Breaking the Boundaries: Monitoring Joint Flexion Using Radio-Frequency Coils

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***Abstract*— This work introduces a novel approach for monitoring joint flexion. Specifically, Radio-Frequency coils (in transmitting and receiving modes) placed symmetrically about the joint are proposed to monitor flexion by leveraging changes in the transmission coefficient as the limb flexes and extends. To demonstrate the idea, simulations in a cylindrical and homogeneous limb model are performed. Results clearly show the feasibility of monitoring joint flexion/extension using the proposed approach. This provides a new way of monitoring joint flexion while overcoming shortcomings in the state-of-the-art. Numerous medical and consumer applications may eventually benefit from the proposed approach.**

I. Introduction

Human subjects move continuously while performing diverse daily activities. In certain cases, movement patterns are intentional, e.g., during running, walking, cooking, or playing. In other cases, movement may be unintentional, e.g., for patients with motor disabilities, such as Parkinson's. Finally, there are cases where movement may unintentionally get distorted (e.g., during sports accidents), leading, in turn, to subsequent neuromuscular and/or brain injuries. Expectedly, the ability to monitor human motion during all aforementioned scenarios can enhance our current understanding of healthy movement patterns (baseline data), assist in personalized treatment of patients with motor disabilities, help improve athlete performance based on certain benchmarks, revolutionize human-computer interfaces, and more.

To date, several technologies have been reported for monitoring human motion. The standard of reference entails Motion Capture (MoCap) Labs that rely on optical/infrared cameras to track markers placed upon the body [1]. As expected, this technology is used only in confined settings. As an alternative, Inertial Measurement Units (IMUs) have been reported for tracking human motion on the go. IMUs consist of either one or combination of accelerometers, gyroscopes and magnetometers [2], [3], and may currently be found in several commercial products (smart watches, fitness bracelets, and so on). However, IMUs suffer from inherent integration drift caused by integrating acceleration and velocity to derive position, require extensive calibration, and are far from reliable. Finally, bending sensors have been reported for monitoring joint flexion as recorded by the strain produced upon the sensor [4]-[7]. Unfortunately, such bending sensors restrict natural movement of the joints and have limited life cycle as attributed to mechanical wear over time.

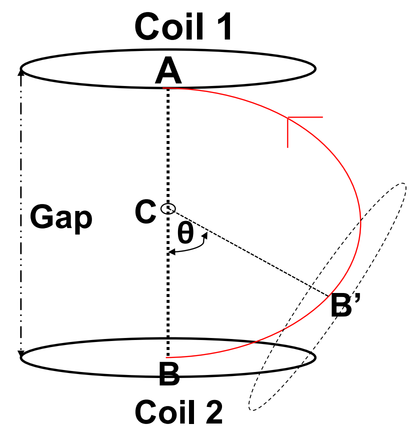

Fig. 1. Proposed RF coil configuration for monitoring joint flexion: schematic of operating principle with Coils 1 and 2 circling around the limb and acting as transmitter and receiver, respectively.

To break the boundaries created by state-of-the-art technologies, we herewith report a novel Radio-Frequency (RF)-based approach for monitoring human motion. Since most movement patterns are made possible by joints, our focus is on joint motion monitoring, and, in particular, joint flexion/extension. In brief, the proposed approach relies on RF coils placed symmetrically about the joint to monitor flexion by leveraging changes in the transmission coefficient as the limb flexes and extends. In this paper, we present the basic operating principle and proof-of-concept simulation results.

II. Operating Principle

Single-turn, copper-wire coils circle around the limb of interest and are placed symmetrically about the joint, as shown in Fig. 1 and Fig. 2. Referring to Fig. 1, coils are positioned such that the center of Coil 1 (A) passes through the center of Coil 2 (B), as well as through the center of joint flexion (C). As the flexion angle (θ per Fig. 1) increases, the center of Coil 2 (B) moves along the trajectory to reach point B' and so on. For joint flexion monitoring, Coil 1 acts as a transmitter that emits an RF signal, while Coil 2 acts as a receiver. As the joint flexes, the transmission coefficient between the two coils

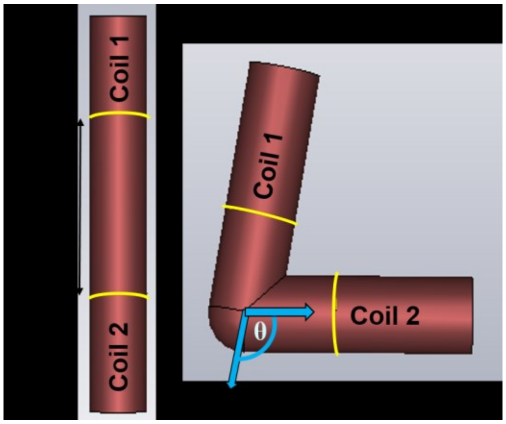

Fig. 2. Cylindrical and homogeneous (2/3 muscle) limb model used in simulations. Both coils are simulated with copper wire material.

