Paper Accepted[*]

Original Article / Оригинални рад

Mirko Ostojić[1,3,†], Milan Milosavljević[1], Aleksandra Kovačević[2], Miodrag Stokić[3,4], Đorđe Stefanović[5], Gordana Mandić-Gajić[6], Ljiljana Jeličić[3,4]

Changes in power of surface electromyogram during breath-holding

Промена снаге површинског електромиограма при задржавању даха

[1]Singidunum University, Faculty of Technical Sciences, Belgrade, Serbia;
[2]Military Medical Academy, Center for Clinical Pharmacology, Belgrade, Serbia ;
[3]Life Activities Advancement Center Institute for Research and Development, Belgrade, Serbia;
[4]Đorđe Kostić Institute for Experimental Phonetics and Speech Patology, Belgrade, Serbia;
[5]University of Belgrade, Faculty of Sport and Physical Education, Belgrade, Serbia;
[6]Medical Faculty of the Military Medical Academy Academy, Belgrade, Serbia

[†]**Correspondence to:**
Mirko OSTOJIĆ
Univerzitet Singidunum, Fakultet tehničkih nauka,
Miloja Zakića 65/11, 11000 Belgrade, Serbia
E mail: **mirko11ostojic@gmail.com**

Changes in power of surface electromyogram during breath-holding

Промена снаге површинског електромиограма при задржавању даха

SUMMARY

Introduction/Objective Numerous studies on surface electromyographic (sEMG) signals in response to different respiratory parameters, particularly on sternocleidomastoid (SCM) muscles and diaphragm (DIA), indicated the promising advantages of their simultaneous monitoring with possible applications in the analysis of their correlation. This motivated a detailed statistical analysis of the average power (P_{AV}) on sEMG signals during prolonged breath-holding, simultaneously measured in the SCM and DIA areas.

Methods The physiological breath-holding method was applied to 30 healthy volunteers (N=30), with sEMG of SCM and DIA regions measured before, during and after the breath-holding exercise. All subjects were sitting in an upward position with nostrils closed by the right index finger and thumb during breath-hold. To synchronize the records, the user would press a special switch using the other hand at the beginning and at the end of breath-holding experiment. The average power of sEMG (P_{AV}) was measured for each 500 ms signal window.

Results The P_{AV} remains constant before and 3 seconds after the exercise. During the ending of breath-holding, at least one region had the P_{AV} afflux of a minimum 91%. Student's t-test between *SCM* signals shows a significant difference of $p < 0.001$, while the *DIA* lacks it. Although the results showed that *SCM* is the dominant region in 76.67% of cases, the exclusive P_{AV} afflux in the *DIA* region was detected in precisely five cases (16.67% of the total population).

Conclusions Our research concludes the necessity of simultaneous measurement of SCM and DIA to observe dominant changes in sEMG during breath-holding. The physiological response of the respiratory center can be observed by approximately doubling P_{AV} in one of SCM or DIA regions.

Keywords: surface electromyogram, breath-holding, muscle sternocleidomastoideus

САЖЕТАК

Увод/циљ Бројне студије површинских електромиографских (*sEMG*) сигнала као одговору на промене различитих параметара дисања, нарочито на стерноклеидомастоидним (SCM) мишићима и дијафрагми (ДИА), указале су на обећавајуће предности њиховог истовременог праћења са могућим применама у анализи њихове корелације. Ово је мотивисало детаљну статистичку анализу просечне снаге (P_{AV}) на *sEMG* сигналима током продуженог задржавања даха, истовремено мерених у *SCM* и ДИА областима.

Методе Физиолошка метода задржавања даха примењена је на 30 здравих добровољаца ($N = 30$), и то мерењем *sEMG*, *SCM* и ДИА области пре, током и након вежбе задржавања даха. Сви испитаници су седели у усправном положају, а нoснице су биле затворене десним кажипрстом и палцем током задржавања даха. Ради синхронизације записа, корисник би притиснуо посебан прекидач другом руком на почетку и на крају експеримента задржавања даха. Просечна снага *sEMG* (P_{AV}) је измерена за сваки сигнални прозор од 500 *ms*.

Резултати P_{AV} остаје константан пре и три секунде после вежбе. Током завршетка задржавања даха, бар једна област имала је P_{AV} прираштај од минимално 91%. Студентов т-тест између *SCM* сигнала показује значајну разлику од $p < 0,001$, док код ДИА изостаје. Мада су резултати показали да је *SCM* доминантна област у 76,67% случајева, ексклузивни P_{AV} прираштај у ДИА области откривен је у тачно пет случајева (16,67% укупног броја испитаника).

Закључак Наше истраживање води закључку о неопходности истовременог мерења *SCM* и ДИА како би се уочиле доминантне промене *sEMG* током задржавања даха. Физиолошки одговор респираторног центра може се приметити приближно удвострученим P_{AV} у једној од *SCM* или ДИА области.

