Detecting Mental Workload in Surgical Teams Using a Wearable Single-Channel Electroencephalographic Device

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OBJECTIVE: To assess the sensitivity of an electroencephalographic (EEG)-based index, the prefrontal beta power, to quantify the mental workload in surgeons in real scenarios. Such EEG-based index might offer unique and unbiased measures of overload, a crucial factor when designing learning and training surgical programs.

DESIGN: The experiment followed a $2 \times 2 \times 2$ within subjects design with 3 factors: (1) *Surgical Role* during the surgery (primary surgeon vs. assistant surgeon), (2) the *Surgical Procedure* (laparo-endoscopic single-site [LESS] surgery vs. multiport laparoscopic surgery [MPS]), and (3) the *Suturing Techniques* (interrupted vs. continuous suture).

SETTING: The study was carried out at the Advanced Multi-Purpose Simulation and Technological Innovation Complex situated at IAVANTE (Granada, Spain).

METHODS: Four surgical teams (primary surgeon and assistant surgeon, experts in MPS) performed 8 surgical exercises on porcine models, under different task complexities. They performed 2 suturing techniques (continuous and interrupted), employing a low complex procedure (MPS) and a high complex procedure (LESS). Surgeons acted as the primary surgeon during half of the exercises, and, as the assistant surgeon, during the rest of them. Simultaneously, we monitored EEG prefrontal EEG beta power spectra of both surgeons, using 2 synchronized wearable EEG devices. We also collected performance and subjective data.

RESULTS: Surgical complexity modulated prefrontal beta power. LESS surgery caused significant higher prefrontal beta power for both suturing techniques for both surgical roles which indicates higher demands than MPS. Perceived task complexity, overall surgical evaluation, and laparoscopic execution time confirmed EEG-based results. Finally, subjective ratings of surgical complexity differentiated between surgical roles within the same exercise, even when prefrontal beta power did not.

CONCLUSIONS: To detect mental overload when surgeons are engaged with complex surgeries, real or simulated, is still guesswork. EEG-based indices have great potential as objective and nonintrusive measures to assess mental overload in surgeons. Furthermore, EEG-based indices might play a relevant role in monitoring surgeons and residents' cognitive state during their training. (J Surg Ed 76:1107−1115. © 2019 Association of Program Directors in Surgery. Published by Elsevier Inc. All rights reserved.)

KEY WORDS: Surgical skills assessment, patient safety, neuroergonomics, coordination, brain synchrony

COMPETENCIES: Practice-Based Learning and Improvement

INTRODUCTION

Surgery is one of the most challenging careers in medicine. It requires both great physical and mental effort, and demands a great level of concentration during long

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stressful events.[1] Mental overload in surgeons, due to either excessive surgical task demands (i.e., complexity level) or the lack of sufficient physical/mental resources (i.e., fatigue level), is a critical factor in surgery. Mistakes at any point of the surgical process pose a serious threat to patient safety as well as for the wellbeing of the surgeon.[2-4] Providing useful tools for detecting mental overload and avoiding such situations is desirable,[3,4] especially for residents. A greater understanding of the mental (over)load imposed by the surgical environment would be particularly helpful to guide the design of learning and training programs.[5] However, detecting mental overload in surgeons, when engaging in high-risk environments such as the operating theatre, is still guesswork. There are few real-time cues available to the mentor (e.g., communication's degradation) to assess how safely the trainee is interacting with the patient and the surgical team.[6] Consequently, effective complementary monitoring aids to assess mental overload are needed.

EEG-based technology offers valid and sensitive research tools to monitor the cognitive state in surgeons, including mental overload. Its use during surgical training might improve the resident's learning curve by enhancing skill assessment methods.[7] Furthermore, thanks to recent technological advances, recording equipment has become increasingly reliable, nonintrusive, and less bulky. These developments have facilitated the surgeon's acceptance and have increased the possibility to collect data during highly engaging tasks.[8,9] Despite all this, collecting EEG data from surgical operations and highly realistic simulations remains a challenge for researchers (for a recent review, see[10]). Thus, research in this filed is limited.

