# Simultaneous transversal/longitudinal Electrical Impedance Miography at frequencies between 1 kHz and 10 kHz

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**Abstract** - *Electrical Impedance Myography (EIM) is a non-invasive method for the analysis of muscle tissue based on it's impedance measurement. Despite EIM is being studied for the past 15 years, some issues still arise, such as comparing impedances with different levels of muscle contraction. In the present study a system for EIM signal acquisition was developed and the impedance behaviour of biceps brachii muscle was investigated in relaxed/contracted states. The muscle impedance was simultaneously measured in longitudinal and transversal directions with respect to muscle fibers. The experiment was conducted in 7 volunteers with three different frequencies (1, 5 and 10 kHz). The results showed significant differences (p<0.05) between relaxed and contracted states for each subject in all frequencies. When considering the group as a whole, impedance changes did not appear to follow a pattern. The difference of muscular impedance between relaxed and contracted state was more prominent in 5 kHz.*

**Keywords**: *Electrical Impedance myography, myography, muscle, anisotropy, contraction.*

## Introduction

Electrical impedance myography (EIM) is a technique of muscle analysis, based on the measurement of electrical potentials generated by the application of an electric current of low amplitude (up to 10 mA) and high frequency (over 1 kHz) on the surface of the skin [1]. This is a noninvasive method that has been developed over the last decade and has shown application for monitoring neuromuscular disorders such as amyotrophic lateral sclerosis (ALS), muscular dystrophy, and allowing the follow-up in physical training [2].

It is known that muscular tissue presents electrical anisotropy due to hierarchic interleaving of myofibrils, fibres and fascicles [3]. Thus muscular impedance may vary depending on the direction of the measurement.When comparing healthy and unhealthy muscle states it is possible to detect differences in the anisotropic patterns of the muscle due to the disorganization of the fibers caused by neuromuscular diseases. The anisotropy can be analyzed based on the ratio of the impedances obtained transversely/longitudinally to the fibers [4].

Furthermore, a few EIM studies analysed muscles at frequencies lower than 10 kHz, specially during contraction. Some of them presented contradictory results of muscle response during exercise [1, 5].

The aim of the present work was to better understand EIM in isometric exercise and its response to different frequencies and directions. The measurements were performed with a data acquisition system developed by the authors at three different frequencies (1, 5 and 10 kHz). Data in transverse and longitudinal directions with respect to muscle fibers where acquired simultaneously to estimate muscle electrical anisotropy.

## Materials and methods

**Data acquisition system:** the developed system consists of a current pump, a multiplexer, a data acquisition (DAQ) board and a computer. Fig. 1 provides an overview of the system's structure:

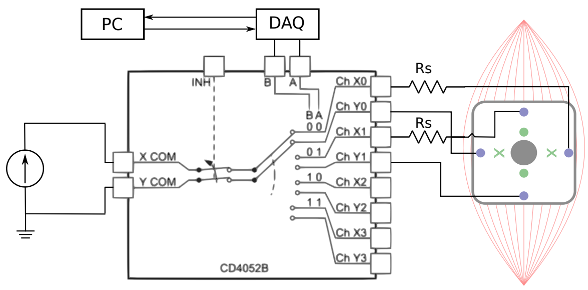


Figure 1 – Block diagram of the system

The voltage controlled current pump was developed according to the modified Howland model (Fig. 2), where the resistor $R_{13}$ sets the gain: the output current is equal to $1/R_{13}$ times input voltage [6]. The circuit was designed to deliver sinusoidal currents up to 2.5 mA to load impedances (ZL) as high as 2.5 kΩ, using a function generator (B&K Precision, model 2190D) as input to the current pump. The resistors where selected based on the relation in Eq. 1 and balanced with a trimmer potentiometer as the resistor $R_{11}$ in a Wheatsone bridge. A LM741 op amp was used and a

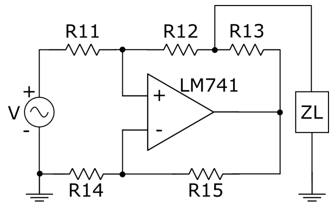


Figure 2 – Modified Howland current pump

$R_S = 30\,\Omega$ shunt resistor was used to assert the actual current being injected into the muscle.

$$\frac{R_{11}}{(R_{12} + R_{13})} = \frac{R_{14}}{R_{15}} \tag{1}$$

The current was multiplexed to the longitudinal and transversal directions using the CD4052B analog switch [7], which was controlled by the acquisition board and powered by a DC voltage source (Edutec, model EEL-8006). The DAQ device (USB-1608FS-Plus, Measurement Computing [8]) has eight individually configurable digital I/O channels along with its eight 16-bit single-ended analog input channels. Two of the digital lines have been used to select the direction of the current, according to the diagram in Fig. 1. Four of the analog channels were used to measure the voltage drops on the shunt resistors, while the remaining four channels measured differences of potential on the muscle.

