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Multi-Utility Wearable Sensors for Motion Capture and Tissue Imaging

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Abstract

We report a novel wearable sensor with multi-utility functionality, capable of monitoring joint kinematics and imaging underlying tissue abnormalities via the same interface. The sensor consists of loops wrapped around the limb, one placed above and one placed below the joint. At low frequencies, magnetic coupling dominates and joint motion can be monitored while being insensitive to tissue properties; at high frequencies, loops act as electromagnetic radiators that are affected by tissues, and can, thus, monitor tissue abnormalities. The sensor can be seamlessly embedded into a garment, bringing forward unprecedented opportunities for numerous applications in healthcare, sports, space, and beyond.

1. Introduction

Monitoring human body kinematics is relevant to applications as diverse as healthcare, sports, gaming, human-machine interfaces, and more. "Gold standard" motion capture entails cameras which are, unfortunately, bounded to contrived environments [1-4]. This motivated the development of Inertial Measurement Units (IMUs) that can be attached to the body [5, 6]. Though explored repeatedly [7, 8], IMUs suffer from integration drift (ever-increasing difference between the actual vs. predicted position), are obtrusive, and become inoperable in proximity to magnetic fields (when magnetometers are employed) or lack of gravity (i.e., in space). Other examples include time-of-flight sensors [9, 10] that require line-of-sight and are hindered by body/fabric shadowing, as well as bending sensors [11, 12] that are known to obstruct movement and degrade over time. That is, there is significant research interest in the development of sensors that can seamlessly and reliably monitor motion in real-world environments.

Another area with immense research potential entails the seamless and reliable imaging of tissue abnormalities. Here, heavily-engineered and non-portable systems that perform pixelized imaging (Computed Tomography [13], Magnetic Resonance Imaging [14], microwave imaging [15, 16]) are the standard. However, as monitoring the mere presence or progression of abnormalities is often all that is required, portable systems are more suitable. Unfortunately, the few available solutions are non-functional in dynamic settings: fringing-field imagers [17] become inoperable with the slightest shift in position, and phase spectroscopy [18] requires the use of complex electronics in static settings.

In this work, we report a new wearable sensor that overcomes limitations in state-of-the-art kinematics sensing and imaging, while also performing both of these modalities using the same interface. That is, the same sensor can concurrently monitor joint motion and monitor underlying tissue abnormalities via a simple switch of the operating frequency. Overall, our sensor provides a new paradigm of multi-utility sensing, relevant to numerous applications (e.g., personalized rehabilitation after Anterior Cruciate Ligament Reconstruction).

2. Operating Principle

As shown in Figure 1, the proposed sensor consists of two loops that are wrapped around the limb. In this example, the transmitting (Tx) loop is placed above the joint and the receiving (Rx) loop is placed below the joint. These two loops perform as a misaligned transformer as the joint flexes. Notably, at low frequencies, magnetic coupling dominates and joint motion can be monitored using Faraday's law, while being insensitive to tissue properties [19, 20]. The latter is due to the fact that tissues are non-magnetic and hence would not alter the coupling between the loops. By contrast, if the same sensor were to operate at high frequencies, then transmission loss between the two loops would strongly depend on the tissue dielectric properties [21, 22]. In turn, operating the sensor at high frequencies provides a means of monitoring underlying tissue abnormalities.

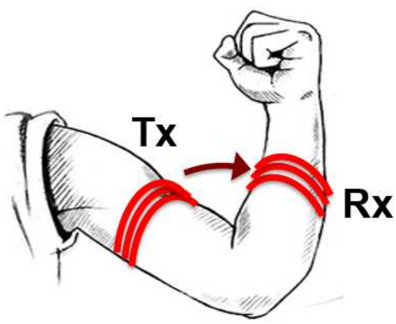

Figure 1. Proposed multi-utility sensor capable of monitoring joint flexion and underlying tissue abnormalities via the same interface.

