Modulation of Visual Alpha Oscillations in Expert and Novice Surgeons Performing Sutures

Sergio Reyes
Universidad de Talca
Matías Quiñones
Universidad de Talca
Johanna Kreither
Universidad de Talca
Javier López-Calderón
Universidad de Talca
María de la L. Aylwin (maaylwin@utalca.cl)
Universidad de Talca

Research Article

Keywords: Alpha oscillations, Electroencephalography, Surgeons, Medical Students, Open Suture and Task demand

Posted Date: September 23rd, 2021

DOI: https://doi.org/10.21203/rs.3.rs-753791/v1

Abstract

BACKGROUND: Surgeons learn to perform highly repetitive movements, improving their speed and precision. Simple movements elicit a synchronization of alpha frequency band (8–12 Hz) in the occipital area, reflecting the inhibition of irrelevant areas. Yet, there is limited evidence on alpha modulation by movement performance and task experience and demands for complex visuo-motor skills. In this study we evaluated the extent of the modulation of the electroencephalogram (EEG) power in the alpha frequency band (8–12 Hz) in the visual areas and its relationship with suture performance to quantify the attentional modulation in expert surgeons and medical students. The EEG based measurements might offer a relevant measure of attentional modulation, to evaluate the progression and outcomes of learning and training surgical programs. Two groups of expert surgeons and medical students performed 6 surgical exercises on a suture pad, under two different task demands. They performed an open suture technique under relaxed conditions and stressed conditions. We obtained the EEG alpha power spectra, using a 20-20 system EEG device while suturing as well as in a baseline, eyes-open, condition as well as the number as sutures as an index of performance.

RESULTS: Surgical expertise resulted in twice the number of sutures and greater task demands increased suture performance by 20%. In contrast, alpha power in the occipital areas is greater in surgeons and medical students performing sutures, relative to the baseline, yet it is not modulated by expertise or task demands. Interestingly, the alpha power correlated positively with suture performance in surgeons, but not in the medical students.

CONCLUSIONS: The modulation of the EEG alpha power is consistent with the inhibitory-attentional hypothesis of alpha rhythm in a complex visuo-motor task, suggesting that the attentional resources allocated to the visual areas are redistributed in the somatosensory and motor areas, in addition to the visual areas during the suture task relative to the baseline. Furthermore, the association of alpha power with suture performance suggests that, unlike medical students, experts have a gradual redistribution of the inhibitory-attentional resources linked to their suture performance.

Background

Surgeons learn to perform highly repetitive manual skills that lead to increased performance with practice [1–3], as a result of greater speed and precision of movements [4–6]. Simple movements modulate the amplitude of the alpha rhythm (8–12 Hz) and its time course in the visual and motor cortices. An increase in the amplitude of the alpha band is observed over visual occipital areas with finger and foot movements [7, 8]. The EEG signal synchronizes specifically in the alpha band while subjects perform the movement [9] or during action observation [10].

The alpha rhythm has been associated to either an absence of sensory processing or an inhibition of task irrelevant networks. The former, known as ‘idle rhythm hypothesis’ [11] holds that alpha synchronization is a consequence of a network inactivity due to the reduced bottom-up sensory input [11, 12]. In contrast, the alpha inhibition hypothesis holds that alpha synchronization reflects active bottom-down inhibition of task irrelevant areas [13–15], through a redirection of sensory processing resources towards areas relevant to the task [16]. Additionally, the alpha rhythm is also modulated by working memory [17], attention [18, 19] and task difficulty [20–22], so that a greater alpha amplitude is observed with higher working memory load and task difficulty.

On the other hand, the modulation of alpha waves has also been attributed to a shift in attentional resources from internal to external stimuli, as occurs with the opening of the eyes in complete darkness, eliciting a reduction of alpha in the occipital areas even in the absence of sensory stimulation [23]. According to the alpha inhibition theory, optimal task performance should correlate with an increase in the alpha amplitude in areas where attentional resources are reduced during task performance compared to baseline no-task condition. However, there is insufficient evidence on the modulation of the alpha rhythm during complex bimanual visuo-motor tasks such as surgical open suturing.

The adequate performance of complex visuo-motor tasks such as surgical suturing likely implies the synchronization of the alpha band in the occipital areas and its modulation by the task demands. Specifically, the inhibition by the switch of the attentional resources towards the task relevant areas, such as tactile, proprioceptive and motor, predicts that optimal suturing performance should correlate with greater amplitude of alpha activity in the occipital areas. Thus, for a continuous visuo-motor task such as open surgical suture, we expect an increase in the power of the alpha band (8–12 Hz) in the occipital areas relative to the baseline eyes-open condition.

Skill learning through practice and subsequent consolidation lead to reorganization of the functional architecture of the brain, evidenced by changes in the strength of regional activation as well as modifications of the connectivity between brain regions, which support the efficient use of neural resources during task performance [24]. Early stages of learning of surgical sutures are characterized by prefrontal cortical activation, which subsequently attenuate with deliberate practice [24]. In a laparoscopic surgical task, Li et al. [25] found a greater alpha power in the occipital areas in good performers as compared to bad performers. Thus, the limited evidence from experts and highly trained subjects suggests that surgical expertise correlates with a greater amplitude of the alpha rhythm during complex movements in visual areas compared to novices. Moreover, there is no evidence about alpha power modulation by task demands during complex visuo-motor tasks. Here, we recorded scalp EEG of experienced and naïve surgeons to test whether the alpha band in the visual areas is modulated by suture performance, surgical expertise and task demands. We obtained the power of the alpha rhythm in occipital areas of surgeons and medical students while performing basic open suture in both relaxed and stressful conditions, and compared it to the eyes-open baseline condition. We hypothesized (i) a greater suture performance in expert's surgeons under higher task demands; (ii) a greater alpha power in visual areas during suture execution relative to baseline condition; (iii) a greater alpha power in medical students while performing sutures, and (iv) a positive association between occipital alpha activity and suture performance in surgeons.

Results

The main goal of this work was to evaluate the modulation of the alpha band activity during a complex visuo-motor task by expertise and task demand. Thus, suture performance and alpha power were compared in expert and novice surgeons under low and high task demand as an indicator of the modulation of the inhibitory-attentional resources. Out of 31 participants, 2 from the medical student group were discarded due to the high noise in the EEG recordings. Consequently, we report the results from 12 surgeons and 17 medical students.

SUTURE PERFORMANCE

To evaluate the efficiency of suture movements in surgeons and medical students, we measured the number of sutures at each of the three 5-minute trials, for the relaxed and stressed conditions, and obtained the mean number of sutures for those trials (Figure 1). As expected, surgeons had approximately twice the mean number of sutures than medical students in both relaxed (M = 10.2, SD = 2.1 vs M = 4.6, SD = 1.5, respectively) and stressed (M = 12.1, SD = 1.5 vs M = 5.5, SD = 1.1, respectively) conditions (Figure 2). Overall, surgeons and medical students had about 20 % more sutures in stressed than in relaxed condition.