Кључне речи: површински електромиограм, задржавање даха, мишић стерноцлеидомастоидеус

INTRODUCTION

In the last decade of the previous millennium, the appearance of the first studies on the topic of surface electromyography (sEMG) started in the correlation with the miscellaneous respirational effects [1]. Given its exponential increase, several reviews of these papers have been published (see [1]). There are at least 10.000 studies, while about 1% had been classified positive in the light of precise settings and repeatability of the experiments [2]. The strict postulates are not firmly grounded, but a consensus has been established on the

placement of surface electrodes, the method of application, as well as on the expected recorded signals [3].

There are three distinct measurement regions "regarding electromyographic (EMG) activation of the sternocleidomastoid muscle (SCM), parasternal muscles (PARA) and the diaphragm (DIA)" [4]. However, a more detailed analysis of recordings ensigns PARA and DIA as the same regions, which could be taken as synonyms.

The sEMG researches have already found their application in at least three areas: "a) advances in surface EMG detection and processing techniques, b) recent progress in surface EMG clinical research applications, and c) myoelectric control in neuro-rehabilitation" (see [2]).

These studies include both sick and healthy volunteers. Thus, in the case of chronic diseases, the most common are patients with Chronic Obstructive Pulmonary Disease (COPD) [5] and asthma [6], with the emphasis on the experiment repeatability. There are also numerous studies conducted on healthy volunteers that measure the different effects of breathing exercises [7] versus changes in the exhaled air [8]. Numerous published papers on sEMG include volunteers with acute cases [9].

The authors have recently demonstrated the possibility of acquiring the sEMG signals in healthy volunteers in the two most often recorded regions, as the answer to the most passive breathing activity, the prolonged breath-holding [10]. The organism's response to breath-holding comes from the main respiratory center in the medulla through a series of electrical impulses in order to activate the respiratory muscles. This response should be especially augmented at the end of breath-holding, due to a permanent increase in activation impulses from the respiratory center. The change in the average sEMG power was the first measurable psychological phenomenon characterized by a push or swallow feeling at the end of breath-holding. In this regard, the main goal of this paper is to detect this involuntary

muscle activity in the SCM and DIA region at the end of breath-holding. Statistical analysis of the entire population should provide an answer as to whether this phenomenon is an individual peculiarity or occurs simultaneously in both zones.

A series of initial signal analyzes had been proposed, but with a lack of clear answer which method should give the most reliable statistical significance.

During the recording of biosignals, noise artifacts from different sources are common and quite noticeable [11]. Having that in mind, we concentrated mainly on the changes in the mean power (P_{AV}) since a large portion of constant noises is permanently present. At least in the first approximation, its influence could be considered constant in all phases of the recordings [12]. This further facilitates a complete statistical analysis.

METHODS

Research sample

Thirty healthy young volunteers, between 19 and 25 years old, students of the sports faculty, were beforehand instructed in the procedure of breath-holding after spontaneous exhalation, as well as in recognizing the response of physiological muscle activity (the "bump") [13] upon prolonged breath-holding [14]. The procedure has the following steps:

- **Phase 1** – Sitting and resting for 5-7 minutes. Complete relaxation of all muscles, including the breathing muscles. This relaxation produces a natural spontaneous exhalation (breathing out).

- **Phase 2** – Pinching the nose with the right thumb and index finger at the end of the exhalation with simultaneous pressing the switch with the left hand (the first switch press) to mark the end of the exhalation and keeping the nose pinched.

- **Phase 3** – The appearance of the first urge to breathe (practice shows that this first desire emerges together with an involuntary push of the diaphragm or swallowing movement in the throat), that we will refer to as "bump".

- **Phase 4** – Pressing the switch a second time (the second switch press) to mark the "bump", releasing the nose and again complete relaxation of all muscles.

Instruments

The typical electrode setup for the SCM and DIA regions followed the suggestions given by the Merletti (see [3]) and Afsharipour [15]. The method is completely non-invasive and only surface electrodes were applied, as shown in Figures 1 and 2.

The measurement was performed using Nihon Kohden Corporation 1200K Neurofax apparatus with surface ring Au-electrodes filled with electro-conductive gel and Electrocap with 19 Ag/AgCl electrodes for EEG measurement (10/20 International Electrode Placement System). The experimental procedure corroborates the ethical standards of the Serbian Medical Society and is labeled by the protocol CE 01342. The procedure has been performed in accordance with the Declaration of Helsinki. The participants gave their written informed consent prior to the experimental procedure.

Although we practically used only two sEMG recorded signals by Au-surface electrodes for this study, the system also contained the following recordings [16]:

- 16 EEG signals,

- ECG according to Einthoven,

- respiratory air-flow signal,

- HD-camera built-in to this system,

- light hand built-in switch for the event labeling.

The sEMG on neck (SCM) was measured at the ends of *Sternocleidomastoideus* muscle (SCM) [17], also illustrated in Figure 3.

