**Systematic Review Paper Submission to Surgery**

**Title of Manuscript**

**A Decade of Imaging Surgeons' Brain Function (Part II): A Systematic Review of Applications for Technical and Non-Technical Skills Assessment**

**Article Authors**

Hemel Narendra Modi MRCS MEd1, Harsimrat Singh PhD1*,* Guang-Zhong Yang PhD FREng2*,* Ara Darzi MD, FRCS, FACS, FMedSci, HonFREng1, 2, Daniel Richard Leff FRCS MS (Hons) PhD1, 2

**Author Affiliation(s)**

1Department of Surgery and Cancer, Imperial College London, United Kingdom

2Hamlyn Centre for Robotic Surgery, Imperial College London, United Kingdom

**Corresponding author & Request for Reprints**

Daniel R. Leff, Department of Surgery & Cancer, Imperial College London, St Mary’s Hospital Campus, 10th Floor, QEQM Building, Praed Street, London W2 1NY

Phone: +44(0)20 3312 1310, Fax: +44(0)20 3312 6950, Email: d.leff@imperial.ac.uk

**Conflicts of Interest and Sources of Funding**

The work was funded through the support of the Imperial NIHR Biomedical Research Centre and the Imperial Cancer Research UK Centre. The authors have no conflicts of interest to declare.

**STRUCTURED ABSTRACT**

*Background:* Functional neuroimaging technologies enable assessment of operator brain function, and can deepen our understanding of skills learning, ergonomic optima and cognitive processes in surgeons. Whilst there has been a critical mass of data detailing surgeons’ brain function, this literature has not been systematically reviewed.

*Methods:* A systematic search of original neuroimaging studies assessing surgeons’ brain function, and published up until November 2016, was conducted using Medline, Embase and PsycINFO databases.

*Results:* Twenty-seven studies fulfilled the inclusion criteria, including three feasibility studies, fourteen studies exploring the neural correlates of technical skill acquisition, and the remainder investigating brain function in the context of intraoperative decision-making (n=1), neurofeedback training (n=1), robot-assisted technology (n=5), and surgical teaching (n=3). Early stages of learning open surgical tasks (knot-tying) are characterised by prefrontal cortical (PFC) activation which subsequently attenuates with deliberate practice. However, with complex laparoscopic skills (intra-corporeal suturing), PFC engagement requires substantial training and attenuation occurs over a longer time-course, following years of refinement. Neurofeedback and interventions that improve neural efficiency may enhance technical performance and skills learning.

*Conclusions:* Imaging surgeons’ brain function has identified neural signatures of expertise which might help inform objective assessment and selection processes. Interventions which improve neural efficiency may target skill-specific brain regions and augment surgical performance.

**ABBREVIATIONS**

EEG: Electroencephalography

fNIRS: Functional near-infrared spectroscopy

fMRI: Functional magnetic resonance imaging

PET: Positron emission tomography

PFC: Prefrontal cortex

**INTRODUCTION**

Neuroimaging has the potential to illuminate our understanding in areas of surgical training and practice for which there remain on-going challenges and controversies, such as expertise development and skills training1-14. However, assessment of surgeons’ brain function was quiescent until approximately a decade ago, when advances in functional neuroimaging techniques made assessments of operator brain function during surgery both tangible and feasible (see Part I). Our team and other investigators have capitalised on developments that enable subjects to be freely mobile to execute complex manoeuvres and allow assessments of brain function in natural and challenging environments. Moreover, there is a critical mass of published research describing the added value of operator brain function in improving surgical training and enhancing patient safety, but which to date has not been reviewed in detail. The current review seeks to address this gap in the literature, specifically focusing on the following research questions:

1. Are there differences in neuroimaging signals obtained from novice and expert surgeons during technical and non-technical skill performance, in which regions of the brain are these differences observed, and how does skills training influence these signals?
2. How do interventions designed to enhance skill acquisition and/or surgical performance modulate brain signals in surgeons?

