
4. Nemani A, Kruger U, Cooper CA, Schwaitzberg SD, Intes X, De S (2019) Objective assessment of surgical skill transfer using non-invasive brain imaging. Surg Endosc 33(8):2485–2494
5. Hardwick RM, Rottschy C, Miall RC, Eickhoff SB (2013) A quantitative meta-analysis and review of motor learning in the human brain. Neuroimage 67:283–297
6. Modi HN, Singh H, Yang G-Z, Darzi A, Leff DR (2017) A decade of imaging surgeons' brain function (part II): a systematic review of applications for technical and nontechnical skills assessment. Surgery 162(5):1130–1139
7. Mitchell EL, Arora S, Moneta GL, Kret MR, Dargon PT, Landry GJ et al (2014) A systematic review of assessment of skill acquisition and operative competency in vascular surgical training. J Vasc Surg 59(5):1440–1455
8. Kramp KH, van Det MJ, Veeger NJGM, Pierie J-PEN (2016) Validity, reliability and support for implementation of independence-scaled procedural assessment in laparoscopic surgery. Surg Endosc. 30(6):2288–2300
9. Saleh GM, Voyatzis G, Voyazis Y, Hance J, Ratnasothy J, Darzi A (2006) Evaluating surgical dexterity during corneal suturing. Arch Ophthalmol Chic Ill 1960 124(9):1263–1266
10. Alaker M, Wynn GR, Arulampalam T (2016) Virtual reality training in laparoscopic surgery: a systematic review & meta-analysis. Int J Surg 29:85–94
11. de Montbrun SL, MacRae H (2012) Simulation in surgical education. Clin Colon Rectal Surg 25(3):156–165
12. Shahbazi M, Poursartip B, Siroen K, Schlachta CM, Patel RV (2018) Robotics-assisted surgical skills evaluation based on electrocortical activity. In Proceedings of the 2018 40th annual international conference of the IEEE engineering in medicine and biology society (EMBC), vol 2018, pp 3673–3676
13. Judkins TN, Oleynikov D, Stergiou N (2008) Objective evaluation of expert and novice performance during robotic surgical training tasks. Surg Endosc 23(3):590
14. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD et al (2021) The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. Int J Surg 88:105906
15. Cook DA, Reed DA (2015) Appraising the quality of medical education research methods: the medical education research study quality instrument and the Newcastle-Ottawa Scale-Education. Acad Med 90(8):1067
16. Cohen J (1960) A coefficient of agreement for nominal scales. Educ Psychol Meas 20(1):37–46
17. Izzetoglu K, Aksoy ME, Agrali A, Kitapcioglu D, Gungor M, Simsek A (2021) Studying brain activation during skill acquisition via robot-assisted surgery training. Brain Sci. https://doi.org/10.3390/brainsci11070937
18. Khoe HCH, Low JW, Wijerathne S, Ann LS, Salgaonkar H, Lomanto D et al (2020) Use of prefrontal cortex activity as a measure of learning curve in surgical novices: results of a single blind randomised controlled trial. Surg Endosc 34(12):5604–5615
19. Nemani A, Yücel MA, Kruger U, Gee DW, Cooper C, Schwaitzberg SD et al (2018) Assessing bimanual motor skills with optical neuroimaging. Sci Adv 4(10):eaat3807
20. Andreu-Perez J, Leff DR, Shetty K, Darzi A, Yang G-Z (2016) Disparity in frontal lobe connectivity on a complex bimanual motor task aids in classification of operator skill level. Brain Connect 6(5):375–388
21. Leff DR, Elwell CE, Orihuela-Espina F, Atallah L, Delpy DT, Darzi AW et al (2008) Changes in prefrontal cortical behaviour depend upon familiarity on a bimanual co-ordination task: an fNIRS study. Neuroimage 39(2):805–813
22. Modi HN, Singh H, Darzi A, Leff DR (2020) Multitasking and time pressure in the operating room: impact on surgeons' brain function. Ann Surg 272(4):648–657
23. Gao Y, Cavuoto L, Dutta A, Kruger U, Yan P, Nemani A et al (2021) Decreasing the surgical errors by neurostimulation of primary motor cortex and the associated brain activation via neuroimaging. Front Neurosci 15:651192
24. Bahrami P, Graham SJ, Grantcharov TP, Cusimano MD, Rotstein OD, Mansur A et al (2014) Neuroanatomical correlates of laparoscopic surgery training. Surg Endosc 28(7):2189–2198
