Estimation of Muscle Fatigue using Surface Electromyography and Near-infrared Spectroscopy

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Abstract This study looks at various parameters, derived from surface electromyography (sEMG) and Near Infrared Spectroscopy (NIRS) and their relationship in muscle fatigue during a static elbow flexion until exhaustion as well as during a semidynamic exercise. We found a linear increasing trend for a corrected amplitude parameter and a linear decreasing slope for the frequency content of the sEMG signal. The tissue oxygenation index (TOI) extracted from NIRS recordings showed a four-phase response for all the subjects. A strong correlation between frequency content of the sEMG signal and TOI was established. We can conclude that both sEMG and NIRS give complementary information concerning muscle fatigue.

1 Introduction

Knowledge of myoelectric and oxygenation mechanisms in muscles is important to understand muscle fatigue [1]. A frequently used definition of muscle fatigue is the one established by Edwards, [2] “Fatigue is defined as a failure to maintain the required or expected force.” As a consequence, a fatigued muscle can not continue the expected force and exhaustion occurs at a specific point in time. Note that the cause of muscle fatigue is not only located in the muscle. Neurological, physiological and circulatory changes influence the development of muscle fatigue. These changes already occur at the beginning of the contraction. At first, the changes can only be

measured with techniques such as surface electromyography (sEMG) for myoelectric changes and near-infrared spectroscopy (NIRS) for oxygenation changes.

sEMG measures the electrical activity of a muscle and is a good indicator of muscle force and fatigue [1]. Standard parameters from sEMG are extracted to analyze the electrical activity of the muscle. NIRS allows the direct and non-invasive measurement of local blood circulation, blood volume, and changes in oxygenated haemoglobin (Hb) and myoglobin (Mb) in working muscles [3]. Muscle oxygenation is the number of Hb saturated with oxygen (O_2) in the blood of the muscle. Oxygenation and blood volume decrease significantly and similarly during restriction of blood flow due to intramuscular pressure as, for example, when caused by exercise [4].

Although considerable research had been devoted to myoelectric or oxygenation changes during fatiguing exercises, rather less attention has been paid to the combination of myoelectric and oxygenation changes during development of muscle fatigue. The aim of this study is to investigate the relationship between sEMG and NIRS parameters in m. biceps brachii until exhaustion due to isometric static (STAT) and semidynamic (DYN) exercises. The parameters utilized are relevant for muscle fatigue and understanding their behaviour can lead to additional information in order to make a better assessment of muscle fatigue.

2 Methods

2.1 Experimental procedure

In total, 48 test subjects (24 male, 24 female, 21 ± 2.0 years) were requested to sit on a chair with the right upper arm relaxed against the body and elbow angle equal to 90°, forearm positioned in supination with hand palm up. A wooden handle attached with a solid rope to a load cell was held in the hand. The subject was instructed to bend his or her elbow using only arm muscles. This static isometric contraction caused activation of m. biceps brachii (BB).

sEMG electrodes and NIRS probe were placed in the direction of muscle fibres on BB symmetrically [5] of the line between medial acromion and fossa cubit at 1/3 from fossa cubit [6].

The exerted force on the load cell was amplified using a volt amplifier (HBM, Germany) and visual feedback of the force was given to the subject by a digital oscilloscope (Hewlett Packard, 54501A). sEMG signals (bipolar pre-gelled Ag/AgCl electrodes) were amplified. The NIRS probe (NIRO 300 ®, Hamamatsu Photonics K.K., Tokyo, Japan) was connected to the NIRO 300 measurement and display unit

for visualization. All signals from sEMG, NIRO 300 and force transducer were digitised with an analog-to-digital converter (National Instruments, cDAQ, 24 bit) before storage on a personal computer.

Initially a maximal voluntary contraction (MVC) was measured. After 5 minutes of rest, the subject performed a static contraction (STAT) at 50% MVC until exhaustion. On the oscilloscope, a line was fixed, representing the target level of force output. At the moment the force of the subject decreased to 90% of the required force, the muscle was defined as exhausted. After a 20 min recuperation, a semi-dynamic contraction (DYN) was exerted in the static position. On the oscilloscope, two horizontal lines representing 20 and 60% MVC and time interval were displayed. Subject performed alternating 4s contractions at 20% MVC and 6s contractions at 60% MVC until exhaustion.

2.2 Muscle fatigue parameters

Surface electromyography (sEMG) is frequently used in kinesiology as an indicator of muscle activation, force production or fatigue index. This objective, non-invasive, and indirect method detects motor unit action potentials (MUAP) in the muscle fibre during muscle activity. The summation of the MUAPs of the underlying muscle detected by the electrodes provides the sEMG signal that results in the ability to estimate non visible phenomena in the muscle such as muscle fatigue [1]. In this study a closer look is taken at the following myoelectric parameters:

- *Root Mean Square* (RMS): statistical measure of the magnitude of a varying quantity, calculated in a window of 0.5s in the signal.

$$RMS(t) = \sqrt{\frac{1}{n}\sum_{i=0}^{n-1} E(t+i)^2}$$

  where n = length of window; E(x) the EMG signal.

