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DIAGNOSIS OF ATHLETE'S PREPAREDNESS BY ANALYSIS OF ELECTROMUSCULAR RESPONSE OF RESPIRATORY MUSCLES

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Abstract

Modern diagnostics of athlete preparation involves the acquisition of a large number of data, which requires superior knowledge, serious logistics, protocols, staff, time, etc. Technological breakthroughs in surface electromyography (sEMG) in measuring the activities of respiratory muscles in vivo opened new possibilities in this direction. The correlation between physical preparedness and the ability to maintain breath has been a theoretical phenomenon for over a century. The result at the duration of the breath holding time (BHT) is generally considered a positive indicator of the volume of respiratory capacity during physical activity. Experimental research determined involuntary activities of auxiliary respiratory musculature at the end of the quiet retention of breath and are determined as a physiological break point of breath holding. The time from the start of the breath holding to the first involuntary breathing movement (IBM) is called the control pause (CP). Since this time is not the physiological maximum of breath holding, it is very important to determine the exact moment of reaching the first IBM and the time-frequency characteristics of sEMG signals during the IBM phase (work problem). Using Wavelet methodology, the analysis of sEMG signals is performed on three skeletal muscles, two inhaling (M. Scalenus - Anterior et Medium - SC, and M. Parasternal Intercostales - IC) and one exhalatory (M. Rectus abdominis - Ra), that in addition to others, have auxiliary role and function in the respiratory cycle, and that are sensitive to physiological changes due to apnea, so in their neuromotor response are a possible indicator of metabolic processes that are detected as involuntary breathing movements. Multiple growths in the electrical activity of these muscles during IBM in certain frequency ranges have enabled precise IBM measurement, thus determining the physiologically acceptable duration of the CP. Observation and analysis of the specific respiratory and muscular response indicate dominations of hypoxic or hypercapnic metabolic condition (subject of research). Based on monitoring these changes in 12 subjects classified in the group categorized amateur athletes, it was determined that better-trained subjects have longer CP and react hypercapnically. The conclusions of this non-experimental case study correspond to the practice of training preparation but open the space for new research, primarily those who should develop an affordable method for non-invasive real-time physical preparation.

Keywords: BREATH HOLDING / SURFACE ELECTROMIOGRAPHY / WAVELET ANALYSIS / HYPOXIA AND HYPERCAPNIA.

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INTRODUCTION

One of the classic questions many coaches ask themselves is how to lead athletes and teams to individually optimal results. An important part of their daily routine consists of planning the development of athletes' training and competitive potential, as well as monitoring and measuring their progress in a standard environment. The primary mission of checking athletes' health status is to avoid adverse conditions during and immediately after training or competition and to ensure the chronic – lifelong effects of exercise. Health integrity challenges for athletes primarily include strokes (serious conditions with loss of consciousness) that can lead to fatal outcomes (Schmidt et al., 2013), as well as heart defects that can remain hidden for years (Panagotakos et al., 2004). During any demanding training cycle, coaches and athletes are expected to structure an optimal training plan and program for each day, week, month, etc. (Foster, 2016). To achieve optimal results and progress, and above all, to preserve athletes' health, it is critically important to make decisions about what to retain and what to change in training. Key strategic decisions are made based on training program analytics and indicators of athlete readiness diagnostics, which in a well-developed athlete monitoring system involves the acquisition of a large number of data points and measurements. These, depending on the sport and discipline, relate to VO_2^{max}, lactate threshold, body fluid biochemistry, EKG, EEG, etc. Due to the measurement of a large number of physiological parameters, the correct interpretation of results is crucial, and it requires highly trained and experienced analysts. Today's sports impose the concept of inter- and multidisciplinary approaches with a tendency to increase the number of knowledge areas and team size. Besides coaches, physiologists, and medical staff, it is not uncommon for information science engineers, biomechanics experts, statisticians, and others to be involved in planning to achieve top sports results. They assist in the acquisition and calculation of TRIMP scores. Foster (2015) emphasizes the effort to integrate as many parameters as possible into a single assessment, which facilitates decision-making for coaches and, in the case of poor results, incentivizes to create even more detailed analyses. This approach requires serious logistics and time, and the cost is not negligible, nor is the significant pressure that this cycle of measurement and testing places on coaches and athletes. Measurements and appropriate test selections are prerequisites for all cognitive efforts, known to "tire" athletes, and are therefore typically done separately from training.

