Muscle Analyzer System: Exploring Correlation Between Novel Microwave Resonator and Ultrasound-based Tissue Information in the Thigh

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Muscle Analyzer System: Exploring Correlation Between Novel Microwave Resonator and Ultrasound-based Tissue Information in the Thigh

Viktor Mattsson*, Mauricio D. Pérez*, Leanne L. G. C. Ackermans†,‖, Maud A.M Vesseur†, Julia L.M. Bels¶,‖,
Marcel C.G. van de Poll†,**, Bappaditya Mandal*, Patricia Sánchez-González‡,§, Alexander P. Seiffert‡,
Enrique J. Gómez‡,§, Paul Meaney†† Jan A. Ten Bosch†, Taco J. Blokhuis†, Robin Augustine*
*Division of Solid State Electronics, Department of Electrical Engineering, Ångström Laboratory,
Uppsala University, SE-75121 Uppsala, Sweden, robin.augustine@angstrom.uu.se
†Department of Traumatology, Maastricht University Medical Centre+,6229 HX Maastricht, The Netherlands
¶Department of Intensive Care Medicine, Maastricht University Medical Centre,
P. Debyelaan 25, 6202 AZ Maastricht, the Netherlands
‖NUTRIM School for Nutrition and Translational Research in Metabolism, Maastricht University,
Universiteitssingel 40, 6229 ER Maastricht, the Netherlands
**Department of Surgery, Maastricht University Medical Centre, P. Debyelaan 25, 6202 AZ, Maastricht, The Netherlands
‡Biomedical Engineering and Telemedicine Centre, ETSI Telecomunicación, Center for Biomedical Technology,
Universidad Politécnica de Madrid, 28040 Madrid, Spain
§Centro de Investigación Biomédica en Red de Bioingeniería, Biomateriales y Nanomedicina (CIBER-BBN),
28029 Madrid, Spain
††Thayer School of Engineering, Dartmouth College, Hanover, NH 03755, USA

***Abstract*—A microwave sensor to safely measure quality of muscle tissue for diagnosis and screening of diseases and medical conditions characterized by fat infiltration in muscle is presented. Fat infiltration in muscle may be seen by a lower dielectric constant of muscle at microwave frequencies corresponding to the large contrast between fat and muscle tissues. A planar resonator based on a bandstop filter and optimized to noninvasively interrogate muscle in the thigh on tissue quality is proposed. Currently, a study based on clinical trials is carried out, and, here, we present a preliminary correlation between skin and fat thicknesses and rectus femoris cross sectional area (CSA) measured with ultrasound and the proposed sensor's resonance frequency. CST simulations based on the ultrasound information guide the analysis. We see that although there are signs of a potential correlation between CSA and resonance, skin and fat variability is still an issue to overcome.**

***Index Terms*—Sensors, Muscle Quality, Bandstop Filter, Clinical Measurements.**

I. INTRODUCTION

Safe measurement of quality in muscle tissue for diagnosis and screening of diseases and medical conditions characterized by fat infiltration, such as sarcopenia, is an important and actual social issue to be addressed. Sarcopenia is a progressive and generalized skeletal muscle disorder that causes loss of muscle mass, strength and function and that is associated with increased likelihood of adverse outcomes, including falls, fractures, physical disability and mortality. Currently, this disorder is under-diagnosed as may be evident by the low agreement, for example, between the diagnosis criteria defined by the revised and the initial European consensus published by the European Working Group on Sarcopenia in Older People (EWGSOP) in 2019 and 2010, respectively, highlighted by different cohort studies, such as [1]. Up to our best knowledge, this is certainly, as EWGSOP suggests, due to the fact that there is a gap in knowledge and diagnostic tools about sarcopenia [2].