The signal measurement was controlled by a routine developed in C for a Linux system (Ubuntu 16.04 LTS, kernel version 4.4.0-47-generic), using the libraries and drivers provided by DAQ manufacturer. A number of acquisition parameters such as sampling frequency, switching frequency, DAQ voltage range, are set by the user by means of a configuration file compatible with the *LibConfig* library for C [9].

**Experimental Protocol:** the data collection was performed on 7 healthy individuals (ages 24 to 66, 4 males / 3 females), with no history of muscle injury. The protocol was approved by the Ethics Committee on Human Research of the Federal University of ABC, CAAE #44576415.9.0000.5594.

The measurements were performed using a electrode array belt built by Morimoto et. al. [10] to improve standardization of the measurements and minimize movement artifacts. The belt was placed over the biceps branchii according to the protocol described in the study [10], as follows: 1) an imaginary line was considered between the acromial protuberance and distal biceps tendon; 2) the volunteer performed elbow flexion to highlight the biceps muscle; 3) the position of larger perimeter of biceps braquii was marked with a pen; 4) the intersection of the imaginary line with position of larger perimeter was marked with a pen; 5) The center of the belt was positioned coincidently with the marked point.

The measurements were performed on the subjects' dominant arm, while they were seated on a height-adjustable chair with the elbow joint at 45° flexion. Data were collected both at resting condition and at maximum voluntary isometric contraction. The current source was configured to provide 0.5 mA in the frequencies of 1, 5 and 10 kHz. DAQ sampling frequency was set to 25 kS/s and the system was configured to switch to longitudinal/transverse direction with a frequency of 1 Hz. Data were acquired over a period of 10 seconds.

**Data analysis:** after digitalization, the amplitude, phase and offset of measured electric potential was obtained by a least-square based demodulation algorithm [11]. The input current is obtained based on the voltage drop on the shunt resistors and the impedances are calculated using the extended Ohm's law ($V = Z \cdot I$). This process was done on small segments of the signal, corresponding to the duration of each switch of the multiplexer, in order to ensure that the wave parameters remain unchanged. This resulted in 10 impedance ($Z = R + jX$) values for each measurement, where $R$ is the resistance, $X$ is the reactance and $j$ is the imaginary unit.

A statistical analysis (Anderson-Darling normality tests and t-tests with a 95% confidence interval) was conducted in order to evaluate the significance of the impedance differences between relaxed and contracted states in both longitudinal and transversal directions. The differences between these parameters along the frequencies was analysed using the ANOVA test.

# Results

Table 1 shows the average longitudinal and transversal resistances and reactances during relaxed and contracted muscle states along the frequencies. The performed normality tests indicated that 91.95 % of the measurements follow a normal distribution with significance of 0.05. The applied statistical analysis indicated significant difference ($p < 0.05$) between the impedance in the relaxed and contracted states for each subject individually in every frequency. However, when considering all subjects as a group, no significant differences were found between the averages. A similar behaviour was observed for the impedances along the frequencies: significant differences ($p < 10^{-4}$) between the impedances in both longitudinal and transversal directions were observed for each volunteer, for the relaxed and contracted states, but the differences considering all subjects as a group were not significant.

Table 1 – Average resistance (R) and reactance (X) values in longitudinal and transversal directions, both in contracted (CTR) and relaxed (RLX) muscle states and over the frequencies of 1, 5 and 10 kHz.

| | | Freq | Longitudinal | | Transversal | |
|---|---|---|---|---|---|---|
| | | (kHz) | Avg | Std | Avg | Std |
| R (Ω) | RLX | 1 | 99.60 | 18.58 | 93.78 | 17.18 |
| | | 5 | 101.91 | 29.74 | 71.93 | 67.19 |
| | | 10 | 93.26 | 18.48 | 88.57 | 20.02 |
| | CTR | 1 | 100.13 | 32.34 | 84.27 | 32.73 |
| | | 5 | 99.55 | 20.79 | 87.68 | 19.8 |
| | | 10 | 96.43 | 21.20 | 90.65 | 23.18 |
| X (Ω) | RLX | 1 | -17.44 | 2.60 | -9.75 | 2.22 |
| | | 5 | -16.49 | 11.34 | -2.03 | 3.84 |
| | | 10 | -20.54 | 3.14 | -13.47 | 1.82 |
| | CTR | 1 | -14.51 | 13.87 | 17.79 | 41.51 |
| | | 5 | -17.66 | 2.04 | -9.54 | 2.49 |
| | | 10 | -21.66 | 2.81 | -16.34 | 4.18 |

The results presented in Fig. 3 show the average anisotropy ratio (tranverse/longitudinal) for resistance and reactance in three different frequencies (1, 5, 10 kHz). The closer to 1 the anisotropy index is, the less anisotropic the tissue is.