**METHODS**

The PRISMA methodology was followed to conduct a systematic database search of Medline, Embase and PsycINFO up to November 2016. Appropriate keywords and MeSH terms were identified and combined using suitable Boolean operators (Supplementary Material). Additional articles were retrieved from bibliographic searches. The search was limited to studies on humans and English language publications. Studies were included for review based on the following inclusion criteria: (a) published original studies, (b) study participants were surgeons, (c) the dependant variable was brain function measured using established neuroimaging modalities, and (d) the independent variable was any technical or non-technical skill, or a skill-enhancing intervention. Retrieved articles were independently analysed by two of the authors (H.N.M. and H.S.) and disagreements over inclusion or exclusion were resolved by consensus. A critical synthesis of the extracted data was undertaken to delineate the brain regions crucial for successful performance of specific technical and non-technical skills in surgery, as well as to assess the impact of specific interventional strategies on brain signals and surgical performance.

**RESULTS**

**Data Extraction**

As illustrated in Figure 1, twenty-seven articles were eligible for inclusion and comprised feasibility studies (n=3), investigations of technical skill acquisition (n=14), intraoperative decision-making (n=1), neurofeedback (n=1), robot-assisted technology (n=5), and surgical teaching (n=3) (Supplementary Material Table 1).

**Technical Skills and Brain Function**

Functional neuroimaging data successfully acquired during open15 and laparoscopic16, 17 task paradigms is repeatable15, reliable15 and resistant to motion artefact17. Variations in brain activation associated with technical expertise, and which subserve motor learning, are discussed according to the brain region of interest.

*Prefrontal Cortex (PFC)*

Changes in PFC activation that accompany expertise development and motor learning in surgery depend upon task complexity (Figure 2). With ‘simple’ tasks, such as open knot-tying, novices exhibit greater PFC activation than expert surgeons1. However, following a period of training and practice, the prefrontal response of the ‘trained’ novices attenuates as performance improves3, 4. For more complex skills, such as laparoscopy, prefrontal engagement requires greater practice, and attenuation requires many years of refinement. For example, Ohuchida et al10 demonstrated that novices failed to activate the PFC during a naïve phase of laparoscopic suturing (i.e. training-naive), but did so following a 2-hour training session10. Similarly, Shetty et al6 observed that anticipated PFC attenuation failed to accompany improvements in laparoscopic suturing skill despite 8 hours of training and near-expert levels of performance upon training cessation6. Indeed, for laparoscopic skills, residents require on average four to five times greater PFC activation than experts14, suggesting that prefrontal demands are alleviated only through years of refinement.

*Motor and Parietal Areas*

The primary motor cortex (M1), the supplementary motor area (SMA), and the premotor area (PMA) are responsible for planning and execution of voluntary movements18. Data from fMRI13, PET12 and fNIRS14 experiments during open13 and laparoscopic12, 14 skills suggest less M1 activation in expert surgeons compared to novices, implying learning-related movement efficiency (e.g. reduced path-length, fewer unnecessary movements)19, 20 is mirrored in efficiencies in motor regions in the brain. In contrast, comparatively greater activation in motor and parietal regions has been demonstrated in experts during motor imagery13 and surgical task planning11.

*Cerebellum*

The cerebellum plays an important role in both motor coordination and cognitive function, such as veridical visual perception21. In the study by Duty et al12 , observing laparoscopic tasksled to enhanced activation of the cerebellum in expert surgeons and relative deactivation in novices12, implying this region may be part of an action observation network21 and be implicated in the storage of an acquired skill in experts18.

*Global Cognitive Function*

Electroencephalography has been used to derive scores for “cognitive engagement”, “mental workload” and “mental state” in novice (beginner), intermediate (competent and proficient) and expert surgeons performing robotic surgical tasks of varying complexity on the da Vinci Surgical System8. Greater expertise correlated with lower mental workload and less cognitive engagement (Figure 2)8. Expert surgeons were found to utilise different cognitive processes based on need during an operation9. For example, manoeuvres associated with greater uncertainty and ambiguity (e.g. ‘adhesiolysis’) led to greater cognitive engagement scores than for automated and repetitive skills (e.g. ‘anastomosis’)9. However, the precise definitions of “cognitive engagement”, “mental workload” and “mental state” were not clarified8, 9, and given the poor spatial resolution of EEG it is challenging to map different cognitive states to brain regions of interest.