EEG-based research in nonsurgical scenarios has largely proven the sensitivity of the (frontal) beta EEG power spectrum (hereafter, β-activity) in detecting variations in operator's arousal [11] due to task demands.[12-14] As the task demands increase, the level of engagement increases,[15] and mental stress intensifies,[16] there is a concomitant increase in β-activity.[17-19] Hence, it seems plausible to assume that β-activity may also reflect nonspecific cognitive states such as mental overload.

In this study, we investigated whether prefrontal β-activity could differentiate the levels of task demands imposed by different surgical procedures of different complexity (high complexity: laparo-endoscopic single-site [LESS] surgery vs. low complexity: multiport laparoscopic surgery [MPS]) while using 2 suturing techniques (interrupted vs. continuous suture). Furthermore, we wonder if prefrontal β-activity could also differentiate between the roles played in the surgical team (primary surgeon vs. assistant surgeon). That is, we wanted to answer the question if prefrontal β-activity could act as a useful cue to indicate surgeon's cognitive state during a realistic training session.

MATERIAL AND METHODS

Ethical Approval

We conducted the study in conformity with the Code of Ethics of the World Medical Association (WMA, Declaration of Helsinki).[20] The experiment was carried out under the guidelines of the University of Granada's Institutional Review Board (IRB approval #899). Written informed consent was obtained from each surgeon prior to the study.

Participants

Four pairs of board certified surgeons (6 females and 2 males) participated in the study (mean age ± standard deviation [SD]: 31.37 ± 2.2 years; average number years of experience ± SD: 6.62 ± 1.78 years). They attended IAVANTE (Andalusian Public Foundation for Progress and Health), in Granada (Spain), for the experiment. Surgical specialties included general surgery (7) and urology (1). All participants had normal or corrected to-normal vision, and were right handed. Overall, participants' average working day length was between 9 and 12 hours (with workweek durations ranging from 41 to 60 hours). They reported an average of 5.8 hours of sleep (SD = 0.99) the night before the experiment. For screening purposes, at the beginning of the experimental session participants filled in the Stanford Sleepiness Scale (SSS) (see *Questionnaires* section).[21] Average SSS score was lower than 3 (SD =±1.06), indicating an optimal quality of alertness at the beginning of the study.[22]

Experimental Design

The experiment followed a $2 \times 2 \times 2$ within subjects design with 3 factors (a) *Surgical Role* during the surgery (primary surgeon vs. assistant surgeon), (b) the *Surgical Procedure* (LESS vs. MPS), and (c) the *Suturing Techniques* (interrupted vs. continuous suture). Thus, each surgeon underwent 8 experimental conditions (8 surgical exercises). Potential learning, practice, and time-on-task effects on the surgical procedures were controlled by a Latin square design across the experimental conditions.

Apparatus and Tasks

Four Spanish domestic pigs (Sus scrofa domestica), one for each surgical team, were used as a model to perform the surgical exercises. Before starting each experimental session, an expert surgeon (author: J.F.R.R.) prepared the anesthetized pig introducing 4 trocars for the experiment (including the TriPort+ for the LESS procedures [Olympus America INC], see Fig. 1). Then he made 8 longitudinal incisions on the surface of the urinary bladder. During the experiment, the surgical team closed these incisions with

stitches using a single, running 6-0 polypropylene suture (interrupted and continuous suturing, see Fig. 1C). The primary surgeon used 2 pairs of Maryland Graspers and suture material, and the assistant surgeon was responsible of the telescope (Hopkins II Autoclavable Laparoscope [10 mm, 0°, 31 cm] with a Telecam One-chip Camera Hed). Once the sutures were completed, the primary surgeon and the assistant surgeon exchanged roles and the surgical exercises were performed again.