## Discussion

The system allowed to observe the behaviour of the biceps brachii muscle impedance over different frequencies of the injected current and in two levels of contraction. While it depends on external equipment such as a function generator and a DC power source, the acquisition system is able to perform reliable measurements.

Changes of absolute impedance ($\Delta||Z||$) between the relaxed and contracted states do not seem to follow a regular pattern for all the volunteers. A slight tendency to increase the impedance at 1 kHz seems to appear both in longitudinal (6/7 volunteers) and in transversal (4/7 volunteers) di-

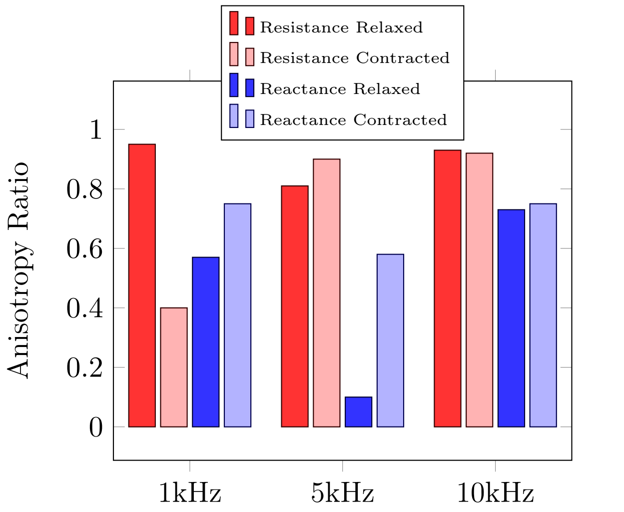


Figure 3 – Anisotropy ratio for different current frequencies (1, 5, 10 kHz) - Resistance and Reactance

rections. In 5 kHz the tendency seems to be reduction of impedance in both directions (6/7 volunteers). At 10 kHz, the impedance decreased in 4/7 volunteers for longitudinal direction and in 5/7 volunteers in transversal direction. The absence of a pattern has been noticed in different studies: Rutkove [1] and Zagar and Krizaj [12] presented a decrease in impedance during isometric contractions while Kashuri et al [5] and Li et al [13] presented an increase in impedance during isometric contractions. These results could be explained by the morfological differences among the subjects, such as the subcutaneus fat layer thickness and positioning of blood vessels [14].

Significant changes in impedance were observed in all volunteers with respect to frequency. Such behaviour is expected due to the capacitive characteristic of the cellular membranes, which are composed by a double layer of phospholipids separating two ionic solutions (the cytosol inside the cell and the extracellular medium). Since the phospholipids conduct electricity poorly, it acts as a dielectric medium between the two conducting solutions, similar to a capacitor, which by definition results in a frequency dependent reactance [15]. When analysing the group as a whole, no differences emerged between the frequencies and the levels of contraction. This might have occurred due to the inter-subject differences, so that in average the values of impedance are similar but for each volunteer individually changes are observed.

In all cases but three the observed difference in impedance with the contraction of the muscle was caused by significant alterations in both resistance and reactance. A previous study [13] has observed a contrastant result, with significant alterations in resistance, but not in reactance . However, the mentioned analysis was done with a frequency of 50 kHz of the injection current. Comparison with the result presented here suggests that lower frequency stimulation might highlight the reactive behaviour of the muscles.

The analysis of the Fig. 3 showed that the anisotropy was higher in the reactance than in the resistance for healthy individuals, in accordance with a previous study [4]. The anisotropy was more prominent at 5 kHz for the contracted muscle, considering the absolute value of impedance ($||Z||$). Additionally a weak anisotropy value was observed for higher frequencies (10 kHz); the study [4] corroborated with this result. This encourage future studies with measurements of muscle anisotropy with unhealthy patients during contraction, since that according to [16], patients with muscle disease presented distorted anisotropy during relaxed analysis.

# Conclusions

This study showed that it is possible to assess muscle impedance from the equipment built. Additionally, it was observed significant differences between the longitudinal and transversal measurements and between the relaxed and contracted muscle. The anisotropy results showed a prominence value for the muscle contracted at 5kHz frequencies. The impedance behaviour in relaxed and contracted muscle presented divergent results with a tendency to rise when muscle contraction was performed. These results encourage for further studies under different conditions of the muscle.

# Acknowledgments

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