We see here an opportunity because to our best knowledge the use of microwave methods is currently and very recently being considered by researchers in Sweden, The Netherlands, USA and India. For instance, we are currently jointly addressing both frequency-domain resonant-based [3]–[5] and non-resonant-based [6] approaches, while a time-domain approach is addressed by another group in [7]. In this last approach, a non-invasive passive flexible Ultra Wide Band (UWB) Myogram antenna sensor is presented, where a blood sample for protein test is required and used in the prediction of muscle mass. In a study of 50 patients, they claim to have correctly predicted in 85 % of the cases, but issues such as the penetration of the microwave signal in to the muscle are not addressed.

This paper is a continuation of the works in [3]–[5], where the idea to use microwave sensors for muscle quality assessment is explored, primarily using a split ring resonator. Alternative sensors were explored via simulations, in order to find a sensor that offers more signal penetration to the muscle layer. One of those alternatives is a bandstop filter which has been manufactured and tested in a measurement campaign, the results of which is presented in this paper. The measurements are taken in the mid-thigh and compared to ultrasound (US) measurements done in the same area. Simulations were performed using the US information to create models to compare the simulations to the measurements.

II. METHODS

A. Sensing Principle

The sensing principle is based on identifying specific changes in features in the frequency response of the microwave resonator, such as the resonance frequency, that correspond to local change in the muscular area under test (AUT). People with sarcopenia and those with lower muscle quality have fat mixed in their muscle tissue, a process which is known as fat-infiltration of the muscle. Due to this infiltrated fat, we hypothesize that the dielectric properties of the AUT are different from a person with normal muscle tissue quality to a person with lower quality. Fat has a dielectric constant (DK) of 5 at 2.45 GHz whereas muscle has approximately 52 at 2.45 GHz [8]. To the best of our knowledge the ratio or percentage of infiltrated fat that can be in a muscle tissue is currently unknown for people with lower muscle quality. Lower muscle tissue is expected to give a higher resonance frequency than normal muscle tissue as shown in Figure 8 in [5] for a sensor based on a bandstop filter.

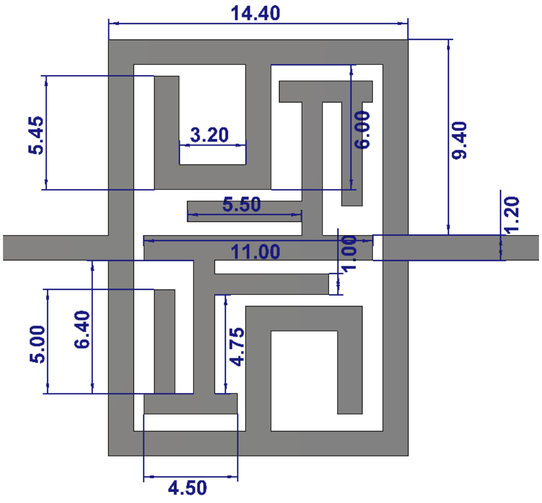
B. Sensor/System

The muscle analyzer system (MAS) in the measurements consists of a miniVNA Tiny (mini Radio Solutions, 2014, WiMo Antennen 85 und Elektronik GmbH, Herxheim, Germany) network analyzer and on a dual-port network consisting of a planar microstrip-made bandstop filter connected to each other directly through SMA connectors. The miniVNA is in turn connected via a USB cable to a laptop which runs and stores the measurements. The bandstop sensor design is shown in Figure 1a and the same consists of closed square loops with a C structure and with a modified interdigital π structure. Moreover, the same is fabricated on FR-4 epoxy material with a thickness of 1.6 mm, DK = 4.4 and tanδ = 0.02. To enhance coupling and prevent direct contact with the lossy human skin a TMM6 superstrate layer, DK = 6 and tanδ = 0.0023, is placed on top of the bandstop structure. Figure 1b show the fabricated bandstop sensor, with the superstrate layer applied shown as the beige surface.

