33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Dynamically Characterizing Bioimpedance of Fingertip Skin Through a Developed CVD Based Electrotactile Rendering System

Yantao Shen, John Gregory, and Claire E. Shelton

Abstract— **In this paper, by combining a newly developed constant-voltage-driver (CVD) based electrotactile rendering system with an on-line identification method, parameters of the resistor-capacitor (R-C) load bioimpedance model of fingertip skin are dynamically characterized and analyzed. The CVD rendering system is capable of producing varying stimulation voltage/current waveforms to fingertip. The proposed on-line identification method is a discrete-time extended least squares (ELS) iterative approach with forgetting factor (FF), which serves as an adaptive law to estimate parameters of the bioimpedance model of fingertip skin during performing the stimulation current tracking control in z-domain. Experimental results demonstrate dynamic characteristics of the identified fingertip skin bioimpedance for the sampled population.**

I. INTRODUCTION

OUR research interest pertains to investigation of the ability to induce touch sensations on the fingertip skin using an electrode array. This mechanism, is also called electrotactile or electro-cutaneous stimulation [1][2][5][8].

Currently, although such electrotactile systems have been extensively investigated, electrotactile stimulation can be uncomfortable because of the highly variable conditions at the electrode-skin interface and bioimpedance of fingertip skin. The quality control of tactile sensation/preference through the electrode-skin interface is still an open research problem [5][7]. Associated with the sensation quality, the stimulation voltage/current level through the electrodes to the skin needs to be carefully and accurately controlled following users' tactile preference so as to avoid unpleasant sensations. Since the desired current is highly dependent on the electrical impedance of the fingertip skin, the sensation under the same stimulation voltage will vary with the skin bioimpedance of different users. It is essential that the bioimpedance needs to be carefully identified and characterized before or during electrical stimulation.

In this paper, we focus on dynamically characterizing the bioimpedance parameters of fingertip skin through a custom-built constant-voltage-driver (CVD) based electrotactile rendering system and an embedded on-line identification method. The goal of our work is to better understand these dynamic characteristics and utilizes them to automatically tune the stimulation voltage or current to a desired sensation level for different users.

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Different from load-independent constant-current-driver (CCD) systems (see [5], for instance), our CVD system uses a synergistic approach by incorporating the power efficiency inherit in a voltage OpAmp driver with a minimal output stage that will use a closed-loop design. The developed CVD rendering system can produce multiple constant voltage pulses with the dependent variable to form stimulation current delivered to the electrode-skin interface. Both the stimulation voltage pulse and current are measurable in our system. These measurements can then be fed back to the proposed bioimpedance identification algorithm based on a discrete-time extended least squares (ELS) iterative approach with forgetting factor (FF) [6]. In this identification scheme, the ELS-FF method serves as an adaptive law to estimate parameters of the selected first-order bioimpedance model of fingertip skin when the stimulation current tracking control is performing in z-domain. The CVD induced stimulation current control is to minimize the difference between the measured stimulation current from real fingertip-electrode interface and the computed stimulation current generated from the estimated bioimpedance model with three R-C parameters. The developed CVD system and identification method are further used for dynamically characterizing the bioimpedance of fingertip skin for the sampled population (N=15). The achieved dynamic results show the identified bioimpedance parameters are dependent on the stimulation current and are time varying. These findings help us to better understand the dynamics of the bioimpedance. They can be used for further development of adaptable and user friendly electrotactile rendering systems for rehabilitation and neuroengineering applications.

This paper is structured as follows: The developed CVD electrotactile rendering system is briefly described in Section II. Skin electrical properties and the first-order bioimpedance model are reviewed in Section III. The proposed bioimpedance identification scheme is introduced in the same section. In Section IV, dynamic characterization results of the bioimpedance are demonstrated and analyzed. Finally, we conclude the work in Section V.

