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NIRS: MEASURING CHANGES IN MUSCLE OXYGENATION AND THE DETECTION OF MUSCLE ACTIVITY

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Abstract – NIRS (Near Infrared Spectrophotometry) is a non-invasive optical method for continuous measurement of tissue oxygenation and hemodynamic, which can be observed as relative changes in the concentration of haemoglobin in the blood and thus indirectly the oxygen content in the blood, ie tissue oxygenation.

In our experiment, we wanted to determine the practical limitations of NIRS method and correlation with an increase in muscle activity in the case of isometric muscle contraction (m. tibialis anterior). Simultaneously a more commonly used EMG (electromyography) method was employed. EMG is a method for the observation of muscle activity, based on the measurement of changes in electrical potential across the membrane of muscle fibres.

We found that the use of NIRS device NIRO2-X2 is impractical for use in the sports field and unreliable for a reproducible measurement. Our results show that in the case of momentary increase of voluntary isometric muscle contraction both NIRS and EMG signals are adequate parameters to determine the beginning of muscle activity increase.

Keywords: NIRS, EMG, oxygenation, haemoglobin, sports medicine

1. INTRODUCTION

Around 40% of total body weight represents skeletal muscles [1]. During physical activity the majority of skeletal muscles are involved in the total consumption of oxygen VO_2. The most frequently used and validated method for the determination of VO_{2max} in sports medicine is the gas analysis. It provides a complete aerobic capacity of the athlete and enabled estimation of the total consumption of oxygen throughout the body [2]. Gas analysis is also used to determine the anaerobic (lactate) threshold of the organism, which is the main criterion for the level of fitness of athletes. At the same time lactate threshold represents the boundary between aerobic and anaerobic processes and the limit for the two different types of training in the training cycle of an athletes.

For clinical medicine it is of special interest the partial oxygen consumption, i.e. the consumption of oxygen in a certain part of the organism, for example, in the tibialis anterior muscle. There are several methods of partial oxygen consumption determination. They are often invasive and not continuous and measure the blood flow in certain muscle groups. A widely established method in clinical environment is transcutaneous oximetry (TcpO2) [3].

One of the non-invasive methods that allow also continuous monitoring of the physiological parameters, is near-infrared spectrophotometer NIRS. NIRS is a technique based on optical properties of tissue observed [2]. It is a method for continuous measurement of tissue oxygenation and haemodynamics [4]. Today it is mainly used for observation of neonatal brain oxygenation. It is based on optical transmission of organic tissue to light in the NIR range and the absorption properties of haemoglobin molecules in oxygenated and deoxygenated form. Relative changes in the concentration of haemoglobin in the blood can be observed by measuring of changes in the absorption of light in the tissue. Thus the oxygen content in the blood, tissue oxygenation is indirectly measured. The sum of oxygenated and deoxygenated haemoglobin is proportional to the blood volume in the tissue [4].

During isometric contraction the oxygen consumption in the muscle increases as compared to the consumption of the relaxed muscle. Two physiological parameters through which the consumption of oxygen in the tissues can be deduced indirectly, are concentration of haemoglobin and mioglobin in muscle [5]. Haemoglobin appears in the form of oxygenated (HbO2), or in the form of deoxygenated (Hb) haemoglobin.

EMG is a method for the observation of muscle activity, based on the measurement of changes in electrical potential across the membrane of muscle fibres. The potential of a muscle fibre in relaxed state is around -90 mV. With appropriate stimulation the potential can increase to +40 mV. This difference in potential (action potential) can be acquired in the form of an EMG signal. EMG signal is usually the result of voluntary contraction of many muscle fibres, or even an entire muscle or muscle group. It depends also on the geometry of the electrodes, the position of the electrodes, the electrical contact electrodes to the skin, tissue thickness, etc [6]. EMG method is simple non-invasive method suitable as an indicator tool for observation of muscle activity using surface electrodes. In our experiment the isometric contraction of m. tibialis anterior, and its isometric dorsal flexion represented muscle activity, which was measured by means of EMG methods.