25. Garbens A, Armstrong BA, Louridas M, Tam F, Detsky AS, Schweizer TA et al (2020) Brain activation during laparoscopic tasks

in high- and low-performing medical students: a pilot fMRI study. Surg Endosc 34(11):4837–4845
26. Irmen F, Karabanov AN, Bögemann SA, Andersen KW, Madsen KH, Bisgaard T et al (2020) Functional and structural plasticity co-express in a left premotor region during early bimanual skill learning. Front Hum Neurosci 14:310
27. Karabanov AN, Irmen F, Madsen KH, Haagensen BN, Schulze S, Bisgaard T et al (2019) Getting to grips with endoscopy—learning endoscopic surgical skills induces bi-hemispheric plasticity of the grasping network. Neuroimage 189:32–44
28. Pelizzo G, Cardinali L, Bonanno L, Marino S, Cavaliere C, Aiello M et al (2020) Training skills in minimally invasive, robotic and open surgery: brain activation as an opportunity for learning. Eur Surg Res 61(1):34–50
29. Gao Y, Yan P, Kruger U, Cavuoto L, Schwaitzberg S, De S et al (2021) Functional brain imaging reliably predicts bimanual motor skill performance in a standardized surgical task. IEEE Trans Biomed Eng 68(7):2058–2066
30. Singh H, Modi HN, Ranjan S, Dilley JWR, Airantzis D, Yang G-Z et al (2018) Robotic surgery improves technical performance and enhances prefrontal activation during high temporal demand. Ann Biomed Eng 46(10):1621–1636
31. Maddox MM, Lopez A, Mandava SH, Boonjindasup A, Viriyasiripong S, Silberstein JL et al (2015) Electroencephalographic monitoring of brain wave activity during laparoscopic surgical simulation to measure surgeon concentration and stress: can the student become the master? J Endourol 29(12):1329–1333
32. Zhu FF, Poolton JM, Wilson MR, Hu Y, Maxwell JP, Masters RSW (2011) Implicit motor learning promotes neural efficiency during laparoscopy. Surg Endosc 25(9):2950–2955
33. Nemani A, Kamat A, Gao Y, Yucel M, Gee D, Cooper C et al (2021) Functional brain connectivity related to surgical skill dexterity in physical and virtual simulation environments. Neurophotonics 8(1):015008
34. Shafiei SB, Hussein AA, Guru KA (2018) Dynamic changes of brain functional states during surgical skill acquisition. PLoS ONE 13(10):e0204836
35. Ridgway PF, Frodl T, D’Souza A, Fagan AJ, Morris MC (2015) Assessment of competence in surgical skills using functional magnetic resonance imaging: a feasibility study. J Surg Educ 72(2):198–204
36. Bocci T, Moretto C, Tognazzi S, Briscese L, Naraci M, Leocani L et al (2013) How does a surgeon’s brain buzz? An EEG coherence study on the interaction between humans and robot. Behav Brain Funct 9(1):14
37. Walia P, Fu Y, Schwaitzberg SD, Intes X, De S, Cavuoto L et al (2022) Error related brain state analysis using electroencephalography in conjunction with functional near-infrared spectroscopy during a complex surgical motor task. Brain Inf 9:29
38. Sun Y, Taya F, Bezerianos A, Graziani I, Borghini G, Arico P et al (2016) Quantitative assessment of the training improvement in a motor-cognitive task by using EEG, ECG and EOG signals. Brain Topogr 29(1):149–161
39. Duty B, Andonian S, Ma Y, Peng S, Shapiro E, Dhawan V et al (2012) Correlation of laparoscopic experience with differential functional brain activation: a positron emission tomography study with oxygen 15–labeled water. Arch Surg 147(7):627–632
40. Ohuchida K, Kenmotsu H, Yamamoto A, Sawada K, Hayami T, Morooka K et al (2009) The frontal cortex is activated during learning of endoscopic procedures. Surg Endosc 23(10):2296–2301
41. Shafiei SB, Jing Z, Attwood K, Iqbal U, Arman S, Hussein AA et al (2021) Association between functional brain network metrics and surgeon performance and distraction in the operating room. Brain Sci 11(4):468
42. Shafiei SB, Iqbal U, Hussein AA, Guru KA (2021) Utilizing deep neural networks and electroencephalogram for objective evaluation of surgeon’s distraction during robot-assisted surgery. Brain Res 1769:147607