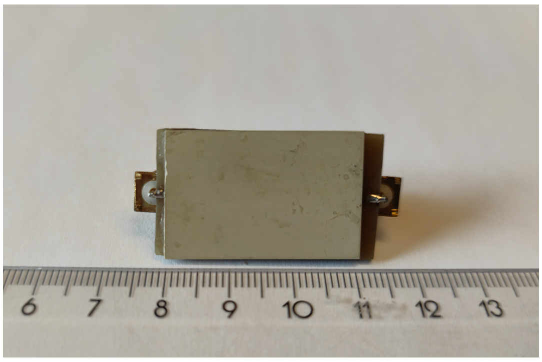
C. Clinical Data Collection

The data presented in this paper was collected in a measurement campaign conducted between March and September of 2021 at the Maastricht University Medical Center (MUMC+). A total of 11 patients were included in the study.

US measurements were also conducted in eight cases, the device used was the Esaote Mylab Gamma (Build F 066002). The measurements were done by placing the sensor/transducer gently, to avoid distortion of the underlying tissue, perpendicular to the long axis of the thigh on its superior aspect, one-third of the distance from the anterior superior iliac spine to the superior patellar border. The measurements with the MAS system is done in both the medial and lateral direction. A study exploring if sarcopenia quantified via US rectus femoris measurements can predict adverse outcomes in patients indicated that sarcopenia can be a biomarker of frailty. In that study a threshold was found that gave the maximum specificity and sensitivity for the diagnosis of frailty was 5.2 cm^2 for the US rectus femoris [9]. In our present work as in this last work, the medial location was considered.



(a) Bandstop filter structure, dimensions given in mm.



(b) Fabricated bandstop sensor.

Fig. 1. Bandstop filter, filter structure and photograph.

The measurement data is analyzed looking at how the resonance frequency changes over time in patients with multiple measurements and a multi linear regression is calculated using the US fat thickness and US rectus femoris cross sectional area as main features.

D. Simulations

Comparative simulations using CST Studio Suite [10] were performed using the data of the US skin and fat measurements. The boundary conditions used in the simulation model assumed the model was infinitely extended in the lateral and medial direction, through application of a perfect matching layer (PML) or Open boundary, and meaning that the muscle had infinite thickness, which prohibited us from using the rectus femoris data. Instead, the information of the skin and fat thicknesses was completely incorporated in the simulation

TABLE I
DATABASE FOR THE COMPLETE MEASUREMENTS AND COMPARATIVE SIMULATIONS.

Patient#. Meas#	US Skin [mm]	US Fat [mm]	US RF, CSA [cm^2]	f_{res}, Meas [GHz]	f_{res}, Sim, DK=52 [GHz]	f_{res}, Sim, DK=12 [GHz]
2.1	2.4	12.1	2.59	1.89	1.840	1.840
2.2	2.5	7.25	2.14	1.97	1.834	1.836
2.3	2.1	8.2	1.81	2.05	1.848	1.850
5.1	1.3	6.4	5.5	2.02	1.882	1.886
7.1	1.9	10.8	4.86	1.97	1.856	1.858
7.2	2.2	8.5	4.91	2.04	1.844	1.846
10.1	2.6	6.3	1.67	2.08	1.830	1.834
10.2	2.3	6.9	1.76	2.06	1.838	1.842

model according to the data collected in the US measurements. The DK of the muscle tissue is varied between two different values; 12 and 52, 52 is our estimation of the DK of normal muscle tissue at 2.45 GHz and 12 is our estimation to simulate the deterioration in the muscle tissue, where 12 would be a muscle tissue with very high fat infiltration.

The simulation data is analyzed using linear regression on the skin and fat data respectively and the same analysis is done on the measurement data investigating if the same model can be applied.