In our experiment, we wanted to verify whether it is possible to determine the oxygenation of tibialis anterior muscle using a simple NIRS measurement. We also expected to detect the simultaneous change of NIRS and

EMG signals detecting the start of muscle activity when the voluntary contraction of a observed muscle is rapidly increased.

2. METHODS

The experiment involved nine healthy volunteers (all active rowers, 2 female and 7 men in the age of 16 to 27 years). All tests were conducted in sitting position. The tested of a subject's leg was fixed in a holder, which provided a rectangular position of the ankle according to the tibia (Fig. 1). The holder was equipped with a torque transducers allowing 3D measurement of force to observe unwanted shift of the foot. Self-adhesive bipolar EMG electrodes (Blue sensor N-00-S, Medicotest, 1 cm^2 area, 3 cm distance between the electrodes) have been positioned in axial direction on the prepared skin of the body of the muscle tibialis anterior. Preparation of the skin included cleaning with alcohol, and no shaving. Besides EMG electrodes the light source and the detector of NIRS device NIRO2-X2 (by Keele University, UK) were attached in the same direction (3 cm apart).

Each person was in sitting position in a comfortable chair to avoid moving of limbs, which was a major source of moving artefacts in the NIRS measurements. For every subject the initial test was measurement of the maximum voluntary isometric dorsal flexion - maximum maximal voluntary contraction (MVC). Maximal MVC was the level of voluntary contraction during which the subject was able to control the strength of the load by observing the torque-meter indicator. After 15 minutes rest period the subject activated the muscle according to the protocol in Fig. 2. The protocol included the relaxation phase, two test trials for subjects to get familiar with the 10% MVC and 50 % MVC load, 15 minutes of activity at 10% MVC, 5 min at 50% MVC and 15 minutes of rest. EMG and NIRS signals were acquired throughout the activities.

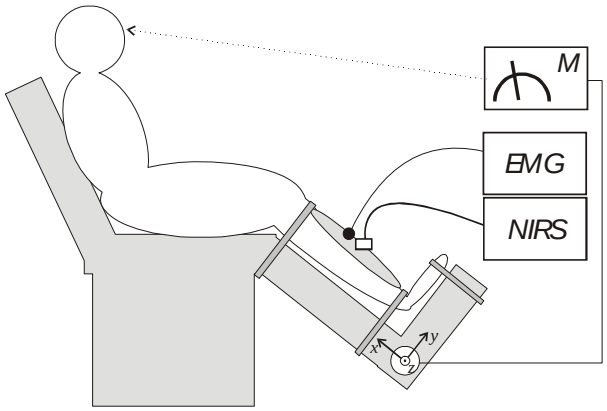

Fig. 1 The setup for acquiring the EMG and NIRS signals. The subject was responsible for regulating priory agreed load with the help of the torque measurement. Torque-meter M contained a three-dimensional force sensor that enabled the correct position of the ankle.

