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Wearable Multi-Frequency and Multi-Segment Body Impedance Spectroscopy in Sports and Rehabilitation Medicine

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Abstract: Body Impedance Spectroscopy (BIS) allows assessing the composition of body districts noninvasively and quickly, potentially providing important physiological/clinical information for sport-medicine or rehabilitation studies. However, neither portable commercial instruments nor more advanced wearable prototypes simultaneously satisfy the demanding needs of unobstrusively recording BIS in different segments at the same time, over a broad frequency range, for long periods and with high measurements rate, as exercise tests often requires. Therefore, aim of this work is to present a new wearable prototype for monitoring multi-segment, multi-frequency BIS, unobtrusively over long periods, for rehabilitation or sport-medicine studies. The system guarantees low weight, small size and low power consumption. An analog board with current injecting and voltage sensing electrodes across 3 body segments interfaces a digital board that generates square-wave current stimuli, digitalizes the sensed voltages and computes impedance at 10 frequencies from 1 to 796 kHz. To demonstrate the information derivable from such class of devices, our system monitored BIS of 3 body segments in a volunteer before, during and after physical exercise and postural shift. We show that it can describe the dynamics of exercise-induced changes and the effect of a sit-to-stand maneuver in active and inactive muscular districts separately and simultaneously.

Keywords: Exercise; blood shift; body composition; electric impedance.

1. Introduction

Bioeletrical Impedance Spectroscopy (BIS) is a noninvasive method for evaluating the body composition. BIS injects a small sinusoidal current in a segment of the body at a given frequency *f*, and provides magnitude and phase of the corresponding electrical impedance, *Z(f)*, by measuring the voltage drop across the segment. Several characteristics of body tissues (like the content of intra- and extra-cellular water) may affect the electrical impedance differently at different frequencies. Therefore BIS may provide useful information for sports medicine studies or rehabilitation protocols, like hydration level, blood shift between body districts, edema formation, or percentages of lean and fat masses [1,2].

However, neither portable commercial instruments nor more advanced wearable prototypes proposed in recent literature simultaneously satisfy the demanding needs of unobstrusively recording BIS in different segments at the same time, over a broad frequency range, for long periods and with high measurements rate, as exercise tests often requires. These are almost insurmountable limits for sports medicine applications, that may require to evaluate impedance changes in specific muscular districts without interfering with movements, or to assess the hydration level during prolonged exercises, like a marathon run. Similarly, rehabilitation medicine may require monitoring BIS in selected body segments during therapeutic protocols, as in free-moving patients with compression stockings to prevent deep venous thrombosis, or in peripheral artery disease patients exercising the lower limbs, when echographic blood flow measurements are not feasible. In these cases, unobtrusive, wearable BIS systems, capable of long term recordings, become mandatory.

To overcome these limits, we showed that a Digital Signal Processor (DSP) can generate the proper waveforms of the stimulation currents and elaborate the measured voltages over the frequency range required for BIS studies [3]. This demonstrated that BIS systems of small size, low weight and power consumption can be implemented, opening the way to a new class of wearable systems capable of long-term BIS monitoring over more body segments simultaneously and unobtrusively. Therefore aim of this work is to present a wearable prototype for monitoring BIS simultaneously over three body segments without interfering with the subject movements, able to collect up to 50 impedance spectra per second over a broad range of frequencies for long periods of time (hours).

The performance of our prototype is illustrated by an application in the fields of sports and rehabilitation medicine, consisting in the quantification of BIS changes in three muscular districts before, during and after a physical exercise and following a postural shift.