III. RESULTS AND DISCUSSION

Data analysis was limited to the measurements taken at the medial position as the US measurements of the rectus femoris correspond to the medial position of the MAS system. Table I shows the total of eight obtained measurements where both US and MAS data was collected, corresponding to four different patients, only four of the eleven patients had MAS and corresponding US measurements. The column US RF CSA is the ultrasound measurement of the cross sectional area (CSA) of rectus femoris muscle. The data in Table I were all collected with only one repetition, except for the US rectus femoris which is the average of 3 repeated measurements. The standard error (SE) was calculated for each case, $SE = std/\sqrt{n}$. The SE was used to look for large variations in the repetitions, None of the eight cases had a higher SE than 5% of their average value, $0.05 \cdot mean > SE$. The patients are all male, as it just happened that all patients eligible were male. The first column correspond the the patient number and which measurement for that patient. For example 2.1 means patient 2, measurement 1.

Comparing the resonance frequency, in Table I, we see that the measurements has on average 0.15 GHz higher resonance frequency than the simulations, but the smallest differences are for the cases with larger fat and skin thicknesses, where we expect less influence from the muscle due to poorer penetration. In these cases, we hypothesize that the simulation model should be more comparable to the measurements. Some patients that were admitted to the hospital for a longer time underwent several measurements, patient 2 had the most measurements, five separate measurements in total over 33 days, Figure 2 shows how the resonance frequency changes over the course of time. In this Figure we have five points for patient 2 but in Table I there are only three measurements for patient 2 since the patient did not undergo US measurements each time a MAS measurement was taken. Patient 2 does however show a very interesting trend, as over the course of time, the resonance frequency increases, and as can be seen in the data in Table I, the cross-sectional area of the rectus femoris decreases in later measurements. Cases 2.1, 2.2 and 2.3 corresponds to the first, second and fourth points in the curve. The Pearson correlation coefficient between f_{res} and US RF for patient 2 is -0.9941, which shows a near perfect linear behavior where f_{res} increases as US RF decreases, and where we can also hypothesize that the skin and the fat thicknesses could be considered invariant for most cases but 2.1.

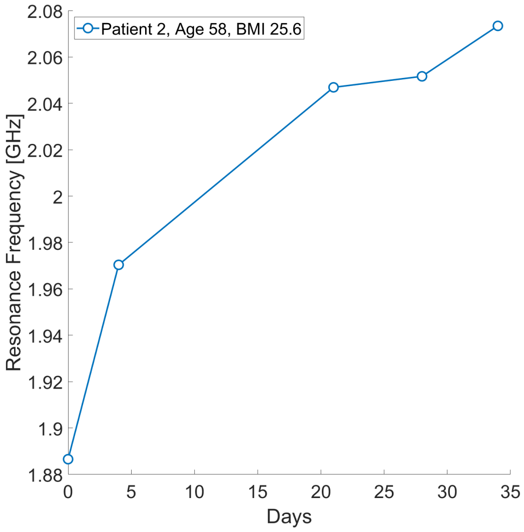


Fig. 2. Evolution of resonance frequency for patients with multiple measurements.

To identify trends in the measurement data a multiple linear regression (MLR) approach was used. The MLR has three features, US fat, US rectus femoris and the two terms multiplied (US fat · US rectus femoris) as well as an intercept term, the output of the MLR model is the resonance frequency. The coefficients are tuned using the 6 points, the points with fat above 10 mm are neglected. A simulation study in [5] shows a low variation in the resonance frequency between normal and deteriorated muscle tissue for the bandstop filter used in these measurements, therefore fat values above 10 mm were neglected. The model is evaluated over the entire range of fat and muscle values. This allows us to see the trends of the MLR, shown in Figure 3. Also, the datapoints are plotted, with a ”guideline” showing where on the xy-plane the datapoints are located.