The 2x2 repeated-measures ANOVA on the number of sutures with between-subject factor of expertise (surgeon, medical students) and within-subject factor of task demand (relaxed, stressed) show main effects of expertise ($F(1, 54) = 18.2$, BF = $3.4 * 10^{10}$) and task demand ($F(1, 54) = 17.4$, BF = 134.6), and no interaction between expertise and task demand ($F(1, 56) = 3.2$, BF = 0.51). The number of sutures was greater in surgeons (BF = $6.0 * 10^{16}$, PH1 = 1.0, unpaired t-test) than in medical students, and in stressed (BF = 97.2, PH1> .99, paired t-test) compared to relaxed conditions. In summary, surgeons were approximately twice as efficient at performing sutures compared to medical students, and suturing under stressed conditions was approximately 20 % more efficient compared to the relaxed condition for both experts and medical students.

MODULATION OF THE ALPHA RHYTHM

The scalp distributions of the power in the alpha band, from surgeons and medical students, are shown in Figure 3. For surgeons (Figure 3A), a referential alpha power in posterior electrodes O1, O2 and Oz was elicited in the baseline condition, while an increase in the alpha power was observed in relaxed and stressed conditions in the same electrodes (Figure 3B and C). A similar pattern was found in medical students, were suture performance increased the power of alpha in the relaxed and stressed conditions (Figure 3 E and F) relative to the baseline condition (Figure 3 D).

To quantify the modulation of the alpha power in surgeons and medical students during open suture, a ROI was defined according to the scalp distribution in the occipital electrodes (O1, Oz and O2, se methods section). The mean values of the alpha power in the eyes-open (EO), relaxed (Rel) and stressed (Str) conditions are showed in Figure 4. In surgeons, mean alpha power was higher when performing sutures for both relaxed and stressed conditions (M = 6.63, SD = 4.21, and M = 8.66, SD = 6.02, respectively) relative to baseline (M = 4.47, SD = 2.47, Figure 4-left). Likewise, in medical students the mean alpha power was higher when performing sutures in the relaxed and stressed condition (M = 9.50, SD = 6.96, and M = 10.64, SD = 7.49 s, respectively) relative to baseline (M = 5.45, SD = 3.83, Figure 4-right).

The 2x3 ANOVA for the individual mean alpha power values with the between-factor of expertise (surgeons, medical students) and within-factor of task demand (eyes open, relaxed, stressed) showed a main effect of task demand (F(1, 83) = 8.0, BF = $1.59*10^3$), no effect of expertise (F(1, 83) = 0.54, BF = 0.26), and no interaction between expertise and task demand (F(1, 83) = 0.26, BF = 0.09). In both surgeons and medical students alpha power was greater in the relaxed (EO-relaxed, BF = 9.4, PH1 = .90) and stressed (EO-stressed, BF = $1.45*10^3$, PH1 > .99, paired t-test) conditions compared to baseline. Interestingly, the EEG spectral data does not support a difference between relaxed and stressed conditions in the alpha power (BF = 1.7, PH1 = .63). In summary, our results show that the strength of the alpha band activity in the occipital areas increases during suture execution in expert surgeons and medical students, in agreement with a shift of the attentional resources away from the visual cortex during the visuo-motor task relative to the baseline.

ASSOCIATION BETWEEN THE ALPHA RHYTHM AND SUTURE PERFORMANCE

In the previous paragraphs we confirmed the substantial evidence that surgical expertise increases the efficiency of surgical movements and showed that the execution of surgical sutures increases the strength of the alpha activity in the occipital areas in both surgeons and medical students. To further explore the relationship between suture efficiency and the alpha band, we assessed whether the occipital alpha power and the suture efficiency are correlated in surgeons and medical students. The scatterplot of the individual alpha power values in surgeons and medical students as a function the number of sutures is shown in Figure 5.

The Pearson correlation shows a strong positive correlation between the occipital alpha band power and the number of sutures for surgeons ($r^2(22) = 0.55$), with a moderate statistical significance (BF = 6.81, pH1 = .87), suggesting that a greater suture efficiency is accompanied by a greater the power in the alpha band. In contrast, no correlation was observed for medical students ($r^2(32) = 0.35$, BF = 1.0 , pH1 = .50). Summarizing, a greater efficiency during the surgical procedure is associated to a greater occipital alpha power in surgeons but not in medical students.

Discussion

We aimed to evaluate the strength of the alpha band activity of the visual areas and its relationship with the efficiency of movements during the execution of open sutures. Specifically, we examined the effect of surgical expertise and task demand on both the occipital alpha power and the number of sutures in surgeons and medical students performing relaxed and stressed sutures.

First, we find that both surgical expertise and high task demand increase the total number of sutures. Second, we find an increase in the occipital alpha power during the execution of open suture in both surgeons and medical students, relative to baseline. Yet, our results do not support a significant effect of task demand on the alpha amplitude. Third, expert surgeons exhibit a positive association between the power of the alpha band and suture efficiency. Overall, these findings are consistent with the inhibitory-attentional theory of the alpha rhythm [14, 15] previously described in motor, attention, working memory and long term memory tasks [17–19, 26–31].

For suture performance, our results show that surgical expertise nearly doubles the number of sutures observed in medical students in both relaxed and stressed conditions, indicating a greater movement efficiency. This experts' advantage is likely rooted in the cognitive control of movements: frontal areas in the novices vs posterior areas in experts [32–36], together with the automation of movements in skilled subjects [37]. Additionally, the higher task demand in the stressed condition increases about 20 % the number of sutures relative to the relaxed condition in both surgeons and medical students, in agreement with a greater speed of movements due to the adequate allocation of attentional resources to task related areas [25]. In summary, these results corroborate previous evidence of surgeons' improved performance [2, 3], in line with greater precision and lower variability of experts' motor execution [4, 5, 38–40].

Regarding the EEG alpha activity, we found a similar alpha activity in surgeons and medical students indicating no effect of expertise in the alpha activity in the occipital areas in the baseline no-task condition as well as in the suture conditions. Prior studies have primarily evaluated the occipital alpha power (i) in simple motor tasks, where a finger or foot flexion increases alpha prior and during the movement execution, revealing a synchronization in this band in parallel to complex synchronization-desynchronization responses in motor areas [7, 8, 26]; and (ii) in motor imagery tasks [8]. Our results suggest that performing a visuo-motor task, such as open suture, switches the attentional resources away from the visual areas towards somatosensory and motor areas, even if the open suture procedure requires the processing of visual information. Thus, our results are consistent with the redirection of attentional resourced away from visual areas in motor [26], auditory [41, 42], somatosensory [27] tasks as well as away from attended visual areas in a spatial attention task [18, 19]. The inhibitory theory of alpha modulation holds that alpha power increases reveal an inhibition of task irrelevant areas. We reason that our results are not fully consistent with an inhibition of visual irrelevant areas during open suture because they are required while performing this task. Thus, our results more likely reflect a redistribution of limited attentional resources between these areas.