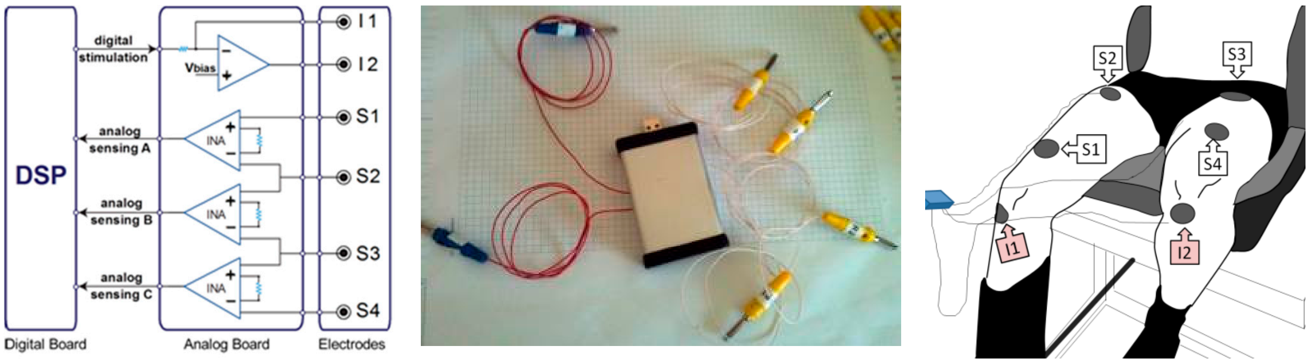
2. Methods

2.1. Description of the BIS Device

Our BIS system consists in two boards: a digital board with a DSP (Texas Instrument C2000 “Piccolo family”, 80 MHz clock) and a custom analog board (Figure 1, a). The DSP generates the stimulus waveforms, samples and digitalizes the voltage across three body segments with an internal 12-bit Analog to Digital Converter (ADC) and computes magnitude and phase of *Z(f)*. The analog board interfaces the DSP with the electrodes. In particular, a transimpedance amplifier is connected to two injecting electrodes, whereas three instrumentation amplifiers (INAs) read the voltages across three body segments by means of four sensing electrodes. By using separate injection and sensing electrodes, measures are independent from the electrode impedance. This allow using small disk electrodes in place of traditional impedance band electrodes of larger area.

The stimulation waveform is not a sinusoid, as in commercial BIS devices, but a digital square wave. Since square waves can be generated easily with the DSP, the use of this specific waveform allows minimizing power consumption, size and costs of the device. The DSP extracts magnitude and phase of $Z(f)$ by Fast Fourier Transform of the sensed voltage only at the fundamental frequency f of the square wave.

The device measures $Z(f)$ for each of the 3 body segments at up to 10 frequencies f roughly equispaced on a log-scale between 1 kHz and 796 kHz. The sampling rate of BIS measures can be set up to 50 impedance spectra per second for each body segment. The system can operate uninterruptedly for several hours recording the data locally on a SD card. It can be also connected via USB2.0 link (Figure 1, b) to a PC to monitor the data in real-time. The instrument size is $8.5 \times 5.5 \times 2$ cm^3, the total weight is less than 100 g, the total power consumption is lower than 100 mW.



(a) **(b)** **(c)**

Figure 1. (a) Scheme of the BIS system composed by a DSP, an analog board, 2 injecting electrodes (I1, I2) and 4 sensing electrodes (S1-S4). **(b)** The realized prototype. **(c)** Example of subject instrumentation for BIS in the right thigh (S1-S2), pelvis (S2-S3) and left thigh (S3-S4).

2.2. Experimental Application

Our BIS system was instrumented on a young male volunteer (Figure 1,c). The electrodes injecting the stimulus current were placed on the right (I1) and left (I2) knees, just below the articulation between femur and tibia. The sensing electrodes were placed close to the distal (S1) and proximal (S2) endings of the rector femoris muscle belly of the right thigh, and close to the proximal (S3) and distal (S4) endings of the controlateral muscle belly. Thus, the monitored body segments were the right thigh (S1-S2), the pelvis district (S2-S3) and the left thigh (S3-S4).

For this application, the device was set for providing impedances measure of the 3 body segments simultaneously every 6 s, at 8 frequencies: 4, 8, 17, 48, 128, 234, 488 and 796 kHz. The experimental session lasted slightly more than one hour. In the first part of the recording, the volunteer sat on a one-legged, knee-extensor ergometer, as in [4]. The experimental protocol in sitting position included: baseline rest for 7 minutes (“baseline”); exercise for 20 minutes (“exercise”); and recovery for 20 minutes (“recovery”). The exercise consisted in repeated kicking by extending the knee of the right (dominant) leg, at the rate of 60 extensions per minute. The ergometer load was set at 25 watts with the exclusion of the initial warm-up (10 watts) and of the last 2 minutes (50 watts). In the second part of the recording the volunteer rested in standing position for 7 minutes (“standing”). Subsequent conditions were spaced by few minutes to exclude transition phases from the analysis.

3. Results and Discussion

Figure 2(a) shows the time course of the impedance magnitude at 48 kHz in the three body segments. Impedance was similar in the two thighs at baseline, but markedly differed between the active and inactive leg during exercise. It decreased in the active leg, with a fast variability component superimposed to the decreasing trend. By contrast, it increased in the inactive leg without fast variability components. The decreasing trend of the active thigh may be due to the increased blood flow in its muscles. An explanation for the fast variability component is that each knee extension contracts the muscles squeezing out blood volume from the thigh, rapidly increasing the impedance.

In the pelvis district, impedance decreased at the start of the exercise warm-up. The pelvis district is located upstream the active thigh and the increased blood flow demand for the exercising muscles may have also increased the blood volume of this body segment during warm up. The increased impedance at the end of warm-up (t=900s) in the pelvis and in the inactive thigh may reflect blood flow redistributions from these non exercising districts to the active leg.