II. CVD BASED ELECTROTACTILE RENDERING SYSTEM

A. System Overview

The diagram of the developed CVD electrotactile rendering system, and circuitry components needed for online electrical bioimpedance identification and dynamic characterization is shown in Fig. 1. The hardware components can be grouped as follows: the digital acquisition board

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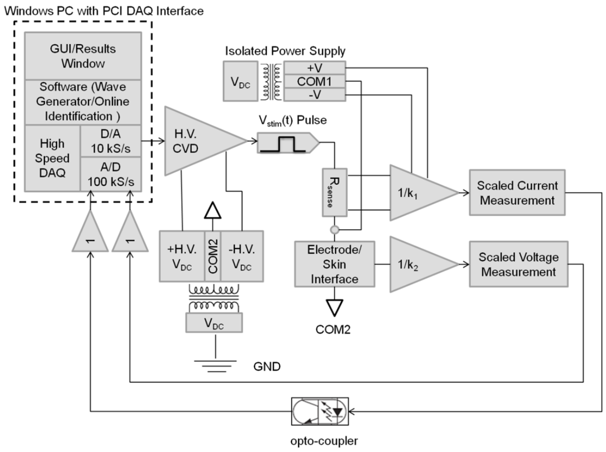


Fig. 1. System level diagram of CVD based electrotactile rendering system.

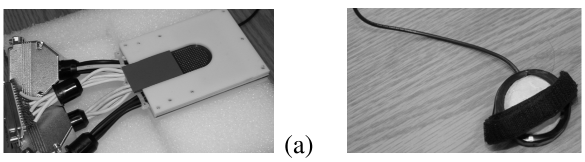


Fig. 2. Custom-built electrotactile rendering terminal: (a) electrode array, and (b) isolated return electrode.

(DAQ)(Measurement and Computing Inc.), custom-built high voltage (H.V.) CVD electrotactile driver, fingertip electrical load (scaled stimulation current and voltage) measurement circuits, two power supplies including a high voltage power supply for the CVD driver and an isolated power supply for the electrical load measurement circuits, and designed rendering terminal. In the system, the closed-loop gain of the CVD OpAmp (PA97, Cirrus Logic) is set at approximately 50 and is limited by the power module to producing maximum bipolar amplitude pulses of approximately 300 Volts and maximum current of 10 mA. The developed system software is responsible for integrating the CVD driver and electrical load measurement circuits with the high speed DAQ board, implementing the bioimpedance identification and dynamic characterization, and presenting a GUI for setting up and controlling the system. As seen in Fig. 1, both the stimulation current and voltage measurement circuits signal-condition and scale down measured load ($\frac{1}{K_1}$ for current and $\frac{1}{K_2}$ for voltage) signals respectively for compatibility when inputting the analog signals to the A/D channel of the DAQ. R_{sense} is a high precision-valued small resistor ($\sim 1K\Omega$) that functions as a bi-directional current-to-voltage transducer. A linear isolation opto-coupler is used to reference the output voltage on the stimulation current sensing circuit to COM2 so that this measurement can be input to the DAQ which is referenced to COM2. COM1 is the ground of the isolated power supply.

B. Electrotactile Rendering Terminal

The developed electrotactile rendering terminal is the direct interface to the fingertip skin so that the user experiences sensations by electronic stimulation, as shown in Fig. 2(a). The dimensions of the rendering area are 3×2 inches. Soft rubber padding resides at the base of the terminal to serve as a stable resting position for the index finger. The electrodes' active area, where stimulation occurs on the fingertip, is $2.74 \times 2.31 cm^2$. Each tin plating electrode diameter of $0.762m$m was a consideration between dielectric breakdown of air, and quality of sensation. The electrodes have $1mm$ pitch. Note that, the electrical impedance of the electrode is in the order of 1 Ω, its effect is omitted in the bioimpedance model. Under the electrodes, a force sensor is installed for measuring the pressing force on the electrodes by fingertip. Fig. 2(b) shows the developed return electrode for the isolated system. It features a large copper cathode return with velcro strap so that the user can easily attach it to the thenar eminence region of the palm without it interfering with other tasks.