Moreover, we found no effect of task demand on the alpha power in occipital areas in surgeons and medical students. Because surgeons are experts in open suture, movements are likely performed with a greater degree of automation [37] and a reduced activation of anterior areas associated to attentional resources and executive function [32, 33, 35, 37, 43], particularly during the relaxed condition. Interestingly, surgeons exhibit a tendency towards lower alpha amplitude while performing suture in the relaxed condition. Conversely, medical students likely perform the sutures in a non-automated manner, involving a high activation of the anterior areas associated to attentional control and executive function, as with early stages of motor skill learning [32, 33, 35, 37, 43]. Thus, a comparable alpha power in the relaxed and stressed conditions in medical students might arise from a saturated switch of attentional resources away from the visual areas.

Finally, there was a positive association between the alpha power in the occipital area and the number of sutures in surgeons, although this correlation had a moderate support from the data. Nevertheless, our results show a greater synchronization of the alpha band as the suture efficiency increases, in agreement with a greater alpha power in the occipital regions in good performers obtained in laparoscopic surgery [25]. For surgeons, suture performance under relaxed and stressed conditions likely reflect different levels of task difficulty [21]. Further studies should be done to confirm this association between the alpha power and suture efficiency in expert surgeons. In contrast, this association was not significant for medical students even though the sample of participants was greater. Medical students have no expertise in surgical movements and they are likely performing at a ceiling level of attention during the relaxed conditions, which cannot further increase in the stressed conditions. Thus, for medical students, suture performance under both relaxed and stressed conditions likely entails a comparable level of task difficulty [21].

While the results presented here contribute to the understanding of the modulation of the alpha rhythm in the occipital areas during the continuous execution of complex movements and the relationship with expertise and task demands, they also have several limitations. First, we compared the total alpha power in the occipital areas during suture execution. Previous studies showed an increase of alpha power in the occipital area during movement execution and a return to the baseline at the end of the movement [26]. Thus, the results presented here correspond to the mean alpha power during the continuous suture execution. Future studies should evaluate the time course of the alpha power in the visual as well as somatosensory and motor areas during a complex visuo-motor task as surgical suture. Secondly, the dissimilar mean age of surgeons and medical students may contribute to differences in the baseline alpha power. However, our results show no difference in the mean alpha power of surgeons and medical students in the baseline condition, indicating that the age difference of surgeons and medical students was not a source of variability for the alpha power during baseline condition.

Conclusions

In summary, here we provide evidence of the modulation in the amplitude of the alpha band in the occipital areas, both in surgeons and in medical students relative to the baseline, eyes-open, condition and its relationship with the efficiency of movements. Surgeons are twice as efficient in the number of open sutures, likely based on the automation of movements in experts. Furthermore, high task demand during stressed suturing increases the suture efficiency by nearly 20 % in both surgeons and medical students, in agreement with an increase in the speed of movements. Interestingly, although the amplitude of EEG alpha band increases during suture performance, it was not modulated by expertise nor task demand, suggesting that suture performance redirects the attentional resources away from visual areas. Surprisingly, we find a positive association between the occipital alpha power and the suture efficiency in surgeons, suggesting that visuo-motor expertise may reshape alpha-related networks. In contrast, medical students have no association between alpha power and movement efficiency, suggesting a ceiling effect on the modulation of attentional resources during suture execution. Taken together, these findings are consistent with a limited-resources hold by the inhibitory-attentional theories of alpha rhythm during a complex visuo-motor task.

Material And Methods

PARTICIPANTS

Thirty one participants with normal or corrected-to-normal vision participated in this study. Nineteen were medical students (8 women and 11 men, mean age of 23.1) and twelve were surgeons (5 women and 7 men, mean age of 49.5), all right-handed. All participants were recruited by invitation and gave written informed consent before the recording session. The procedures were conducted in accordance with Protocol #46-2020, approved by the Ethics Committee (Comité Ético Científico) of the Universidad de Talca.

PROCEDURE

To evaluate the amplitude of the alpha oscillations in experts and novices surgeons, we performed EEG measurements while participants performed suture in both relaxed and stressed conditions, as well as in the (eyes-open) baseline condition. Novices were fourth-year medical students with 1 to 2 hours of standardized training in a suture workshop in the School of Medicine, University of Talca. Experts were established physicians with a minimum of 3 years and a maximum of 20 years, with regular suture procedures during their practice as surgeons.

In a quiet room, participants were seated in front of a small table containing the surgery pad, tools and suture, plus a lamp pointing at the table (Figure 1 A). All participants were instructed on how to perform the sutures in a simulation model 3/0 of 75 cm (Braun a video the surgical technique) in a wound closure pad (Jig Mk 3 skin pad, Limbs and things, GA, USA), standard surgical instruments and 75 cm nylon 3/0 sutures (Braun Hessen, Germany).

Scalp EEG recordings from participants were obtained in 2 conditions: baseline and suture. In the baseline condition, participants were resting for 3 min with their eyes open, and another 3 min with their eyes closed. The order of these trials was randomly defined and balanced across participants. In the suture condition, participants performed 6 suture trials of 5 minutes each (Figure 1 B). These trials were divided into 3 trials at their own pace, hereinafter referred as relaxed, and 3 trials in which they were subjected to stressful and distracting stimuli, from now on referred as stressed. The inter-trial interval was 2 minutes for all conditions. In the relaxed condition, participants were instructed to perform sutures, whereas in the stressed condition they were instructed to perform as many sutures as possible. Additionally, in the stressed condition only, participants received feedback about the remaining time, and information about performance of other participants, every minute. The sequence of the relaxed and stressed trials was randomized and balanced across participants.

EEG RECORDINGS

The electroencephalogram (EEG) was continuously recorded while participants completed all conditions, using a 37-channel BioSemi ActiveTwo system (BioSemi B.V., Amsterdam, Netherlands): 32 scalp sites (Fp1, Fp2, F7, F3, Fz, F4, F8, T7, C3, Cz, C4, T8, P9, P7, P5, P3, P1, Pz, P2, P4, P6, P8, P10, PO7, PO3, POz, PO4, PO8, O1, Oz, O2, and Iz) according to the modified 10–20 System (American Electroencephalographic Society, 1994), left and right mastoids, and 3 electro-oculogram (EOG) channels (at outer canthi of each eye, and below the right eye). All signals were recorded in single-ended mode. The EEG and EOG were low-pass filtered with a 5th-order sync filter (half-power cutoff at 208 Hz) and digitized at 1024 Hz.