Studies interrogating technical skill acquisition are hampered by small sample sizes, and several studies included ten or fewer subjects8, 11-13. In our own experience, imaging modalities such as EEG and fNIRS require a considerable amount of set-up time, constraining the number of attendings. Age-related cortical atrophy can affect the optical properties of brain tissue, particularly depth of penetration and optical pathlength22, and less marked task-induced cortical activation is a feature of older populations23, 24. However, the difference in mean age between ‘young’ and ‘old’ cohorts in these studies was nearly forty years23, 24, whilst the difference in mean age between expert and novice surgeons in the neuroimaging studies reviewed ranged between 9.4 to 24.4 years4, 5, 12.

**Non-Technical Skills and Brain Function**

*Intra-operative Decision-Making*

Functional neuroimaging has been used to expose differences in decision-making (DM) systems used by novice and experts surgeons during surgery, based on patterns of prefrontal activation25. When observing simulated surgical scenes in the absence of operative cues (“unprimed” scenes – in which the next operative manoeuvre is hidden), novice surgeons use effortful DM processes that require increased attention and concentration, and significant activation in the dorsolateral, ventrolateral and medial PFC25. However, decision cues (“primed” scenes – in which the next operative manoeuvre is apparent) leads to acceptance of the observed decision and prefrontal disengagement, suggesting reduced attention25. In contrast, no difference in PFC activation between primed and unprimed scenarios is observed amongst more experienced surgeons25.

**Performance-Enhancing Interventions**

*Neurofeedback*

Neurofeedback involves the self-regulation of electrical signals from the brain in order to enhance function, maximise performance and minimise errors26, 27. In the study by Ros et al28, EEG-based neurofeedback was employed in an attempt to modulate technical performance during a simulated cataract operation. Twenty ophthalmic trainees received either sensory motor rhythm-theta (SMR-T) or alpha-theta (AT) feedback training28. SMR-T training aims to elevate sensorimotor rhythm (12-15Hz) and depress theta activity (4-7Hz), reducing sensorimotor interference in basal ganglia/thalamocortical circuits29 and enhancing attention and perception26. Indeed, SMR-T training led to a significant improvement in technical performance and a reduction in reported anxiety (Figure 2)28. In contrast, neither of these outcomes changed significantly in the AT group28, suggesting that SMR-T neurofeedback may improve surgical performance by enhancing attentional executive function. However, the authors were unable to report any long-term follow-up data to demonstrate whether neurofeedback-related improvements in performance were retained.

*Laparoscopy versus Robotic Surgery and Robot-Assisted Intervention*

Investigators have begun to explore the effect of robotic surgical platforms on operator cognition in order to help realise the neuroergonomic advantages over conventional laparoscopy. The intraparietal sulcus (IPS) plays a vital role in visuo-spatial attention and hand-eye coordination31. Miura et al32 observed maximum IPS activation at a 75° optical axis-to-target view angle and suggested this camera angle to be optimal for robotic surgery32. Similarly, Bocci et al33, observed stronger intra-hemispheric EEG coherence between motor areas with the laparoscopic approach in the theta and lower alpha bands, and greater inter-hemispheric EEG coherence with the robotic approach in the beta and upper alpha bands (Figure 2)33. Since functional interactions in alpha and beta bands are vital for visual perception and attention34, these results may imply that robotic platforms enhance higher cognitive skills to greater extent than laparoscopy.

Novel and emerging assistive technologies designed to enhance robotic surgical performance are now being investigated for neuroergonomic advantages. For example, James et al35 observed that gaze-contingent motor control, in which robotic instrument control is constrained by the gaze of the user36, resulted in greater improvements in performance36, more rapid attenuation of PFC activity and focusing of parietal cortex (PC) activation37 compared to the free-hand learners.

*Surgical Teaching*

The impact of tele-monitoring on trainee’s brain function has also been investigated using neuroimaging techniques. For example, in the study by Leff et al38, trainer gaze behaviour was utilised to visually guide residents performing a simulated biopsy on a robotic platform38. Compared to verbal guidance, visual guidance resulted in more focused visual search patterns, less occipitoparietal activation and superior performance (i.e. greater number of successful biopsies, shorter path-length)38. As Figure 2 illustrates, improvements in technical performance and neural efficiency have also been observed when surgical skills are learned using random practice schedules (tasks presented in a non-sequential unpredictable order)39 or implicit learning strategies (low conscious awareness of learning taking place)40.