The method of placing the DIA electrodes was according to the internationally agreed topographic lines of the thorax, which also include the actual lines for this study: linea mediana anterior (extends from the incisura jugularis to siphysis pubica) and linea sternalis (extends parallel along the lateral edge of the sternum) (see [3]). First, a small extension at the end of the sternum (prosessus xyphoideus) located in the direction of the linea mediana anterior was defined by palpation, in order to mark the initial position (upper point). The direction of the linea sternalis was then determined. The last step was to draw a line from point A to the direction of the linea sternalis perpendicularly in order to obtain the marking location (lower point) where the upper electrode was placed on the abdomen. The lower electrode was placed in the marked position located in the direction of the linea sternalis, and below the upper electrode, at a distance of 10 *cm* [18].

The signal values are expressed in *μV* per unit resistance, allowing simple squaring to obtain power in *μW*.

The whole recording procedure is non-invasive, lasts less than five minutes and allows the export of signals for the specific analysis on different platforms [19]. In order to perform the original signal analysis, we initially used the signal processing toolbox of MATLAB [20], and custom C-programs [21].

RESULTS

After the performed measurement of all 30 participants, the quality continuous ECG, RESP, SCM and diaphragmatic EMG signals were obtained. A sample of recorded signals during normal breathing and the "bump" phase are shown in Figures 4A and 4B, respectively.

Figure 5 shows the power spectral density (PSD) of SCM signal during the breath-hold and after the breath-hold phase. The spectrum belongs principally to the same area as the standard EEG signal and practically does not exceed 40 *Hz*. Power line interference is clearly visible at 50 *Hz*.

Figure 6 demonstrates the change of pattern of SCM during "bump" at the end of breath-holding period. Exact periods of individual heart beats are extracted from the ECG signals and marked in Figure 6 as red circles to demonstrate the effect of ECG in SCM.

The common method with overlapping processing windows has been used to calculate the average power of sEMG in SCM and DIA regions [22]. Since DIA is heavily contaminated with ECG, we used a 1 *s* window to minimize the influence of ECG on signals. For example, the average RR interval of the signal represented in Figure 5 is 1.02 *s*. In the case of a sampling frequency of 200 *Hz*, with time overlap between windows of 50 samples or 75% overlap between two consecutive windows.

The visible influx of power was observed immediately before the "bump" in all cases, mainly in the SCM region [23].

The volunteers S08, S14, S18, S24 and S25 showed the "bump" in the DIA region.

It is noticeable that the return to the initial values in the DIA region is no longer than 3 seconds. The different artifacts by breathing musculature should be kept in mind here. The properly performed exercise was supposed to be done in such a way that volunteers should keep holding the breath for at least 2 seconds after the switch is pressed before resuming normal breathing [24].

Table 1 shows the overall results for the whole group of 30 volunteers.

The increase for ΔP^{SCM} and ΔP^{DIA} is positive in most cases where a simple averaging gave surplus of 425.16% and 133.19% for the SCM and DIA regions, respectively. However, for each case at least one of ΔP^{SCM} and ΔP^{DIA} values showed a significant increase. Such

instances are bolded in their respective columns. This is more frequent for the ΔP^{SCM}, although the exclusive P_{AV} enlargement in the DIA region can be observed in exactly five cases (16.67 % of the whole population). The overall view of the completed results imposes the conclusion that both muscle regions must be recorded in order to spot the P_{AV} enlargement for every volunteer. For the whole population, the P_{AV} relaxation period is below 3 seconds.

The t-test for the SCM region data only, P^{SCM}_{rest} and P^{SCM}_{bump}, shows the significant statistical difference ($t = 1.69913$, $p < 0.001$), contrary to the DIA region, since P^{D}_{rest} and P^{D}_{bump} show no significant statistical difference. However, the newly formed group ΔP^{MAX} (defined as the maximum increase of the SCM and DIA regions) shows even one order higher significant statistical difference, e.g. $t = -6.09$, $df = 32.12$, $p < 0.0001$.

DISCUSSION

We recorded sEMG during breath-holding exercise on thirty healthy participants. The analysis of P_{AV} changes during breath-holding was a simple method that provides effective assessment of sEMG changes in real time. An increase of P_{AV} was observed in the pilot study with five participants. In this paper, we present a complete statistical analysis for all 30 subjects, and P_{AV} return time to the initial rest values.

P_{AV} changes of the EMG signals practically showed at least a doubling of its value related to the rest state and very quickly returned to its initial state, within 2.2 seconds as the maximum value. In Table 1, we saw that the changes could be observed literally in every case, with the particular necessity of observing both EMG signals.

The visible influx of power was observed immediately before the "bump" in all cases [25], mainly in the SCM region, but not exclusively. Five of the 30 volunteers showed an exclusive increase of P_{AV} in the *DIA region*. This confirms many statements that "the neck

region is more prone to fatigue than the intercostal one" [26, 27]. In his book, Professor Rakimov summed up the feelings of more than a thousand volunteers to the physiological answer to breath-holding. His conclusion supports our findings, as he claims that "... most people feel the sensation in the neck rather than in the diaphragmatic region..." (see [24]).

We have already mentioned that it is possible to prolong the breath-holding even after a physiological response for a certain period of time [28], which was expected to happen during our experiment.

Recently, professor Lejun's group published papers on changing the pedaling performance of elite cyclists, showing changes in the average power output of the sEMG signals of different locomotor muscles due to fatigue, as well as during the recovery period [29]. Their result showed significant changes in two of the four measured groups.