PRACTICAL CHALLENGES OF ASSESSING ATHLETE READINESS

The primary motivation of any training regimen is to shift demands within a unit of time—an incremental effect that maintains the stability of skill and movement technique. In the practical implementation of the strategy or theory of training load and recovery, two concepts are thoroughly studied: NFOR (non-functional overreaching) and OTS (overtraining syndrome) (Meeusen et al., 2012). On one hand, the athlete must be overloaded to step out of the comfort zone of their current training level. If the chronic impact of OTS is not recognized, it can disrupt sports readiness, and if NFOR is not recognized, time is lost for preparation and reaching maximum readiness. These two conditions are challenging to distinguish for an inexperienced coach or an athlete lacking an understanding of training effects and accompanying conditions. The main problem in responding to the challenges of this process is the qualitative and quantitative recognition of the training structure, as well as the objective tests developed that realistically connect laboratory and field measurements. Karl Foster highlighted the practical issues in distinguishing between OTS and NFOR, noting that prolonged adaptation is the most common difficulty in their differentiation. In this process, a range of medical conditions must first be excluded. If there are no indicators among them, the next step is to check for disturbed homeostasis, numerous hormones, and then a series of blood samples to check: blood lactates, creatine kinase, and glutamate. If none of these are outside normal limits, then mental readiness can also play a role—in this sense, numerous psychological questionnaires have been developed (So et al., 2016).

A training plan, once established, needs to be followed for each day of the program, but this must be approached with caution. An athlete may be lazy and need to be stimulated to complete the daily plan, but if they have an objective problem fulfilling the daily plan at any stage of their life and training, this can lead to uncontrolled load attributes, making continued exercise counterproductive. The measurement method, selection of adequate tests, their acquisition, and individual analysis are conditioned by numerous factors primarily (Foster, 2015):

- **The time frame of training** is the first and decisive/key factor. Obtaining relevant and reliable results, from testing to proper interpretation, sometimes takes so long that it questions their immediate informational and strategic capacity.
- **The logistics** of such measurements are demanding: having the necessary equipment and laboratory at hand is difficult, as typical measurements require access to several different devices/modules.
- **The financial aspect**, such as the cost of equipment, test development, and their correct interpretation by specialists, determines whether the method can be practically applied or not, i.e., at what level of sports engagement this is possible (Matthew et al., 2010).
- **The psychological/sociological factor** is closely related to the reliability of a particular method. For example, EKG in top athletes is full of "abnormalities" in 50% of cases. These are not pathogenic changes in heart rhythm; misinterpreting the EKG can unnecessarily exclude an athlete from a competition they may have been preparing for years (Corrado et al., 2010). The consequence for the athlete's psyche is clear, and the financial effect cannot be ignored either.

It remains apparent that today's athlete monitoring is challenging, strenuous, and stressful. Using simpler methods would contribute to better training stimulus planning and individual athlete progress. This paper proposes a conceptual solution that can meet metric requirements based on the acquisition of parameters related to the body's physiological response during prolonged breath-holding.

Physiological Response to Prolonged Breath-Holding and Its Use in Research and Coaching Practice

Despite significant variations in the human physiological response to prolonged breath-holding, which is also attributed to the mammalian diving reflex, its critical function is preserving oxygen to maintain cerebral function. This includes two central processes that describe (I) peripheral vasoconstriction associated with initial hypertension, mediated by the sympathetic nervous system, and (II) bradycardia associated with decreased cardiac output, mediated by the vagus nerve (Lindholm & Lundgren, 2009; Foster & Scheel, 2005; Bain et al., 2018).

The initial increase in mean arterial pressure coincides with the contraction and expulsion of "fresh" blood from the spleen, providing "new oxygen" in the bloodstream, which has an apparent beneficial effect at the start of breath-holding (Palada et al., 2008).

During induced apnea, two main phases are observed: the "easy-going" phase, characterized by the absence of EMG activity of respiratory muscles, and the "struggle" phase, marked by rhythmic fluctuations in lung pressure and rhythmic EMG signals and their demarcation point. Identifying this transition represents a physiological breakpoint, a consequence of metabolic and dynamic responses of the respiratory muscles, considered the first involuntary breathing movement (IBM). The "struggle" phase is characterized by increasingly stronger IBM contractions of the respiratory muscles due to a series of metabolic adjustments, reflecting the excess CO2 concentration in the blood, which in turn affects the central respiratory system by producing a respiratory drive. These changes are accompanied by a feeling of air hunger, during which motivated but naive subjects will interrupt breath-holding and resume the breathing process (Parks, 2006; Bain et al., 2018). The frequency and intensity of IBM increase towards the end of apnea duration, indicating that this state has a discernible impact on IBM. Despite strong evidence, the role, and thus the reliability of IBM, is blurred by the fact that in some subjects, IBM cannot be detected even during extended breath-holding periods (Willie et al., 2015). The period of involuntary respiratory movement induces short-term increases in mean arterial pressure with positively correlated oscillations in cerebral blood volume and hemoglobin oxygenation, likely due to chemoreceptor stimulation and consequent efferent respiratory motor response (Willie et al., 2015; Joulia et al., 2003). It is accompanied by a decrease in spleen blood volume and the process of maintaining hemodynamics, which probably facilitates the use of the last oxygen reserves before the end of breath-holding (Palada et al., 2008).