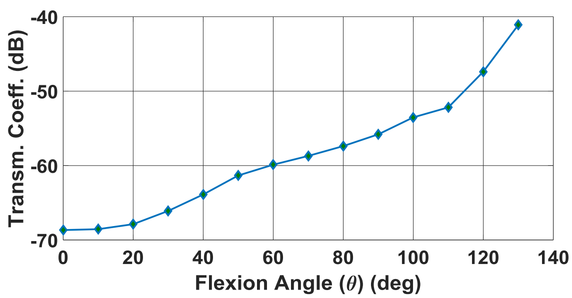

Fig. 3. Results displaying the variation of transmission coefficient ($|S_{21}|$) with flexion angle (θ)

changes as well. In turn, changes in the recorded transmission coefficient can be used to monitor joint flexion.

III. Simulation Set-Up

As a proof-of-concept, simulations are performed using the cylindrical arm model of Fig. 2, with a sphere used to emulate the joint. The limb diameter is selected as 3.9 cm, as corresponding to the size of an average arm. The limb-simulating material is chosen as 2/3 muscle which represents the average human body properties [8], [9]. Single-turn, copper wire coils circle around the limb at an example Gap of 20 cm (per definition in Fig. 2). The frequency of operation is selected as 927 MHz, which corresponds to the self-resonant frequency of the coils. At this frequency, both transmit and receive coils act as loop antennas.

Numerical studies are performed using the frequency-domain solver of Computer Simulation Technology Microwave Studio® (CST MWS). Simulations are performed while the flexion angle (θ) varies from 0^0 to 130^0 in steps of 10^0.

IV. Simulation Results

Simulation results are summarized in Fig. 3. Specifically, Fig. 3 plots the transmission coefficient between Coil 1 and Coil 2 as a function of the flexion angle at 927 MHz. As seen, as the flexion angle changes, the transmission coefficient changes accordingly. That is, each flexion angle has a corresponding transmission coefficient value that can be used to create one-to-one mapping.

The mapping identified in Fig. 3 can, eventually, be used to retrieve the flexion angle based on the transmission coefficient value obtained as the limb flexes or extends. This confirms the feasibility of monitoring joint flexion using the reported approach. Concurrently, our approach is not limited to confined environments (unlike MoCap Labs), does not involve any integration drift (unlike IMUs), and does not obstruct the natural joint movement (unlike strain-based bending sensors).

V. Conclusion

In this paper, we introduced a new concept for monitoring joint flexion using RF coils that circle around the human limb. Simulation results for copper-wire coils acting as loop antennas at 927 MHz and placed around a cylindrical arm model confirmed the feasibility of our approach. The proposed coils are envisioned to be realized on e-textiles and, eventually, integrated into garments for seamless monitoring of joint flexion on the go. By overcoming shortcomings in the state-of-the-art, the reported approach brings forward unique capabilities for numerous healthcare and sports applications, among others.

Acknowledgement

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References

[1] V.B. Zordan, and N.C. Van Der Horst, “Mapping optical motion capture data to skeletal motion using a physical model,” Eurographics Symposium on Computer Animation, pp. 245-250, Jul. 2003.

[2] S. Fantozzi, A. giovanardi, F.A. Magalhaes, R. Di Michele, M. Cortesi, and G. Gatta, “Assessment of 3-D joint kinematics of the upper limb during simulated swimming using wearable inertial-magnetic measurement units,” Journal of Sports Sciences, vol. 34, no. 11, 2016.

[3] J. K. Lee and E. J. Park, "A Fast Quaternion-Based Orientation Optimizer via Virtual Rotation for Human Motion Tracking," in IEEE Transactions on Biomedical Engineering, vol. 56, no. 5, pp. 1574-1582, May 2009.

[4] B. Bonroy, K. Meijer, P. Dunias, K. Cuppens, R. Gransier, and B. Vanrumste, “Ambulatory monitoring of physical activity based on knee flexion/extension measured by inductive sensor technology,” Hindawi ISRN Biomedical Engineering, vol. 2013, 2013.

[5] C.A. McGibbon, A. Sexton, M. Jones, and C. O’Connell, “Elbow spasticity during passive stretch-reflex: clinical evaluation using a wearable sensor system,” Journal of Neuroengineering and Rehabilitation, vol. 10, no. 61, pp. 1-14, 2013.

[6] T.W. Shyr, J.W. Shie, C.H. Jiang, and J.J. Li, “A textile-based wearable sensing device designed for monitoring the flexion angle of elbow and knee Movements,” MDPI Sensors, vol. 14, no. 3, pp. 4050-4059, 2014.

[7] S.I. Lee, J.F. Daneault, and L. Weydert, “A novel flexible wearable sensor for estimating joint-angles,” 13th IEEE Int. Conf. on Wearable and Implantable Body Sensor Networks, 2016.

[8] P. Soontornpipit, C. M. Furse and You Chung Chung, "Design of implantable microstrip antenna for communication with medical implants," in IEEE Transactions on Microwave Theory and Techniques, vol. 52, no. 8, pp. 1944-1951, Aug. 2004.

[9] C. Furse, D. A. Christensen, C. H. Durney, “Electric and Magnetic Fields: Basic Concepts,” in *Basic Introduction to Bioelectromagnetics* 2nd ed., Boca Raton : CRC Press, 2009 pp. 30-34.