Our result of 16.6% of volunteers showing a significant influx exclusively in the DIA region is in a range of human left-handedness. "There has been very little change in the proportion of left-handers since the Upper Paleolithic Age about 10,000 years ago and it is estimated to be around 10%", although "subtle prejudice against this minority group is still present and visible", showing finally "that the prevalence of left-handedness is lower in Serbia than in Western Europe (5-10% vs. 11-14%)" [30].

Statistical analysis of the three pairs of signals can be considered as follows. The lack of statistical significance for the DIA region implies that the results from this region would solely be insufficient and would not be credible if performed independently. On the other hand, a statistical difference measured between the two SCM signals ("bump" state *versus* rest state) of $p < 0.001$ cannot give a false result, but seems to be able to miss some positive cases. The newly formed ΔP^D variable depicts the dominant group, defined as the maximum increase of ΔP^{SC} and ΔP^D columns. It can report every case with minimal time delay, without false reports.

The practical development of a dominant group would not be a difficult task. The core of the electronic device should contain one digital comparator followed by the collecting register of the higher signal.

CONCLUSION

Our research shows the influx in P_{AV} of 91% minimally at least in one measured region, SCM or DIA, with a return to the initial values in less than 3 seconds during the prolonged breath-holding. Simultaneous measurement of both regions is necessary to observe changes in the average power of sEMG in each case.

This indicates that the physiological response of the respiratory center in the medulla to a prolonged breath-holding can be observed by approximately doubling P_{AV} in one of SCM or DIA regions.

It would be beneficial to repeat this research on a larger population, as well as on different cases of health etiology.

ACKNOWLEDGMENT

Conflict of interest: None declared.

REFERENCES

1. Cabral EEA, Fregonezi GAF, Melo L, Basoudan N, Mathur S, Reid WD. Surface electromyography (*sEMG*) of extradiaphragm respiratory muscles in healthy subjects: A systematic review. J Electromyogr Kinesiol. 2018 Oct; 42:123-135. DOI: 10.1016/j.jelekin.2018.07.004. PMID: 30077087. Epub 2018 Jul 19

2. Dos Reis IMM, Ohara DG, Januário LB, Basso-Vanelli RP, Oliveira AB, Jamami M. Surface electromyography in inspiratory muscles in adults and elderly individuals: A systematic review. J Electromyogr Kinesiol. 2019 Feb; 44:139-155. DOI: 10.1016/j.jelekin.2019.01.002. PMID: 30658230. Epub 2019 Jan 11

3. Merletti R, Muceli S. Surface EMG detection in space and time: Best practices. J Electromyogr Kinesiol. 2019 Dec; Vol. 49. DOI: 10.1016/j.jelekin.2019.102363

4. Walterspacher S, Pietsch F, Walker DJ, Röcker K, Kabitz HJ. Activation of respiratory muscles during respiratory muscle training. Respir Physiol Neurobiol. 2018 Jan; 247:126-132. DOI: 10.1016/j.resp.2017.10.004. PMID: 29037769. Epub 2017 Oct 14

5. Basso-Vanelli RP, Di Lorenzo VAP, Ramalho M, Labadessa IG, Requeiro EMG, Jamami M, et al. Reproducibility of inspiratory muscle endurance testing using PowerBreathe for COPD patients. Physiother Res Int. 2018 Jan; Vol. 23(1). DOI: 10.1002/pri.1687. PMID: 28394092. Epub 2017 Apr 10

6. Costa IP, Politti F, Cahalin LP, de Carvalho EFT, Costa D, Corrêa JCF, et al. Acute Effects Using Light-Emitting Diode Therapy (LEDT) for Muscle Function during Isometric Exercise in Asthma Patients: A Pilot Study. Biomed Res Int. 2019 Jan 16; 2019:7501870. DOI: 10.1155/2019/7501870. eCollection 2019. PMID: 30775383

7. Ramsook AH, Molgat-Seon Y, Schaeffer MR, Wilkie SS, Camp PG, Reid WD, et al. Effects of inspiratory muscle training on respiratory muscle electromyography and dyspnea during exercise in healthy men. J Appl Physiol (1985). 2017 May 1;122(5):1267-1275. DOI: 10.1152/japplphysiol.00046.2017. PMID: 28255085. Epub 2017 Mar 2

8. Trevisan ME, Boufleur J, Soares JC, Haygert CJ, Ries LG, Corrêa EC. Diaphragmatic amplitude and accessory inspiratory muscle activity in nasal and mouth-breathing adults: A cross-sectional study. J Electromyogr Kinesiol. 2015 June; 25, 463-468. DOI: 10.1016/j.jelekin.2015.03.006. PMID: 25900327. Epub 2015 Apr 6

9. Luiso D, Villanueva JA, Belarte-Tornero LC, Fort A, et al. Surface respiratory electromyography and dyspnea in acute heart failure patients, PLoS One, 2020 Apr; 15 (4):e0232225. DOI: 10.1371/journal.pone.0232225.eCollection 2020.