- *Mean Power Frequency* (MPF): windowed measure of frequency content

$$MPF(t) = \frac{\int_0^{f_s/2} f \cdot S_{E_{t\to t+n}}(f)}{\int_0^{f_s/2} S_{E_{t\to t+n}}(f)}$$

  where n length of window; S(f) the Power Spectral Density of EMG fragment E(t→t+n); $f_s$sampling frequency.

- *Activity* (ACT): proportional with the isometric contraction. This parameter has a lower sensitivity to a slowly changing baseline [7]

$$ACT(t+1) = p \cdot ACT(t) + \left|E(t+1) - E(t)\right|^{1/2}$$

where E(x) the EMG signal; p constant value of 0.9938.

- *RMS/ACT*: fatigue parameter, less dependent on produced force [7].

Near-infrared spectroscopy (NIRS) is a non-invasive technique that can be used for the measurement of tissue oxygenation. This method is based upon the relative transparency of biological tissue to light in the near-infrared (NIR) part of the light spectrum. Signal detection is based on levels of light directed through the muscle and picked up by the detector after the light has travelled through tissue. Tissue oxygenation index (TOI) is a NIRS parameter and indicates the dynamic balance between O_2 supply and O_2 consumption in tissue capillaries, arterioles and venules [8,9].

$$TOI = \frac{k \cdot HbO_2}{k \cdot HbO_2 + k \cdot HbR}$$

where k = constant scattering distribution; HbO_2 concentration in oxidized haemoglobin; HbR concentration in reduced haemoglobin.

3 Results and Discussion

All subjects successfully completed the protocol. The results are given in Table 1. MVC force produced by men was significantly larger than that produced by women ($p<0.001$) and women could maintain the DYN test for a significantly longer period of time as compared with men ($p<0.01$). The DYN test was significantly longer than the STAT test for all subjects ($p<0.001$) indicating that local muscle exhaustion was reached faster during the STAT test.

Table 1. Duration of tests and MVC force[a]

	STAT time (s)	DYN time[b] (s)	MVC force (N)
Total	78 (20)	147 (46)	175 (7)
Men	73 (20)	123 (24)	235 (5)
Women	83 (19)	172 (51)	116 (3)

[a] Data are given as mean (SD)

[b] During DYN test 31 subjects were tested, 16 men and 15 women

Figure 1 shows the mean value of the sEMG parameters over all subjects during both tests (A: STAT, B: DYN). The time scale was normalised to the total contraction time until exhaustion.During both tests for all the subjects, we found increasing RMS and RMS/ACT slopes, a decreasing MPF slope and an almost stable ACT slope. The sEMG parameters confirm that muscle fatigue is an ongoing linear process that initiates from the very beginning of the contraction [7]. Both pictures show that RMS/ACT corrects for movement compensation during the fatigue test. The RMS/ACT curve is more of an increasing straight line as compared to the RMS curve, which is generally used in literature. This confirms the finding of [7] that RMS/ACT is a better parameter to estimate muscle fatigue. The RMS/ACT ratio and MPF are clear indicators for the myoelectric activity of local muscle fatigue.

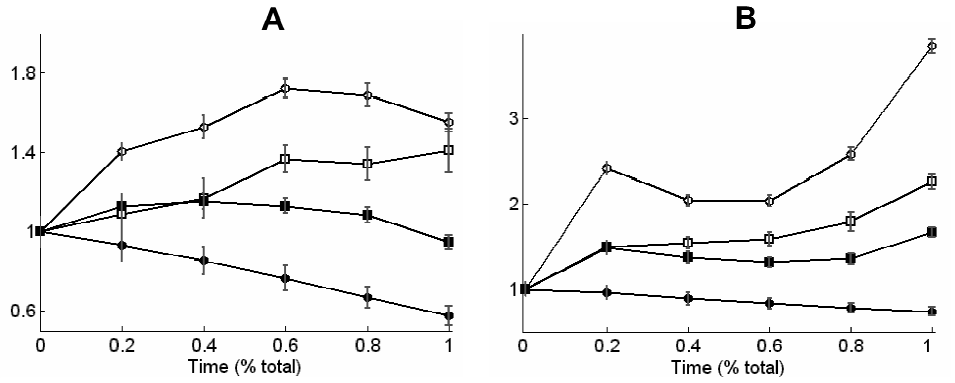

Fig. 1. Mean value of sEMG parameters over all subjects during the STAT test (A) and the DYN test (B) in normalized units. Confidence intervals ($\alpha = 0.025$) are shown. ○ = RMS; □ = RMS/ACT; ■ = ACT; ● =MPF