**DISCUSSION**

This systematic review critically evaluates the findings from published neuroimaging studies involving surgeons, with consideration as to how the results may benefit the wider surgical community. The majority of studies have focused on surgical skill acquisition1-14, however intraoperative decision-making25, neurofeedback, and the impact of new surgical technologies on operator cognition32, 33 have also been investigated, and these merit separate discussion. Table 1 summarises some of the key findings with respect to brain region and the implications for surgical practice.

**Technical Skill Acquisition**

There is substantial evidence regarding the contribution of the PFC during novel motor skills acquisition1-4, 6, 10, given its importance in attentional processes, sensorimotor integration, working memory, and learning by trial and error18. The PFC is recruited to a greater extent in novice compared to expert surgeons1, 3, 4, and PFC attenuation accompanies the acquisition of complex bimanual co-ordination tasks2-4. Similarly, automated performance in expert surgeons in whom skills are ingrained with years of repeated and refined execution, is less reliant on the PFC1, 3. The lack of PFC attenuation after periods of training on more complex laparoscopic drills despite a significant improvement in dexterity toward ‘expert’ levels6, suggests neuroplastic shifts in brain activation might better reflect differences between ‘trained’ and ‘expert’ surgeons beyond the attainment of technical proficiency benchmarks.

Interestingly, Ohuchida et al10 found that without training, novices failed to exhibit PFC responses during laparoscopic tasks, affording them a pattern of brain activation similar to experts10. Unlike experts, in whom PFC attenuation likely reflects skills automation, the lack PFC recruitment in naïve surgeons may herald a need for cognitive training. Tasks which are too difficult may preclude novices from developing a cognitive strategy for successful motor performance, requiring them to rely more on luck rather than skill during initial attempts5. Therefore, distinguishing an expert surgeon from a naïve learner on the basis of PFC activation alone may be challenging, and improved discrimination may require analysis of activation from other motor regions (e.g. M1, cerebellum) and/or connectivity analysis. Indeed, recent work suggests that frontal lobe *connectivity* may be more sensitive than changes in *activation* in discriminating novice and expert operators during laparoscopic tasks7. Specifically, stronger connectivity in prefrontal and premotor regions is observed among novice surgeons, whereas experts display greater motor connectivity7. Moreover, reduced motor activation in line with surgical expertise is concordant with findings from fMRI studies involving professional pianists in whom less activation in primary and secondary motor areas is observed compared with musically-naïve controls during finger movement tasks41, and suggests that consolidation of skills results in greater neural efficiency in motor regions, allowing experts to focus on the finer aspects of motor control as the primary task is more ingrained.

Overall the changes observed support the hypothesis that the PFC functions as a ‘scaffold’ during the early stages of learning, which is then phased out as expertise develops42. For assessment purposes, attenuated PFC and M1 responses during task performance would suggest learning success, whereas sustained PFC and/or M1 activation might identify those in need of further training43.

**Intraoperative Decision-Making (DM)**

Expertise in DM is difficult to assess because the internal thought processes that underpin action selection do not have quantifiable behavioural correlates, and hence functional neuroimaging may provide a way of objectively assessing DM processes. Novices are characterised by excessive prefrontal activation at times of uncertainty which suggests they engage in goal-directed effortful DM processes that require attention and mental effort25. In contrast, experts use habitual intuitive DM strategies in which solutions are selected from a repertoire of implicit knowledge or experience, and which is characterised by reduced PFC activation25. Neural responses to DM scenarios may be utilised in the assessment of DM skill or to coach improvement, with excessive prefrontal activation indicating a novice surgical decision-maker and diminished activation characterising an expert.

**Neurofeedback and Neural Efficiency**

Assistive technologies and specific learning schedules improve technical performance of surgeons, enhance neural efficiency and facilitate the development of an ‘expert’ pattern of brain activation35, 37, 40. From the reviewed literature, researchers are using operator brain function in three distinct approaches. Firstly, there is limited evidence that certain neural feedback regimens (e.g. SMR-T training) may enhance technical skills28, however there is no data describing the effect of feedback on changes in brain activation or neural efficiency. Although more studies are required, neurofeedback may optimise learning of complex surgical procedures that require integration of cognitive and sensorimotor skills, critical in an era of condensed training time. Secondly, behavioural interventions such as implicit learning strategies40, random practice schedules39 and expert gaze-assistance38 appear to modulate the way in which learning progresses and may improve operator neural efficiency and performance. Finally, technological approaches (e.g. gaze stabilisation) may shorten learning curves as well as minimise costs and improve efficiency of operator brain networks35.

