Wearable Loops for Unobtrusive Electromagnetic Detection of Joint Effusion

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***Abstract*—Joint effusion is associated with synovial fluid build-up in or around a joint. Current state-of-the-art medical imaging methods such as X-ray, ultrasound, and Magnetic Resonance Imaging (MRI) can provide high-resolution images but are resource-intensive and limited to specialized medical facilities, preventing them from being used for long-term, continuous and real-time monitoring. In this work, we propose an alternative, wearable method for detecting joint effusion which addresses these shortcomings. The method relies on monitoring changes in the transmission coefficient (S_{21}) between two conducting loops placed around the limb near the joint region. Using electromagnetic simulations on a simplified arm-effusion model, a clear trend is presented between the magnitude/phase of S_{21} and effusion radius. Particularly, for the best design, 0.5-cm variations from 1 to 3 cm in spherical effusion radius can be detected with a minimum required S_{21} precision of 1.02 dB for magnitude or/and 13.50° for phase. Significance of this approach lies in early stage detection and ease of treatment for such medical conditions.**

I. Introduction

Joint effusion is a medical condition characterized by synovial (joint) fluid buildup in or around a joint due to trauma, arthritis, or infection. It is typically detected and diagnosed via a combination of physical examination, medical imaging (X-ray, ultrasound, or MRI), and extraction of synovial fluid for laboratory analysis [1]. Notably, this process requires the appropriate medical facilities and staff, can be intrusive to the affected region, and does not allow for changes to be monitored over time. In addition, such precise examination and imaging is done (and is required) only at a later stage of the condition when the patient reports it. Hence, we envision a technology that can monitor such fluid build-up in real-time, and over a period of time. The goal is early detection and diagnosis to ultimately ameliorate the condition and ease the treatment process both for patients and doctors. Some development in this direction is done in [2], but this approach targeted edema (fluid buildup) detection using inductive phase shift spectroscopy in the brain rather than in joints. Also, this approach was limited to low frequencies of operation and detection of only very small (<6°) changes in phase.

In this work [3], we introduce a wearable technology for detection and diagnosis of joint effusion that shows promise in the direction of the aforementioned vision. This technology consists of two conducting wearable loops (with three designs: no lumped element, a lumped capacitor, and a lumped inductor) that monitors the electromagnetic behavior of the joint region based on changes in the wireless transmission between the two, thereby detecting the status of joint effusion.

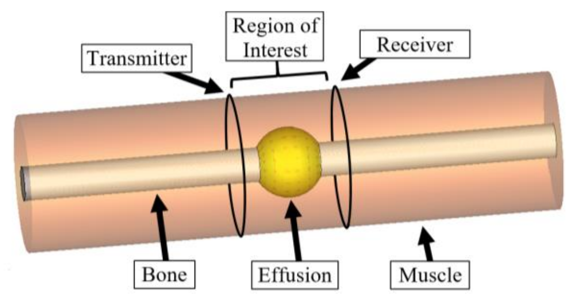

Fig. 1. Depiction of wearable conducting loops around arm model for detection and diagnosis of joint effusion size using change in electromagnetic propagation governing magnitude and phase of transmission between the loops.

II. Operating Principle

The proposed wearable technology consists primarily of a transmitter and a receiver loop (with/without lumped elements connected in series) positioned around a joint at a specific gap that are capable of transmitting and receiving electromagnetic (EM) waves as shown in Fig. 1. Within the region of interest between the loops, the underlying biological materials (e.g. synovial fluid, muscle, bone), have their own frequency-dependent permittivity and conductivity which affect the propagation of EM waves. Expectedly, changes in the amount or type of each material in the region due to joint effusion will change the overall dielectric behavior of the region, thereby affecting the EM signal sent from the transmitter to the receiver. Changes in the dielectric properties due to the accumulation of synovial fluid can be monitored by measuring the transmission coefficient S_{21} between the loops.

III. Simulations and Results

A. Joint Effusion Model and Simulation Setup

A simplified model of the elbow region, shown in Fig. 1, was created using a 1-cm-radius cylinder of bone surrounded by a 3.9-cm concentric cylinder of muscle tissue, each 30 cm in length. In the center of the model, a spherical ring of synovial fluid surrounds the bone with a variable radius which can be