Surgical Performance

We allowed a maximum time of 1800 seconds (30 minutes) for each surgical exercise. Then, we used the time to complete each of them (execution time) as an indicator of the effect of task complexity on performance. However, as per the adage "a fast surgeon is not always a good surgeon," the performance of each surgical team was also evaluated by an expert surgeon (author: J.F.R.R.) using a modified version of the rating scale for operative performance.[23]

Questionnaires

All surgeons filled in the SSS before starting the experimental session. This provides a global measure of how alert someone is feeling.[21]

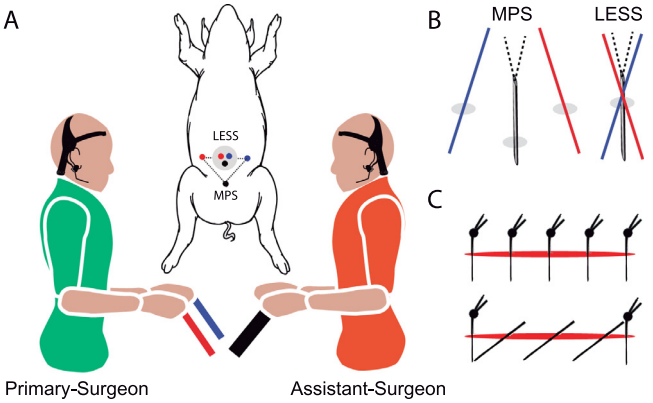

FIGURE 1. (A) A surgical team wearing the mobile EEG-devices while performing the surgical exercises. The green figure denotes the primary surgeon and the orange figure denotes the assistant surgeon. Real porcine models were used for the experiment. (B) The multiport laparoscopic surgery (MPS) triangulated work configuration is represented (on the porcine model) by the 3 small dots connected by a dotted line. The hand instruments are directed from 2 points of entry (colored points) and the telescope is placed just apart from them (black dot). The images were displayed on a 15" LCD TFT monitor facing the surgical team (element not shown). The illustration of trocars placement and the porcine model has been adapted from Consten et al.[30] The laparo-endoscopic single-site (LESS) surgery triangulated laparoscopic work configuration is represented (on the porcine model) by the big grey dot. The hand instruments, as well as the telescope, are directed from a single point of entry. Furthermore, at the point of entry, the hand instrument cross like a chopstick: the surgeon's right hand controls the left instrument (and vice-versa). (C) Two suturing techniques were performed: interrupted suture (upper figure) and continuous suture (lower figure).

After each surgical exercise, surgeons also filled in the NASA-Task Load Index (NASA-TLX), as an indicator of the degree of complexity that they experienced while performing each surgical exercise.[24] The NASA-TLX is a multidimensional rating scale with 6 bipolar dimensions: mental demand, physical demand, temporal demand, own performance, effort, and frustration. The first 3 dimensions (mental demand, physical demand, and temporal demand) reflect task-related factors such as task complexity.[25] The NASA-TLX has a score ranging from 0 (minimum task load) to 100 (maximum task load).[26]

A modified version of the rating scale to evaluate operative performance was used, with scores ranging from 1 (better performance) to 5 (worse performance).[23] This scale was adapted to only focus on the self-assessment of psychomotor skills demonstrated during the surgical exercise.

EEG Recordings and Analyses

We performed simultaneous recordings of the surgical team's EEG activity (at 512 Hz) using 2 NeuroSky MindWave Mobile headsets (NeuroSky Inc., San José, California). These devices use a monopolar montage with a single dry electrode placed at Fp1, according to the International 10/20 system,[27] referenced to the left earlobe (for a detailed description, see[28]). Before electrode placement, the pertinent area of the surgeons' skin was cleaned with a slightly abrasive paste and alcohol. Then, the dry electrode was placed and secured with surgical tape. Both devices sent EEG raw data to 2 recorder units via Bluetooth connections. We collected the raw EEG data into 2 synchronized EDF+ files using an ad-hoc LabVIEW software script (National Instruments Co., Austin, TX). Then, we imported the EDF+ files, preprocessed and analyzed them using Matlab (Mathworks Inc., Natick MA). To remove physiological artifacts from eye activity, we filtered the signal using an order 10 Chebyshev type II filter, with a flat pass band between 0.1 Hz and 45 Hz, and an independent customized algorithm to remove blinks. After that, data from each surgical exercise (and surgeon) were divided into 2-second segments. We considered artifacts and discarded segments with amplitudes out of the (−100, 100 μV) range. Then, we used the fast Fourier transform (window size of 512 samples and overlapping of 256 samples) implemented in the EEGLAB Matlab toolbox to perform spectral analysis and to calculate power spectra of the beta frequency band (13-30 Hz).[29] Finally, we computed the average β-activity for each of the 8 surgical exercises.

