Tissue phantom to mimic the dielectric properties of human muscle within 20 Hz and 100 kHz for biopotential sensing applications

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***Abstract*— Tissue-mimicking materials for phantoms are fabricated for research purposes to simulate the mechanical or electrical properties of real human tissues and promote better understanding of their properties. This research investigated the dielectric properties (from 20 Hz to 100 kHz) of five promising muscle mimicking materials including matrix materials (gelatin powder and agar powder), and fillers (sodium chloride, glycine and aluminum powder) for the development of muscle phantoms. The mechanical behaviors were verified as well. This research determined the effects of electrode polarization (EP) on the dielectric properties of each material and then used a mathematical model to reduce these unwanted effects. Additionally, the results indicated the very low dielectric properties of gels-only samples. Both electrical conductivity and relative permittivity increased with increasing concentrations of fillers. Moreover, all fillers had their own capabilities to alter the levels and trends in the increments of dielectric values, which provide a wider selection to muscle-mimicking materials. Theoretically, it is feasible to achieve desired dielectric properties by mixing these fillers together with certain ratios. In this way, low-cost muscle phantoms can be produced and used as experimental subjects for biopotential sensing application.**

I. Introduction

Skeletal muscle accounts for the largest proportion of human tissues at approximately 30% of body mass in women and 40% in man [1]. However, muscle disease occurs in all age groups and can cause serious physical disability. Unfortunately, the clinical science and pathology of muscle are still incomplete because its properties always depend on size, age, type, and morphology. In the medical arena, there are various techniques to detect abnormal changes in muscle tissue, including Palpation, Ultrasound (US) Elastography, Magnetic Resonance Elastography (MRE), Electromyography (EMG) and Electrical Impedance Tomography (EIT).

The dielectric properties of biological tissues (including muscle) have been well established and modelled through several works [2]–[4]. Mathematically, the dielectric response of all biological tissues can be modelled either through multi-debye dispersions (based on Debye theory for dielectric dispersion) [5] or, more accurately through multi-Cole dispersions (based on Cole-Cole theory [6]):

$$\hat{\varepsilon}(\omega) = \varepsilon_\infty + \sum_n \frac{\Delta\varepsilon_n}{1+(j\omega\tau_n)^{(1-\alpha_n)}} + \frac{\sigma_i}{j\omega\varepsilon_0} \qquad (1)$$

where the magnitude of dispersion was described as $\Delta\varepsilon = \varepsilon_s - \varepsilon_\infty$, ε_∞ is the permittivity at infinity angular frequency, ε_s is that at zero angular frequency, σ_i is the static ionic conductivity, and α is a measure of the broadening of dispersion, and $j^2 = -1$. One of the major electrical measurement confounders is Electrode polarization (EP), which is caused by the accumulation of a spatial charge on the surface of electrodes. The dissolved free ions in tissues or phantoms tend to move towards the interface between the electrodes and the sample, and ionic double layers generate in these areas [7]. This phenomenon is a major nuisance in bio-impedance studies, especially at low frequency ranges (up to 100 kHz, 1 MHz) and with more conductive materials. The factors affecting EP are very diverse, such as the conductivity of samples, the temperature of samples, the materials and structure of the electrodes, etc. From a microscopical perspective, EP can depend on electrode surface topography and chemistry. Therefore, no simple correction method has become widely accepted [8].

For biomedical research purposes there are limitations to use living human tissues [9]. Tissue-mimicking materials for phantoms are fabricated for research purposes to simulate the mechanical or electrical properties of real human tissues and promote better understanding of their properties. Specifically, muscle phantoms were used for the calibration and verification of diagnostic techniques and monitoring systems, such as EIT technique [10]. However, most of the previous works have focused on developing phantoms to mimic the dielectric properties at higher frequencies (100MHz to 10GHz) for microwave imaging applications, which ignores the effects of noises and confounders like polarization errors that occur in the lower frequency ranges [3]. In recent years, with better understanding of electrical properties, there have been significant advances in diagnostic techniques measuring bio-impedance at lower frequencies in the fields of symptomatic therapies, medicine, and sports science [9], [11]. A recent study [12] has proposed a human forearm phantom within the β dispersion frequency range, therein, the dielectric properties of muscle tissue were mimicked through saline and propylene glycol. This work aims to identify the contribution of gels and

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978-1-5386-1311-5/19/$31.00 ©2019 IEEE

filler materials to the dielectric properties of potentially muscle tissue-mimicking materials between 20Hz and 100kHz.

