Computers in Biology and Medicine 59 (2015) 1–9

Contents lists available at ScienceDirect

Computers in Biology and Medicine

journal homepage: www.elsevier.com/locate/cbm

Empirical mode decomposition analysis of near-infrared spectroscopy muscular signals to assess the effect of physical activity in type 2 diabetic patients

Filippo Molinari [a,*], Roshan Joy Martis [b], U. Rajendra Acharya [c,d], Kristen M. Meiburger [a], Riccardo De Luca [e], Giuliana Petraroli [e], William Liboni [f]

[a] Biolab, Department of Electronics and Telecommunications, Politecnico di Torino, Torino, Italy
[b] Department of Electronics and Communication Engineering, St. Joseph Engineering College, Mangalore, India
[c] Department of Electronics and Computer Engineering, Ngee Ann Polytechnic, Singapore 599489, Singapore
[d] Department of Biomedical Engineering, SIM University, Singapore, Singapore
[e] Diabetes Health Districts 8-9-10 Diabetes Unit ASL TO1 di Torino, Torino, Italy
[f] "Un passo insieme" ONLUS Foundation, Valdellatorre, Torino, Italy

ARTICLE INFO

Article history:
Received 5 November 2014
Accepted 13 January 2015

Keywords:
Sample entropy
Higuchi fractal dimension
Hurst exponent
Empirical mode decomposition
Near-infrared spectroscopy
MANOVA
Type 2 diabetes
Muscle metabolism

ABSTRACT

Type 2 diabetes is a metabolic disorder that may cause major problems to several physiological systems. Exercise has proven to be very effective in the prevention, management and improvement of this pathology in patients. Muscle metabolism is often studied with near-infrared spectroscopy (NIRS), a noninvasive technique that can measure changes in the concentration of oxygenated (O2Hb) and reduced hemoglobin (HHb) of tissues. These NIRS signals are highly non-stationary, non-Gaussian and nonlinear in nature.

The empirical mode decomposition (EMD) is used as a nonlinear adaptive model to extract information present in the NIRS signals. NIRS signals acquired from the tibialis anterior muscle of controls and type 2 diabetic patients are processed by EMD to yield three intrinsic mode functions (IMF). The sample entropy (SE), fractal dimension (FD), and Hurst exponent (HE) are computed from these IMFs. Subjects are monitored at the beginning of the study and after one year of a physical training programme.

Following the exercise programme, we observed an increase in the SE and FD and a decrease in the HE in all diabetic subjects. Our results show the influence of physical exercise program in improving muscle performance and muscle drive by the central nervous system in the patients. A multivariate analysis of variance performed at the end of the training programme also indicated that the NIRS metabolic patterns of controls and diabetic subjects are more similar than at the beginning of the study.

Hence, the proposed EMD technique applied to NIRS signals may be very useful to gain a non-invasive understanding of the neuromuscular and vascular impairment in diabetic subjects.

1. Introduction and background

Type 2 diabetes mellitus is a commonly diffused pathology and it is increasing at an alarming rate. According to Adeghate et al. [1] diabetes will affect 300 million people by 2025 and Kaul et al. [2] state that 97% of patients will suffer from type 2 diabetes who have insulin resistance and insulin deficiency. Moreover, the global prevalence of diabetes is not limited to only industrialized or only emerging countries, but is rather increasing in both. Type 2 diabetes mellitus is associated with cardiovascular diseases [3], neuropathy [4], peripheral vascular insufficiency [5], lung dysfunction [6], and retinopathy [7].

Various studies have shown how a specific change in life-style, such as diet, weight loss, and exercise, are very effective in the prevention, management and improvement of this pathology in patients [8]. Exercise in particular has shown promising results, improving vascular protection and insulin resistance [9] and reducing the negative effects of neuropathy [10].

Exercise has positive effects on different aspects of muscular action, and it can often be difficult to correctly assess the actual improvement that exercise has on type 2 diabetes patients. Bagai et al. [11] analyzed the variation of the surface myoelectric signal (EMG—electromyogram) in diabetes patients as a result of

* Correspondence to: Biolab, Department of Electronics and Telecommunications, Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129 Torino, Italy.
Tel.: +39 11 564 4135.
E-mail address: filippo.molinari@polito.it (F. Molinari).

http://dx.doi.org/10.1016/j.compbiomed.2015.01.011
0010-4825/

polyneuropathy. Other experiments have shown how the spatial distribution of the EMG of the vastus lateralis is different when comparing patients with healthy controls [12]. However, two very important factors in the assessment of diabetic patients, the local muscular metabolic rate and the efficiency of the peripheral muscle vascularization, cannot be fully captured by the EMG despite their importance in the determination of muscle contraction and performance.

Near infrared spectroscopy (NIRS) has been used to monitor patients suffering from lower-extremity arterial disease [13] and diabetes [14]. This technique is portable, non-invasive, and low-cost, making it easy for patients to use during exercise and rest. Electrochemical systems based on reverse iontophoresis are more accurate than NIRS systems in the glucose concentration monitoring [15]; however NIRS systems are a good choice for this study as they are less invasive and real-time. The light sources of the NIRS system emit electromagnetic radiation and the absorption of light of different tissues at certain wavelengths allows measuring the chromophore concentration in the observed tissue. Two main chromophores that are present in human tissue are oxygenated and reduced haemoglobin. Haemoglobin shows two different absorption peaks in the NIR spectrum: at 850–900 nm if in its oxygenated (i.e. oxidized) form (for simplicity, indicated by O2Hb from here on out), and at 730–750 nm if in its deoxygenated (i.e. reduced) form (HHb). These different properties, the concentration of each haemoglobin type, can be easily estimated by irradiating the tissue at two separate wavelengths [16]. Features extracted from NIRS recordings of diabetics during exercise have proven to be useful to assess the neuromuscular and peripheral pattern [17].