Procedure

The experiment was carried out at the Advanced Multi-Purpose Simulation and Technological Innovation Complex situated at IAVANTE. This complex houses several

operating rooms and laparoscopic/robotic simulators, which provide health professionals with general clinical skills and specific surgical training.

Before starting the experiment, each surgical team signed the consent forms, and filled in the SSS. Then, we recorded date of birth, sex, hand dominance, average daily shift length, and weekly worktime, as well as hours of sleep the night before. Afterwards, the surgical team received a demonstration on how to perform the surgical exercises. An expert surgeon (author: J.F.R.R.) with expertise in both surgical procedures (LESS and MPS) performed this demonstration. Then, the surgical team began to operate. After each exercise, surgeons filled in the NASA-TLX and the rating scale for operative performance. The expert surgeon (author: J.F.R.R.) also filled in the rating scale for operative performance, for an external evaluation of the surgical team performance. The surgical team took a short break in the middle of the study. During the break, surgeons could go out from the operating room without leaving the building.

Statistical Analyses

To analyze the overall effect of our manipulation, we performed separate 2 (*Surgical Role*) × 2 (*Surgical Procedure*) × 2 (*Suturing Techniques)* repeated-measures ANOVAs on the main dependent variables (i.e., β-activity, NASA-TLX scores, and operative performance scores). We analyzed the external expert evaluations of the surgical team, as well as the execution times following a 2 (*Surgical Procedure*) × 2 (*Suturing Techniques*) repeated-measures ANOVAs. For all dependent variables, we compared each surgeon/surgical team to him/herself/itself across the surgical exercises, and, therefore, variability between surgeons/surgical teams was part of the error terms. We used the Bonferroni adjustment to correct for multiple comparisons. Finally, the Kolmogorov-Smirnov test and a graphical assessment were used to verify that both data and residuals were normally distributed. Both assumptions were confirmed in all cases. Significance levels were always set at $\alpha \leq 0.05$.

RESULTS

Effectiveness of the Surgical Complexity Manipulation

Surgeons' perceived task complexity (NASA-TLX scores) changed accordingly to our manipulation: the task load experienced by the primary surgeons was higher than the assistant surgeons, $F(1, 7) = 43.31$, $p < 0.001$, and sutures (continuous and interrupted) executed using LESS procedure were perceived as more demanding than the ones executed using MPS procedure, $F(1, 7) = 43.84$, $p < 0.001$. However, interrupted and continuous sutures were perceived as having the same task complexity (F-value < 2.3) (Table 1). Furthermore, participants perceived their operative performance being worse during LESS procedures than during the MPS ones, $F(1, 7) = 23.56$, $p < 0.05$, and while they acted as the primary surgeon than as an assistant-surgeon, $F(1, 7) = 10.13$, $p < 0.05$.

The surgical teams needed more time to perform the sutures (continuous and interrupted) utilizing the LESS procedure than the MPS procedure, $F(1, 7) = 9.20$, $p < 0.05$ (average execution time ± SD: LESS = 1512 ± 375 seconds vs. MPS = 1126 ± 387 seconds). Based on external evaluation, performance was less accurate utilizing the LESS procedure, $F(1, 7) = 51.33$, $p < 0.001$ (average external evaluation ±SD: LESS = 4.27 ± 0.36 vs. MPS = 2.89 ± 0.52). No other main or interaction effects were significant (all F-values < 3.1).

Effects of the Surgical Complexity on β-activity

Task complexity modulated β-activity, overall interaction: $F(1, 7) = 8.41$, $p < 0.05$ (see Fig. 2 and Table 1). Within the same surgical role, we observed higher

TABLE 1. The Effects of Task Complexity on β-Activity, Subjective Ratings of Task Complexity, and Operative Performance