10. Ostojic M, Milosavljevic M. The Possibility of Electromyography Measuring as The Answer to Breath Holding. Sinteza 2019; 307-312. DOI: 10.15308/Sinteza-2019-307-312

11. van Leuteren RW, Hutten GJ, de Waal CG, Dixon P, van Kaam AH, de Jongh FH Processing transcutaneous electromyography measurements of respiratory muscles, a review of analysis techniques. J Electromyogr Kinesiol. 2019 Aug 1; 48:176-186. DOI: 10.1016/j.jelekin.2019.07.014. PMID: 31401341. Epub 2019 Aug 1

12. Holcman D, Schuss Z. Asymptotics of Elliptic and Parabolic PDEs: and their Applications in Statistical Physics, Computational Neuroscience, and Biophysics. 1st ed. Churchill College: Cambridge; 2018.

13. Ostojić M. Umeće Disanja. Pesić & Sinovi: Belgrade; 2018.

14. Kim EB. Ganong's Review of Medical Physiology, 26th Ed. 26th ed. New York: McGraw-Hill Education; 2019.

15. Afhsripour B, Soedirdjo S, Merletti R. Two-dimensional surface EMG: The effects of electrode size, interelectrode distance and image truncation, Biomed Signal Process Control. 2019 March; 49:298-307. DOI: 10.1016/j.bspc.2018.12.001.

16. Schetteler K. F. The aEEG Booklet, Nihon Kohden, Duesseldorf, 2018. Available from: https://www.nihonkohden.com/

17. Guyton AC. Physiology of the human body. John E. Hall PhD (Author), Guyton and Hall Textbook of Medical Physiology, 13th ed. Sunder College Publishing: Philadelphia; 2016.

18. Vigotsky AD, Halperin I, Lehman GJ, Trajano GS, Vieira TM. Interpreting Signal Amplitudes in Surface Electromyography Studies in Sport and Rehabilitation Sciences, Front Physiol. 2018 Jan; 4;8:985. DOI: 10.3389/fphys.2017.00985. eCollection 2017. PMID: 29354060

19. Jenkins DM, Housh TJ, Bergstrom HC, Cochrane KC, Hill EC, Smith CM, et al. Basic reporting and interpretation of surface EMG amplitude and mean power frequency: a reply to Vitgotsky, Ogborn, and Phillips. Eur J Appl Physiol. 2015 Dec; 116(3):659-661. DOI: 10.1007/s00421-015-3315-5. PMID: 26705244

20. Ingle VK, Proakis JG. Digital Signal Processing Using Matlab, Cengage Learning: Stanford; 2017.

21. Milosavljevic M. Robust Digital Processing of Speech Signals. Springer: New York; 2017.

22. Alessio SM. Digital Signal Processing and Spectral Analysis for Scientists, Signals and Communication Technology. Springer: Cham; 2016.

23. Devaprakash D, Weir GJ, Dunne JJ, Alderson JA, Donnelly CJ. The influence of digital filter type, amplitude normalisation method, and co-contraction algorithm on clinically relevant surface electromyography data during clinical movement assessments, J Electromyogr Kinesiol. 2016 Dec; 31:126 – 135. DOI: 10.1016/j.jelekin.2016.10.001. PMID: 27810649. Epub 2016 Oct 13

24. Rakimov A. Normal Breathing. Amazon Digital Services: Toronto; 2014.

25. Young HH. Searching for the neural signatures of conscious veto: A novel approach on the Libet paradigm using Template Matching Analysis, The University of Auckland, 2017, Available from: http://hdl.handle.net/2292/37371.

26. Segizbaeva, Donina ZhA, Timofeev NN, Korolyov YN, Golubev VN, Aleksandrova NP. EMG analysis of human inspiratory muscle resistance to fatigue during exercise, Adv Exp Med Biol. 2013;788:197-205. DOI: 10.1007/978-94-007-6627-3_29. PMID: 23835979

27. Segizbaeva MO, Timofeev NN, Donina ZhA, Kur'yanovich EN. Effects of inspiratory muscle training on resistance to fatigue of respiratory muscles during exhaustive exercise. Adv Exp Med Biol. 2015; 840:35-43. DOI: 10.1007/5584_2014_20. PMID: 25248344

28. Maoz U, Yaffe G., Koch C, Mudrik L. Neural precursors of decisions that matter--an ERP study of deliberate and arbitrary choice. bioRxiv September 2017. DOI: https://doi.org/10.1101/097626

29. Lejun W, Qineng S, Guoqiang M, Mingxin G, Wenxin N, Jun Q. Pedaling Performance Changing of Elite Cyclists Is Mainly Determined by the Fatigue of Hamstring and Vastus Muscles during Repeated Sprint Cycling Exercise. BioMed Research International. Jan 2020; DOI: 10.1155/2020/7294820

30. Milenkovic S, Belojevic G, Paunovic K, Dragana D. Historical Aspects of Left-handedness, Journal Serbian Archives of Medicine, Dec 2019; 147:11(2):782-785. DOI: 10.2298/SARH190522095M