Measuring breath-holding has been used for over 100 years as an important readiness factor for active military pilots (Flak, 1920). Non-invasive measurement of calm breath-holding to the IBM physiological response is among the least stressful of all breath-holding varieties. Since the 1960s in the Soviet Union (Kazarinov, 1990), breath-holding measurement has proven to be an excellent indicator of health status and energy capacity across a wide range of subjects, from cosmonauts to the seriously ill. However, this phenomenon could not be fully detected and explained by the physiological analyses of that time, especially in tracking changes in the activity of muscle groups involved in the breathing process (respiratory musculature).

Breath-holding after normal breathing and following spontaneous exhalation does not lead to any tension (Ostojić & Stefanović, 2020). The time period from the start of breath-holding in this way to the first IBM was called CP (control pause) by the Soviet group around K.P. Buteyko, and the length of this period is used to indicate the subject's readiness and overall health. IBM can occur in two topographical zones, in the neck region or the plexus (Stefanović, 2020). Until the recent breakthroughs in surface electromyography in analyzing respiratory phenomena, objective insight into the work of the respiratory musculature and the exact moments of IBM was not possible. Manual detection of IBM was previously mostly performed using subjective methods of tactile discrimination, palpating the plexus with fingers, placing a bell or plethysmograph on the region to feel twitching or trembling, while the neck followed the feeling as if the subject was performing a swallowing act. IBM reaction exclusively in the plexus is present in about 16% of subjects, in the neck in most (76%), and 20% of subjects react in both regions (Ostojić et al., 2020).

When practically measuring CP, a twofold problem is observed. If the subject merely "imagines" they have experienced IBM, the obtained result is shorter than the real one. In the case of breath-holding after IBM, the result is falsely longer. It should be noted here that the objectively maximum possible breath-holding time is up to 30% longer than CP, and this percentage decreases with longer breath-holding to about 10% (Ostojić, 2017). It is clear that the breath-holding time itself can be divided into several classes based on which the health and readiness of the subjects could be classified. However, the question arises of the reliability of CP measurement, and whether it is possible to derive a quick and accurate assessment of the health status and readiness of athletes based on the characteristics of IBM signals from the indicated body regions.

METHOD

The acquisition of sEMG data from selected muscles was carried out using the non-invasive research Delsys TrignoTM wireless sEMG system, known for its high performance. This system enables a sampling frequency of 1926 Hz, using four hybrid mobile sEMG sensors and a 16-bit A/D converter. Hardware filtering was applied, including a high-pass FIR filter of 7 Hz, a second-order Butterworth band-pass filter between 20 ± 5 Hz and 450 ± 50 Hz, and a narrow band-stop filter around 50 Hz.

Previous studies have shown that an initial sampling frequency of 200 Hz was insufficient to capture the full dynamics of the signal (Ostojić et al., 2020; Ostojić & Milosavljević, 2019). Therefore, a higher sampling frequency was applied to ensure higher quality parallel signals and to facilitate a simple, self-sufficient setup for acquisition. Measurement of the first IBM after a calm exhalation has been published in a previous study (Mišić et al., 2023), where it was demonstrated that these effects could be recorded and analyzed using wavelet spectral analysis, provided that the signals are sampled at a sufficiently high frequency.

The motivation for selecting the muscles was to include primary inspiratory and expiratory muscles. Scalenus anterior et medium (SC) and Parasternal Intercostales (IC) are primary inspiratory muscles, while Rectus Abdominis (RA) is a primary expiratory muscle. IC is an intersection between SC and RA, where most people exhibit a reaction, making it suitable for diagnostic purposes. M. Pectoralis is active during deep or forced inhalation but does not play a primary role in breathing during exhalation and was not measured. M. Brachioradialis, a locomotor muscle that does not participate in respiration, was measured as a reference muscle to aid in noise removal, See Figure 1.

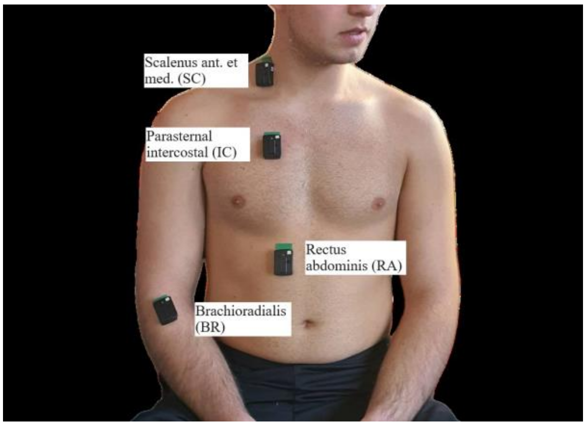

Figure 1 Placing of Delsys TrignoTM wireless sensors for one-sided (right side) recording the myoelectric activity of the three respiratory and one locomotor muscle

Note: Auxiliary inspiratory muscle Scalenus anterior et medium (SC), Primary inspiratory muscle Parasternal Intercostales (IC), Auxiliary expiratory muscle Rectus Abdominis (RA), and a locomotor muscle Brachioradialis (BR)).