	Primary Surgeon				Assistant Surgeon			
	MPS		LESS		MPS		LESS	
	Contin.	Interrup.	Contin.	Interrup.	Contin.	Interrup.	Contin.	Interrup.
β-activity (dB μV^2/Hz)	28.91 (0.71)	28.89 (0.76)	29.62 (1.81)	29.00 (1.40)	28.39 (0.66)	28.32 (0.89)	29.16 (1.13)	29.24 (1.32)
NASA-TLX [0-100]	45.42 (14.32)	50.52 (19.85)	64.27 (14.25)	75.00 (17.47)	22.81 (12.57)	29.58 (17.47)	49.27 (20.18)	49.79 (13.63)
Operative performance	2.5 (0.57)	2.25 (0.55)	3.47 (0.39)	3.72 (0.93)	1.78 (0.45)	2.28 (0.49)	2.93 (0.65)	2.97 (0.82)

Average values and, in brackets, standard deviations calculated from all participants (n = 8). For the NASA-Task Load Index (NASA-TLX), higher scores indicate higher perceived levels of task complexity. Operative performance scores range from 1 to 5, with values closer to 1 indicating better performance.
Note. Contin., continuous suture; Interrup., interrupted suture; LESS, laparo-endoscopic single-site; MPS, multiport laparoscopic surgery.

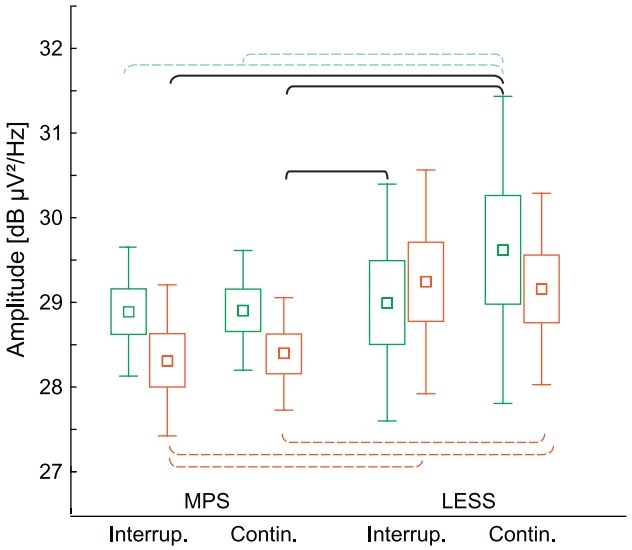

FIGURE 2. The effects of task complexity on β-activity. Primary surgeon data are represented in green, assistant surgeon in orange. Differences within the same surgical role are indicated with dotted square brackets. Differences between surgical roles are indicated with solid square brackets. For each experimental condition, the inner boxes represent the mean (M) and the external ones the standard error of the mean (±SE). The error bars represent the standard deviation (±SD). All values are calculated across participants ($n = 8$). Interrup., interrupted suture; Contin., continuous suture.

β-activity when participants performed either suture (interrupted and continuous) using the more complex surgical procedure (LESS) (all corrected p values < 0.05). These results seem to confirm previous findings on the (extra) cognitive cost associated to LESS procedures when compared to the MPS ones.[31,32] Furthermore, within the same 4 surgical exercises (continuous or interrupted suturing techniques employing LESS or MPS), β-activity did not differentiate between the surgical roles. No other main or interaction effects were significant (all F-values < 3.2). Note: We obtained similar results performing non parametric statistics (repeated-measures Friedman [ANOVAs $(8, 7) = 12.3$ $p = 0.090$] and Wilcoxon Matched Pairs Tests [all p values < 0.05]).

DISCUSSION

In healthcare settings, as in any safety-critical system, an optimal operator cognitive state is the key element to learn, develop, and refine fundamental skills that ensure high levels of performance. Good performance should lead to greater patient safety. Nowadays, successful surgical performance relies not only on the physical conditions of the surgeon (e.g., getting sufficient rest between shifts), but also on his/her ability to cope with arduous and mentally overloading situations (for a recent review, see[1]). Thus, the operator's mental overload has long been recognized as an important factor to consider to enhance patient safety and quality of care.[33]

Here, we examined how surgical complexity affects brain activity during realistic exercises. Our results show the sensitivity of an EEG-based index, the prefrontal β-activity, in detecting mental workload variations in surgeons. Additionally, we demonstrated the feasibility of using a wearable EEG device to collect unbiased measures of surgeons' mental workload. Data indicate that highly demanding procedures (i.e., sutures performed with LESS) induced higher prefrontal β activity, whereas less demanding procedures (i.e., sutures performed with MPS) induced lower β activity.