III. SELECTED BIOIMPEDANCE MODEL AND ON-LINE PARAMETERS IDENTIFICATION

A. Bioimpedance Model of Fingertip Skin

A first-order bioimpedance model with time and spatial varying properties is described, as shown in Fig. 3. The model is comprised of a resistor R_p in parallel with a capacitor C_p and in series with another resistor R_s [3]. Here, R_p accounts for the natural protective barrier resistivity of the stratum corneum (SC), top layer of skin. C_p models the bulk capacitance that is a result of the skin cell membrane structure in relation with water and ion content in the extra- and intra-cellular regions of the skin. R_s models the deep tissue resistance in the skin. In addition, the much larger return electrode is attached to thenar area on the palm to complete the circuit. The parameters R_p and C_p in the model are functions of multiple variables, including the measured stimulation current I_{stim}, skin location of electrode contact ζ_{loc}, effective skin-electrode contact area A_{eff}, the fingertip pressing force on the electrode F_{app}, and time t. R_s is only dependent on the pressing force F_{app} and electrode skin contact area A_{eff}. Since some of the parameters are a function of the stimulation current, the model is not linear in the parameters. In Fig. 3, I_{stim} will be taken as measured current output of the underlying fingertip-electrode interface with V_{Load} as the actual input. Here, V_{Load} is related to the CVD driver output V_{CVD} by: $V_{Load} = V_{CVD} - I_{stim}R_{sense} \approx V_{CVD}$.

Without loss of generality, we have lumped above multiple variables into time and spatial varying properties and the simplified s-domain model in transfer function form is then given by

$$\hat{I}_{stim}(s, \zeta_{loc}) = \frac{1 + R_p(\cdot)C_p(\cdot)s}{R_p(\cdot) + R_s(\cdot) + R_p(\cdot)C_p(\cdot)R_s(\cdot)s} V_{Load}(s) \tag{1}$$

where $\hat{I}_{stim}$ is the current generated by the estimated bioimpedance model when all parameters are known.

B. On-line Identification of Bioimpedance Parameters

The developed on-line identification method is based on a model-based adaptive control scheme. The scheme regulates

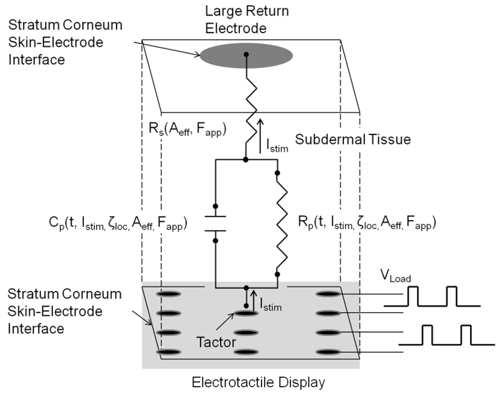


Fig. 3. The first-order bioimpedance model of fingertip skin under electrotactile stimulation.

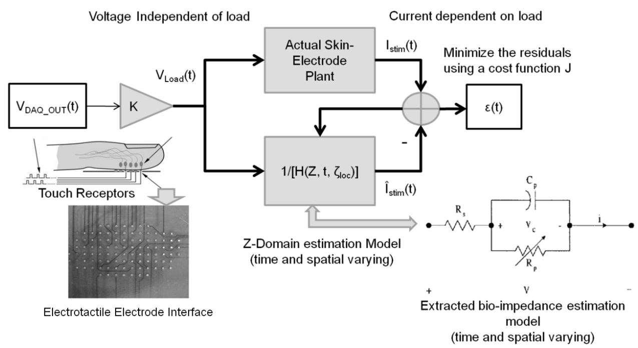


Fig. 4. Model-based adaptive control scheme for on-line identification of bioimpedance parameters.