**Limitations**

Due to the heterogeneity in study designs, task paradigms, imaging modalities and study populations, quantitative pooling of data as a meta-analysis was not feasible. Standard experimental and analytical frameworks need to be developed before a meta-analysis is achievable. Moreover, current quality scoring systems (e.g. STROBE44), cannot be easily extrapolated to brain imaging research in surgeons. Nonetheless, based on our own experience using fNIRS22, there are a number of criteria which should be adhered to when conducting neuroimaging research, which may form the basis of a novel and specific quality scoring system (see Part I). The absence of any power calculations or sample size estimations in the reviewed studies is likely to be due to the limited previous literature in this emerging field of research. Variations in heart rate and blood pressure during cognitively demanding tasks are known to influence cerebral blood flow and HbO2 concentration45, and yet in the reviewed literature, systemic physiology was rarely recorded.

**CONCLUSIONS & FUTURE DIRECTIONS**

Functional neuroimaging is able to identify the neural correlates of surgical expertise and may inform future selection and assessment of surgeons. Neuromonitoring technologies enable the impact of training interventions and biofeedback techniques to be assessed as to the degree to which they accelerate learning, enhance performance and improve neural efficiency. Intra-operative stress can have a detrimental impact on surgical performance46, however objective methods for measuring mental workload in surgeons are lacking. Future work could focus on the assessment of brain function to expose the dynamic relationship between mental workload and executive control processing, helping to characterise the neurobiology that may underpin “choking under pressure”47 in the operating room.

**CONFLICT OF INTEREST & FINANCIAL DISCLOSURE**

We would like to acknowledge the work was funded through the support of the Imperial NIHR Biomedical Research Centre and the Imperial Cancer Research UK Centre. The authors declare no conflicts of interest.

|  |
| --- |
| TABLE 1. Summary of findings by brain region and implications for surgical training and practice. |
| Brain Regions | **Summary of Findings** | **Implications** |
| Prefrontal Cortex (PFC) | ***Technical Skills:**** Activation increases in early stages of learning and attenuates with practice
* Practice-related attenuation in activation takes longer with complex laparoscopic tasks compared to simple open tasks

***Intraoperative Decision-Making:*** | * PFC functions as a ‘scaffold’ for motor learning
* Assessment of PFC activity may help establish whether a technical skill has been consolidated and ingrained
 |
| * Increased activation in novices during ‘unprimed’ intraoperative decisions
* Deactivation in novices during ‘primed’ intraoperative decisions
 | * Novices use effortful decision-making processes, whereas experts engage in habitual decision-making
* PFC activity may provide an objective marker for decision-making expertise
 |
| Primary Motor Cortex (M1) | * Less activation in experts than novices during motor skill execution
* Greater activation in experts than novices during surgical task planning
* Stronger intra-hemispheric co-activation between motor areas in laparoscopy, but greater inter-hemispheric co-activation with robotic surgery.
 | * Greater neural efficiency in M1 suggests task automaticity, allowing expert surgeons to focus on finer aspects of motor control
* Robotic platforms enhance higher cognitive skills more than laparoscopy
 |
| Primary Visual Cortex | * Increased BOLD activity (fMRI) in experts versus novices during task imagery
 | * Expert surgeons have greater perceptual skill compared to novices
 |
| Cerebellum | * Greater activation in experts versus novices during task observation
 | * Cerebellum is important for storage of acquired skill in expert surgeons
 |
| Intraparietal sulcus | * Maximum activation occurs at a 75° camera angle in robotic surgery
 | * Attention should be paid to operating room setup to optimise the neuroergonomics for the surgeon
 |
| Parietal Cortex | * Expert visual guidance during skills training leads to reduced activation in the occipitoparietal cortex and superior performance of residents during a simulated robotic biopsy task.
 | * Visual guidance from a trainer reduces the cognitive burden of residents during task performance, thereby liberating attentional resources that can be used to focus on other safety-critical aspects of a procedure.
 |