31. Sekiguchi H, Tamaki Y, Kondo Y, Nakamura H, Hanashiro K, Yonemoto K, et al. Surface electromyographic evaluation of the neuromuscular activation of the inspiratory muscles during progressively increased inspiratory flow under inspiratory-resistive loading, Physiol Int. 2018 Mar 1;105(1):86-99.   DOI: 10.1556/2060.105.2018.1.3

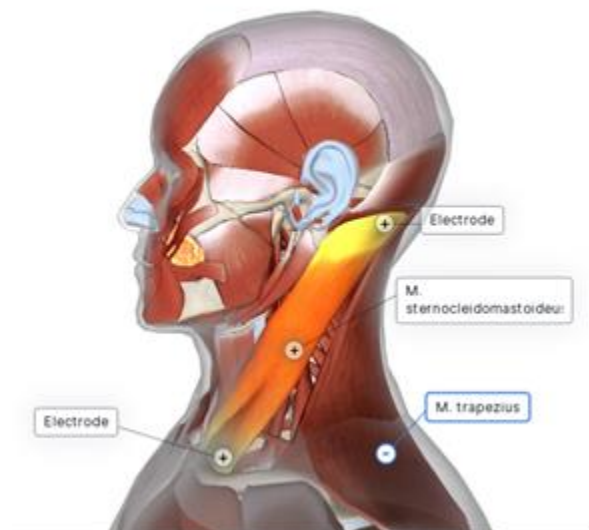**Figure 1:** Electrode setup at *Neurofax* equipment

