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A bioimpedance measurement device for sensing force and position in neuroprosthetic systems

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Abstract— **This contribution investigates the use of bioimpedance measurements on the limbs for the control of electrically stimulated muscles. Movements of the limbs and muscle contractions cause changes in the absolute value of the complex impedance. A four-electrode bioimpedance measurement system will be presented which can be used while the electrical muscle stimulation of the neuroprostheses is active. A constant sinusoidal current at 50 kHz with an amplitude of less than 0.25 mA is generated by a programmable function generator connected to a voltage controlled current source and is applied via two current electrodes.**

Bioimpedance changes are measured by voltage sensing electrodes. The voltage is amplified by a customized instrumentation amplifier with high common mode rejection. To allow measurements during stimulation the amplifier possesses a fast artifacts recovery below 1ms to allow immediate bioimpedance measurements after stimulation pulses.

As the changes in bioimpedance are modulated to 50 kHz, low frequency disturbances which are caused by EMG and movement artifacts can be suppressed by a high-pass filter of 25 kHz.

Finally, the absolute value of the bioimpedance is obtained by using an amplitude demodulation circuit. The measurement system is operated by a microcontroller. The resulting signal is sampled by a 24 bit ADC and transmitted via an optically isolated serial interface to a control device (PC). The measurement frequency is 1.6 kHz to allow the out blanking of stimulation artifacts and real-time control of the electrical stimulation. Fault detection of the current generation is also realized by the microcontroller. The device was successfully employed to measure the angle of the ankle joint within a drop-foot stimulator and to assess gripping force during isometric muscle contractions.

Keywords— **Bioimpedance, Functional Electrical Stimulation, Isometric Contraction, Angle Measurement.**

I. Introduction

Bioimpedance can be used to measure changes in the tissue which are caused by limb movement or muscle contractions. After calibration joint angles or isometric muscle forces can be estimated from bioimpedance.

The correlation between bioimpedance and different angles or produced force is studied in some literature. Measurement of wrist-joint and elbow-joint angle using bioimpedance was described in [1]. Optimal electrode configuration for knee-joint angle and ankle-joint angle measurement using bioimpedance was investigated in [2]. The correlation between gripping force during isometric contractions and bioimpedance of the forearm flexor muscles was described in [3]. It is also possible to measure complex movements, as the change in bioimpedance is the sum of all tissue changes caused by limb movements and muscle contractions around the measured area. In [4] the complex movement of a tennis serve was analyzed using the strong relationship between angular velocity and rate of bioimpedance change.

Closed-loop control in neuroprosthetic devices which restore functional movements improves the quality of the resulting motion. Therefore measurement of the controlled output is needed. Such measurement is difficult to realize in neuroprosthetic devices which use electrical stimulation of muscles and do not have any mechanical parts. Otherwise there is a need in cosmetically acceptable, easy to mount, safely and robustly sensors [5].

A new hardware realization for a bioimpedance measurement device which can detect bioimpedance changes during applied electrical muscle stimulation is presented in this contribution. Nothing more than additional electrodes are needed for measuring. Together with functional electrical stimulation bioimpedance measurements can be utilized to help people controlling their impaired limbs. This can either permanently compensate motor function deficits or can be used for training.

II. Measurement system

Bioimpedance (BI) is measured by the voltage drop caused by a sinusoidal current flow though the tissue. A four electrode method was used to measure BI to have a better control of the measured zone and to avoid the effects of current carrying measurement.

The structure of the BI measurement system is shown in Figure 1. The system consists of four parts. First part is the current source which generates the sinusoidal measurement current. The current source is programmed and clocked by a

microcontroller. Second part is the voltage measurement module which amplifies the voltage signal 500 times. The amplitude demodulation of the measured voltage is the third part and by the final part the voltage is converted into a digital signal and transmitted to a PC.