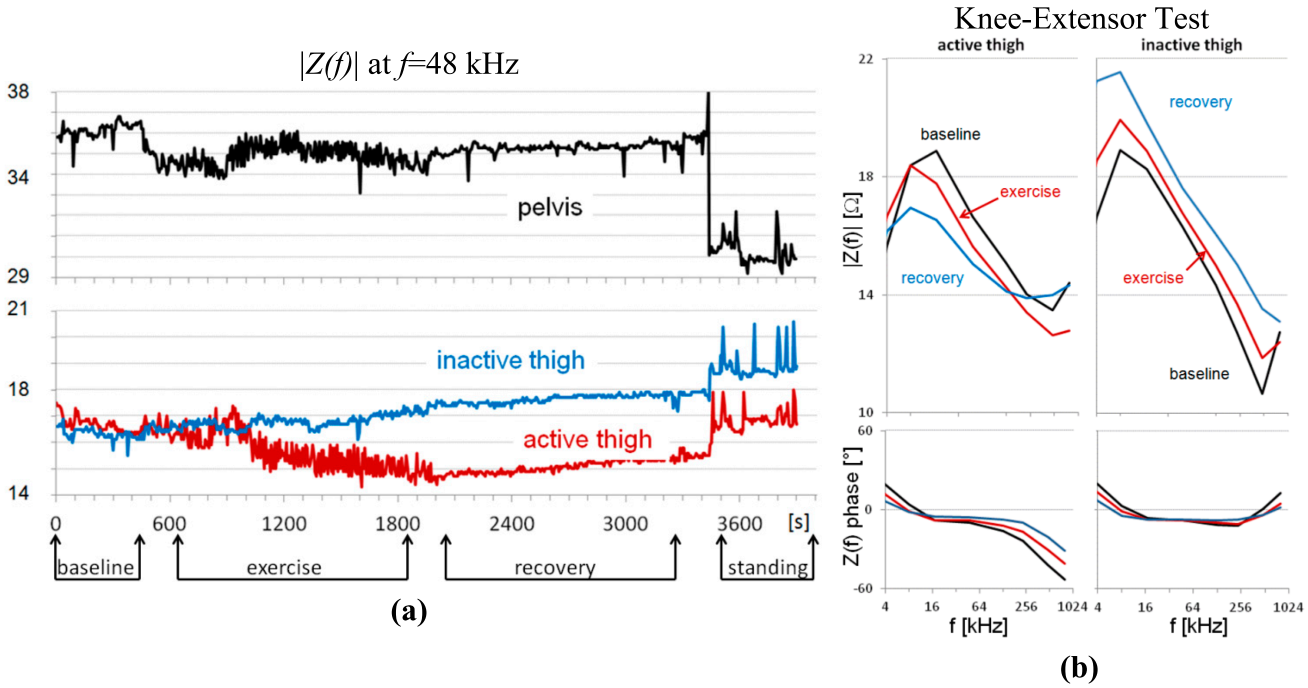
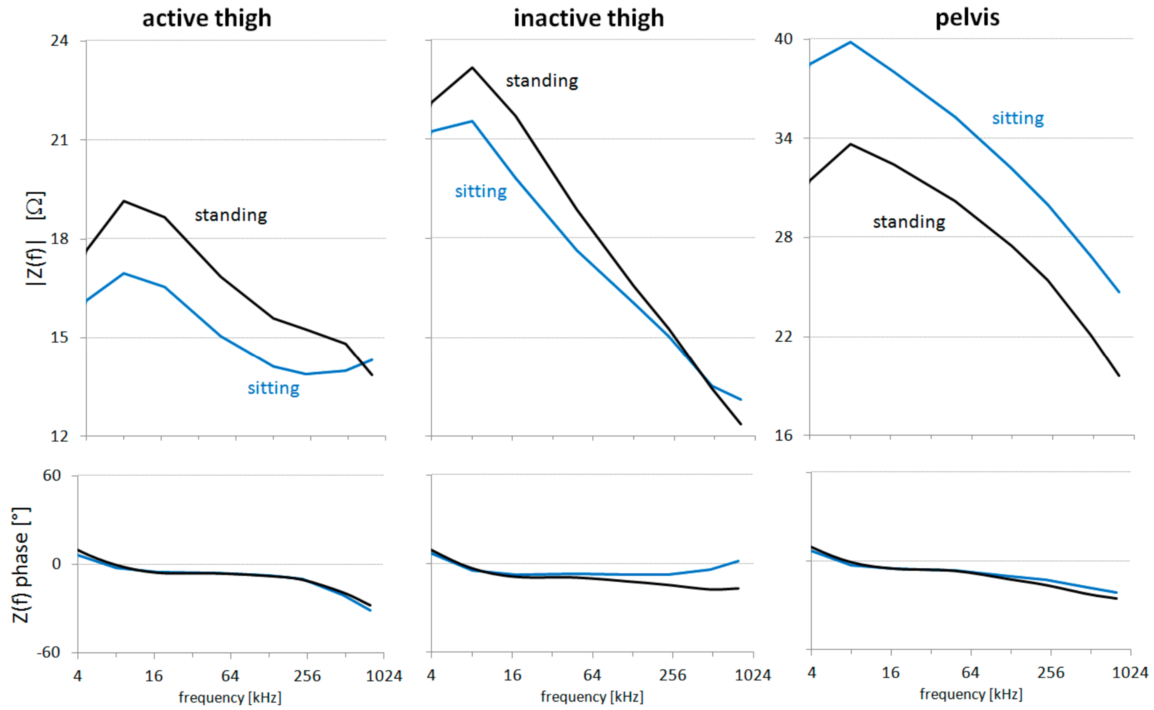


