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Study of muscular tissue in different physiological conditions using electrical impedance spectroscopy measurements

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ABSTRACT

While performing physiological functions, muscles modify their intrinsic characteristics. As has already successfully done in various clinical fields, the technique of electrical impedance spectroscopy (EIS) measurement can be applied in order to study tissue changes. The aim of this study was to study changes in the electrical properties of muscular tissues due to an isometric contraction and successive relaxation.

For this work, the electrodes lay out and trials protocol were carefully designed, also according to studies concerning muscle fatigue. A device previously tested and employed for in vivo EIS measurements was used. Impedance measurements were carried out on the forearm flexor muscles in a group of sixteen healthy adult subjects. In order to have a quantitative index of spectral impedance variation, the relative variation of the area under curve of Nyquist plots was computed to study the different muscle states under consideration (rest, contraction and 4 min after contraction).

The index introduced showed itself to be sensitive to different muscular conditions. Results from healthy subjects showed statistically significant differences in the impedance data in the various muscle conditions under examination.

1. Introduction

An important aspect of biomechanics is the development of diagnostic tools with which to study physical, mechanical and biochemical processes in muscle tissue. With this aim in mind, comprehensive studies of muscular activities, involving biological measurements, have the potential to correlate tissue structural parameters to functional activities [1].

Skeletal muscles are tissues that change characteristics, composition and architecture during their physiological functions (relaxation, contraction, muscle fatigue, etc.), in response to various kinds of physical stresses (i.e. those resulting from treatment of instrumental physical medicine),

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during rehabilitation treatments and in presence of diseases [2–5].

One of the most useful methods for analyzing muscular activity is electromyography (EMG), which studies electrical signals generated and controlled by different neuromuscular processes [6]. A host of changes are involved when a muscle exerts a force and EMG is very often employed to study them. A drawback to this technique is the fact that, even if EMG signals vary their characteristics during the contraction of muscle fibers, this technique relies on the generated electrical activity analysis and does not permit the detection of intrinsic tissue modifications. Other techniques, such as biopsy or measurement of the lactic acid, employed to evaluate the effects on tissues of muscular activities, are more invasive [6].

In order to characterize biological tissues, electrical impedance measurement (often called bioimpedance) is used in different clinical fields and is considered among the most promising techniques. It, essentially, consists of the application of a low intensity electrical current injected at set frequencies into the body through surface electrodes, and in the measurement of the resulting voltage over a selected part of the body. Spectral impedance is defined as the complex relation between this voltage and the current computed for each considered frequency [7]. The method of bioimpedance measurement is quite simple and fast, totally non-destructive and not bleeding. It has the ability to highlight anomalies in biological tissues by detecting changes in the impedance of the examined part of the body. Indeed, in recent years bioimpedance measurements have been widely used commercially (i.e. body composition monitors) and in interesting clinical applications. Impedance measurements have also been proposed as a method to detect tissue ischemia [8] as well as cancerous tissue [9,10]. More recently, impedance measurements have been successfully used to evaluate the bone-integration of metallic implants [11].

Since changes in impedance value reflect muscle intrinsic features and biochemical modifications, they can also reveal the condition of skeletal muscles [3]. Shiffman et al. [3] and Zagar and Krizaj [12], reported that other authors employed impedance measurements, sometimes reported as electrical impedance myography (EIM) [2], to measure the properties of a relaxed muscle, focusing, for example, on what might be called its architecture. Results reported in their work show differences in impedance measurements of a contracted muscle compared to a relaxed one [3,12].

Nevertheless, there is a lack of reliable clinical studies due to the absence of devices specifically designed, approved and then commercially available for muscle impedance measurement and also a lack of a standard in measurement lay out [2,13] to be used at clinical level too. Furthermore, in bioimpedance literature, measurements are generally carried out by applying current at a fixed frequency (usually 50 kHz), but a more complete and more detailed study of the structural and physiological properties of tissues under examination is based on measurements of electrical impedance spectroscopy (EIS) using a sinusoidal electrical current across a range of frequencies [2,14]. Another limitation of the use of this methodology in clinical application is the lack of a standard for the lay out of electrodes – the lay out of the electrodes greatly affects impedance values [2].

Thus, EIS measurements provide promising results even if relatively little research is available in the literature concerning this specific topic. Clearly, additional investigation is needed to fully understand the complex mechanisms involved in tissue changes [2,14]. Impedance measurement methodology is not yet fully developed; it is still being studied in order to assess its full clinical potential as an indicator of neuromuscular diseases and/or as diagnostic tool [2]. Besides, EIS measurements provide a vast amount of data, whereas, for practical clinical use, it is often helpful to have only a few concise parameters.

The work presented here aimed to explore the changes of electrical properties in muscles by studying three different muscle conditions (rest, contraction and phase after contraction), by means of a concise index. Analyses were carried out by applying EIS technique to the group of the forearm flexor muscles in vivo in 16 subjects (for a total of 32 tests).

In the following Section 2, the adopted measurement system in all its parts, the lay out of the electrodes and the designed protocol are described. In Section 3, the results which are discussed in Section 4, are reported.

2. Materials and methods

2.1. *Impedance measurements*

When a current I flows in a body section a potential V can be measured on the tissue under test. Thus, the impedance can be computed by means of the formula:

$$Z = \frac{|V|}{|I|} e^{j(\theta_V - \theta_I)}$$

where $|I|$, θ_I and $|V|$, θ_V represent, respectively, modulus and phase of the injected current signal and of the acquired sinusoidal voltage [15].

In this work, tetrapolar measurements were employed mainly to reduce the effects of electrode polarization [2], but also because it is known that the use of four electrodes can help to isolate an area of interest.

2.2. *Measurement system*

2.2.1. *Hardware*

The prototyped proof demonstrator is based on a battery-powered notebook PC equipped with an AD/DA board and an analog interface [16]. The system, described elsewhere in a different set up [17], was used, in clinical tools, for EIS measurements of transcutaneous implants during the process of osseointegration [11] and for a preliminary evaluation of muscle tissue [16].

The digital I/O board was a PCMCI DAQCard-6062E (National Instrument™, Austin, TX), with two DACs and 16-channels ADC, all with a 12-bit resolution [16].

In the analog interface [15], the instrumentation amplifier makes the A− electrode a virtual ground, thus the current through the tissue is the same as that flowing through a transimpedance amplifier. The voltage drop across the tissue was gathered between the V+/V− electrodes by means of another high-accuracy differential amplifier (chosen to