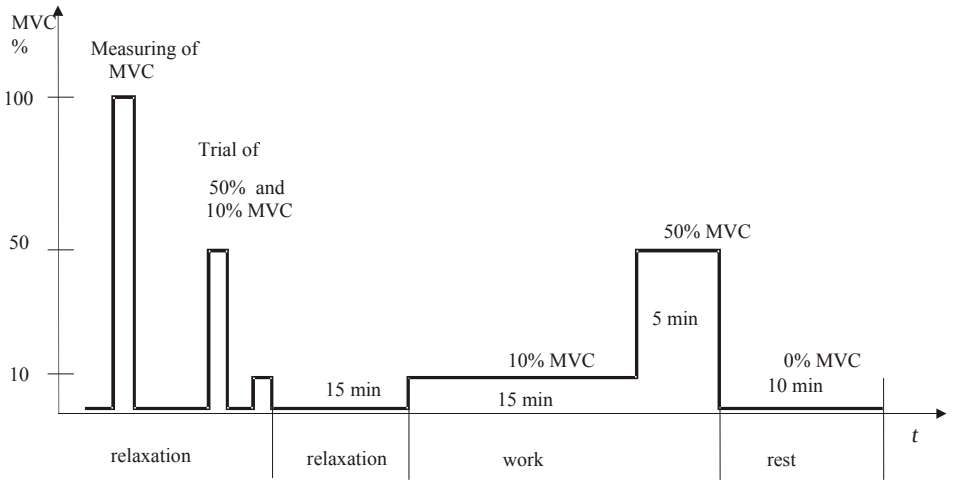

Fig. 2. Test protocol of a 60 minute measurement for a single subject.

The relative changes of oxygenated (Hb) and deoxygenated (HbO_2) form of haemoglobin were acquired using a NIRO2-X2 device. NIRO2-X2 has four semiconductor lasers with 775, 805, 845, 904 nm wavelengths. Raw data was processed using Matlab software package. Since the absolute path of IR light in the tissue is not known, the NIRS signal does not represent the absolute value of haemoglobin and mioglobin concentrations. Only changes in concentrations against level in the relaxed state can be determined [5]. Torque was measured with three-dimensional torque gauge and was only an aid for the subject to maintain a certain percentage of MVC protocol during the measurement. The direction of the force was important not to activate other muscle groups. Surface EMG electrodes were connected to electromyographs Myolab II, Model MC-200, Iomed Inc.., Salt Lake City, USA. The torque meter and EMG were connected via MP100 data acquisition system Biopac

Systems Inc. unit., Goleta, CA, USA, to a personal computer. EMG signal was sampled with a sampling frequency of 5000 Hz every 30 seconds for 1 second long and filtered with band pass filter (5 to 500 Hz). Using the software package AcqKnowledge III 3.2, Biopac Systems Inc.., Goleta, CA, U.S. values were processed by employing the fast Fourier transform (Blackmann window) every second segment separately. For each power spectrum section the median frequency was calculated.

4. RESULTS

During muscle contraction, muscle fibres press on the walls of blood vessels leading to the occlusion of arteries and veins. During the occlusion HbO_2 decreases because of oxygen consumption, and fresh blood cannot reach the issue. And vice versa for concentration of Hb. Hb_{tot} is the sum of the two forms of haemoglobin.

$$[Hb_{tot}] = [HbO_2] + [Hb] \quad (1),$$

where the value in square brackets are the concentration of substances. Concentration of Hb_{tot} is proportional to the volume of blood in the tissue [4, 7].

Hb_{dif} is defined as the difference of the two forms of haemoglobin.

$$[Hb_{dif}] = [HbO_2] - [Hb] \quad (2)$$

Hb_{dif} is an indicator of the level of oxygenation of tissue. Oxygenation is the response to occlusion or muscle activity. Hb_{dif} is an indicator of oxygenation, which is the expected reaction to occlusion and muscle activity The absolute value of Hb_{dif} is increasing during muscle activity [1].

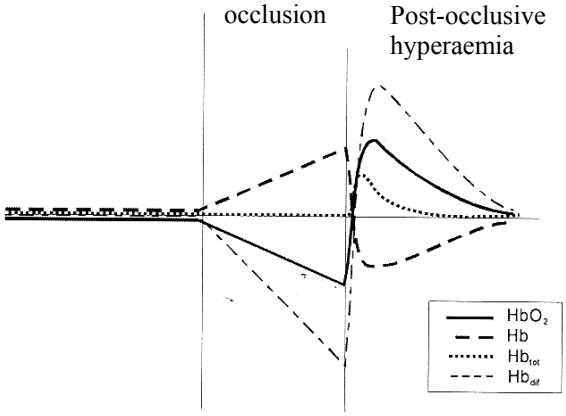

Fig. 3. Idealized signals of NIRS parameters as a function of time [1].