The MLR shows that the highest resonance frequency is expected when the fat and rectus femoris thickness is at their

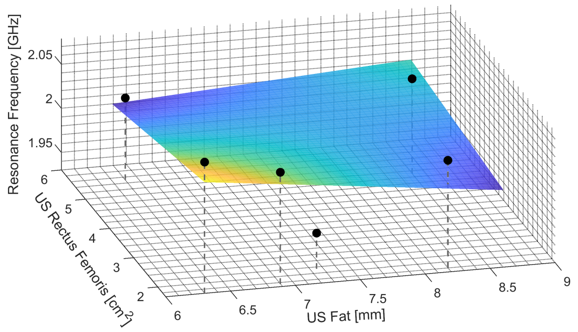


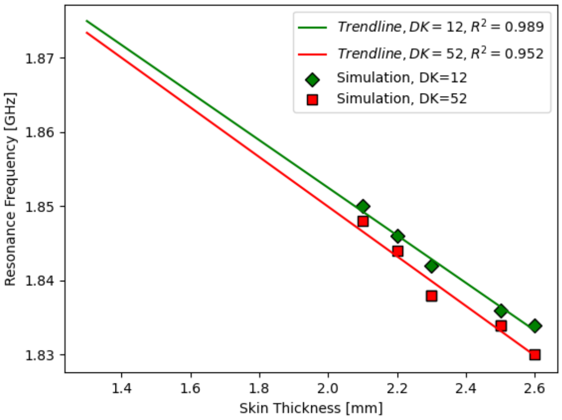
Fig. 3. Multiple linear regression calculated using US measurements of rectus femoris and fat.

respective lowest (fat: 6.3 mm, RF: 1.67 mm, f_{res}: 2.056 GHz). The fat and rectus femoris data have similar impact on the resonance frequency since maximum rectus femoris value and minimum fat value (fat: 6.3 mm, RF: 5.5 mm, f_{res}: 2.017 GHz) give nearly the same resonance frequency as minimum rectus femoris and maximum fat value (fat: 8.6 mm, RF: 1.67 mm, f_{res}: 2.018 GHz). The MLR model help us to explain what is seen in Figure 2. For instance, the shift in resonance frequency shown between cases 2.2 and 2.1 corresponds in trend to keeping RF constant and moving from fat = 6.3 to 8.6 mm. A similar trend can be seen between cases 2.3 and 2.2 keeping fat constant and increasing RF.

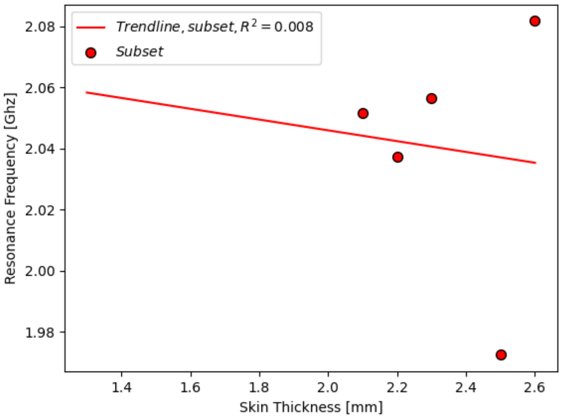
To analyze the simulation results the linear regression (LR) was trained using either the skin and fat data as input and the resonance frequency from either the measurements and the simulations as output. For the simulation data separate regressions were calculated using the normal muscle tissue (DK 52) and muscle with DK 12. The measurement that had skin of 1.3 mm was neglected here due to it being almost 1 mm thinner than the average (average skin: 2.26 mm). A total of six LR models, separate models for simulated data with DK 12 and DK 52 as well as the measurement data, for fat and skin respectively, were trained, Table II lists the slopes and R^2-score of these models. The slopes of the normal and deteriorated muscle data from the simulations are similar for both the skin and fat. Although the slope for the measurements is slightly different they show the same trend, a higher skin thickness yields lower resonance frequency and higher fat thickness indicates a higher resonance frequency.

TABLE II
Slopes and R^2-score of linear regression,
unit of slope GHz/mm

	Simulation, DK12		Simulation, DK52		Measurement	
	Slope	R^2	Slope	R^2	Slope	R^2
Skin	-0.032	0.989	-0.033	0.952	-0.017	0.008
Fat	0.006	0.709	0.007	0.731	-0.011	0.063



(a) LR of the simulations and scatter plots simulation points.