For the entire experimental setup, the right side of the body was chosen for acquisition to minimize interference from heart activity signals, which are more pronounced on the left side. Additionally, subjects were instructed to avoid activating their peripheral muscles, except when indicating the beginning and end of breath-holding. This indication was a cue for the operator to place or remove the nose clip. This signal was given by slowly raising and lowering the index finger of the left hand to further avoid activity on the right side of the body during the critical phase of measurement (the beginning and end of the breath-holding (BH) maneuver).

In addition to the classical measurement of breath-holding duration (BHD), the main focus of this study is the time-frequency characteristics of sEMG signals during IBM movements of involuntary breathing. Both types of results are generally modulated by many factors. Apart from individual factors such as sex, age, body size, chest shape, diaphragm position, thoracic blood volume, blood hemoglobin content, metabolic rate, obesity, illness, etc., other common factors such as initial lung volume and posture significantly impact sEMG signals and BHD (Lumb, 2017a; Lumb, 2017b). Most breath-holding studies are based on holding the breath with fully inflated lungs. Still, such an initial lung volume creates tension in all respiratory muscles to overcome increased inhalation resistance and lung pressure. This produces an inflation reflex and increases the influence of the aforementioned individual factors (McCulloch et al., 2012). Given that this study mainly limited the research objectives to the sEMG response of respiratory muscles to hypoxic and hypercapnic stimuli, the common factors mentioned were chosen to minimize their impact on EMG activity by reducing additional unwanted elastic forces in the respiratory muscles and changes in lung volume, thereby reducing unwanted stimulation of respiratory center control. These factors can be overcome by breath-holding during fully relaxed respiratory muscles, which is characteristic of lung volume at the end of a normal exhalation, i.e., functional residual capacity (FRC).

Regarding posture, a supine position increases abdominal pressure on the diaphragm, thereby preventing the diaphragm from fully relaxing at the end of exhalation and significantly reducing thoracic volume, which thus affects the lung volume at the end of resting exhalation or FRC. Compared to an upright sitting position, the supine position decreases the elasticity of the chest and diaphragm, reduces chest compliance by 30%, and overall static compliance of the respiratory system by 60% (Ostojić et al., 2020). Additionally, breath-holding from FRC and upright sitting reduce pulmonary blood flow resistance and volume, thus preventing or reducing unwanted receptor stimulations. All these reasons led us to design the experiment with the BHM maneuver in an upright sitting position with a straight spine, without lumbar support, in a calm environment with occasional and timely notification of the remaining time until the approximate start of breath-holding.

Measurement protocol

The schematic representation of the BH maneuver, along with its tasks, phases, and durations, is presented in Scheme 1 (with time frames of spontaneous breathing established based on Stewart & Bain, 2021; Perini et al., 2008). Breath-holding commenced after a spontaneous exhalation to FRC, with subjects being instructed to refrain from preparatory hyperventilation, and concluded with spontaneous inhalation through the following phases:

- Calm, Passive Phase: The subject sat for approximately 3 minutes with their hands resting quietly on their thighs and all electrodes in place. They breathed quietly through their nose with normal inhalation and spontaneous exhalation, relaxing their entire muscular system.
- Active Phase, Breath-Holding: At their discretion, after a spontaneous exhalation, the subject raised their index finger to signal the operator to close the nostrils with a diving clip. The subject mentally continued to relax all muscles, went through a phase of easy maintenance, and allowed respiratory contractions to develop "naturally" towards the end of breath-holding (struggle phase, beginning of the physiological breakpoint, and the onset of IBM signals). The subject held their breath for as long as possible until spontaneous termination, at which point they signaled the operator to release the clip, allowing them to resume normal breathing.
- Calm Final Phase: The subject remained calm, as at the beginning of the exercise, for at least three more minutes, breathing quietly and relaxing their entire musculature while heart activity, breathing, and metabolic processes returned to normal.

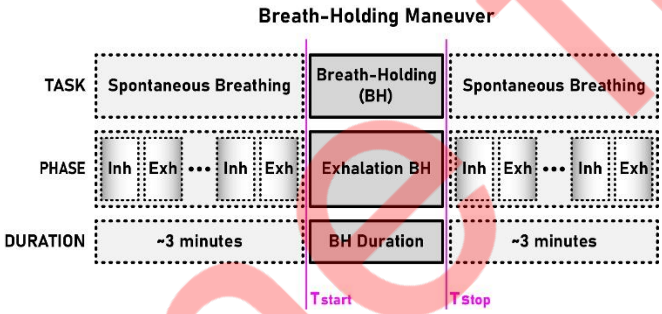

Figure 2 Breathing pattern in the breath-holding experiment.

Note: Breath-holding began after spontaneous expiration to functional residual capacity and ended with spontaneous inspiration to normal lung capacity. Markers Tstart and Tstop define the beginning and end of the breath-holding cycle).