DATA ANALYSIS

The data from this study is available in http://dx.doi.org/10.17632/xb8fzmrf8j.1.

Data analyses were conducted using a combination of EEGLAB [44] and ERPLAB [45], running on MATLAB 2019b (MathWorks, Natick, MA, USA). EEG signals were bandpass filtered offline using a non-causal Butterworth infinite impulse response filter, with half-power cutoffs at 0.1 and 40 Hz, and a roll-off of 12 dB/octave, and then down-sampled to 256 Hz. Eye-movement artifacts and eye blinks were corrected using independent component analysis (ICA). Subsequently, scalp channels were referenced offline to the average of the left and right mastoids, and the three EOG signals, plus Fp2, were used to create two new bipolar vertical and horizontal EOG derivations in order to explore remaining ocular artifacts.

For each EEG recording, the first 4 seconds of data were removed from all conditions to minimize the presence of artifacts. After that, data segments of 2.5 and 4.5 minutes were extracted from baseline and suture trials, respectively. Thus, the EEG trials for baseline were 2.5 minutes of data and the EEG trials for suture conditions were merged resulting in 13.5 minutes of data. EEG data were subjected to a Fast Fourier Transform through a 4-sec, 50% overlap, Hanning-taper, artifact-free moving window. Power spectra with a number of averaged windows of less than 180 were eliminated from further analysis. The grand average power spectra (μV^2) were computed for each EEG channel for all recordings. Thus, based on the scalp distribution of the alpha power (8-12 Hz) in the occipital areas (see Figure 3), a ROI was defined by averaging the alpha power at three occipital electrodes (O1, O2 and Oz). Finally, mean values of the power in the alpha band, from each participant's ROI, were compared across conditions. In addition, we obtained the number of sutures (stitches) from each participant, for each condition.

STATISTICAL ANALYSIS

Statistical differences were estimated by Bayesian analysis using the Bayes Factor Toolbox for Matlab (https://github.com/klabhub/bayesFactor in Matlab written by Bart Krekelberg) based on Rouder et al. 2012 [46]. Statistical differences in power values were evaluated by a two-factor analysis of variance (ANOVA), with between-subjects factor of expertise (two levels: expert and novice) and within-subject factor of condition (three levels: baseline, relaxed and stressed). Statistical differences between the numbers of sutures were evaluated using a two factor ANOVA. Main effects for the ANOVA were estimated as the ratio of the Bayes factors for the full model and the restricted model, obtained by excluding the factor for the main effect. Differences between means were assessed as the Bayes factor (BF) for paired or unpaired t-tests. Statistical significance for t-tests was set to a probability from data $\geq$ 0.90 (BF $\geq$10), and for correlations was set to probability for the alternative hypothesis (pH1) $\geq$ 0.90 (BF $\geq$10). Again, a BF for the alternative hypothesis between 2 and 10 was considered as moderate non-conclusive evidence.

To evaluate the association between alpha power and the efficiency of suture movements, we computed the Bayes factor for the Pearson product-moment correlation coefficient. A strong correlation was defined when r^2 values were equal or greater than 0.5, and a moderate correlation when r^2 values were between 0.45 and 0.5. Unless otherwise specified, all values are reported as mean $\pm$ SD in the main text and as mean $\pm$ SEM in the figures.

Abbreviations

EEG: Electroencephalogram; EOG: Electro-oculogram; Rel: relaxed; Str: stressed; ROI: Region of interest; BF: Bayes Factor; ANOVA: Analysis of variance; SD: standard deviation; SEM: standard error or the mean

Declarations

Ethics approval and consent to participate

The procedures were conducted in accordance with Protocol #46-2020, approved by the Scientific Ethics Committee (Comité Ético Científico) of the Universidad de Talca.

Consent for publication:

Not applicable

Availability of data and materials

The datasets supporting the conclusions of this article are available in the Mendeley repository, Reyes, Sergio; Quinones, Matias; Kreither, Johanna; Lopez-Calderon, Javier; Aylwin, Maria (2021), “Alpha Waves Open Suture”, Mendeley Data, V1, DOI: 10.17632/xb8fzmrf8j.1

Competing interests:

The authors declare that they have no competing interests

Funding

This work was supported by Convenio U. de Talca - U. de Chile (#1557) and PIA en Ciencias Cognitivas, Universidad de Talca

Authors' contributions

SR designed the experiment, collected and analyzed the data, edited the article; MQ collected and analyzed the data; JK analyzed the data and wrote the article; JLC analyzed the data and wrote the article; MLA designed the experiment, analyzed the data and wrote the article. All authors read and approved the final manuscript.

Acknowledgements

Not applicable

References

1. Ching SS, Mok CW, Koh YX, Tan SM, Tan YK: **Assessment of surgical trainees' quality of knot-tying.** *J Surg Educ* 2013, **70:**48-54.
2. Mashaud LB, Arain NA, Hogg DC, Scott DJ: **Development, validation, and implementation of a cost-effective intermediate-level proficiency-based knot-tying and suturing curriculum for surgery residents.** *J Surg Educ* 2013, **70:**193-199.
3. Huang E, Chern H, O'Sullivan P, Cook B, McDonald E, Palmer B, Liu T, Kim E: **A better way to teach knot tying: a randomized controlled trial comparing the kinesthetic and traditional methods.** *Am J Surg* 2014, **208:**690-694.
4. Gölz C, Voelcker-Rehage C, Mora K, Reuter EM, Godde B, Dellnitz M, Reinsberger C, Vieluf S: **Improved Neural Control of Movements Manifests in Expertise-Related Differences in Force Output and Brain Network Dynamics.** *Front Physiol* 2018, **9:**1540.
5. Hofstad EF, Våpenstad C, Chmarra MK, Langø T, Kuhry E, Mårvik R: **A study of psychomotor skills in minimally invasive surgery: what differentiates expert and nonexpert performance.** *Surg Endosc* 2013, **27:**854-863.
6. Horeman T, Blikkendaal MD, Feng D, van Dijke A, Jansen F, Dankelman J, van den Dobbelsteen JJ: **Visual force feedback improves knot-tying security.** *J Surg Educ* 2014, **71:**133-141.
7. Pfurtscheller G, Lopes da Silva FH: **Event-related EEG/MEG synchronization and desynchronization: basic principles.** *Clin Neurophysiol* 1999, **110:**1842-1857.
8. Pfurtscheller G: **Induced oscillations in the alpha band: functional meaning.** *Epilepsia* 2003, **44 Suppl 12:**2-8.