Figure 2 shows the TOI response of a representative subject during the STAT (A) and the DYN test (B). The TOI showed a four-phase response during both tests, which was also demonstrated in earlier studies [5]. In the first phase, there is a small increase of the TOI during the first 2-3 seconds, indicating an increase in muscle oxygenation. Secondly, a fast linear decreasing phase was noticed (deoxygenation). The duration of this decline seems parallel with the use of phosphocreatine (CP) as energy source for the contraction, which lasted, according to the literature, for 15-30s [10]. The alteration for phase I and II was similar for both contraction modalities. In the third phase, the TOI is on group level almost constant and dependent on the type of contraction. There is a flat line for the STAT test, while the trace of the TOI during the DYN test is following the contraction intensity, indicating an increased supply of

oxygen during the 20% MVC contraction, leading to recuperation. The energy during this third phase is probably mainly taken from glycogen in anaerobic glycolysis due to a deficit in oxygen because the mechanical obstruction of the blood flow in the muscle during a contraction limits the supply of enough oxygen. This leads to the accumulation of lactic acid followed by an oxygen debt resulting in muscle exhaustion [10]. The duration of phases I and II were similar during both tests for all the test subjects, while the length of the third phase was dependent on the length of the contraction. After the exercise, during the fourth phase, there is an overshoot of the TOI revealing an increase in oxygen supply for recuperation. Within the 20 minutes of recuperation between the STAT and the DYN test, TOI has recovered to the initial value at the beginning of the test.

The ΔTOI, which is the difference between the initial value during phase I and the constant value of phase III (the mean value is taken during the DYN test), correlates negatively with the total exertion time (STAT: $r = -0.56$, $p<0.001$; DYN: $r = 0.66$, $p<0.001$). Higher differences in the TOI value resulted in a shorter duration of exercise and, consequently, exhaustion occurs faster. Also, subjects with a small negative TOI slope in phase II could maintain both tests longer (STAT: $r=-0.64$, $p<0.001$; DYN: $r=-0.74$, $p<0.001$). The negative correlation between ΔTOI and total exertion time reveals that higher deoxygenation results in early exhaustion of the muscle. A higher deoxygenation during phase II causes a larger oxygen debt resulting in a faster fatiguing process. Despite the evidence in sEMG that fatigue is an ongoing linear process, this is not revealed by NIRS. On the other hand, a NIRS parameter gives an indication of the velocity of the fatigue process.

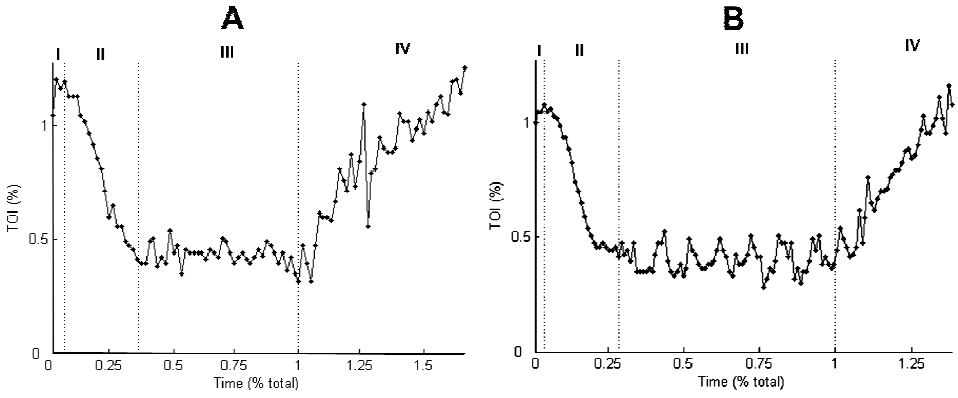

Fig. 2. TOI from a representative subject during the STAT test (A) and the DYN test (B) in normalized units.

The MPF and the TOI slope during phase 2 are significantly correlated during both the STAT and DYN test ($p>0.001$). During the DYN test, a significant negative correlation between the TOI slope during phase II and the RMS/ACT ratio is seen ($p<0.01$), however, this correlation was not significant during the STAT test. In earlier studies, a strong positive correlation was reported between muscle oxygenation and MPF [5,8].

4 Conclusions

This study shows that although sEMG and NIRS measure two separate physiological phenomena of muscle fatigue, there is a link between both measurements. The MPF of the myoelectric signal is strongly correlated with the muscle oxygenation. On the other hand, only sEMG shows that muscle fatigue is an ongoing linear process that starts from the beginning of the contraction, while the duration of the contraction was correlated with a parameter from the TOI. We can conclude that both sEMG and NIRS give complementary information concerning muscle fatigue.

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