Participants

This study included 12 healthy, regularly physically active, non-smoking volunteers divided into two equally sized groups based on their level of sports engagement—professional and amateur. For each participant, their primary sports discipline/activity, age, gender, height, weight, and status as a professional or amateur athlete were recorded. The participants selected were healthy individuals with an average body weight and a body mass index (BMI) ranging from 21.8 to 25.3 kg/m². All participants received necessary explanations and instructions and provided written consent, acknowledging that they understood the study's objectives and procedures and agreed to participate voluntarily. Each participant underwent the procedure depicted in Figure 1 twice, resulting in a total of 24 signals (12 participants x 2 sessions) that should contain IBM. Previous subjective measurements did not determine the presence of IBM, but with this equipment and protocol, we aim to identify it more accurately.

RESULTS

Participants with similar characteristics within each of the two study groups demonstrated significant variability in muscle physiological responses to the BH maneuver (Scheme 1), reducing the statistical consistency of the results. To draw valid conclusions from the variable data, the focus was on understanding the correlation between physiological responses and individuals' estimated physical fitness/training levels (Mišić et al., 2023). The physiological implications were analyzed and interpreted mainly in the context of hypoxic and/or hypercapnic responses, as well as muscle fiber subtypes.

Wavelet and statistical analysis of surface electromyography (sEMG) signals from three respiratory muscles (two inspiratory, SC and IC, and one expiratory, RA) and one locomotor muscle (BR) was performed during the BH maneuver to identify the most suitable muscle for detecting and characterizing involuntary breathing movements, as well as assessing responses to tissue hypoxia and hypercapnia. The measurement results are shown in Table 1, where the participants are categorized into groups of athletes and amateurs, with other recorded data and BH duration measurements for each of the two trials presented in the last two columns.

The long-term goals of this study are to improve physical fitness tests (Mišić et al., 2023). Several wavelet analysis methods were used: scalograms (continuous wavelet transform) for signal visualization and qualitative analysis and discrete wavelet transform (DWT) in redundant form, known as maximal overlap DWT (MODWT), for quantitative analysis. Based on MODWT, several analyses were performed, with the main ones being: 1) multiresolution analysis to determine wavelet energy spectra (WES) of signals, 2) correlation analysis of WES distributions using probability density estimation and classification by different criteria (level of sports activity, muscle types, and MODWT components) to determine the reproducibility of the IBM phenomenon, 3) wavelet variance analysis with a moving window of fixed width for individual MODWT components to analyze transient phenomena during IBM, particularly determining characteristic frequency ranges, and 4) comparative analysis of changes in relative energy of MODWT components and BH duration.

Table 1 Breath-holding duration (BHD) of categorized and amateur athletes (N=12)

	Training Level	Discipline	Gender	Age (years)	Height (cm)	Weight (kg)	BMI (kg/m^2)	BHD1 (s)	BHD2 (s)
1	Professional	Swimming	Female	20.9	168	63	22.3	24	27
2	Professional	Rowing	Female	29.4	180	75	23.2	31	28
3	Professional	Rowing	Male	30.5	195	92	24.2	51	53
4	Professional	Rowing	Male	26.9	197	90	23.2	64	81
5	Professional	Athletics	Male	25.1	192	85	23.1	57	52
6	Professional	Scuba diving	Male	27.2	186	80	23.1	70	66
	PROFESSIONALS		**MEAN**	**26.7**	**186.3**	**80.8**	**23.2**	**49.5**	**51.2**
			SD	**3.1**	**10**	**9.8**	**0.5**	**16.7**	**19.3**
7	Amateur	Volleyball	Male	20.6	204	95	22.8	27	29
8	Amateur	Jujutsu	Male	36.7	185	76	22.2	43	52
9	Amateur	Jujutsu	Male	19.2	178	69	21.8	34	37
10	Amateur	Jujutsu	Male	44.9	180	80	24.7	40	57
11	Amateur	Jujutsu	Male	40.1	180	82	25.3	36	49
12	Amateur	Yoga	Male	45	197	93	24	21	24
	AMATEURS		**MEAN**	**34.4**	**187.3**	**82.5**	**23.5**	**33.5**	**41.3**
			SD	**11.7**	**10.7**	**10**	**1.4**	**7.5**	**12.2**
	TOTAL		**MEAN**	**30.5**	**186.8**	**81.7**	**23.3**	**41.5**	**46.3**
			SD	**9.1**	**10.3**	**9.9**	**1**	**15.2**	**16.9**

This pilot study preliminarily indicated high reproducibility of predetermined respiratory muscle responses, as well as the detection of dominant respiratory muscle responses and IBM signals either in the inspiratory IC or the expiratory RA. The difference was associated with training status, with categorized athletes showing longer BH duration and a stronger hypercapnic response in the expiratory RA compared to recreational athletes, who exhibited a stronger hypoxic response in the inspiratory IC. Additionally, frequency ranges were determined: the hypoxia-sensitive inspiratory IC activated in a shorter time and gradually within the frequency range of 250-450 Hz for recreational athletes (independent of the individual and BH duration), whereas the hypercapnia-sensitive expiratory RA activated only with longer BH duration but abruptly in the frequency range below 250 Hz, depending on the individual and BH duration. Comparison of BH duration and wavelet characteristics of sEMG signals showed changes consistent with the mechanism of motor unit recruitment and the transition from slow-twitch oxidative muscle fibers (type 1) to fast-twitch (low-oxidative) glycolytic muscle fibers (type 2). The study also revealed certain parameters indicating disorders, some of which were consistent with findings in existing literature. Overall, the research demonstrated that using sEMG techniques and wavelet analysis could non-invasively assess oxygen storage in skeletal muscles, suggesting the potential to improve physical fitness tests by establishing a closer link between physical condition, BH duration, and sEMG characteristics of increased myoelectric activity in IC and RA muscles during BH.