the stimulation output current generated by the selected first-order fingertip skin bioimpedance model to approach the stimulation output current measured from the fingertip-loaded electrotactile rendering terminal (plant), as shown in Fig. 4. Note that, both currents have the CVD high voltage pulse as the input. During the regulation, the unknown R-C parameters of first-order fingertip skin bioimpedance model are iteratively identified (estimated) and updated in z-domain using an adaptive law. Following the identification strategy shown in Fig. 4, it is assumed that the input and output samples of the bioimpedance model are related to a first-order rational model in z-domain, we then have

$$\hat{I}_{stim}(z,\zeta_{loc}) = \frac{\beta_2+\beta_1 z^{-1}}{1+\alpha_1 z^{-1}} V_{Load}(z) + \frac{c_1}{1+\alpha_1 z^{-1}}\varepsilon(z) \quad (2)$$

where $\hat{I}_{stim}(z,\zeta_{loc})$ is the z-domain model stimulation current output when the parameters are known. $V_{Load}(z)$ is the z-domain measured stimulation voltage. $\varepsilon(z)$ is the z-domain current output error. The coefficients $\alpha_1, \beta_1, \beta_2$ and c_1 are the z-domain parameters that are related to the s-domain bioimpedance parameters. These z-domain parameters can be estimated using the discrete-time extended least squares iterative approach with forgetting factor λ, simplified as ELS-FF algorithm. The detail of the ELS-FF can be found in [6]. As illustrated in Fig. 4, the goal of the proposed adaptive control scheme is to use the ELS-FF law that gives the set of estimated parameters for the z-domain model which minimizes the difference ε between measured and estimated stimulation current output. In addition, as shown in the figure, a function is used to map the z-domain estimated parameters (*i.e.*, $\alpha_1, \beta_1, \beta_2$ and c_1) to the s-domain estimated bioimpedance model parameters of eqn. (1) (*i.e.*, R_p, R_s, and C_p). To iteratively estimate the bioimpedance parameters associated with the s-model in eqn. (1) from the estimated coefficients in z-domain, we assume $\varepsilon(z)$ is small and reduced, giving us the following equation related to the change in the estimated output current:

$$\Delta\hat{I}_{stim}(z,\zeta_{loc}) = \frac{\beta_2+\beta_1 z^{-1}}{1+\alpha_1 z^{-1}}\Delta V_{Load}(z). \quad (3)$$

The bioimpedance parameters can then be found from the estimated parameters in eqn. (3) through the domain transformation:

$$\begin{aligned} Z_{skin}(s,\zeta_{loc}) &= \frac{\Delta V_{Load}}{\Delta\hat{I}_{stim}} \quad (4) \\ &= \frac{R_p(\cdot)+R_s(\cdot)+R_p(\cdot)C_p(\cdot)R_s(\cdot)s}{1+R_p(\cdot)C_p(\cdot)s}. \end{aligned}$$

To produce the filter equivalence, the Tustin transform is applied to the model in eqn. (3):

$$z \approx \frac{1+\frac{sT_s}{2}}{1-\frac{sT_s}{2}} \quad (5)$$

where T_s is the DAQ's A/D sampling rate. Since the mapping by the Tustin transform is one-to-one, the frequency response is the same in both domains. Based on eqns. (3)-(5), the mapping functions from estimated z-domain coefficients to the bioimpedance parameters in s-domain are:

$$R_s = \frac{1-\alpha_1}{\beta_2-\beta_1}, \quad (6)$$

$$R_p = \frac{1+\alpha_1}{\beta_2+\beta_1} - R_s, \quad (7)$$

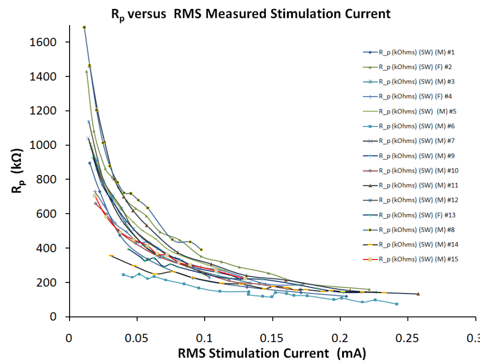
$$C_p = \frac{T_s}{2}\left(\frac{\beta_2-\beta_1}{\beta_2+\beta_1}\right)\frac{1}{R_p}. \quad (8)$$

The developed identification method and the CVD rendering system can then be used for dynamically characterizing the bioimpedance of fingertip skin. The results are presented in the following sections.