9. Neuper C, Pfurtscheller G: **Event-related dynamics of cortical rhythms: frequency-specific features and functional correlates.** *Int J Psychophysiol* 2001, **43:**41-58.
10. Di Nota PM, Chartrand JM, Levkov GR, Montefusco-Siegmund R, DeSouza JFX: **Experience-dependent modulation of alpha and beta during action observation and motor imagery.** *BMC Neurosci* 2017, **18:**28.
11. Adrian ED, Matthews BHC: **The Berger rhythm: potential changes from the occipital lobes in man.** *Brain* 1934, **57:**355-385.
12. Pfurtscheller G, Stancák A, Jr., Neuper C: **Event-related synchronization (ERS) in the alpha band--an electrophysiological correlate of cortical idling: a review.** *Int J Psychophysiol* 1996, **24:**39-46.
13. Suffczynski P, Kalitzin S, Pfurtscheller G, Lopes da Silva FH: **Computational model of thalamo-cortical networks: dynamical control of alpha rhythms in relation to focal attention.** *Int J Psychophysiol* 2001, **43:**25-40.
14. Klimesch W, Sauseng P, Hanslmayr S: **EEG alpha oscillations: the inhibition-timing hypothesis.** *Brain Res Rev* 2007, **53:**63-88.
15. Jensen O, Mazaheri A: **Shaping functional architecture by oscillatory alpha activity: gating by inhibition.** *Front Hum Neurosci* 2010, **4:**186.
16. Sadaghiani S, Scheeringa R, Lehongre K, Morillon B, Giraud AL, Kleinschmidt A: **Intrinsic connectivity networks, alpha oscillations, and tonic alertness: a simultaneous electroencephalography/functional magnetic resonance imaging study.** *J Neurosci* 2010, **30:**10243-10250.
17. Jensen O, Gelfand J, Kounios J, Lisman JE: **Oscillations in the alpha band (9-12 Hz) increase with memory load during retention in a short-term memory task.** *Cereb Cortex* 2002, **12:**877-882.
18. Sauseng P, Klimesch W, Stadler W, Schabus M, Doppelmayr M, Hanslmayr S, Gruber WR, Birbaumer N: **A shift of visual spatial attention is selectively associated with human EEG alpha activity.** *Eur J Neurosci* 2005, **22:**2917-2926.
19. Worden MS, Foxe JJ, Wang N, Simpson GV: **Anticipatory biasing of visuospatial attention indexed by retinotopically specific alpha-band electroencephalography increases over occipital cortex.** *J Neurosci* 2000, **20:**Rc63.
20. Başar E, Başar-Eroglu C, Karakaş S, Schürmann M: **Gamma, alpha, delta, and theta oscillations govern cognitive processes.** *Int J Psychophysiol* 2001, **39:**241-248.
21. Cooper NR, Croft RJ, Dominey SJ, Burgess AP, Gruzelier JH: **Paradox lost? Exploring the role of alpha oscillations during externally vs. internally directed attention and the implications for idling and inhibition hypotheses.** *Int J Psychophysiol* 2003, **47:**65-74.
22. Cooper NR, Burgess AP, Croft RJ, Gruzelier JH: **Investigating evoked and induced electroencephalogram activity in task-related alpha power increases during an internally directed attention task.** *Neuroreport* 2006, **17:**205-208.
23. Ben-Simon E, Podlipsky I, Okon-Singer H, Gruberger M, Cvetkovic D, Intrator N, Hendler T: **The dark side of the alpha rhythm: fMRI evidence for induced alpha modulation during complete darkness.** *Eur J Neurosci* 2013, **37:**795-803.

24. Modi HN, Singh H, Yang GZ, Darzi A, Leff DR: **A decade of imaging surgeons' brain function (part II): A systematic review of applications for technical and nontechnical skills assessment.** *Surgery* 2017, **162:**1130-1139.
25. Li G, Li H, Pu J, Wan F, Hu Y: **Effect of brain alpha oscillation on the performance in laparoscopic skills simulator training.** *Surg Endosc* 2021, **35:**584-592.
26. Pfurtscheller G: **Event-related synchronization (ERS): an electrophysiological correlate of cortical areas at rest.** *Electroencephalogr Clin Neurophysiol* 1992, **83:**62-69.
27. Bauer M, Kluge C, Bach D, Bradbury D, Heinze HJ, Dolan RJ, Driver J: **Cholinergic enhancement of visual attention and neural oscillations in the human brain.** *Curr Biol* 2012, **22:**397-402.
28. Händel BF, Haarmeier T, Jensen O: **Alpha oscillations correlate with the successful inhibition of unattended stimuli.** *J Cogn Neurosci* 2011, **23:**2494-2502.
29. Bonnefond M, Jensen O: **Alpha oscillations serve to protect working memory maintenance against anticipated distracters.** *Curr Biol* 2012, **22:**1969-1974.
30. Jokisch D, Jensen O: **Modulation of gamma and alpha activity during a working memory task engaging the dorsal or ventral stream.** *J Neurosci* 2007, **27:**3244-3251.
31. Meeuwissen EB, Takashima A, Fernández G, Jensen O: **Increase in posterior alpha activity during rehearsal predicts successful long-term memory formation of word sequences.** *Hum Brain Mapp* 2011, **32:**2045-2053.
32. Coynel D, Marrelec G, Perlbarg V, Pélégrini-Issac M, Van de Moortele PF, Ugurbil K, Doyon J, Benali H, Lehéricy S: **Dynamics of motor-related functional integration during motor sequence learning.** *Neuroimage* 2010, **49:**759-766.
33. 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?** *Ann Surg* 2008, **247:**540-543.
34. Sun FT, Miller LM, Rao AA, D'Esposito M: **Functional connectivity of cortical networks involved in bimanual motor sequence learning.** *Cereb Cortex* 2007, **17:**1227-1234.
35. Floyer-Lea A, Matthews PM: **Distinguishable brain activation networks for short- and long-term motor skill learning.** *J Neurophysiol* 2005, **94:**512-518.
36. van Dijk H, Schoffelen JM, Oostenveld R, Jensen O: **Prestimulus oscillatory activity in the alpha band predicts visual discrimination ability.** *J Neurosci* 2008, **28:**1816-1823.
37. Krakauer JW, Mazzoni P: **Human sensorimotor learning: adaptation, skill, and beyond.** *Curr Opin Neurobiol* 2011, **21:**636-644.
38. Uemura M, Tomikawa M, Kumashiro R, Miao T, Souzaki R, Ieiri S, Ohuchida K, Lefor AT, Hashizume M: **Analysis of hand motion differentiates expert and novice surgeons.** *J Surg Res* 2014, **188:**8-13.
39. Guru KA, Shafiei SB, Khan A, Hussein AA, Sharif M, Esfahani ET: **Understanding Cognitive Performance During Robot-Assisted Surgery.** *Urology* 2015, **86:**751-757.
40. Huffman E, Anton N, Martin J, Timsina L, Dearing W, Breece B, Mann I, Stefanidis D: **Optimizing Assessment of Surgical Knot Tying Skill.** *J Surg Educ* 2020, **77:**1577-1582.

