Expertise Related Disparity in Prefrontal-Motor Brain Connectivity

F. Deligianni[1*], H. Singh[2*], H.N. Modi[2], A. Darzi[2], D.R. Leff[2], G.Z Yang[1]

[1]Hamlyn Centre for Robotic Surgery, Imperial College London

[2]Department of Surgery and Cancer, Imperial College London
fani.deligianni@imperial.ac.uk

INTRODUCTION

Surgery requires both dexterous motor skills as well as the ability to maintain cognitive control under stressful and time-pressurised conditions (e.g. control bleeding). Several factors can affect operative performance which depend on the mental demands of the task as well as surgical proficiency. Neuroimaging using functional Near Infrared Spectroscopy (fNIRS) quantifies changes in brain oxygenation that reflect neuronal activation. It has been shown that under stress, prefrontal cortex attenuation is associated with performance degradation, whereas prefrontal engagement accompanies task success [1, 2]. However, technical skill relies not only on prefrontal or executive control but rather interactions between these areas and the motor cortex (M1). In this context, it remains unknown whether patterns of prefrontal-motor connectivity change under temporal demand and if these changes are expertise-dependent.

Therefore, this paper builds upon prior work based on activation analyses to better understand the interplay between motor skills (M1) and cognitive (prefrontal) performance under stress, which is important in human-robot interaction. We contrast brain networks based on partial connectivity derived based on shrinkage algorithms for covariance estimation. Subsequently, reliable connectivity differences between junior and senior surgeons are identified based on Network Based Statistics (NBS).

MATERIALS AND METHODS

Connectivity estimation in brain networks: Typically, large scale functional connectivity derived from fNIRS data is modelled as a network or a graph. The nodes of the graph represent brain regions and in this case, each region or *"node"* is associated with an fNIRS measurement channel.

We characterize brain connectivity based on partial correlation, which is an undirected measure of synchrony that disentangles the influence of indirect connections on the connectivity between each pair of brain regions. In other words, it provides a measure of the signal transmitted directly between two regions [3]. Since, it is estimated based on the inverse covariance matrix, it is important to be well conditioned.

We estimate the covariance matrix of the fNIRS signal based on the 'Oracle Approximating Shrinkage' (OAS) estimator [4]. In high dimensional problems of small sample number, shrinkage methods aim to better condition the covariance matrix and in general result in improved performance. This approach builds upon the Ledoit-Wolf (LW) estimator which minimizes the mean-squared error [5]. For small sample sizes OAS outperforms LW significantly under the assumption of a Gaussian distribution. This is reflected in the stability of the inverse covariance matrix.

Comparing brain networks: We exploit Network Based Statistics (NBS) to identify *"edges"* that are statistically different between brain networks [6]. This method alleviates the problem of false discovery rate which arises in a large number of univariate edge-wise hypothesis tests. Instead, NBS uses clustering to identify subgraphs and associates the hypothesis test with a global network measure. In particular, an F-test is estimated for each graph edge and thus a supra-thresholded graph is constructed. Subsequently, connected edges are identified as component and a p-value is associated by comparing with the null distribution. In this way, NBS provides greater power to detect differences between networks.

RESULTS

Subjects: Twenty-nine surgeons enrolled in the study (median age 33, range 29-57, 9 females) and were classified based on their prior training into 'junior' (n=11), 'intermediate' (n=10), and 'senior' residents (n=8). Technical skill was objectively assessed using four performance parameters: Task Progression Score, Error Score, Leak Volume, and Knot Tensile Strength.

Experimental Design: Participants were instructed to perform a laparoscopic suturing (LS) task using an intracorporeal technique on a laparoscopic box trainer (iSim2, iSurgicals, UK). The task involved inserting a 2-0 Vicryl® suture (Ethicon, Somerville, NJ) as close to pre-marked entry and exit points on either side of a defect in a Penrose drain. To tie a knot laparoscopically, participants were instructed to formulate one double throw followed by two single throws of the suture.

All subjects performed the task under two experimental conditions: (1) *'self-paced'* (SP), in which residents were permitted to take as long as required to tie each knot, (2) *'time pressure'* (TP), in which, a two-minute per knot time restriction was applied. Participants performed the LS task five times under each experimental condition with 30second inter-trial rest periods interspersed between each knot. The order of conditions was randomized for each subject.

Data Acquisition: The ETG-4000 Optical Topography System (Hitachi Medical Co, Japan) was used to measure activation across 24 prefrontal and 22 motor cortical locations ('channels'), based on the international, 10-20 system of probe placement.