Figure 2: The electrode setup

Figure 3: Sternocleidomastoides (*SCM*). The picture shows this biggest neck muscle and the positions by applied surface electrodes
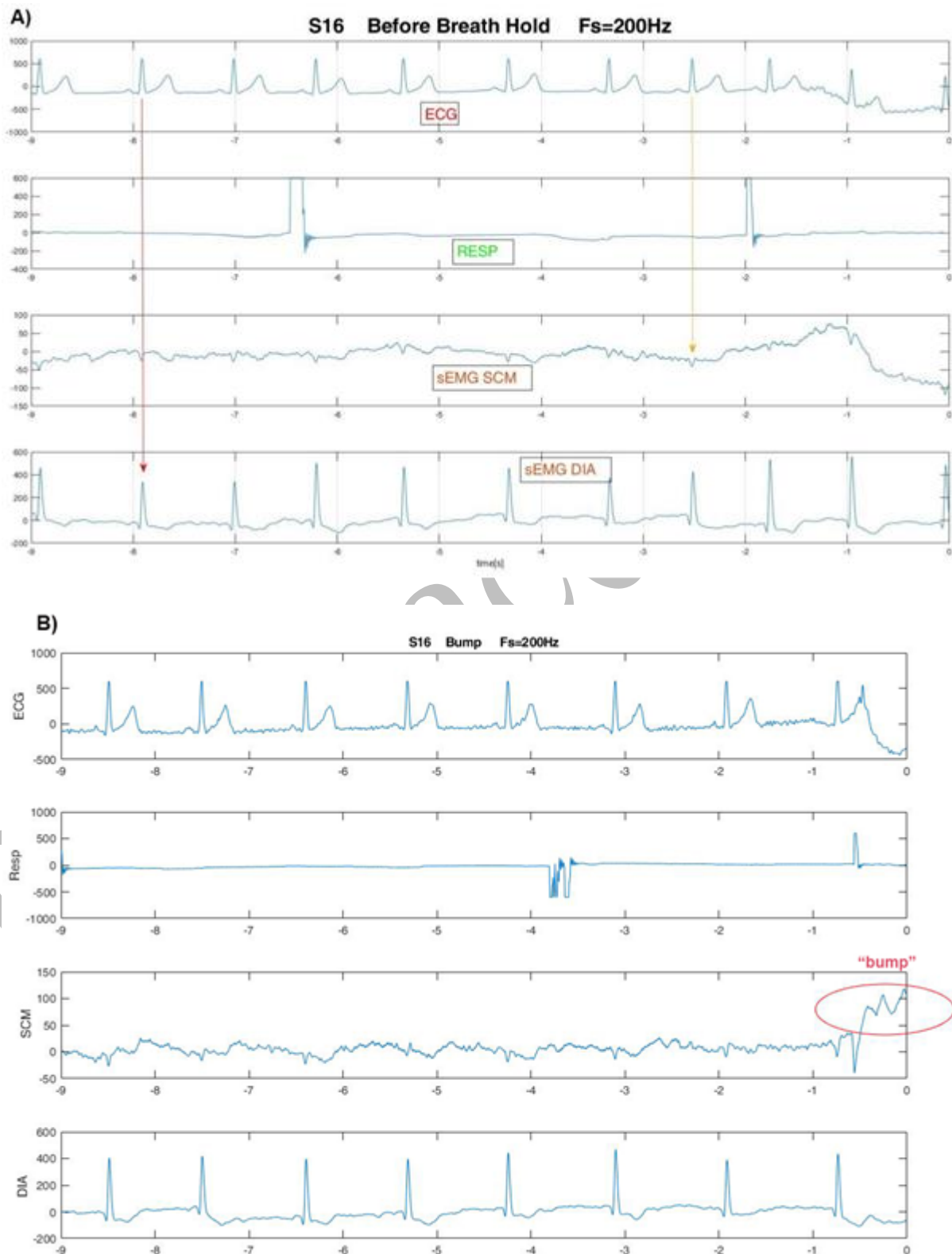
Figure 4: Signals recorded during A) normal breathing (*Phase 1* in Methods) and B) end of breath-holding – the "bump" phase (*Phase 3*); ECG, Respiration, sEMG SCM, sEMG DIA; signal amplitude is in [μV]. The influence of R peak on sEMG signals is visible, particularly on sEMG DIA, due to the vicinity of the heart.
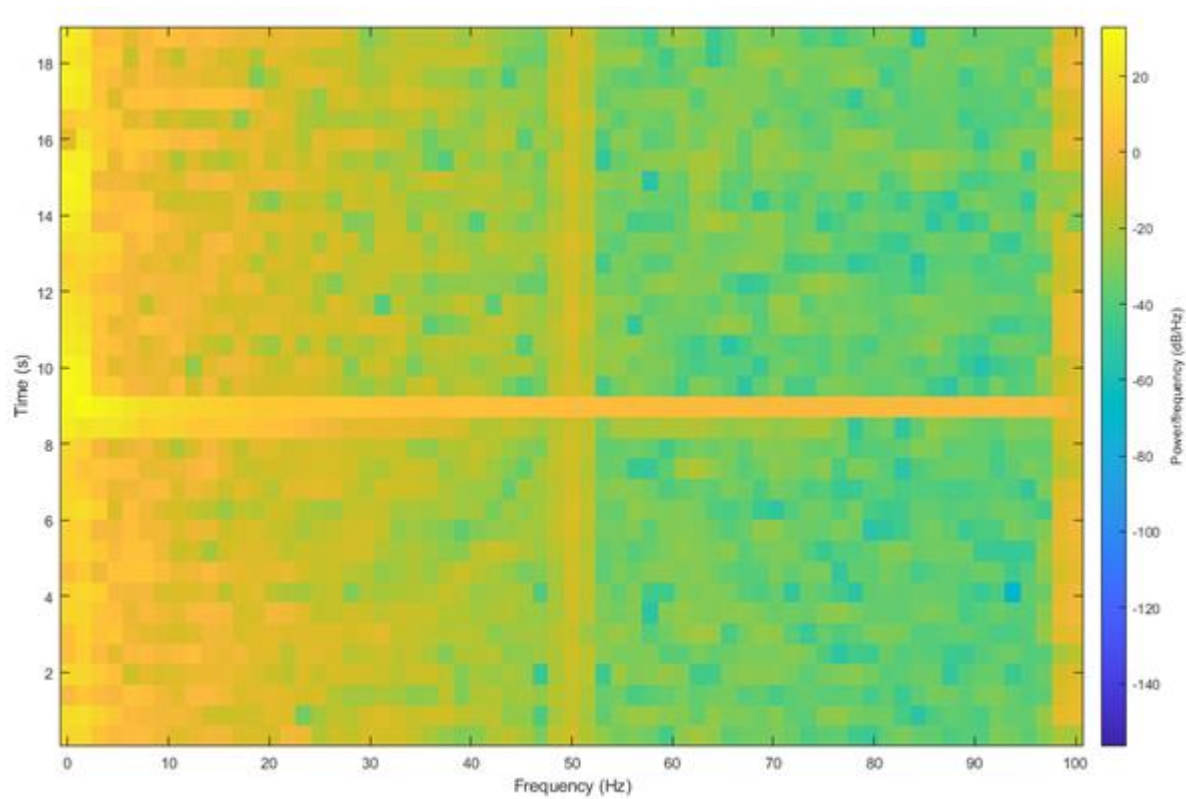
Figure 5: Power spectral density of SCM during breath-holding; "bump" recorded at *t* = 9 *s*; Sampling frequency *Fs*=200 *Hz*, Hanning window; *NFFT*=128; Noverlap = 108 samples
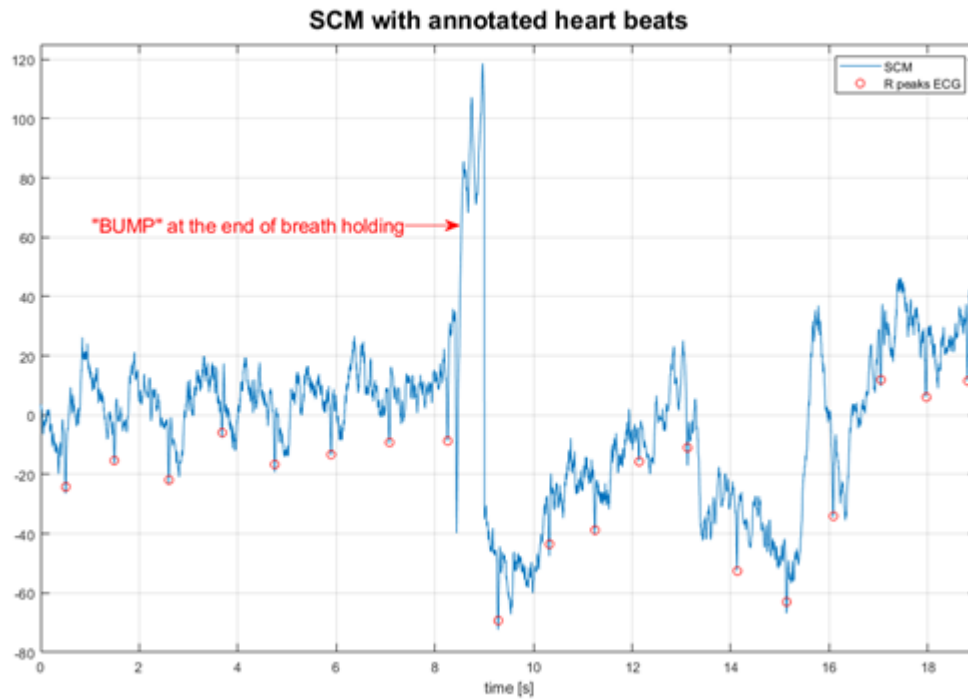
Figure 6: Changes of SCM at the end of breath-holding; "bump" recorded at $t = 9\ s$; exact moments of heart beats marked with red circles