43. Ciechanski P, Kirton A, Wilson B, Williams CC, Anderson SJ, Cheng A et al (2019) Electroencephalography correlates of transcranial direct-current stimulation enhanced surgical skill learning: a replication and extension study. Brain Res 1725:146445
44. Keles HO, Cengiz C, Demiral I, Ozmen MM, Omurtag A (2021) High density optical neuroimaging predicts surgeons’s subjective experience and skill levels. PLoS ONE 16(2):e0247117
45. Leff D, Orihuela-Espina F, Atallah L, Athanasiou T, Leong J, Darzi A et al (2008) Functional prefrontal reorganization accompanies learning-associated refinements in surgery: a manifold embedding approach. Comput Aided Surg 13(6):325–339
46. Kwon JW, Lee SB, Sung S, Park Y, Ha JW, Kim G et al (2021) Which factors affect the stress of intraoperative orthopedic surgeons by using electroencephalography signals and heart rate variability? Sensors (Basel). https://doi.org/10.3390/s21124016
47. Wu C, Cha J, Wachs J, Proctor RW, Yu D, Sulek J et al (2021) Sensor-based indicators of performance changes between sessions during robotic surgery training. Appl Ergon 90:103251
48. Morales JM, Ruiz-Rabelo JF, Diaz-Piedra C, Di Stasi LL (2019) Detecting mental workload in surgical teams using a wearable single-channel electroencephalographic device. J Surg Educ 76(4):1107–1115
49. Plazak J, DiGiovanni DA, Collins DL, Kersten-Oertel M (2019) Cognitive load associations when utilizing auditory display within image-guided neurosurgery. Int J Comput Assist Radiol Surg 14(8):1431–1438
50. Leff DR, Yongue G, Vlaev I, Orihuela-Espina F, James D, Taylor MJ et al (2017) “Contemplating the Next Maneuver”: functional neuroimaging reveals intraoperative decision-making strategies. Ann Surg 265(2):320–330
51. Modi HN, Singh H, Orihuela-Espina F, Athanasiou T, Fiorentino F, Yang GZ et al (2018) Temporal stress in the operating room: brain engagement promotes “coping” and disengagement prompts “choking.” Ann Surg 267(4):683–691
52. Leff DR, Leong JJH, Aggarwal R, Yang G-Z, Darzi A (2008) Could variations in technical skills acquisition in surgery be explained by differences in cortical plasticity? Ann Surg 247(3):540–543
53. Suárez JX, Gramann K, Ochoa JF, Toro JP, Mejía AM, Hernández AM (2022) Changes in brain activity of trainees during laparoscopic surgical virtual training assessed with electroencephalography. Brain Res 1783:147836
54. Kelly AMC, Garavan H (2005) Human functional neuroimaging of brain changes associated with practice. Cereb Cortex 15(8):1089–1102
55. Galvin D, Toth AJ, O’Reilly B, O’Sullivan R, Campbell MJ (2023) M1 transcranial direct current stimulation augments laparoscopic surgical skill acquisition. Sci Rep 13(1):13731
56. Shafiei SB, Shadpour S, Intes X, Rahul R, Toussi MS, Shafqat A (2023) Performance and learning rate prediction models development in FLS and RAS surgical tasks using electroencephalogram and eye gaze data and machine learning. Surg Endosc. https://doi.org/10.1007/s00464-023-10409-y
57. Armstrong BA, Nemrodov D, Tung A, Graham SJ, Grantcharov T (2023) Electroencephalography can provide advance warning of technical errors during laparoscopic surgery. Surg Endosc 37(4):2817–2825
58. Natheir S, Christie S, Yilmaz R, Winkler-Schwartz A, Bajunaid K, Sabbagh AJ et al (2023) Utilizing artificial intelligence and electroencephalography to assess expertise on a simulated neurosurgical task. Comput Biol Med 152:106286

59. Shafiei SB, Shadpour S, Mohler JL, Sasangohar F, Gutierrez C, Seilanian Toussi M et al (2023) Surgical skill level classification model development using EEG and eye-gaze data and machine learning algorithms. J Robot Surg. https://doi.org/10.1007/s11701-023-01722-8
60. Atesok K, Hurwitz S, Anderson DD, Satava R, Thomas GW, Tufescu T et al (2019) Advancing simulation-based orthopaedic surgical skills training: an analysis of the challenges to implementation. Adv Orthop 2019:2586034
61. Windsor JA (2009) Role of simulation in surgical education and training. ANZ J Surg 79(3):127–132