41. Foxe JJ, Simpson GV, Ahlfors SP: **Parieto-occipital approximately 10 Hz activity reflects anticipatory state of visual attention mechanisms.** *Neuroreport* 1998, **9:**3929-3933.
42. Fu KM, Foxe JJ, Murray MM, Higgins BA, Javitt DC, Schroeder CE: **Attention-dependent suppression of distracter visual input can be cross-modally cued as indexed by anticipatory parieto-occipital alpha-band oscillations.** *Brain Res Cogn Brain Res* 2001, **12:**145-152.
43. Halgren M, Ulbert I, Bastuji H, Fabó D, Erőss L, Rey M, Devinsky O, Doyle WK, Mak-McCully R, Halgren E, et al: **The generation and propagation of the human alpha rhythm.** *Proc Natl Acad Sci U S A* 2019, **116:**23772-23782.
44. Delorme A, Makeig S: **EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis.** *J Neurosci Methods* 2004, **134:**9-21.
45. Lopez-Calderon J, Luck SJ: **ERPLAB: an open-source toolbox for the analysis of event-related potentials.** *Front Hum Neurosci* 2014, **8:**213.
46. Rouder JN, Morey RD, Speckman PL, Province JM: **Default Bayes factors for ANOVA designs.** 2012, **56:**356-374.

Figures

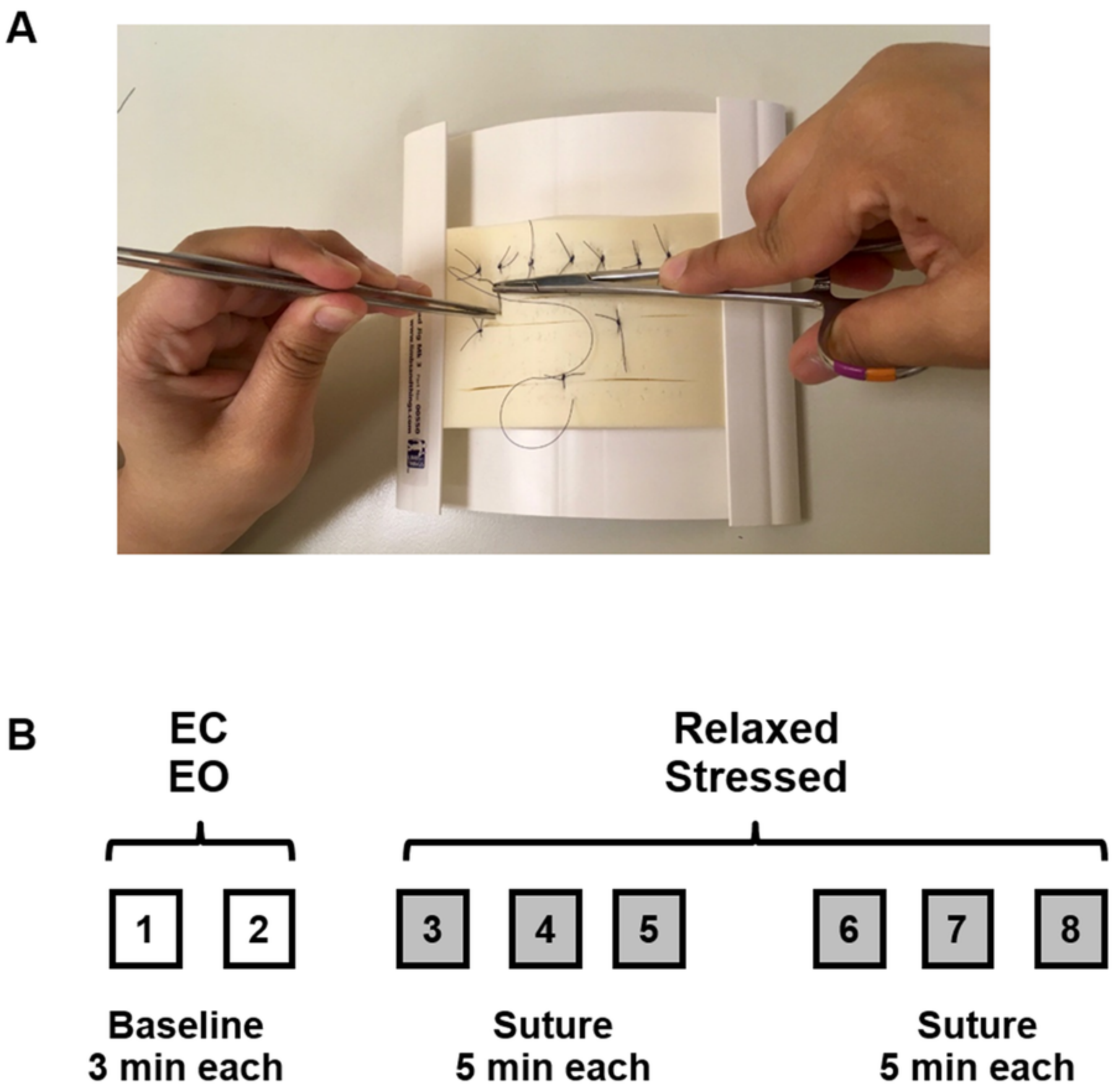

Figure 1

Experimental setting and protocol A. Experimental setting showing a participant performing sutures in a wound closure pad with standard surgical instruments. B. A scheme of the trial sequence, baseline with either eyes-closed (EC) or eyes-open (EO) and suture under either relaxed or stresses conditions.