**FIGURE LEGENDS**

**FIGURE 1. PRISMA diagram of systematic search strategy.**

**FIGURE 2. Summary of neuroimaging studies investigating surgical skill acquisition and expertise development.** Above: Longitudinal changes in PFC activation with skill learning during three different surgical tasks (open knot tying, laparoscopic knot tying and a natural orifice task), based on results from fNIRS studies1, 3, 5, 6, 10. Attenuation of PFC activation occurs following training and practice on a simple open knot tying task3. With more complex tasks (e.g. laparoscopic knot tying or natural orifice tasks), similar changes in the PFC occur only after an extended period of practice5, 6, 10. Below: Findings from learning-related EEG studies. Guru et al8: Expertise in robotic surgical tasks can be determined from measurements of cognitive function (mean scores shown); Zhu et al40: Implicit motor learning results in greater neural efficiency in novices during a laparoscopic tracking task, highlighted by less co-activation between motor planning and verbal-analytic regions; Ros et al28: Lower SMR-Theta ratio is associated with low improvers among ophthalmic trainees performing a simulated cataract operation, suggesting less brain computational power with better skill acquisition; Bocci et al33: Robotic suturing tasks elicits a larger representation of upper alpha and beta frequencies compared to laparoscopic suturing.

**REFERENCES**

1. Leff DR, Orihuela-Espina F, Atallah L, Darzi A, Yang GZ. Functional near infrared spectroscopy in novice and expert surgeons--a manifold embedding approach. Medical image computing and computer-assisted intervention : MICCAI International Conference on Medical Image Computing and Computer-Assisted Intervention. 2007;10:270-7.

2. Leff DR, Orihuela-Espina F, Leong J, Darzi A, Yang GZ. Modelling dynamic fronto-parietal behaviour during minimally invasive surgery--a Markovian trip distribution approach. Medical image computing and computer-assisted intervention : MICCAI International Conference on Medical Image Computing and Computer-Assisted Intervention. 2008;11:595-602.

3. Leff DR, Orihuela-Espina F, Atallah L, Athanasiou T, Leong JJ, Darzi AW, et al. Functional prefrontal reorganization accompanies learning-associated refinements in surgery: a manifold embedding approach. Computer aided surgery : official journal of the International Society for Computer Aided Surgery. 2008;13:325-39.

4. Leff DR, Elwell CE, Orihuela-Espina F, Atallah L, Delpy DT, Darzi AW, et al. Changes in prefrontal cortical behaviour depend upon familiarity on a bimanual co-ordination task: an fNIRS study. NeuroImage. 2008;39:805-13.

5. James DR, Orihuela-Espina F, Leff DR, Sodergren MH, Athanasiou T, Darzi AW, et al. The ergonomics of natural orifice translumenal endoscopic surgery (NOTES) navigation in terms of performance, stress, and cognitive behavior. Surgery. 2011;149:525-33.

6. Shetty K, Leff D, Orihuela-Espina F, Yang G, Darzi A. Persistent prefrontal engagement despite improvements in laparoscopic technical skill. JAMA Surgery. 2016.

7. Andreu-Perez J, Leff DR, Shetty K, Darzi A, Yang GZ. Disparity in Frontal Lobe Connectivity on a Complex Bimanual Motor Task Aids Classification of Operator Skill Level. Brain connectivity. 2016.

8. Guru KA, Esfahani ET, Raza SJ, Bhat R, Wang K, Hammond Y, et al. Cognitive skills assessment during robot-assisted surgery: separating the wheat from the chaff. BJU international. 2015;115:166-74.

9. Guru KA, Shafiei SB, Khan A, Hussein AA, Sharif M, Esfahani ET. Understanding Cognitive Performance During Robot-Assisted Surgery. Urology. 2015;86:751-7.

10. Ohuchida K, Kenmotsu H, Yamamoto A, Sawada K, Hayami T, Morooka K, et al. The frontal cortex is activated during learning of endoscopic procedures. Surgical endoscopy. 2009;23:2296-301.

11. Chennat JS, Schiel M, Waxman I, Small S. Functional MRI (fMRI) comparison novice and expert endoscopists: are we all wired the same? Gastrointestinal Endoscopy. 2010;71:273.