DISCUSSION

Conceptual solution of a method for the health check and sports preparedness

The conceptual solution for assessing the health and readiness of athletes revolves around monitoring three apnea-related muscles: IC, RA, and SC. SC is particularly measured to control breathing technique, ensuring that participants perform exercises correctly without preparatory hyperventilation.

Building on previous findings, there is a demand for precise and rigorous preparation of participants and protocols to ensure high-quality raw data, minimizing interference and facilitating accurate interpretation.

Classical methods reliably measure CP only in well-trained individuals who can relax, whereas results often prove unreliable in stressed or tense subjects. To mitigate this, subjects should be relaxed before measurements through activities such as conversation, music, ionization, static electricity elimination, etc.

Additional activities and monitoring are proposed to observe patterns better and facilitate result interpretation:

- Visual monitoring of participant reactions and behaviors via camera to verify unexpected signal occurrences retrospectively.
- Expansion of measurements to include additional respiratory muscles, particularly adding diaphragm measurements.
- Measure pulse rate intervals (ECG) to study variability over time and attempt sinus rhythm detection for establishing central respiratory rhythm and IBM signal during breath-holding (Parks, 2006).
- Monitoring post-exercise heart rate recovery time as an indicator of athlete fitness level, comparing it with recovery time derived from sEMG signals (explained later in Figure 5).
- Isolation of heart signals from sEMG signals and correlation with ECG to ascertain whether pulse can be reliably obtained from IC and RA sEMG respiratory signals.
- Standard tissue oxygenation measurement methods using near-infrared spectroscopy (NIRS) were added to calibrate oxygenation linkage with sEMG muscle measurements.
- A larger sample size is needed to detect better patterns and statistically group results by sports branches/disciplines, gender, training type, body size, etc.
- Pre- and post-training sEMG measurements should be conducted to qualitatively assess muscle response to fatigue alongside standard measurements such as EKG, EEG, biochemistry, lung capacity, etc., correlating them to possibly replace standard measurements with sEMG muscle measurements.
- To establish the relationship between FRK (functional residual capacity) and breath-holding duration (BHD), for a better understanding of the neuromuscular response to breath-holding and to generate reference values for ТЗД in healthy individuals corresponding to the control pause and maximum positive pause, several considerations are pertinent. When predicting maximum breath-holding duration, lung capacity should also be taken into account, as individuals with greater lung capacity are expected to have longer maximum breath-holding durations. Specifically, Buteyko posits that maximum breath-holding duration can be increased through diving training and developing the diving reflex, but not the control pause. Control pause can only increase if CO_2 deposits in cells are elevated to a physiological optimum of approximately 6.5-7.5% for healthy individuals (Yakovljeva, 2013). The FRK should be theoretically calculated based on height, age, and BMI (Lumb, 2017a), and this theoretical capacity should be measured and compared. This comparison will calibrate the rough prediction of expected breath-holding periods in healthy individuals.
- Utilizing Finapres for blood pressure measurement, capable of detecting IBM, would enhance the comprehensive assessment.

The sEMG signal is divided into frequency bands D1 (480–960 Hz), D2 (240–480 Hz), D3 (120–240 Hz), D4 (60–120 Hz), D5 (30–60 Hz), D6 (15–30 Hz), D7 (7–15 Hz), D8 (4–7 Hz), and S8 (0–4 Hz) using wavelet analysis. From previous measurements, it was concluded that the response of most participants in the IC inspiratory muscle is such that energy gradually increases in the 120-480 Hz range (D2-D3), while energy decreases in the 7.5-30 Hz range (D5-D6). There is a particularly pronounced energy decrease for participants with poorer results in the D6 range of 15-30 Hz. On the SC muscle, there was observed energy increase from 240-480 Hz (D3), and somewhat less from 120-240 Hz (D2), while energy decrease was present from 15-120 Hz (D4-D6). In contrast, while the increase on IC and SC muscles is gradual, it is abrupt on the RA muscle, and mainly present for the most trained participants who have BHD>50s, in the range of 60-240Hz (D3-D4), and partially in 240–480 Hz (D2). These regularities and values form a reference that will be compared to new measurements to classify new measurements in relation to the existing reference.