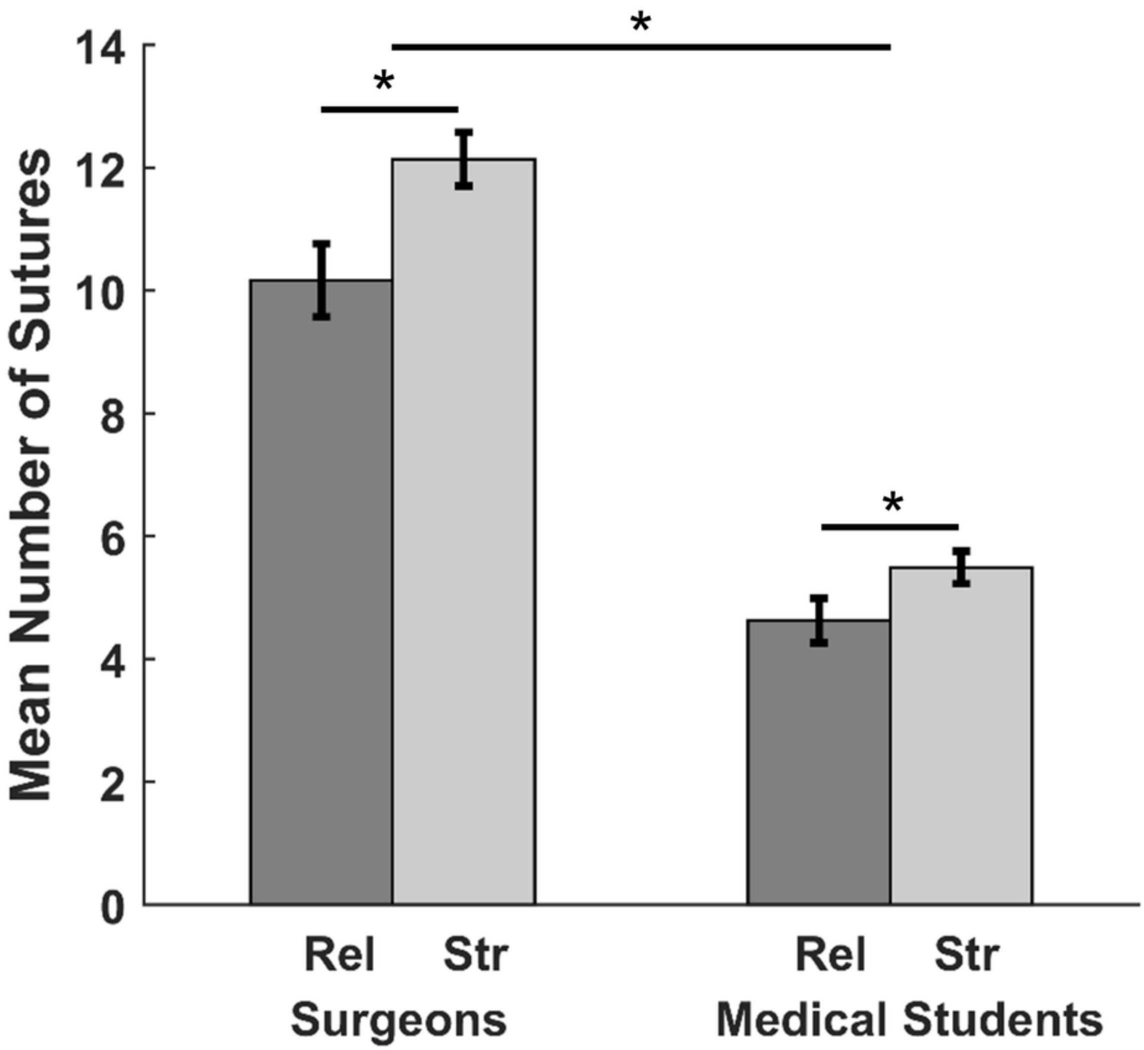

Figure 2

Mean number of sutures in surgeons and medical students. Left. Mean number of sutures in surgeons during relaxed suture (Rel) and stressed suture (Str). Error bars are standard error of the mean (SEM). Asterisks indicate statistical differences between means (*, Probability from data > 0.99).

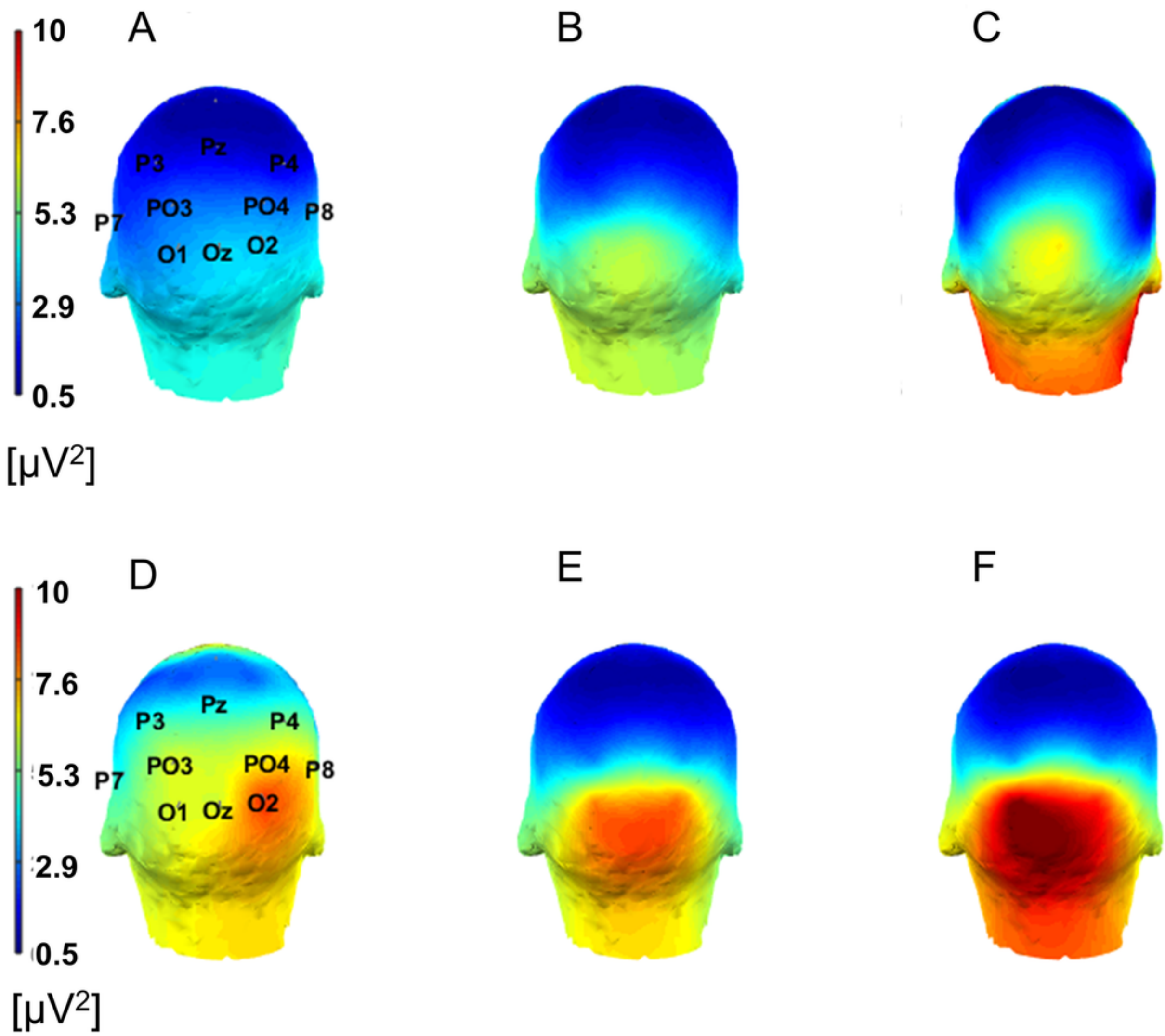

Figure 3

Grand-averaged scalp maps in surgeons and medical students during baseline and while performing sutures in relaxed or stressed conditions. Surgeons (A, B, C), medical students (D, E, F); baseline (A, D), relaxed (B, E) and stressed (C, F) conditions.