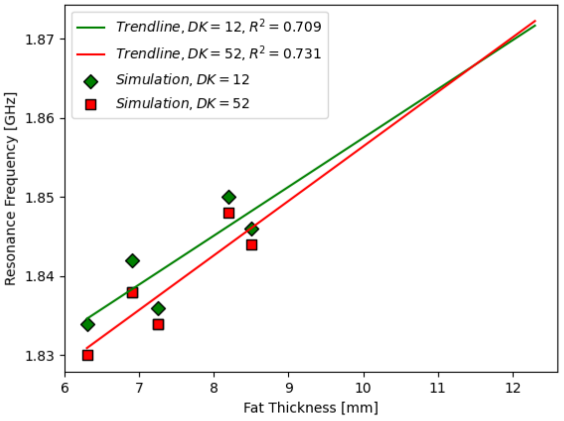
(b) LR of the measurements and scatter plot of the measurement data used.

Fig. 4. Linear regression calculated using the simulations (a) and the corresponding measurements (b) for the skin data.

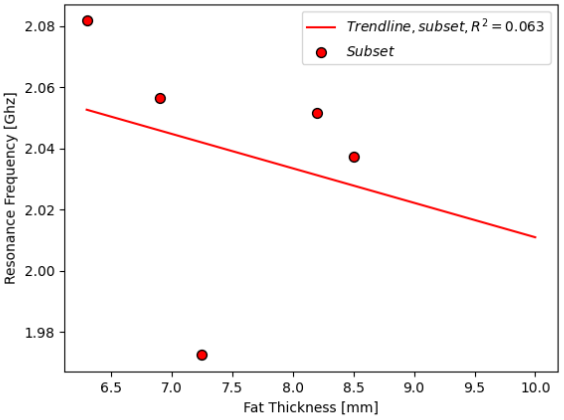
Figures 4 and 5 show the trendline, they are evaluated between the extreme values of the skin or the fat data, including the neglected points, from the linear regression, of the simulated (Figures 4a and 5a respectively) and measured data (Figures 4b and 5b respectively) for the skin and fat data respectively. The slope of each trendline is given in Table II.

As Figures 4, 5 and Table I show the resonance frequency for the simulations with lower muscle quality is higher than the normal tissues, in all cases except for when the fat thickness is above 10 mm where they are the same, but as previously mentioned this was expected per [5].

The R^2-score is considerably lower for the measurements than the simulations, indicating a worse fit of the linear regression. For the simulations the score is close to 1 which indicate a very good fit. This could suggest that a linear model is not a good representation of the measurements but in the results there are only 6 points, a better fit could be found once more data has been collected. The reason for using the linear model here is that it worked very well with the simulated data and we want to use the same model for the measurements.



(a) LR of the simulations and scatter plot of the data used.



(b) LR of the measurements and scatter plots simulation points.

Fig. 5. Linear regression calculated using the simulations (a) and the corresponding measurements (b) fat data.

IV. CONCLUSIONS

In this paper the idea to assess muscle quality by using microwave sensors and predict sarcopenia was further evaluated, from the progress made in [5]. The results of the first clinical measurements using the bandstop filter are presented and analyzed. These measurements are evaluated against US measurements that are done in the anterior medial thigh. A multi-linear regression model built based on the US and MAS measurements suggest that resonance frequency may increase while both fat and cross sectional area of rectus femoris decreases, and this behavior could be linearly independent. Simulations are done using the US data to create models that can be used in this and future analyses. The simulations show clear linear trends, for both deteriorated and normal muscle tissue, the high R^2-score indicate a linear model is suitable for this data. These trends are not reciprocated to the same degree in the measurement data, although this could change once more data has been collected.

To further evaluate the feasibility of this system and the bandstop sensor more data needs to be collected and analyzed in a similar manner. A study using artificial tissue emulating phantoms will also be conducted where the tissue thicknesses can be varied in a controlled manner to build more of a database of measurements that can be used to create a statistical model to assess the muscle quality.

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