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ORIGINAL ARTICLE / ОРИГИНАЛНИ РАД

Changes in power of surface electromyogram during breath-holding

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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, with sEMG of SCM and DIA regions measured before, during, and after the breath-holding exercise. All the 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 of 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 namber of participants).

Conclusions Our research concludes that there is 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

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 [1]. There are at least 10,000 studies, while about 1% have 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" [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) and asthma, with the emphasis on the experiment repeatability [5, 6]. There are also numerous studies conducted on healthy volunteers that measure the different effects of breathing exercises versus changes in the exhaled air [7, 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

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Figure 1. Electrode setup with Neurofax equipment

Figure 2. The electrode setup

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 analyses 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 this in mind, we concentrated mainly on the changes in the mean power (P_{AV}), since a large amount 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, 19–25 years old, students of a 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") upon prolonged breath-holding [13, 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 of 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 the "bump."
- Phase 4 – pressing of the switch the 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 Merletti and Muceli [3] and Afsharipour et al. [15]. The method is completely non-invasive and only surface electrodes were applied, as shown in Figures 1 and 2.

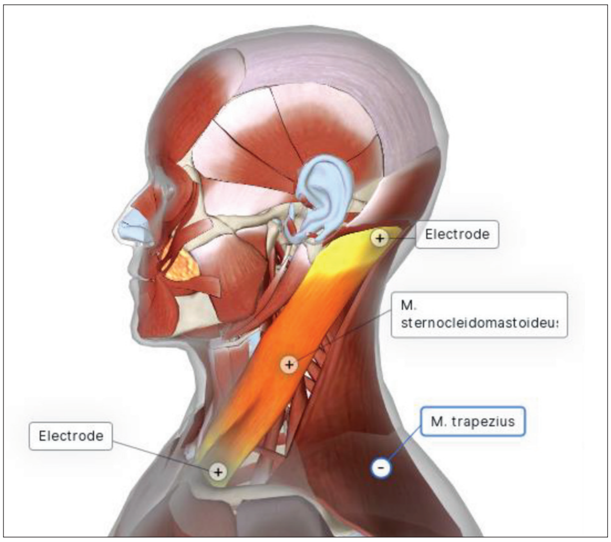

Figure 3: Sternocleidomastoid – the figure shows this biggest neck muscle and the positions of the applied surface electrodes

The measurement was performed using the 1200K Neurofax apparatus (Nihon Kohden Corporation, Tokyo, Japan) with surface ring Au electrodes filled with electroconductive gel and electrocap with 19 Ag/AgCl electrodes for electroencephalography (EEG) measurement (10/20 international electrode placement system). The experimental procedure is corroborated by the ethical standards of the Serbian Medical Society and is labeled by 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,
- electrocardiography (ECG) according to Einthoven,
- respiratory air-flow signal,
- HD camera built into this system,
- light hand built-in switch for the event labeling.

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

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) [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 entire 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, and custom C-programs [20, 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.