After the occlusion of arteries or muscular activity the phase of reactive post occlusive hyperaemia occurs. Fresh arterial blood streams in the tissue, and the concentration of HbO_2 raises and grows well above the baseline value before occlusion. And vice versa for the concentration of Hb. The result of both phenomena is an increase in the concentration of Hb_{tot}. Physiological reason is that the influx of fresh arterial blood in the tissue is greater than the outflow of venous blood.

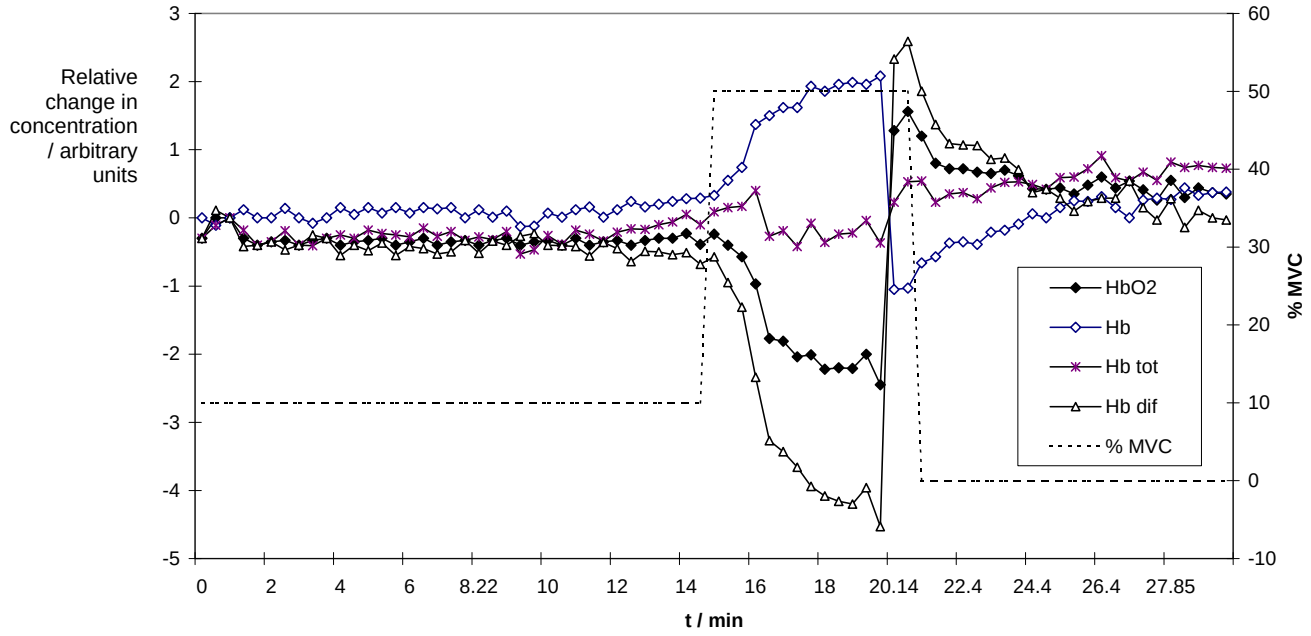

Fig. 4. NIRS signals (subject 1). At minute 16 the activation from 10 % MVC to 50 % MVC occurred. Moving artefacts were priory eliminated.

In 10% MVC region of the protocol the observed median frequency of EMG signal was fairly stable; the average value during the 15 minutes was 91.2 Hz, with standard deviation of 5.8 Hz (Fig. 5). In 50% MVC region, the median frequency increased to 144.9 Hz, and then decreased with time (Fig. 5). Decreasing indicates fatigue of the muscle, which corresponded to the results from the literature [8, 9].