12. Duty BMD, Andonian SMD, Ma YP, Peng SP, Shapiro EMD, Dhawan VP, et al. Correlation of Laparoscopic Experience With Differential Functional Brain Activation: A Positron Emission Tomography Study With Oxygen 15-Labeled Water. Archives of Surgery. 2012;147:627-32.

13. Morris MC, Frodl T, D'Souza A, Fagan AJ, Ridgway PF. Assessment of competence in surgical skills using functional magnetic resonance imaging: a feasibility study. Journal of surgical education. 2015;72:198-204.

14. Nemani A, Intes X, De S. Surgical motor skill differentiation via functional near infrared spectroscopy. Biomedical Engineering Conference (NEBEC), 2015 41st Annual Northeast2015. p. 1-2.

15. Leff D, Koh PH, Aggarwal R, Leong J, Deligianni F, Elwell C, et al. Optical Mapping of Frontal Cortex in Surgical Knot-Tying Task, Feasibility Study. Medical Imaging and Augmented Reality: Springer-Verlag Berlin Heidelberg; 2006. p. 140-7.

16. Bahrami P, Graham SJ, Grantcharov TP, Cusimano MD, Rotstein OD, Mansur A, et al. Neuroanatomical correlates of laparoscopic surgery training. Surgical endoscopy. 2014;28:2189-98.

17. Bahrami P, Schweizer TA, Tam F, Grantcharov TP, Cusimano MD, Graham SJ. Functional MRI-compatible laparoscopic surgery training simulator. Magnetic resonance in medicine : official journal of the Society of Magnetic Resonance in Medicine / Society of Magnetic Resonance in Medicine. 2011;65:873-81.

18. Halsband U, Lange RK. Motor learning in man: A review of functional and clinical studies. Journal of Physiology-Paris. 2006;99:414-24.

19. Grantcharov TP, Bardram L, Funch-Jensen P, Rosenberg J. Learning curves and impact of previous operative experience on performance on a virtual reality simulator to test laparoscopic surgical skills. The American Journal of Surgery. 2003;185:146-9.

20. Datta V, Chang A, Mackay S, Darzi A. The relationship between motion analysis and surgical technical assessments. The American Journal of Surgery. 2002;184:70-3.

21. Sokolov AA, Gharabaghi A, Tatagiba MS, Pavlova M. Cerebellar engagement in an action observation network. Cerebral cortex (New York, NY : 1991). 2010;20:486-91.

22. Orihuela-Espina F, Leff DR, James DRC, Darzi AW, Yang GZ. Quality control and assurance in functional near infrared spectroscopy (fNIRS) experimentation. Physics in Medicine and Biology. 2010;55:3701-24.

23. Herrmann MJ, Walter A, Ehlis AC, Fallgatter AJ. Cerebral oxygenation changes in the prefrontal cortex: Effects of age and gender. Neurobiology of Aging. 2006;27:888-94.

24. Mehagnoul-Schipper DJ, van der Kallen BF, Colier WN, van der Sluijs MC, van Erning LJ, Thijssen HO, et al. Simultaneous measurements of cerebral oxygenation changes during brain activation by near-infrared spectroscopy and functional magnetic resonance imaging in healthy young and elderly subjects. Hum Brain Mapp. 2002;16:14-23.

25. Leff DR, Yongue G, Vlaev I, Orihuela-Espina F, James D, Taylor MJ, et al. "Contemplating the Next Maneuver": Functional Neuroimaging Reveals Intraoperative Decision-making Strategies. Annals of surgery. 2016.

26. Gruzelier J, Egner T, Vernon D. Validating the efficacy of neurofeedback for optimising performance. Progress in brain research. 2006;159:421-31.

27. Prinzel Iii LJ, Pope AT, Freeman FG. Physiological Self-Regulation and Adaptive Automation. The International Journal of Aviation Psychology. 2002;12:179-96.

28. Ros T, Moseley MJ, Bloom PA, Benjamin L, Parkinson LA, Gruzelier JH. Optimizing microsurgical skills with EEG neurofeedback. BMC neuroscience. 2009;10:87.

29. Sterman MB, Egner T. Foundation and practice of neurofeedback for the treatment of epilepsy. Applied psychophysiology and biofeedback. 2006;31:21-35.

30. Aftanas LI, Golocheikine SA. Human anterior and frontal midline theta and lower alpha reflect emotionally positive state and internalized attention: high-resolution EEG investigation of meditation. Neurosci Lett. 2001;310:57-60.