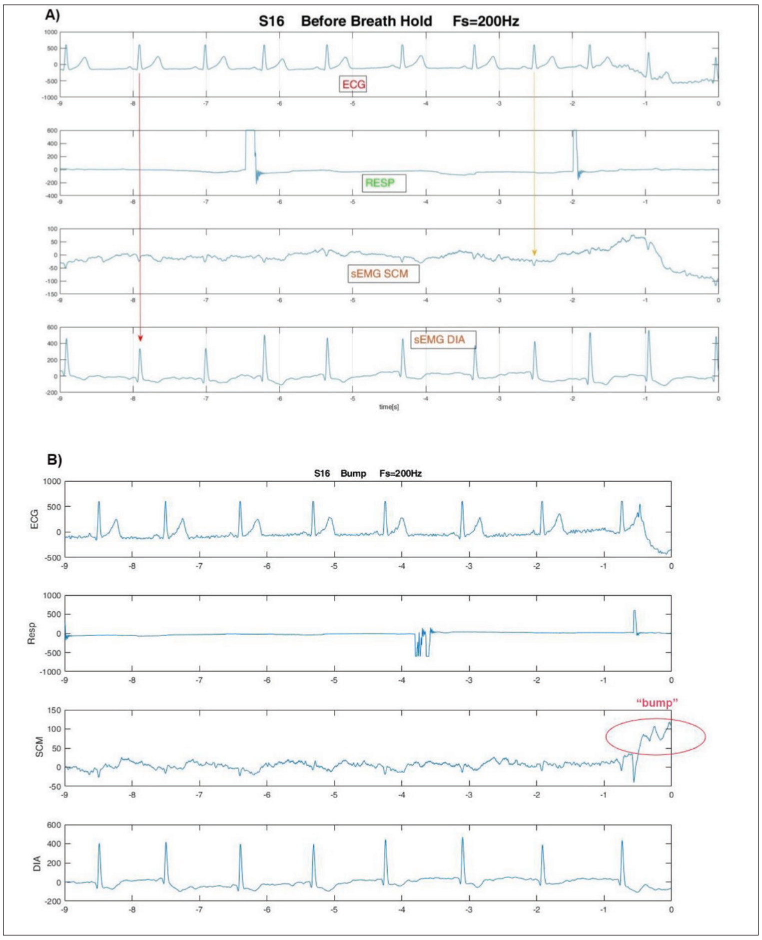

Figure 4. Signals recorded during A) normal breathing (Phase 1 in Methods) and B) the end of breath-holding – the "bump" phase (Phase 3); electrocardiography (ECG), respiration, surface electromyography (sEMG) sternocleidomastoid (SCM), sEMG diaphragm (DIA), signal amplitude is in [μV]; the influence of R peak on sEMG signals is visible, particularly on sEMG DIA, due to the vicinity of the heart

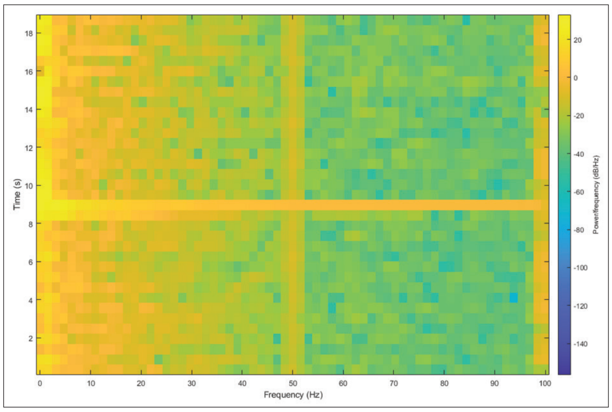

Figure 5. Power spectral density of sternocleidomastoid during breath-holding; "bump" recorded at t = 9 seconds; sampling frequency Fs = 200 Hz, Hanning window; nonequispaced fast Fourier transform (NFFT) = 128; noverlap = 108 samples

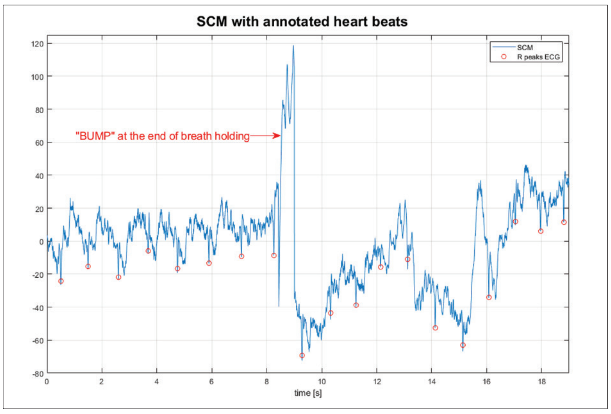

Figure 6. Changes of sternocleidomastoid at the end of breath-holding; "bump" recorded at t = 9 seconds; exact moments of heart beats marked with red circles

Figure 5 shows the power spectral density (PSD) of SCM signal during 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 the "bump" at the end of the 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 second 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 seconds. The typical 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-second window to minimize the influence of ECG on signals since the average RR interval of the signal represented in Figure 5 is 1.02 seconds. In the case of a sampling frequency of 200 Hz, the overlapping size between two consecutive windows is equal to 100 samples.

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 a 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 total number). 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 all the participants, 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 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 as much as 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 30 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 can see that the changes can 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, mainly in the SCM region, but not exclusively [25]. 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, Rakimov [24] 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

Table 1. The overall results for the entire 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
				SD	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 sternocleidomastoid (SCM) region, while similarly P^{D}_{rest} is the rest and P^{D}_{bump} is the "bump" value of P_{AV} in the diaphragm (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 SD 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

that "... most people feel the sensation in the neck rather than in the diaphragmatic region..."

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

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 the 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 *vs.* 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 in at least one measured region, SCM or DIA, with the 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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Промена снаге површинског електромиограма при задржавању даха

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САЖЕТАК

Увод/Циљ Бројне студије површинских електромиографских (*sEMG*) сигнала као одговор на промене различитих параметара дисања, нарочито на стерноклеидомастоидним мишићима (*SCM*) и дијафрагми, 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 областима *SCM* и дијафрагме.

Методе Физиолошка метода задржавања даха примењена је на 30 здравих добровољаца, и то *sEMG* мерењем области *SCM* и дијафрагме пре, током и после вежбе задржавања даха. Сви испитаници су седели у усправном положају, а носнице 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}) измерена је за сваки сигнални прозор од 500 *ms*.

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

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

Кључне речи: површински електромиограм; задржавање даха; стерноклеидомастоидни мишић