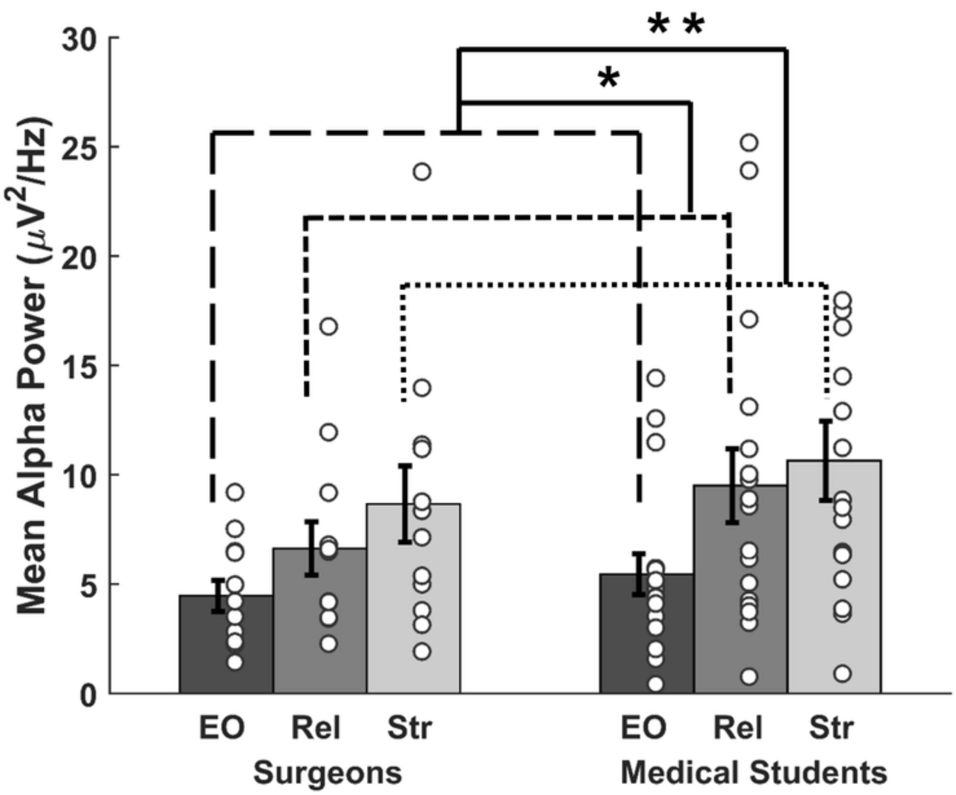

Figure 4

Individual and mean alpha power values for surgeons (left) and medical students (Right) in resting eyes open (EO), relaxed suture (Rel) and stressed suture (Str). Error bars are SEM. Asterisk indicate statistical difference between means (*, Probability from data > 0.90, **, Probability from data > 0.99).

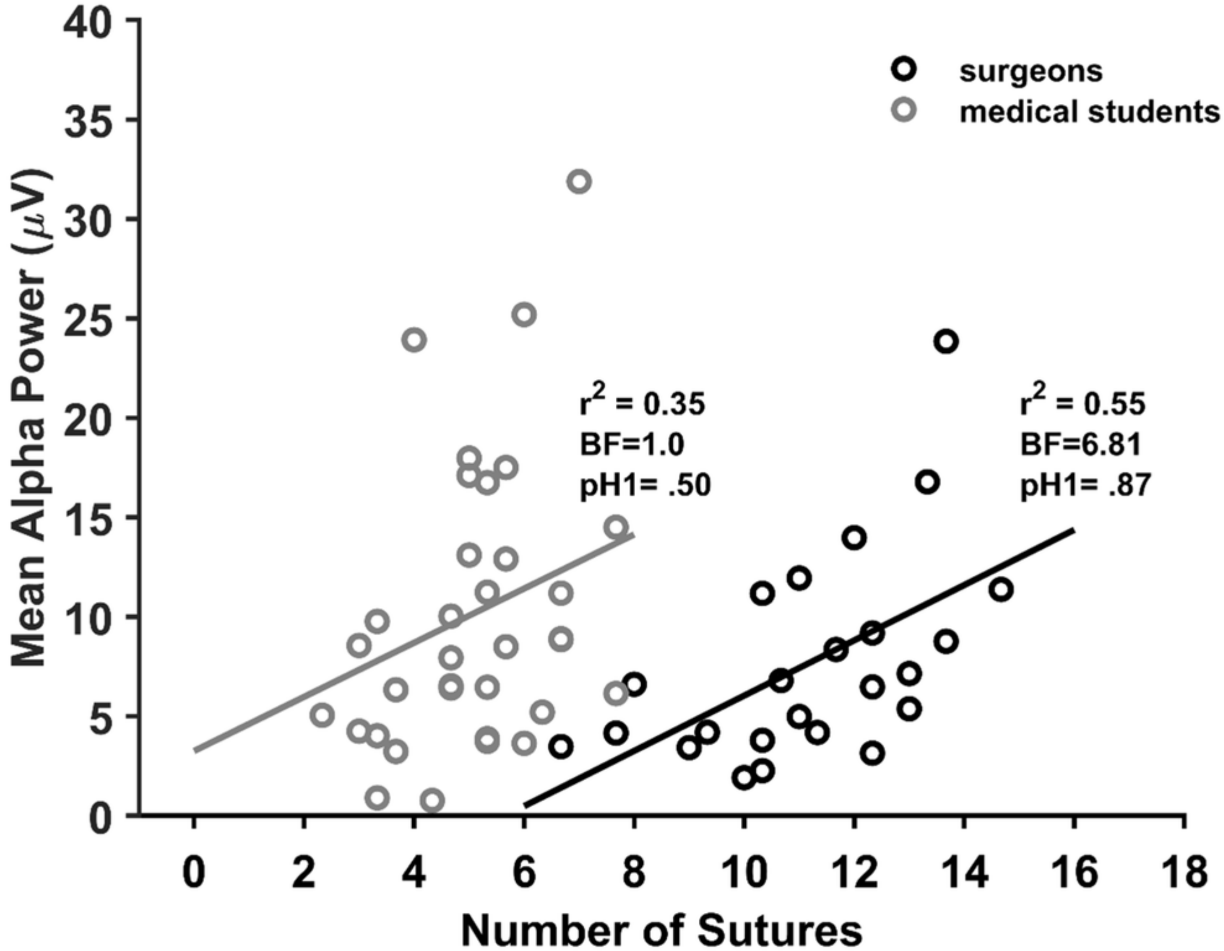

Figure 5

Association between Alpha power and number of sutures in surgeons and medical students. Pearson correlation of the individual mean alpha power and the number of sutures for surgeons and medical students. Lines represent a linear regression.