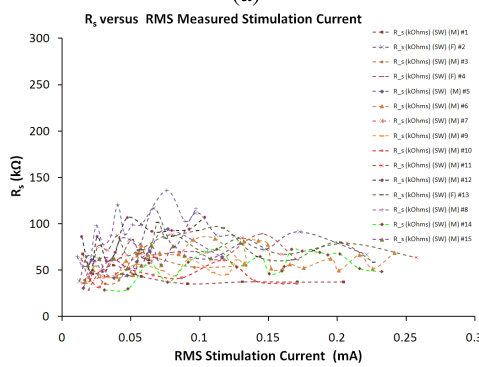
IV. DYNAMIC CHARACTERIZATION & ANALYSIS

Prior to the dynamic characterization of fingertip skin bioimpedance, we have experimentally validated the whole system including the closed-loop CVD rendering system and on-line identification method, which is detailed in [9]. The achieved results verify the high performance of the developed system, that is, it is capable of effectively performing such a dynamic characterization.

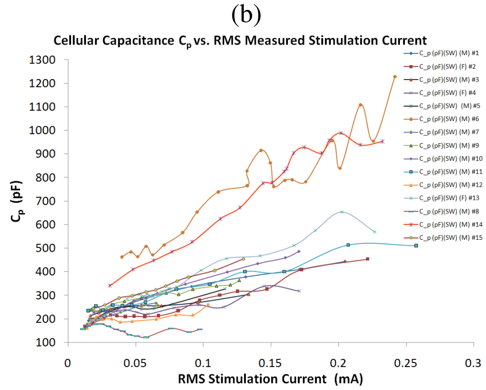
In the characterization, the sampled population size, N, was 15. The sample group consisted of individuals 19 to 33 years of age with approximately two-thirds of participants male. The index finger was kept free of sweat or moisture and otherwise not altered any other way for the entire experiment. Fig. 5 plots the characterization results of the stratum corneum-modeled electrical resistance R_p, the deep dermal tissue modeled electrical resistance R_s, and the intracellular capacitance C_p for each subject as a function of the root-mean-square (RMS) stimulation current. The CVD input was a software set square wave for one second identification and recording time. The voltage pulses began at 30 Volts for all subjects and ended at the increment when the subjective pain threshold for the subject was reached. In Fig. 5(a), R_p decreases an order of magnitude over the entire stimulation current region for almost all individuals. Another observation is that the variability in R_p for low stimulation currents is initially large but takes on similar minimal magnitudes as stimulation current increases to each subject's maximum threshold. The R_p minimal magnitude asymptotically goes to about 100KΩ at the maximum pain stimulation threshold possible for any member of the sampled population. It was also observed from Fig. 5(b) that R_s is smaller (between 30KΩ and 150KΩ) in magnitude than R_p over the entire stimulation current domain. In contrast to R_p, R_s is relatively constant for different users and current stimulation amplitudes because of increased isotropy of the environment compared to the stratum corneum [3][4]. In Fig. 5(c), the trend shows an increase in capacitance as stimulation current increases, which occurred for almost every individual. In addition, the increase appears affine linear for most individuals as a function of stimulation current. The rate of increase is less than that of R_p over the region of interest; except for two outliers, the change in value of C_p was at most a factor of 3 for any individual, whereas R_p can vary greater than a factor of 10 for the same stimulation current domain. As well, the capacitance values are grouped closer together over the stimulation current domain. The outliers are likely a result of increased ionic moisture content at the point of stimulation that facilitates dielectric polarization. These experimental findings facilitate better understanding of the dynamics of the bioimpedance and provide a scientific reference for applications in rehabilitation and neuroengineering.



(a)



(b)



(c)

Fig. 5. Dynamic characterization of (a) R_p, (b) R_s, and (c) C_p as a function of stimulation current and subject (N=15).

V. CONCLUSIONS

This paper presents our work on dynamic characterization of parameters of the resistor-capacitor (R-C) load bioimpedance model of fingertip skin. The characterization was successfully implemented through a custom-built CVD electrotactile rendering system embedded with an on-line identification algorithm ELS-FF. The significance of our work is that it will be a major step towards advancement of adaptable and user friendly electrotactile technology.

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