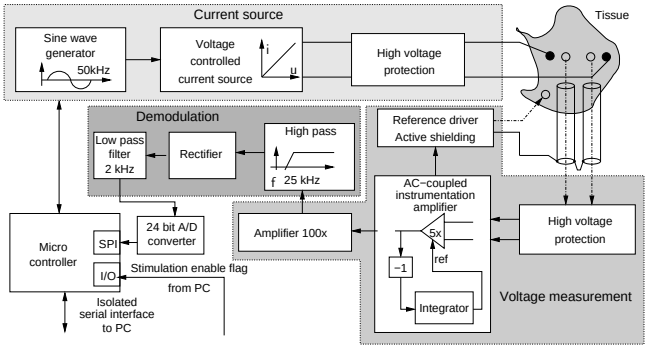

Fig. 1 Block diagram of measurement device.

A. Current source

A programmable waveform generator AD9833 (Analog Devices) produces a sinusoidal voltage of 50 kHz. The voltage is converted into a current using a voltage to current converter based on [6]. The current amplitude is set to 250 μA and the current source can handle a maximal load of 10 kΩ.

Voltage drop on a shunt resistor is used for fault detection. The current source can be disconnected from the patient by using two photoMOS-switches. The output is protected against the stimulation impulses by using two Z-diodes.

B. Voltage Measurement

The voltage drop over both voltage electrodes is amplified five times using an INA129 (Texas Intruments) instrumentation amplifier. The amplifier is alternate current coupled to allow a second amplification of 100 times without going into saturation. The input is protected against high stimulation impulses. Additionally a resistor is placed in series on both inputs of the instrumentation amplifier to achieve faster recovery from stimulation impulses. Figure 2 shows the recovery from stimulation impulses. The square wave signal is the stimulation enable flag which is send from the PC to the microcontroller to allow later software blanking of the stimulation period. The signal is 10 ms enabled. The other signal is the output of the voltage measurement module. The device is in less then 0.75 ms back in normal operating mode. As the time resolution was set to 2 ms per division the sinusoidal voltage is not identifiable. The Y-Axis resolution was set to 100 mV per division.

The cables to the voltage electrodes are shielded by active shielding to prevent disturbances caused by cable movement [7]. As the instrumentation amplifier could go into saturation for its common mode voltage operation a right leg driver is necessary [7]. Under some circumstances the output could became unstable. In order to prevent instability the output of the right leg driver is low pass filtered with a corner frequency of 100 Hz and the used operational amplifier MAX492 (Maxim) has a very low bandwidth.

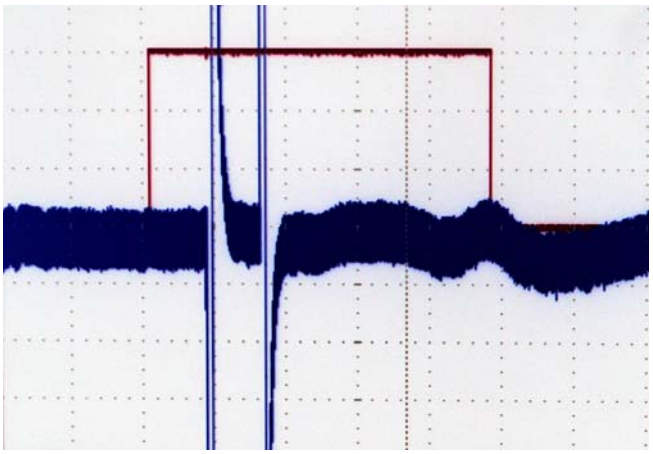

Fig. 2 Two stimulation impulses during bioimpedance measuring.

C. Demodulation

The absolute value of BI is obtained by using an amplitude demodulation circuit. As changes in BI are modulated to 50 kHz, low frequency disturbances which are caused by EMG and other low frequency artifacts can be suppressed by a high pass filter with a cut-off frequency of 25 kHz. The positive part of the signal is extracted in the next step and then the sinusoidal carrier signal can be removed by a second order low pass filter with 2 kHz corner frequency.