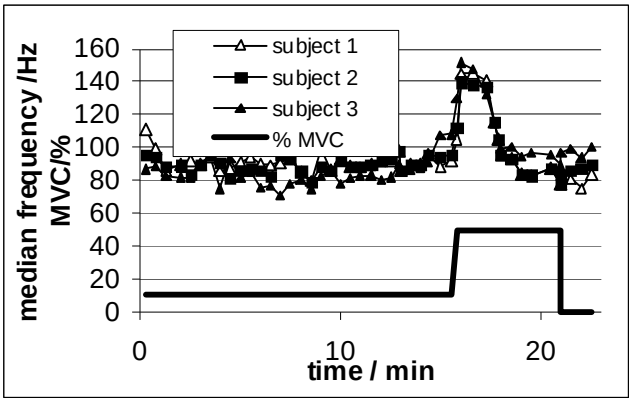

Fig. 5. Time dependency of median frequency of EMG signal power spectrum (sampling frequency 5 kHz, length of 1 second every 30 second, FFT, Blackmann window).

In the range of 10% MVC part of protocol the median EMG frequency was relatively constant (typically has changed by less than 6 Hz / s if calculated from linear functions by the method of least squares). In the transition to 50% MVC most subjects started to suffer of muscle fatigue, but all endured until the end of the test. At about 3 minutes 50% MVC two subjects experienced uncontrolled moving of the leg, which has brought additional artefacts in the measurements.

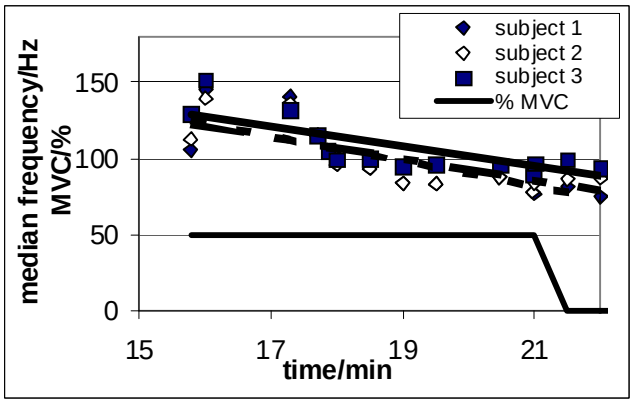

Fig. 6. Time decay of median frequency of EMG signal in 50 % MVC part of protocol, fitted by a linear function (Student t-test:p_1= 0.026, p_2 = 0.017, p_3 = 0.006).

Table 1. Median frequency of EMG signal in 10% MVC part of the protocol and maximal value of median frequency in 50 % MVC part for three subjects.

subject	10 % MVC		50 % MVC
	f_{EMG} /Hz	stdv(f_{EMG}) /Hz	f_{EMG}/Hz
1	91.2	5.6	145.0
2	89.6	4.6	139.7
3	83.9	7.1	151.7