II. Materials and Methods

A. Selection of Muscle-mimicking Materials

In this study, gelatin powder and agar powder were selected as the matrix materials, because the high-water content of gel-based phantom can provide a suitable environment for adding other fillers. At the beginning, various concentrations of gelatin powder and agar powder were mixed with deionized water to produce gel-only samples and determined both their mechanical and dielectric properties to inform the next stages of the research process. The selection of fillers followed two principles: (1) Muscle tissue is a high-water content tissue with conductivity from approximately 0.2 S/m at 20 Hz to 0.36 S/m at 100 kHz. Pure deionized water should have no conductivity, thus various proportions of aqueous sodium chloride (NaCl) solution were added in mixture to enhance its electrical conductivity; (2) The permittivity of muscle tissue is more than that of water below 100MHz [13]. Therefore, materials with higher permittivity were considered. Glycine ($C_2H_5NO_2$) was a promising filler, because an aqueous solution of glycine has a permittivity appreciably greater than that of water [14]. Additionally, aluminum powder was another filler material which has been indicated the capability to increase permittivity of phantom samples [15].

B. Phantom samples fabrication

Fig. 1 illustrates the process of samples fabrication. All ingredients were weighed by mass fraction (*wt%*). According to the standard of test devices, the thin film samples were manufactured for electrical test, and cylinder samples were produced for mechanical test (see Fig 2). However, the low viscosity of the agar solution caused stratification of the aluminum powder and solution. Moreover, it is necessary to keep stirring at the lowest speed when removing the solution to prevent the aluminum powder from sinking.

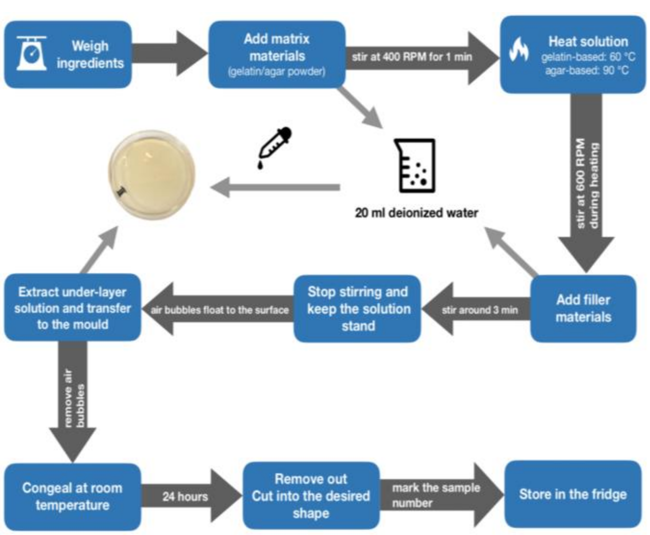

Figure 1. Flow chart of samples fabrication.

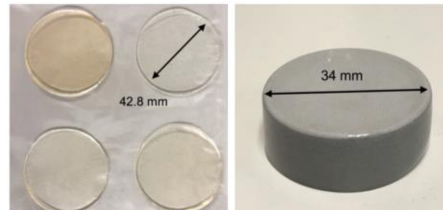

Figure 2. Phantom samples: film samples (left) and cylinder sample (right).

C. The Mechanical Test

The compression test was performed for the cylinder samples after congealing for 24 h with the TA. XT Plus texture analyzer. The purpose was to verify the contribution of each material on the mechanical behaviors and then control the values in a reasonable range to ensure the durability of phantoms.

D. The Electrical Test

The measurements of dielectric properties were performed using the Keysight® E4980A Precision LCR meter (20 Hz to 2 MHz), the Keysight® 16089B Kelvin clip leads (5 Hz to 100 kHz), and two circular copper electrode plates (diameter is 42.8 mm). In this project, the parallel plate capacitor method was used as the measurement technique, which involves sandwiching a thin sample between two electrodes to form a capacitor (see Fig. 3). The total impedance and phase angle from 20 Hz to 100 kHz were measured by LCR meter, and the thickness of the sample were measured using Vernier calipers.

Mathematical Self-correction Method was used to characterize EP by fitting a function model to the raw experimental data. All processes were performed on MATLAB (R2017b). The experimental measured impedance (Z_m) is composed of EP impedance (Z_p) and sample impedance (Z_s). Schwan (1968) explained that the sum of EP impedances appeared in series with the sample, and the total polarization impedance composed of the real part resistance (R_p) and the imaginary part capacitance (C_p) as follows [7]:

$$\boldsymbol{Z_p = R_p + \frac{1}{j\omega C_p}} \tag{2}$$

Both R_p and C_p decrease with increasing frequency. Based on other research [7], [8], the frequency dependent R_p and X_p were estimated as power-law functions of angular frequency ω:

$$\boldsymbol{R_p(\omega) = A\omega^{-n}, \quad X_p(\omega) = B\omega^{-m}} \tag{3}$$

where A, B, n, and m are positive constants. Moreover, the Z_s should correspond with the Cole-Cole equation (Equation 1) according to the bio-tissue phantom's purpose. Consequently, the measured impedance was expressed as:

$$\boldsymbol{Z_m = Z_s + Z_p = \frac{R_0 - R_\infty}{1+(j\omega\tau)^\alpha} + \frac{A}{\omega^n} + j\frac{B}{\omega^m}} \tag{4}$$

where R_0 is the resistance at zero frequency, R_∞ is the resistance at infinite frequency, and τ is the time constant. The resistance (R_s) and reactance (X_s) of samples were then calculated.