Figure 3 shows the sEMG response of the third participant in the IC inspiratory muscle by frequency scales, where the RMS energy of the signal is shown calculated as the square of the wavelet coefficients of individual scales, averaged over a window of 1.5 s (so that it covers two heartbeats). A significant gradual increase in response in the 120-480 Hz range (D2-D3) is noticeable somewhere from the middle of the inspiratory process, representing the energy "signature" of the hypoxic IBM process. Figure 4 shows the RMS energy (square of the wavelet coefficients) of the sEMG signal of the fourth participant on the RA expiratory muscle. We notice a significant sharp increase in energy in the frequency range from 60-480Hz (D2 – D4) but closer to the end of the inspiratory process, which is the energy "signature" of the hypercapnic IBM process.

Existing TRIGNO equipment can be used for measurements, with a software component added for signal processing: noise removal and signal division into wavelet components (as shown in Figures 3 and 4). By observing sEMG response across frequency scales, such as D2 scale on IC muscle and D3 scale on RA muscle, the following parameters can be measured (see Figure 5):

- The start of CP measurement is marked as T_{start}, representing the universal timer start when the index finger signals the closing of nostrils.
- The duration of the easy-going period T_1 is measured from the cessation of breathing to the beginning of the struggle period characterized by the increase in sEMG signal. A longer T_1 indicates better preparedness of the subjects and typically equals half of the CP (Bain et al., 2017), which has been experimentally verified.
- During the struggle period T_2, significant muscle responses are observed, marking the recruitment of motor units with more oxidative slow-twitch muscle fibers (type 1) and/or fast-twitch glycolytic muscle fibers (type 2). Muscle response increases until the first IBM contraction occurs at a certain moment (which gives us the IBM period T_{ibm}, see the moment marked by the green arrow in Figure 5), where CP = T_{ibm}.
- After the first IBM contraction, the respiratory muscle relaxes (energy decrease), followed by periodic subsequent IBM contractions of increased intensity and frequency. Towards the end of the struggle period, very strong contractions occur (sharp energy decreases and increases, see the red arrow in Figure 5). Shortly thereafter, breathing is restored at moment T_{stop}: longer T_2 times indicate better preparedness of the subjects.
- After breathing is restored, recovery time is measured, i.e., the return of the sEMG signal to normal (recovery time T_{rec}). A shorter recovery time indicates better preparedness.
- Increase in energy over time compared to the nominal reference energy (E_{nom}) from the beginning of breath-holding (averaged over a 1s window, after the first 2s from the beginning of breath-holding).
- The rate of energy increase from nominal to maximum value (E^{max} - E^{nom}) / T_2.

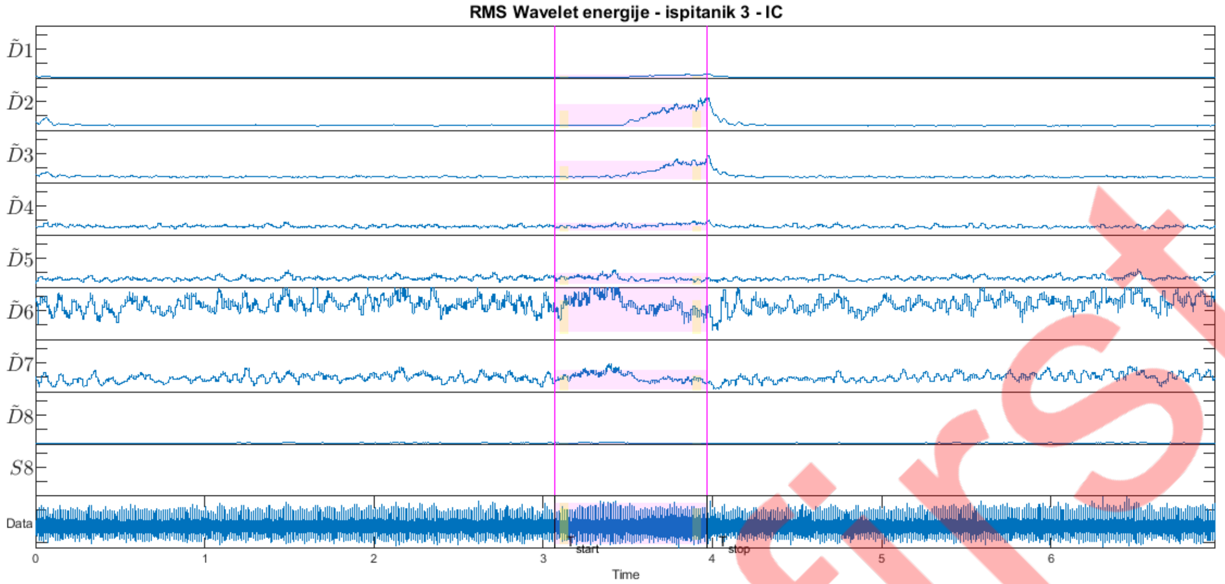

Figure 3 RMS signal energy calculated as the square of the wavelet coefficients (wk^2) in the third subject, the IC muscle shows a significant increase in responsiveness at the moment of IBM, in freq. range 120-480 Hz (D2-D3).