D. Microcontroller and AD conversion

The microcontroller (MC) MSP430F1611 (Texas Instruments) initializes at first the AD9833 and sends continuously a period clock signal to this device.

As the changes in BI are small a 24 bit analog digital converter (ADC) is necessary to get a good signal to noise ratio. The used LTC2442 (Linear Technology) works at a sample rate of 1.6 kHz, to be able to blank the stimulation period later in the PC.

In a cyclic manner the MC is doing the following: At first the MC sends the information about the selected channel and chosen sample frequency over the SPI bus to the ADC. After waiting for a finishing signal from the ADC, the MC gets the data via SPI and sends the data together with the status of the stimulation flag to the PC over an isolated serial bus (USB). The stimulation flag is generated by the PC during active stimulation and is hold for at least 10 ms by using a DAQ-card (Figure 2). The output of this card is connected to one port of the MC. This allows marking of measurement data which is disturbed by stimulation impulses. After the transmission into the PC the marked data will be blanked. This is necessary because of the unknown time delays in communication.

E. Software on a PC

A PC running LINUX with the RTAI extension was used for data acquisition. Automatic real time code generation was performed by the tool chain RTAI-Lab in combination with the open source program Scilab/Scicos [8].

In the used diagram the stimulator is activated every 50 ms. The stimulation flag is set before the electrical stimulation starts and is hold for at least 10 ms. The flag is send over a data acquisition card to the MC.

To access BI a new Scicos block was written in C. The block monitors the serial interface and converts arriving bytes into usable integer values. This block has an additional output for the stimulation flag. If this flag is enabled, the last valid BI value will be hold in order to blank out the disturbed BI data. In the next step this signal is low pass filtered and then saved.

When the BI measurement is used in a feedback controller which controls the stimulation intensity, the low pass filtered data will be down sampled to the stimulation frequency. This is necessary as the sample time in the control loop is the stimulation frequency.

III. EXPERIMENTAL SETUP AND RESULTS

A. Isometric force measurement

The device was successfully used to measure the gripping force caused by electrical muscle stimulation.

The externally controllable stimulator RehaStim (HASOMED GmbH, Magdeburg, Germany) was employed to stimulate two muscles to achieve gripping force without visible wrist flexion. Figure 3 shows the electrode configuration. The first stimulation channel stimulates the M. flexor digitorum superficials. The second channel activates the M. extensor carpi radialis longus/brevis. The wrist extensor was stimulated to compensate undesired wrist flexion. The stimulation current for both channels was 20 mA. The pulse width was changed equal for both channels in a range from 0 to 250 µs.

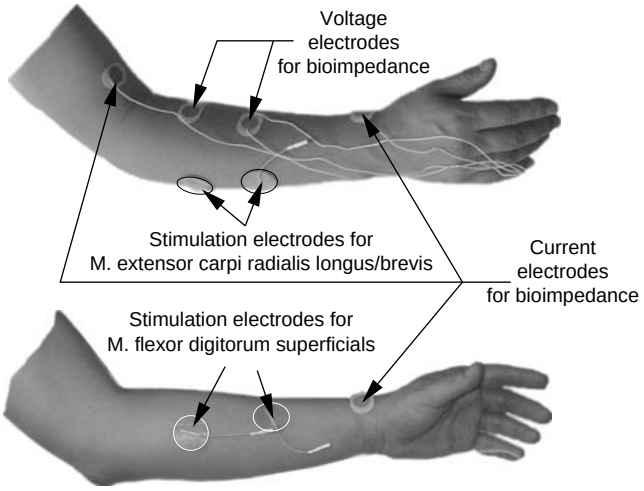

Fig. 3 Electrode positions.

The electrode setup for bioimpedance measurement is similar as described in [3]. The voltage sensing electrodes were placed that they can measure changes in the area of the stimulated forearm flexor muscle.

