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Changes in power of surface electromyogram during breath-holding

Промена снаге површинског електромиограма при задржавању даха

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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 sternocleidomastoidus

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 respiratory 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 (proscessus 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 $\mu V$ per unit resistance, allowing simple squaring to obtain power in $\mu W$.

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 $\Delta P^{SCM}$ and $\Delta P^{DIA}$ 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 $\Delta P^{SCM}$ and $\Delta P^{DIA}$ values showed a significant increase. Such
instances are bolded in their respective columns. This is more frequent for the $\Delta P^{SCM}$, 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 $\Delta P^{MAX}$ (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 $\Delta P^D$ variable depicts the dominant group, defined as the maximum increase of $\Delta P^{SC}$ and $\Delta P^D$ 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.

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Conflict of interest: None declared.
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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 $[\mu V]$. 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 $t = 9 \text{ s}$; Sampling frequency $F_s=200 \text{ Hz}$, 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 | P³⁰⁰⁰ rest | P³⁰⁰⁰ bump | P⁰⁰⁰ rest | P⁰⁰⁰ bump | ΔP³⁰⁰⁰ | ΔP⁰⁰⁰ | ΔP³⁰⁰⁰ max | T max (ms) | Tr (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    |         |

The column \(P^{³⁰⁰⁰}_{\text{rest}}\) depicts the rest and \(P^{³⁰⁰⁰}_{\text{bump}}\) the \(P_{AV}\) value during the “bump” period in the SCM region, while similarly \(P^{⁰⁰⁰}_{\text{rest}}\) is the rest and \(P^{⁰⁰⁰}_{\text{bump}}\) 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 \(\Delta P^{³⁰⁰⁰}\) and \(\Delta P^{⁰⁰⁰}\), respectively. The maximum influx for each volunteer

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