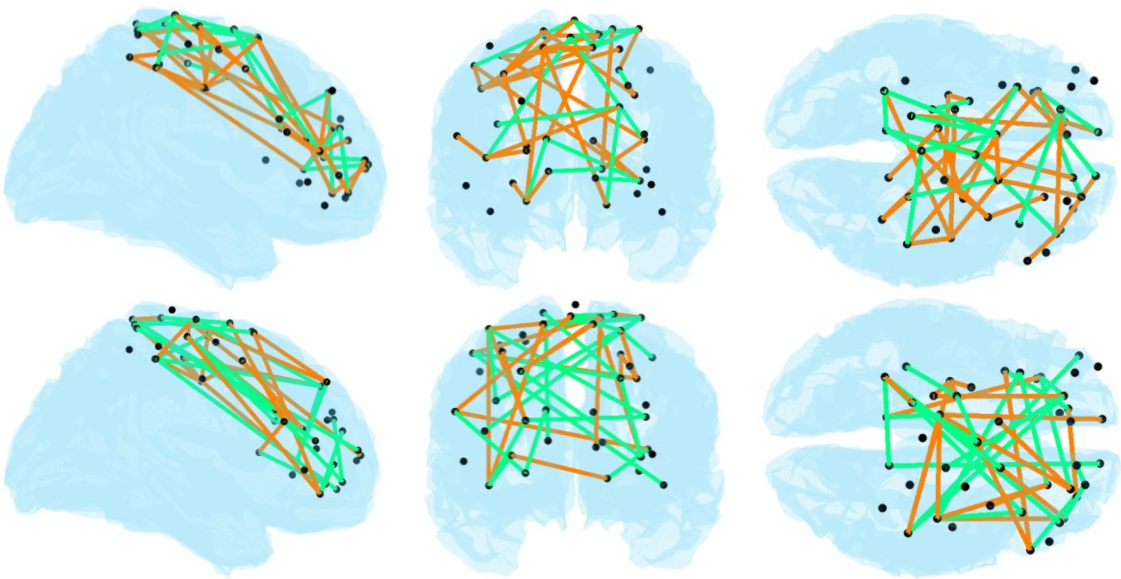

Fig. 1: Between-group differences in pre-frontal M1 connectivity amongst junior and senior surgeons visualised in sagittal, coronal and axial views, respectively. Significantly stronger connectivity amongst expert group (green line) versus greater connectivity amongst juniors (orange line). The top row illustrates results of self-paced' (SP), and bottom row the results of 'time-pressure' (TP) conditions respectively.

Preprocessing: Optical data was pre-processed using a customized HOMER2 [7]. A low-pass filter (0.5Hz) was applied to minimise noise and electrocardiographic effects on the data. Data was de-trended, baseline corrected and averaged across blocks to increase the signal-to-noise ratio. Raw mean intensity values were converted to changes in optical density relative to the mean of each channel across the whole task period. Channel-wise motion detection and spline correction were performed. Relative changes in light intensities were converted into changes in HbO_2 and HHb concentration using the modified Beer-Lambert Law.

Brain Connectivity Results: We used NBS to compare connectivity between conditions and subject expertise based on one-way ANOVA.. Striking between-group differences in connectivity are observed. We detected statistically significant differences between brain networks of junior and senior surgeons ($p<0.001$), Fig. 1. Junior residents demonstrate enhanced connectivity under self-paced conditions and attenuation under stress, Table 1. Conversely, more expert surgeons depict sparse inter-hemispheric connectivity during self-paced conditions and upregulation of connectivity strength under stress.

DISCUSSION

We observe that strengthening of prefontal-M1 connectivity amongst senior surgeons compared to junior surgeons emerges under 'time-pressure' conditions. This may reflect significant cross-talk between motor and prefrontal cortex regions related to the advanced training and ability to better cope with stress. Similarly, relative connectivity attenuation under calm conditions is understood as a "small-world" network optimised for maximum efficiency when cognitive demands are low.

Table 1: Comparison of connectivity strength between juniors (JS) and senior (SS) surgeons.

	Self-Paced	Time-Pressure
Total Number of Different Edges	46	42
Edges with higher strength in SS	37%	55%

REFERENCES

[1] H. N. Modi, H. Singh, G. Z. Yang, A. Darzi, and D. R. Leff, "A decade of imaging surgeons' brain function (part II): A systematic review of applications for technical and nontechnical skills assessment," *Surgery,* vol. 162, pp. 1130-1139, Nov 2017.

[2] H. N. Modi, H. Singh, F. Orihuela-Espina, T. Athanasiou, F. Fiorentino, G.-Z. Yang, *et al.*, "Temporal Stress in the Operating Room: Brain Engagement Promotes "Coping" and Disengagement Prompts "Choking"," *Annals of Surgery,* vol. 267, pp. 683-691, 2018.

[3] F. Deligianni, E. Robinson, C. F. Beckmann, D. Sharp, A. D. Edwards, and D. Rueckert, "Inference of Functional Connectivity from Direct and Indirect Structural Brain Connections," *ISBI,* pp. 849-52, 2011.

[4] Y. L. Chen, A. Wiesel, and A. O. Hero, "Shrinkage Estimation of High Dimensional Covariance Matrices," *IEEE International Conference on Acoustics, Speech, and Signal Processing,* vol. 1-8, pp. 2937-40, 2009.

[5] F. Deligianni, G. Varoquaux, B. Thirion, E. Robinson, D. J. Sharp, A. D. Edwards, *et al.*, "A Probabilistic Framework to Infer Brain Functional Connectivity from Anatomical Connections," *IPMI,* vol. 6801, pp. 296-307, 2011.

[6] A. Zalesky, A. Fornito, and E. T. Bullmore, "Network-based statistic: Identifying differences in brain networks," *Neuroimage,* vol. 53, pp. 1197-1207, 2010.

[7] T. J. Huppert, S. G. Diamond, M. A. Franceschini, and D. A. Boas, "HomER: a review of time-series analysis methods for near-infrared spectroscopy of the brain," *Applied Optics,* vol. 48, pp. 280-98, 2009.