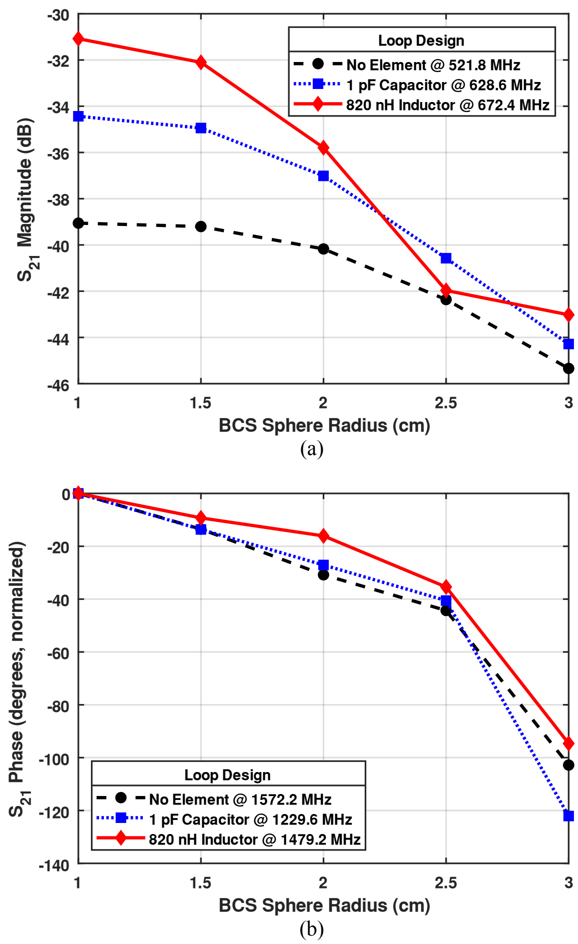

Fig. 2. Simulation results showing trends between S_{21} (a) magnitude or (b) phase and effusion radius. Each magnitude and phase plots consist of three cases, viz. no lumped element, lumped capacitor, and lumped inductor. The best result in magnitude is observed with a lumped inductor while the best result in phase is observed with no lumped element.

increased to emulate fluid buildup (i.e. joint effusion). Dielectric properties from 200 MHz to 2 GHz were included for each material. Properties for muscle tissue and bone were used from the IFAC's database for the Dielectric Properties of Body Tissues. The dielectric properties of Bovine Calf Serum (BCS), a material commonly used to emulate synovial fluid due to its similar composition and mechanical properties [4], were used in place of synovial fluid. Two 4-cm-radius loops of 30-AWG copper wire were placed 6 cm apart from each other around the effusion to maximize transmission magnitude while containing an effusion radius up to 3 cm in the region of interest. The addition of lumped components such as a capacitor or inductor to tune the resonance frequency of the loop was also considered. This led to a total of three design set-ups, viz. no lumped element, a lumped capacitor, and a lumped inductor based design. In Computer Simulation Technology (CST) Microwave Studio, the frequency-domain solver was used to calculate the transmission coefficient S_{21} between the loops from 200 MHz to 2 GHz as a parametric sweep was performed on the BCS sphere radius from 1 cm to 3 cm in 0.5 cm increments for all three designs.

B. *Simulation Results*

The simulated relationship between the transmission coefficient and BCS sphere radius for the proposed detection method is shown in Fig. 2. Frequencies within the spectrum tested were analyzed to determine whether a correlation was present between S_{21} and radius for all deviations in radius. At the selected frequencies for each design shown in Fig. 2, a clear trend exists between the magnitude or phase of S_{21} and effusion radius for all three designs.

Further analysis is performed to identify the best design amongst three for each magnitude and phase. The utility of each trend for detecting 0.5-cm radius increments can be evaluated by observing the minimum S_{21} differential for each trend, i.e. the required measurement sensitivity needed to differentiate between each radius. Using this metric, the best magnitude trend appeared for the design with an 820 nH inductor at a frequency of 672.4 MHz, where the S_{21} sensitivity required to detect 0.5-cm changes in radius is 1.02 dB. The best phase trend was present at 1572.2 MHz for the design without lumped element and has a required sensitivity of 13.50°. Note that the above sensitivity numbers represent the worst-case scenario and that the difference (for magnitude and phase) tends to increase as the effusion radius is increased (see Fig. 2). Hence, change in effusion radius can be easily detected as radius increases. Also, the above sensitivity values are quite large and even smaller change in radius can be detected with lower required sensitivity values (i.e. higher measurement precision).

IV. Conclusion

This work introduced a new method for detecting and monitoring the size of joint effusion via transmission of EM waves between two conducting loops by monitoring changes in the aggregate dielectric properties of the joint region. This method can be implemented as a wearable device to provide unobtrusive, real-time and continuous monitoring, thereby allowing early stage detection and an easier treatment. Using a model of muscle, bone, and BCS (to emulate synovial fluid), CST simulations were performed for three different designs, demonstrating the feasibility of the proposed method for all three designs. For the best of these designs, change of as small as 0.5 cm in radius corresponds to change of as large as 1.02 dB in magnitude (for design with lumped inductor) and 13.50° in phase (for design without lumped element) in the worst-case scenario. Our future work will include *in vitro* experimental studies to further validate this technique.

References

[1] M. Johnson, "Acute Knee Effusions: A Systematic Approach to Diagnosis," American Family Physician, vol. 61/8, pp. 2391-2400, 2000.

[2] C. González and B. Rubinsky, "The detection of brain oedema with frequency-dependent phase shift electromagnetic induction," Pysiological Measurement, vol. 27, pp. 539-552, 2006.

[3] Z. Dalisky, "A Wearable Electromagnetic Technology for the Detection and Diagnosis of Joint Effusion," B.S. Thesis, Dept. Elec. and Comp. Engr, Ohio St. Univ., Columbus, OH, to appear.

[4] E. Bortel, B. Charbonnier, and R. Heuberger, "Development of a Synthetic Synovial Fluid for Tribological Testing," Lubricants, vol. 3, pp. 664-686, Dec 2015.