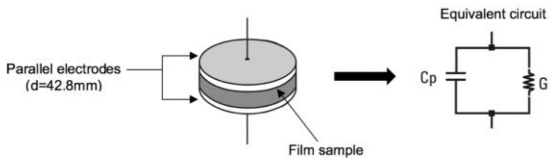

Figure 3. Parallel plate capacitor method.

The sample was equivalent to a resistor in parallel with a capacitor. Thus, the resistance X_s and the capacitance R_s can also be expressed as follows:

$$\boldsymbol{X_s} = -\frac{\omega R_S^2 C_S}{1+(\omega R_S C_S)^2}, \quad \boldsymbol{R_s} = \frac{R_S}{1+(\omega R_S C_S)^2} \tag{5}$$

Electrical conductance is the reciprocal of the capacitance. Therefore, conductivity and relative permittivity were calculated using the following functions:

$$\boldsymbol{\sigma} = \frac{l}{R_S A_S}, \quad \boldsymbol{\varepsilon_r} = \frac{l C_S}{\varepsilon_0 A_S} \tag{6}$$

where l is the thickness of the film sample, and A_s is the contact area. After data processing, the effects of EP on dielectric properties of each material were indicated by comparing the corrected data and the measured data. Moreover, the dielectric properties of each materials were further determined.

III. RESULTS AND DISCUSSION

A. Mechanical behaviors of muscle phantom

The effects of gels concentrations and storage time on Young's modulus are illustrated in Fig. 4. Moreover, the results indicated breaking stress and breaking strain increase with increasing gel concentration. However, agar-based samples were more easily broken because of the high notch sensitivity of agar gels. Additionally, all filler materials showed positive influence on mechanical behaviors.

B. Dielectric Properties of Muscle Phantoms

1) The effects of electrode polarization

Generally, the main contribution of EP is the increment of measured impedance caused by unwanted electrical double layers on the interface of the sample and electrodes. All samples showed a reducing trend of the magnitudes of EP impedance with increasing frequency, but the extents were different. The gelatin with aluminum powder samples showed the greatest EP impedance across the range of frequencies up to 100 kHz. This phenomenon was the result of aluminum powder not dissolving into solution, and the resulting large contact areas caused more single polarization regions. Isopropyl alcohol was added into NaCl samples to limit the movements of ions and therefore conductivity, and the results confirmed that lower the ionic conductivity of a material, the smaller the EP effects [16].

2) Matrix materials

Both conductivity and relative permittivity increased with increasing gel concentration. However, even if the weight of gels was doubled, their dielectric properties changed only slightly compared with the data for muscle tissue. The results indicated that matrix materials have much lower conductivity and permittivity than muscle tissue below 100MHz. Therefore, the influences of gels on dielectric properties can be neglected.

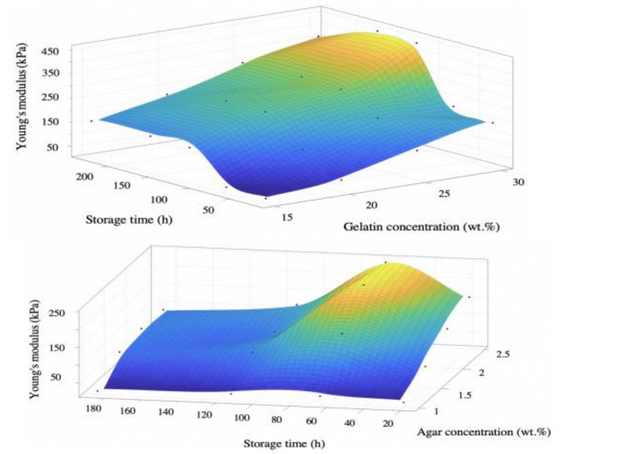

Figure 4.3D surface graph of Young's modulus as a function of storage time for various gel concentrations (Piecewise cubic interpolant, SSE=0, R^2=1).