31. Grefkes C, Fink GR. The functional organization of the intraparietal sulcus in humans and monkeys. Journal of Anatomy. 2005;207:3-17.

32. Miura S, Kobayashi Y, Kawamura K, Nakashima Y, Fujie MG. Brain activation in parietal area during manipulation with a surgical robot simulator. International journal of computer assisted radiology and surgery. 2015;10:783-90.

33. Bocci T, Moretto C, Tognazzi S, Briscese L, Naraci M, Leocani L, et al. How does a surgeon's brain buzz? An EEG coherence study on the interaction between humans and robot. Behav Brain Funct. 2013;9:14.

34. Howells FM, Stein DJ, Russell VA. Perceived mental effort correlates with changes in tonic arousal during attentional tasks. Behavioral and Brain Functions. 2010;6.

35. James DR, Leff DR, Orihuela-Espina F, Kwok KW, Mylonas GP, Athanasiou T, et al. Enhanced frontoparietal network architectures following "gaze-contingent" versus "free-hand" motor learning. NeuroImage. 2013;64:267-76.

36. Mylonas GP, Kwok KW, James DR, Leff D, Orihuela-Espina F, Darzi A, et al. Gaze-Contingent Motor Channelling, haptic constraints and associated cognitive demand for robotic MIS. Medical image analysis. 2012;16:612-31.

37. James DR, Orihuela-Espina F, Leff DR, Mylonas GP, Kwok KW, Darzi AW, et al. Cognitive burden estimation for visuomotor learning with fNIRS. Medical image computing and computer-assisted intervention : MICCAI International Conference on Medical Image Computing and Computer-Assisted Intervention. 2010;13:319-26.

38. Leff DR, James DRC, Orihuela-Espina F, Kwok KW, Sun LW, Mylonas G, et al. The impact of expert visual guidance on trainee visual search strategy, visual attention and motor skills. Frontiers in Human Neuroscience. 2015;9.

39. Shewokis PA, Ayaz H, Panait L, Liu Y, Syed M, Greenawald L, et al. Brain-in-the-Loop Learning Using fNIR and Simulated Virtual Reality Surgical Tasks: Hemodynamic and Behavioral Effects. In: Schmorrow DD, Fidopiastis MC, editors. Foundations of Augmented Cognition: 9th International Conference, AC 2015, Held as Part of HCI International 2015, Los Angeles, CA, USA, August 2-7, 2015, Proceedings. Cham: Springer International Publishing; 2015. p. 324-35.

40. Zhu FF, Poolton JM, Wilson MR, Hu Y, Maxwell JP, Masters RS. Implicit motor learning promotes neural efficiency during laparoscopy. Surgical endoscopy. 2011;25:2950-5.

41. Krings T, Topper R, Foltys H, Erberich S, Sparing R, Willmes K, et al. Cortical activation patterns during complex motor tasks in piano players and control subjects. A functional magnetic resonance imaging study. Neurosci Lett. 2000;278:189-93.

42. Petersen SE, van Mier H, Fiez JA, Raichle ME. The effects of practice on the functional anatomy of task performance. Proceedings of the National Academy of Sciences of the United States of America. 1998;95:853-60.

43. Leff DR, Leong JJ, Aggarwal R, Yang GZ, Darzi A. Could variations in technical skills acquisition in surgery be explained by differences in cortical plasticity? Annals of surgery. 2008;247:540-3.

44. von Elm E, Altman DG, Egger M, Pocock SJ, Gøtzsche PC, Vandenbroucke JP. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) Statement: Guidelines for reporting observational studies. International Journal of Surgery. 2014;12:1495-9.

45. Tachtsidis I, Leung TS, Chopra A, Koh PH, Reid CB, Elwell CE. False positives in functional near-infrared topography. Adv Exp Med Biol. 2009;645:307-14.

46. Arora S, Sevdalis N, Nestel D, Woloshynowych M, Darzi A, Kneebone R. The impact of stress on surgical performance: a systematic review of the literature. Surgery. 2010;147:318-30, 30 e1-6.

47. Lee TG, Grafton ST. Out of control: diminished prefrontal activity coincides with impaired motor performance due to choking under pressure. NeuroImage. 2015;105:145-55.