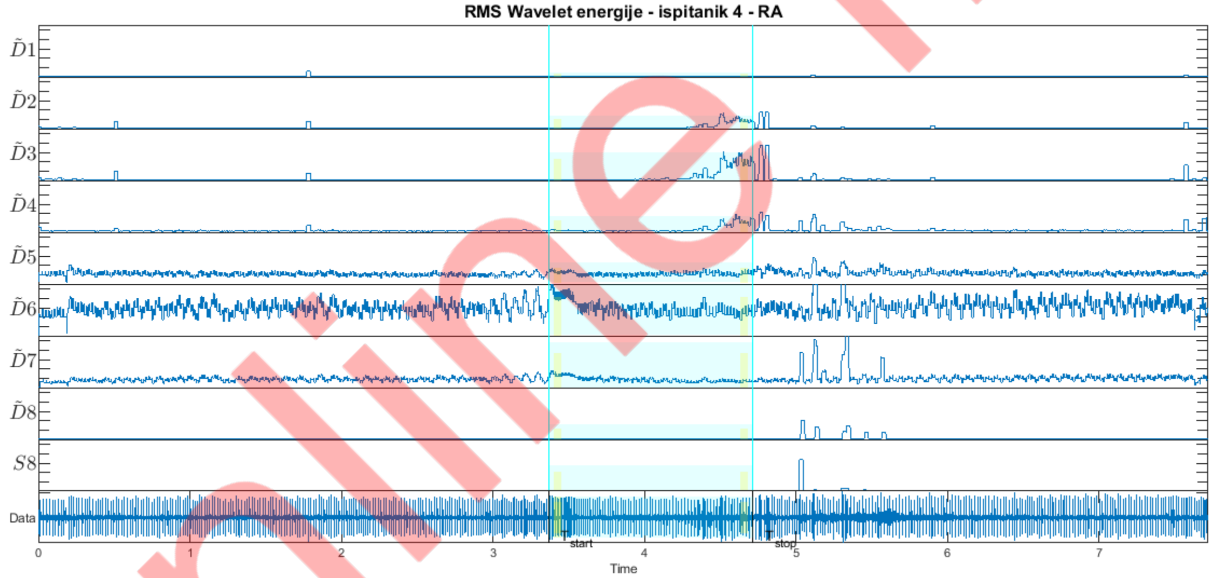

Figure 4 The RMS signal energy calculated as the square of the wavelet coefficients (wk^2) in the fourth subject on the RA muscle shows a significant increase in the IBM response in the frequency range of 60-480 Hz (D2 – D4).

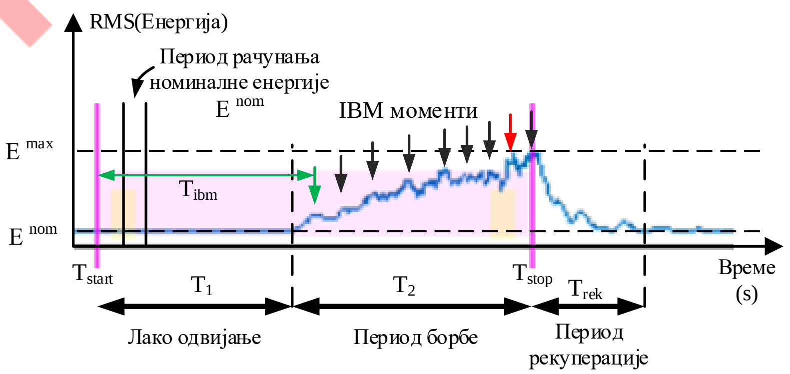

Figure 5 Measurement of BH parameters: easy-going period times T_1, period of struggle T_2, breath holding time (BHT) T_1+T_2, recuperation time T_{rec}, the time till the first IBM-a T_{ibm}, nominal E^{nom}, and maximal E^{max} energy.

CONCLUSION

In this non-experimental observation, a protocol for assessing the health and readiness of athletes based on the specific response of respiratory musculature to apnea was proposed. Analysis revealed that detecting specific changes during IBM through sEMG recordings of IC, RA, and SC muscles is possible. Responses were observed in all three regions in most subjects, along with some specific changes.

Dynamic analysis of spectrum changes throughout the entire procedure unequivocally demonstrated significant alterations ranging from 60 Hz to over 600 Hz. There was no significant muscle response in some subjects, likely because they did not reach IBM. Although they could have held their breath longer, they did not. This underscores the importance of correctly conducting measurements for experiment success, achievable through high-quality subject training and complementary measurements such as infrared and conventional camera measurements, sEMG measurements of the diaphragm, heart rate, etc., contributing to a better understanding of the studied phenomena.

One intriguing possibility is correlating and calibrating sEMG results with other physiological diagnostics. The initial achievement could confirm existing diagnostic methods that are expensive, inaccessible, or time-consuming to process, all while ensuring comfort and non-invasiveness. If correlation is confirmed, partially replacing existing testing methodologies with the new sEMG method using original parameters becomes feasible.

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