3) Filler materials

Fig. 5 shows the conductivity was highly sensitive to small changes in salt concentration for all samples. Interestingly, NaCl also increased the relative permittivity. 1.5% ager sample with 0.4% NaCl exhibited the closed results to muscle above 20 kHz. However, gelatin-based samples showed be better changing trend. Additionally, the same concentration of salt in gelatin-based samples showed higher dielectric properties than that in agar-based samples at all frequencies. This phenomenon can be explained as gelatin-based samples had more aqueous components, because their conductivity should be dominated by the aqueous phase [17]. Aluminum powder samples showed the different changing trend from the others that their conductivity grew dramatically at all frequencies. Moreover, aluminum powder showed the highest

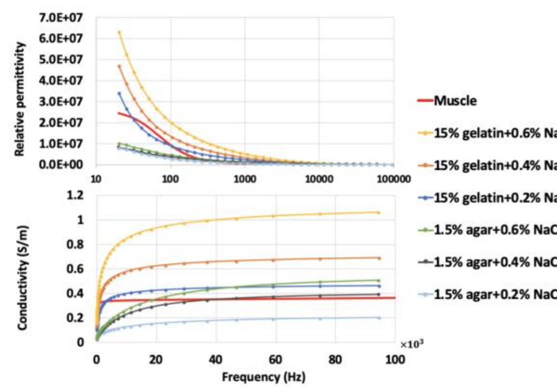

Figure 5. The effects of various NaCl concentrations on conductivity and relative permittivity of gel-based samples.

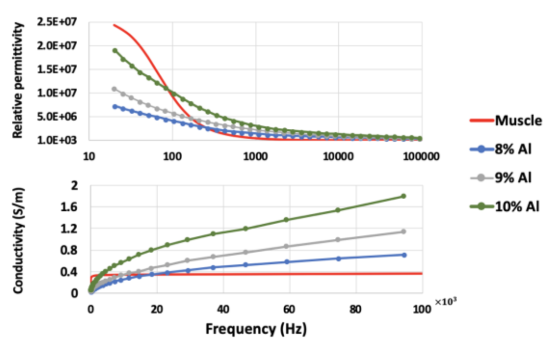

Figure 6. The effects of various aluminum powder concentrations on conductivity and relative permittivity of 10% gelatin-based samples

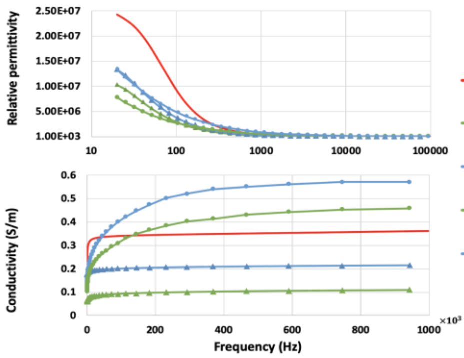

Figure 7. The effects of various glycine concentrations on conductivity and relative permittivity of 10% gelatin-based samples

permittivity across the entire frequency range. These special properties were the result of the metal content of the samples. Glycine-only samples didn't show significant increasing conductivity as others (see Fig. 7). Moreover, their impacts on relative permittivity were smaller than anticipated [18]. Hereon, 0.1% NaCl was added to enhance the dielectric properties. The results proved the high conductivity of saline samples, while there were minor influences on permittivity. For agar-based samples, the concentrations of glycine were from 10% to 20%, but these showed very low conductivity (within 0.1 S/m), and no further analysis was therefore performed.

The importance of adding each material to mimic muscle properties was identified. NaCl contributed to the bulk conductivity whereas Al powder contributed to dielectric behavior. Glycine was found to be more suitable for stable dielectric response at higher frequencies. The future work can mix more fillers together to adjust the changing trend and achieve the target values by altering their ratios. Additionally, an ideal bio-tissue phantom should exhibit a Cole-Cole behavior, whereas some samples didn't show the good agreements, leaving scope for further analysis.

IV. Conclusion

This work investigated the mechanical and dielectric properties of potential muscle mimicking materials for the development of muscle phantoms at low frequencies from 20 Hz to 100 kHz. A mixture of Gelatin, Aluminum powder with a small NaCl concentration was found to mimic muscle dielectric properties within 100 kHz. The analysis also verified the effects of gel concentration and storage time on Young's modulus. This research also determined the influence of EP on the dielectric properties of each material and then used a mathematical model to reduce these unwanted effects. The significance of this paper was to indicate the relationships between dielectric properties and the concentration of proposed materials, which provided more selections for muscle phantoms. Also, a novel recipe for mimicking the dielectric properties of muscle tissue was proposed, which can be used as for biopotential sensing research and experimentation. Future work may be directed towards removing the adverse effects of electrode polarization at lower frequencies for a more accurate determination of permittivity. Also, similar procedure may be adopted for mimicking other tissue layers to be used in biomedical applications and related research.

Acknowledgment

This research was supported by Institute of Biomedical Technologies, Auckland University of Technology, Auckland 1010, New Zealand.

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