EEG power reflects the amount of neurons that discharge at the same time.[34] This discharge generates oscillatory activities that are task dependent; that is, oscillations occur more frequently during more demanding tasks.[35] Thus, EEG power is thought to be related to the cortical resources employed for information processing.[36] Here, we recorded EEG activity from the prefrontal cortex. This area plays an important role in attention, concentration, and executive functions (including planning, selecting, and ongoing regulation of goal-directed behaviors).[37,38] Variations in this area, associated with a task complexity modulation, provide quantitative evidence of compensatory strategies used to deal with different task loads imposed by the environment. Our results confirm recent investigations in surgical scenarios using the fNIRS technique that showed that prefrontal excitation is subject to task difficulty modulations.[39-41] Furthermore, our results are in line with those obtained in nonsurgical scenarios: an increase in β-activity has been associated with increased task demands[17-19,29,42] and mental stress,[16] which may also be due to the importance of the task at hand.[43] Finally, considering that task complexity is also a modulator of arousal,[44-46] and arousal influences EEG power, it is plausible to assume that changes in β-activity actually reflect the surgeon's mental workload due to task complexity.

Prefrontal β-activity did not differentiate between surgical roles, whereas perceived task complexity did distinguish between the primary surgeon and assistant surgeon roles. There are several explanations for this apparent dissociation between self-reported and psychophysiological indices while measuring task load.[47-49] The most plausible explanation is that personal and motivational factors (e.g., social desirability bias, halo and leniency effects, and nonconscious activation) might have biased the reliability of the NASA-TLX scores.[50] That is, even though the surgical teams were blind to the hypotheses behind the study, they might have suspected that the surgical role was one of the main factors of the experimental design, and consequently they might answer accordingly. Thus, the presence of this bias is therefore likely to have modulated the results

obtained in our self-reported data. Notwithstanding the above, our results are in line with previous studies that were able to differentiate across the surgical team roles and the surgical procedure (MPS vs. LESS) using similar self-reported tools[32,51-53] (for a recent summary on this topic, see[32]).

Furthermore, comparisons are often drawn between the operating room and the aircraft cockpit.[54] Indeed our data suggests a similar synchronicity effect between the members of the surgical team as to that previously observed inside the cockpit between pilots.[55,56] That is, β activity was similar for primary surgeons and assistant surgeons performing the same surgical exercises, suggesting synchronized brain activity across surgical teams over the operations.[55,57] It has been shown, that enhancing performance requires the team to be highly concentrated (EEG-synchronized) over specific periods of time.[58,59]

Finally, because the EEG signal is considered to be too noise prone to allow the recording of the brain dynamics during normal working interactions, and, considering that the physical nature of the surgeon's tasks implied constant movements, one might wonder if the EEG-based indices are inappropriate to monitor surgeon's task load in real working conditions. This possibility seems unlikely in light of the new artefact removal procedures that allows analysis of EEG signals recorded during walking and running.[60] In this vein, future studies are needed to examine the plausibility of reliable EEG recordings outside of surgical settings, where the surgical team members will be moving.

CONCLUSION

Despite early interest in the 1990s in the application of the EEG technology to the surgical field,[61] studies are still rare (for a recent review, see[10]). Here, we monitored the surgical team's cognitive state during realistic surgical procedures. Real-time EEG monitoring not only would allow instantaneous detection of overload situations. Additionally, it could provide real-time feedback to the team allowing time to introduce countermeasures to prevent a sentinel event (perhaps even by automated equipment). Furthermore, the application of these tools will help to create effective learning experiences, making surgical simulations appropriately difficult so that they will be sufficiently challenging but not so difficult that learning cannot happen. Finally, for future work we are taking into consideration the option of monitoring the whole surgical team[32,62] to get a fuller picture of the mental and physical demands, as well as the use of briefing sessions[63] as a way to improve the rapport between surgical team members and, consequently, the learning experience.

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SUPPLEMENTARY INFORMATION

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