The reference gripping force was measured using the device AFG 500N (Mecmesin, UK) und was used to calibrate the force measurement using BI.

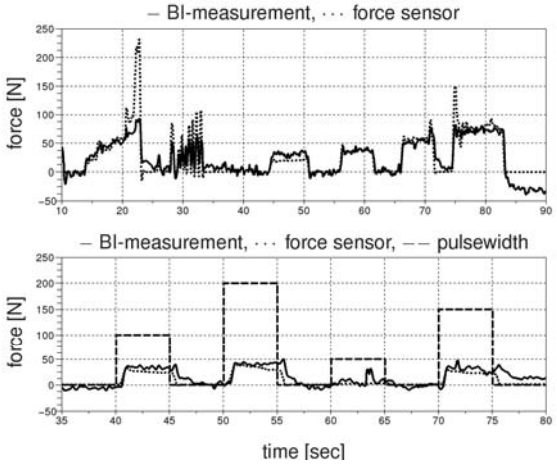

Fig. 4 Results.

The experiment was conducted with one neurologically intact subject. The subject was asked to let the arm hang down and to keep the force sensor in the hand without pushing it.

Figure 4 presents the results of two experiments for measuring gripping force using bioimpedance. In both graphs the force measurement via BI is shown as solid line. For comparison, the reference measurement by the force sensor is shown as dotted line. In the upper subplot stimulation was switched off and the test person was asked to produce voluntary force on his own. The lower subplot shows the produced force for different stimulation intensities. In this subplot the stimulation pulse width is shown as dashed line.

B. Ankle-joint angle measurement

The device was successfully employed to measure the ankle-joint angle within a drop-foot stimulator. The setup and results of this experiment are described more detailed in [9]. Figure 5 shows the used electrode positions which are adapted from [2]. The BI measurement was used in a feedback controlled drop-foot stimulator. The root mean square of the difference between reference (optical system AS202 (Lukotronic, Austria)) and BI signal over 10 steps including swing and stand phases was 1.4 degrees. The measurement is accurate enough for the considered application and reliable for at least two hours

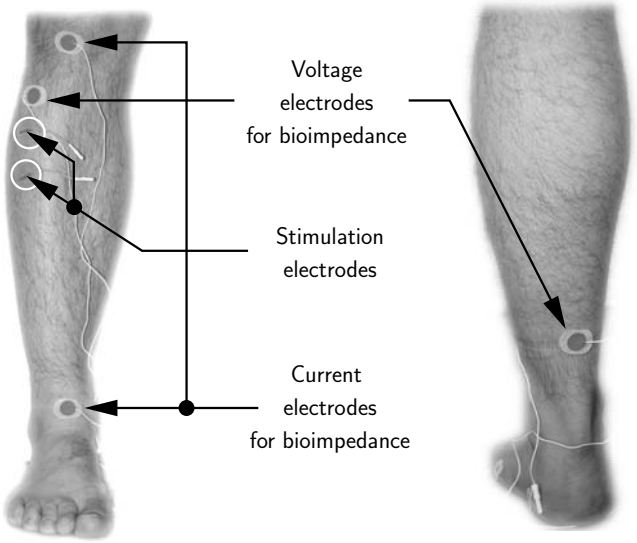

Fig. 5 Electrode positions for ankle-joint angle measurement.

IV. DISCUSSION AND CONCLUSIONS

This study shows that it is possible to access BI during applied electrical muscle stimulation. It seems to be not imported for the measurement results whether the muscle is controlled from the brain or externally stimulated. BI measurement could be a usable sensor in neuroprosthetic systems using functional electrical stimulation.

The obtained results still need to be verified with patients. A larger number of test subjects is necessary.

A disadvantage of the presented approach is the large number of electrodes to be attached. An elastic textile with integrated stimulation and bioimpedance electrodes is under development.

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