Table 1. The overall results for the whole group of 30 volunteers.

No	P^{SC} rest	P^{SC} bump	P^D rest	P^D bump	ΔP^{SC}	ΔP^D	AP^{max}	T_{RLX} (ms) Tra.x(*ms]*
1	9	34.5	36	36	283.33%	0%	283.33%	800
2	7	38	500	1550	442.86%	210%	442.86%	1800
3	10	120	48	350	1100%	629.17%	1100%	1200
4	10	29.50	11	35.5	195%	222.73%	222.73%	750
5	6	21	40	40	250%	0%	250%	1100
6	23	51	200	200	121.74%	0%	121.74%	700
7	5	45	100	180	800%	80%	800%	600
8	18	49	18	110	172.22%	511.11%	511.11%	1500
9	5	33	25	32	560%	28%	560%	2100
10	32	42	20	70	31.25%	250%	250%	2050
11	2	22	60	20	1000%	-66.67%	1000%	2000
12	5.2	18.3	4.5	4.50	251.92%	0%	251.92%	1900
13	20.3	99.8	50	50	391.63%	0%	391.63%	800
14	100	30	37	72	-70%	94.59%	94.59%	1200
15	12	23	42	42	91.67%	0%	91.67%	1800
16	2.30	50	15	15	2073.91%	0%	2073.91%	1200
17	7	120	90	120	1614.29%	33.33%	1614.29%	700
18	8	41	5	23	412.5%	360%	412.5%	1700
19	9	72	200	160	700%	-20%	700%	1800
20	12	23.5	25	17	95.83%	-32%	95.83%	1100
21	6	19.5	10	10	225%	0%	225%	1400
22	20.5	28.5	38.5	13200	39.02%	242.86%	242.86%	1800
23	21	120	120	120	471.43%	0%	471.43%	600
24	26	14	20	106	-46.15%	43%	430%	1400
25	8	8	10	120	0%	1100%	1100%	1100
26	5.80	11.80	35	34	103.45%	-2.86%	103.45%	900
27	4	12	10	4	200%	-60%	200%	800
28	7	41	160	130	485.71%	-18.75%	485.71%	1900
29	4	29	30	30	625%	0%	625%	600
30	9	21	24	25	133.33%	4.17%	133.33%	400
AVG	13.80	42.25	66.13	127.93	425.16%	133.19%	509.5%	1256.67
				St.dev	489.23%	255.4%	467.4%	523.21
				Δ+ min	91.67%	94.59%	91.67%	400
				Δ+max	2073.91%	1100%	2073.91%	2100

The column P^{SC}_{rest} depicts the rest and P^{SC}_{bump} the P_{AV} value during the "bump" period in the SCM region, while similarly P^D_{rest} is the rest and P^D_{bump} is the "bump" value of P_{AV} in the DIA region, according to the labeling by the Japanese group [31]. The P_{AV} influx in percentages for the SCM and the DIA regions are denoted by ΔP^{SC} and ΔP^D, respectively. The maximum influx for each volunteer

is given in the following column, depicted as ΔP^{MAX}. T_{RLX} is the relaxation period in milliseconds after the P_{AV} was returned to the values equal to the initial state. The raw *AVG* shows the simple average value for all columns, while *St. dev* shows the standard deviation for the last four columns on the right. The most important values in the first (No), sixth (ΔP^{SC}) and seventh (ΔP^{D}) columns are in bold. While Δ_{MIN} shows the minimal increase, Δ_{MAX} shows the maximum increase for the last two columns on the right. However, *Δ-raws* for the ΔP^{SC} and ΔP^{D} columns are given for the bold values.