Ph.D. Thesis Report

Candidate: Mohamed Fawzy Ibrahim Issa

Title: Novel Methods for Removing EEG Artifacts and Calculating Dynamic Brain Connectivity

Reviewer: Balázs Benyó

Preface

I had the opportunity to review this thesis before the home defense of Mr. Mohamed Fawzy Ibrahim Issa. I was happy to see that the author's revisions adequately reflect all my comments and questions, further improving the scientific merit of the thesis.

Summary

The thesis deals with the current problems of Electroencephalography (EEG) signal processing. EEG is a relatively noisy biological signal enabling the diagnosis of several pathological states of the human nervous system. EEG feature extraction required for accurate clinical diagnostic decisions must be supported by active noise filtering. Automation of these filtering methods has particular importance as typically long EEG signal recordings are used in the clinical practice.

The author of the thesis introduces novel noise filtering methods removing the most common artifacts from the EEG signal: the heart-related artifacts (so-called Electrocardiography [ECG] artifacts) and the eye-movement related artifacts (so-called Electrooculography [EOG] artifacts). In the second part of the thesis, the author proposes novel functional connectivity metrics for monitoring and quantifying stroke patients' recovery progress.

Formal notes

The overall outlook and presentation of the thesis – including the thesis booklet – is far above the average. Adequate figures and tables well support the presented material. In general, it is easy to follow the description of methods. The English of the thesis and the thesis booklet is good, especially if we consider that the author is not a native speaker of English.

Chapter 1

This chapter properly introduces the motivation of the research, the need for EEG artifact removal methods, and clinical situations where brain connectivity biomarkers can be applied. The preface states the outline of a rationally developed thesis.

Chapter 2

This chapter is a strong introduction of current EEG signal processing methods, the measurement process, the signal processing pipeline, including the preprocessing, feature extraction, and classification or patent recognition. Brain connectivity analysis methods are introduced in the last subsection of the chapter.

Chapter 3

This chapter is a literature review of EEG artifact removal, including the applied algorithms and the artifact removal methods proposed by the author. EOG and ECG artifact removal methods are discussed separately. This chapter has a good number of references and provides a solid foundation for Chapters 4 and 5, describing the author's original contribution in the field of EEG artifact removal.

Chapter 4

This chapter presents the novel method suggested by the author to remove EOG artifacts from the EEG signal. The method applies Independent Component Analysis to identify the EOG related signal components and remove these components from the reconstructed filtered EEG signal. The steps of the method are introduced in detail. The proposed method is validated by using three data sets and compared by similar methods published recently by other authors. These validation results and the comparison are convincingly proving the benefits of the proposed EEG signal processing method. Altogether, I accept these results as new scientific findings of the author. The presented results are well published, among others, in a peer-reviewed international journal.

Chapter 5

This chapter presents the original contribution of the author concerning ECG artifact removal. The primary considerations behind this method are the same as the idea used in the EOG artifact removal algorithm: Independent Component Analysis is applied to the EEG signal. However, in this case, QRS detection is used to recognize heart-related noise, and these signal components are omitted in the EEG reconstruction. Extensive validation of the proposed method is presented. Three clinical data sets were selected from the PhysioNet EEG datasets, and an additional clinical data set with 61 EEG recordings were used in the evaluation process. The research results presented in this chapter are appropriately supported by real patient data based validation. The comparison of the performance of the method with similar recently published results proves the efficacy of the proposed EEG signal processing method. Based on the presented material, I accept these results as new scientific findings of the author.

Chapter 6

The author proposes several metrics to describe the brain region's connectivity appropriate in the diagnosis of ischemic stroke. The description of the different metrics is detailed enough. Compared to the preliminary version of the thesis, the discussion of the results is extended and some further experimental results are added adequately supporting the author's statements. The results presented in this chapter are original contributions of the author.

Chapter 7

This chapter proposes a novel method for analyzing the brain's dynamic functional connectivity using Ensemble Empirical Mode Decomposition. The description of the method is given with appropriate details. The proposed algorithm's efficacy is demonstrated in a synthetic signal; the practical applicability is validated in human experiments. This chapter is significantly extended compared to the previous version of the thesis making the validation much more convincing. The presented measurement method has definite benefits from the clinical applicability point of view.

Chapter 8

Chapter Conclusions systematically summarizes all the significant and important results outlining cross-references and the connections between the methods and metrics used. The overall importance of the results is also briefly discussed.

Chapter 9

The main contributions in the form of scientific statements are summarized in this chapter. The statements are well formulated, containing the important features and benefits of the methods and metrics proposed.

Evaluation of the scientific statements

Thesis I: Novel method for removing EOG artifacts

The author proposed an original method for EOG artifact removal; their applicability is appropriately supported by real patient data set based validation. The comparison of the performance of the method with similar recently published results proves the efficacy of the proposed EEG signal processing method. Based on the presented material, I accept these results as original scientific findings of the author.

Thesis II: Novel method for removing ECG artifacts

The author proposed an original method for ECG artifact removal. The results were adequately validated and compared with previously published works. Based on the description presented, I accept these results as original scientific contributions of the author.

Thesis III: Functional connectivity biomarkers for stroke monitoring

The author proposed functional connectivity biomarkers. The presented experiments demonstrated their clinical relevance in stroke monitoring. I accept these results as original scientific findings of the author. However, I note that the concrete clinical interpretation and application of these metrics are subject to further research.

Thesis IV: New method to increase the temporal resolution of dynamic functional connectivity

The author proposed a novel method to increase the temporal resolution of the functional connectivity of brain regions. The benefits of the method are demonstrated in benchmark signals and human experiments. I accept these results as original scientific contributions of the author.

Questions and comments:

1. *The functional connectivity biomarkers suggested in Thesis III and in chapter 6 are demonstrated to reflect the changes in the recovery process after the stroke. However, their concrete clinical interpretation and the benefits are just briefly introduced. Can you explain their clinical benefits and the potential research challenges to be solved for their use in clinical practice?*

2. *A brief discussion of the achieved results' limitations would enhance the result's evaluation and help define potential directions for further research. Can you make your comments on the limitations of your results?*

Minor typos:

- *page 64: …length (Shortest… → …length (**s**hortest…*
- *Page 68 (Table 6-1): jobb → **right***
- *Page 73: …there is increase… → …there is **an** increase…*
- *Page 85: …(dotted vertical lines. → …(dotted vertical lines**)**.*
- *Page 86: …components, respectively → …components, respectively**.***
- *Page 95: Since Visual inspection… → Since **v**isual inspection…*
- *Page 95: … ICA methods → … ICA methods**.***
- *Page 95: visual inspection… → **V**isual inspection…*
- *Thesis booklet, page 7: …képes sztrók betegek … → …képes **sztrókon átesett** betegek…*
- *Thesis booklet, page 7: Remove **a)** from the end.*

Overall Summary and Recommendation

The thesis is very well structured and easy to read. The author demonstrated his significant knowledge in biomedical engineering, especially in EEG signal processing and experiences in interpretation and understanding of clinically relevant problems. The original contribution of the author is clearly outlined; I have accepted all the four original scientific statements of the author. The results presented in this thesis have been published in peer-reviewed international conferences and journals.

Overall, the research undertaken made a significant original contribution to science concerning novel physiological signal processing methods and suggesting clinically relevant biomarkers. I strongly support the acceptance of the PhD thesis.

Budapest, October 30, 2020.

dr Benyó Balázs

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Benyó Balázs