NIRS signals can typically tend to present a marked non-stationary nature [17, 18]. Very low frequency components associated with long-term regulatory mechanisms makes the baseline of the NIRS signals vary [19], and the signal power depends on the local metabolic rate and oxygen consumption. Moreover, NIRS signals present a time dependent average value, which reflects the concentration changes of the chromophore. Due to the nonlinear nature of the NIRS signal, linear, frequency and time–frequency domain methods may not be able to fully extract the small variations from the signals, whereas nonlinear interrelationships in the NIRS data can provide more accurate information. Previous studies have demonstrated how non-stationary and nonlinear methods are needed to analyze glucose levels [20] and insulin sensitivity [21] of diabetic subjects. Also, bispectral analysis has been used for epilepsy diagnosis [22,23], sleep stages [24], cardiac abnormalities [25], EEG signals [26], and myoelectric signals [27]. Moreover, the entropy analysis of NIRS signals, coupled with unsupervised clustering, has proven to highlight the changes in muscle contraction performance of diabetic patients as a consequence of exercise [28]. The results of these specific types of analysis can sometimes be difficult to interpret and understand. In a previous work, we analyzed the NIRS signals recorded during muscle contractions of diabetic patients by using higher-order spectra, bispectral and sample entropies [28]. We demonstrated that physical activity improved the muscle metabolism and, specifically, that the NIRS pattern of diabetic subjects after physical activity is close to the healthy controls. Our previous study had two major limitations. Methodological point of view, we did not investigate the nonlinear architecture of the NIRS signals. Also from a physiological point of view, we only analyzed the NIRS signals recorded during muscle activation, but not during resting (i.e. baseline conditions).

A simple, adaptive and local structure based, nonlinear measure, such as the empirical mode decomposition (EMD), can instead provide more intuitive understanding of the data. In this paper, we show how the EMD analysis of NIRS signals can highlight the changes in muscle contraction performance of diabetic patients. We tested a group of subjects with type 2 diabetes who underwent a year of an exercise programme, specifically adapted to their age and physical condition. NIRS captured the changes in the metabolic aspect of muscle contraction and showed that after the one-year training programme, the muscle metabolic pattern of diabetics as found with EMD is similar to those of healthy controls.

2. Patient demographics and experimental setup

Twenty-four diabetes type 2 subjects were enrolled in the study along with sixteen healthy controls. The diabetic patients were non-consecutive and enrolled with the following inclusion criteria: age >50 years; body mass index (BMI) between 18 and 23 kg/m^2, and diabetes onset at least 10 years before the study. Exclusion criteria were only related to possible physical or mental states that precluded the possibility of following a long physical activity programme. All the diabetic subjects underwent daily physical activity for one year. Of the 24 patients, the physical activity for 15 of the patients was an adapted physical training (APT) program (age: 66.7 ± 5.7 years), whereas the remaining 9 practiced fit walking (FW) (age: 66.0 ± 6.2 years). APT consisted in low load exercised for the lower and upper limb muscles, whereas FW consisted in walking at a constant pacing. Expert exercise physiologists and therapists followed each patient and set the intensity of each exercise. For the control group, the 16 healthy subjects were age-matched (age: 65.3 ± 3.9 years) and physically active. Table 1 summarizes the patient demographics, including also their glycated haemoglobin (HbA1c) level [29] and the neuropathy disability score (NDS) [4]. The Gradenigo Hospital institutional review board, where all tests were performed, gave the approval for this study. All of the patients were informed about the study methods and goals and signed an informed consent before the test.

The NIRO300 NIRS system (Hamamatsu Photonics, Japan) was used to record the NIRS signals of each patient before, during, and after the physical exercise. The NIRO300 emitting probe consists of four laser diodes at the following wavelengths: 775 nm, 813 nm, 853 nm, and 910 nm. In order to convert the light absorbance into concentration, the NIRS systems used the modified Beer-Lambert law [30]. This law empirically models the light absorption in a highly scattering medium:

$$A = \log\left(\frac{I_0}{I}\right) = \alpha \times c \times B \times d + G \quad (1)$$

where A is light attenuation, I_0 the emitted light intensity, I the received intensity, c the concentration of a chromophore (in our study oxygenated or reduced hemoglobin), α is the extinction coefficient of the chromophore at a given wavelength, and d is the source-receiver distance. Scattering causes photon loss (i.e. photons that are emitted by the source but that are scattered so

Table 1
Demographics of the patients and of the healthy controls.

	APT group (15 patients)	FW group (9 patients)	Controls (16 subjects)
Age (years)	66.7 ± 5.7	66.0 ± 6.2	65.2 ± 3.9
Males	10	14	8
HbA1c (%)	7.8 ± 1.0	7.4 ± 0.9	5.2 ± 1.6*
HbA1c (mmol/mol)	62 ± 14	57 ± 14	33 ± 6*
BMI (km/m^2)	19.3 ± 2.2	20.2 ± 1.9	19.5 ± 1.5
Duration diabetes (years)	19.0 ± 9.9	18.7 ± 10.1	–
Neuropathy disability score (NDS)	2.04 ± 1.92	1.82 ± 1.87	–

* The values are statistically different from those of patients ($p < 0.1$).