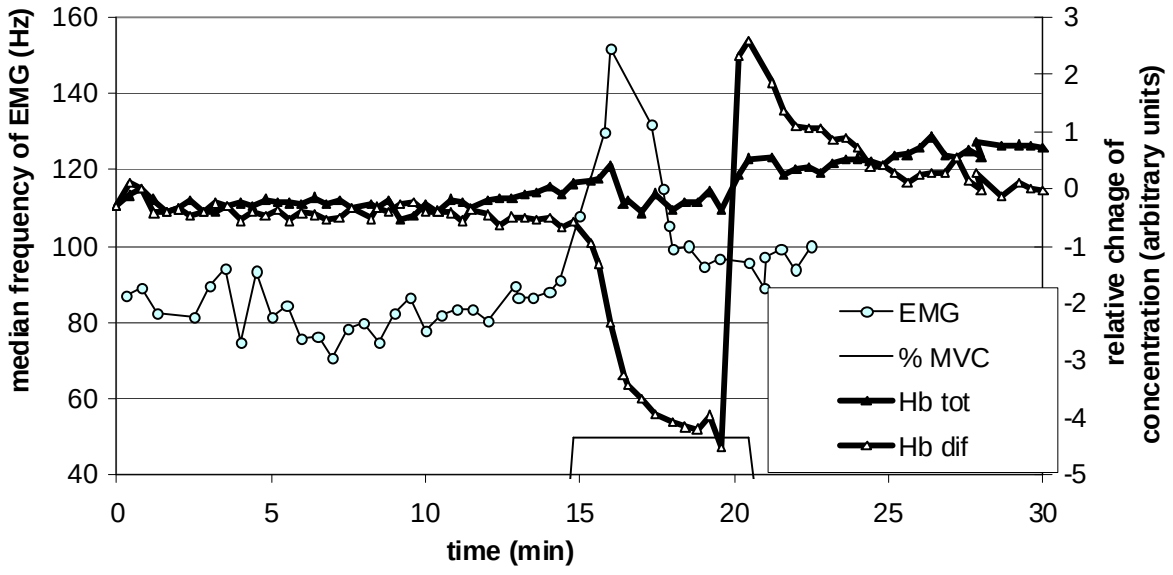

Fig. 7. Time series of all measured signals in a test for subject 3..

4. CONCLUSIONS

In this simple experiment, we tried to determine the possibility of measuring oxygenation of tibialis anterior muscle during voluntary isometric dorsal flexion. We were interested also in the correlation between muscle activity and its NIRS and EMG signals. Where EMG was used to directly measure the muscle activation, whereas the NIRS signals were used to assess oxygenation, which are an expected reaction to the muscle activity.

The biggest problem of the measurements in our experiment was high sensitivity to the movements of the NIRS probes attached to the skin. Each voluntary or involuntary moving artefact was marked by a marker in the raw data, which we later-on during data processing excluded.

14 tests we performed with nine active rowers. In rowing, the tibialis anterior muscle is one of the more activated at the end of stroke allowing the return of the rowers back to the beginning of stroke.

From our results we can conclude that in 10% MVC period of the protocol the muscle fatigue has not occurred; median EMG frequency was relatively stable (average median EMG frequency of 91 Hz, with standard deviation of about 6 Hz). The cause may be in too low load, i.e. too low level of MVC.

In the range of 50% MVC all subjects noted a decrease of median frequency of EMG. We assume that the decrease of the frequency signal resulted from the muscle fatigue, which corresponds to the results from the literature [8, 9, 10]. From the processing of EMG signals we are proposing a unified way for observing the decrease of the signal; in the form of a linear function formed by a least squares method of the measurements in 50 % MVC part of the protocol.. This would be in way for further studies to observe the dynamics of median EMG frequency decrease, and could be a test of the repeatability of measurements when testing the same subjects successively. A similar method was also used in [11].

NIRS is in principle a very simple device for observation of oxygenation of muscles. As a non-invasive method it would be an ideal help for any coach trying to determine the level of fitness of his athletes. At present, the apparatus NIRO2-X2 is far too sensitive to extraneous parameters to be used on-site. Conditionally it could be useful in the laboratory environment.

In the future, further tests would be required to record data from significantly larger number of subjects. Thus also the dynamics HbO_2 and Hb as measured by NIRS could be investigated. At the same time the dynamics of decrease in median frequency EMG signal induced by fatigue could be investigated. Using these simple measuring techniques it would be possible to quantitatively evaluate the correlation between changes in both parameters. In the future test also simultaneous observation of lactate level in the blood will be investigated, but measuring activation of a larger skeletal muscle (thigh muscle). Our results can be compared with the results of [5], which found a correlation between the lactate threshold and maximal differential of the NIRS curve during decrease of [HbO2].

The results of our research are based on the evaluation of only three athletes. Initially, nine athletes were involved in the experiment, but only measurements of three were used. Mainly due to the hypersensitive recording of NIRS signals and presence of excessive noise and other problems in data acquisition (missing data in the measurement of torque, moving artefact because of muscle cramps, erroneous storage of NIRS data, in part detached EMG electrodes, etc).

From the results of our experiments we can conclude that both signals, NIRS and EMG, indicate the activity of a muscle, especially the clear and apparent beginning of muscle activity in case of isometric contraction. In comparison with the NIRS, EMG method proved to be much more robust, insensitive and to moving artefacts inherently less burdened method for measuring the activity of muscle. Our conclusions match the ones in [11]. We are well aware that such a small sample of athletes, as it was used in our experiment, is not representative.

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