Figure 2. **(a)** Profiles of |*Z(f)*| at *f*=48 kHz in the 3 districts during the whole experimental session. **(b)** *Z(f)* in the two thighs during the knee-extensor test (“baseline”, “exercise” and “recovery” periods).

During exercise, also the pelvis impedance showed a fast variability component. It is likely that part of the blood volume squeezed out by the contracting muscles of the active thigh was pushed into the pelvis district producing a fast periodic component as in the active thigh. This fast variability disappeared when the muscle contractions stopped at the start of recovery, while the impedance difference between inactive and active thighs persisted during the whole recovery period. The change of posture from sitting to standing suddenly increased |*Z(f)*| in both the thighs, likely because of contraction of anti-gravitational muscles pushing a fraction of blood volume out of the thighs. At the same time, the pelvis district decreased |*Z(f)*| dramatically, suggesting that this body segment received a large volume of blood in the large splancnic capacitance vessels.

Impedance spectra of the two thighs, averaged in sitting position over “baseline”, “exercise” and “recovery” periods, showed opposite trends: |*Z(f)*| decreased from baseline to exercise and from exercise to recovery in the active thigh, while it increased from baseline to exercise and recovery in the inactive thigh (Figure 2b). Interestingly, changes induced by exercise were more pronounced in the 16-64 kHz range for the active thigh, and in the 4-16 kHz range for the inactive thigh. At higher frequencies (≥488 kHz), small differences between the thighs are expected due to an inductive effect of stray capacitances affecting the more distal segment from the current injecting electrode (inactive thigh) [3].

During recovery, |*Z(f)*| increased from sit to stand in both the thighs (figure 3a-b), and the increase was more pronounced at the lower frequencies. By contrast, from sit to stand |*Z(f)*| of the pelvis district decreased markedly and uniformly over the whole frequency band (figure 3c).



(a) **(b)** **(c)**

Figure 3. Impedance spectra in sitting position during recovery and in standing position.

4. Conclusions

The prototype we presented has the lightness, wearability and unobstrusiviness that “real field” studies of sports and rehabilitation medicine require. The use of a DSP and of proper stimulations waveforms allows monitoring more segments simultaneously and continuously for long periods. This makes it possible describing in details alterations in the composition of specific body segments in physiological and clinical settings where traditional BIS systems cannot be used.

The exercise test illustrated clearly the information derivable from such class of wearable devices. We showed that BIS can be quantified over different time scales, from the fast dynamics of each muscle contraction or of the sit-to-stand postural shift, to the long-term dynamics of exercise recovery. Monitoring different body segments simultaneously allowed detecting shifts of blood volumes among contiguous districts (as between active and inactive muscular districts). This would not be possible with traditional BIS devices, designed to monitor one body segment at a time. Moreover, we reported that one-leg extension exercise affected components at different frequencies on the active and inactive thighs, suggesting that the blood shift between legs is associated with different ratios of intra-cellular and extra-cellular liquids. This finding would not be observed with traditional monofrequency systems.

However, some intrinsic limitations of BIS methodology have to be considered also when using our system. First, the interpretation of $Z(f)$ variations in terms of changes in tissues composition of a given body segment is based on statistical population models that might be inaccurate in specific cases. Second, these models assume that body segments are composed by parallel cylinders of homogeneous conductors, oversimplifying the real tissutal structure of large body segments. However, this limitation is mitigated by splitting individual body districts in a series of smaller segments, an approach that can be easily realized with multisegment devices as our prototype.

Author Contributions

All authors contributed to design of the experiment and interpretation of its data; to drafting the article or revising it critically. Additionally, F.V and A.M. designed and realized the device; G.M and P.C. collected the data; P.C. analyzed the data and led the writing of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest

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