3. Performance Results

Loops are simulated in CST, wrapped around a 4-cm-radius cylindrical phantom with average body properties (2/3 muscle [23]), Figure 2(a). Both loops are single-turn and attached to 95 pF capacitors to make them resonant for optimal power transfer. We eliminate tissue interference via a 34 MHz resonance frequency in the inductive regime: the tissue relative permeability of ~1 means the tissues have no effect upon magnetic coupling, ensuring robustness to inter-/intra-subject variability and ease of testing (e.g., Styrofoam rather than tissue phantoms can be used), Figure 2(b). As the flexion angle (θ_f) changes (see Figure 2(c)), the transmission coefficient ($|S_{21}|$) also changes. Symmetry also implies invariable $|S_{21}|$ with limb rotation, which is important for applications monitoring only flexion. Our copper loop measurements agree also perfectly with simulations (dots vs. solid lines).

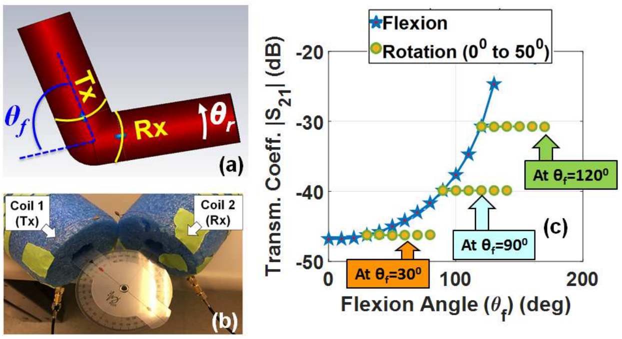

Figure 2. Inductive monitoring of joint flexion: (a) simulation setup, (b) experimental setup, and (c) transmission coefficient vs. flexion angle results.

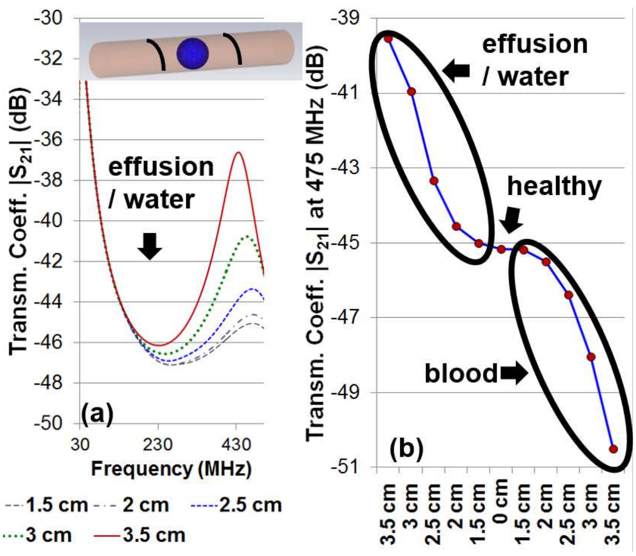

Figure 3. Tissue abnormality monitoring (lengths refer to abnormality radii): (a) transmission coefficient vs. frequency results for a water-based abnormality, (b) transmission coefficient vs. abnormality size results at 475 MHz for diverse abnormality materials.

The same loops are then wrapped around a 2/3 muscle [23] cylinder with a ball emulating joint effusion. The simulated $|S_{21}|$ for diverse ball radii (effusion levels) are shown in Figure 3(a). At low frequencies, the loops couple inductively and are insensitive to tissues; at higher frequencies, the loops radiate and the effusion impacts $|S_{21}|$. Here, we see optimal $|S_{21}|$ changes at 475 MHz. This frequency may vary per loop size, shape, etc. Notably, the nature of certain abnormalities (e.g., effusion vs. blood) may also be identified (see Figure 3(b)). Since water has a lower loss tangent than 2/3 muscle [24], $|S_{21}|$ increases with effusion levels; the opposite is true for blood. Although similar properties may make some abnormalities hard to differentiate (e.g., effusion vs. tumor), such cases are uncommon in real life.

4. Conclusion

We reported new multi-utility sensors by virtue of frequency sweep, i.e., the same wrap-around loops monitor joint flexion (low frequency) and tissues (high frequency). This is a novel paradigm in the area of multi-utility sensing that also overcomes limitations in the state-of-the-art by empowering seamless monitoring in real-world settings. In the future, we will realize these sensors using e-textiles, embed them in garments, and validate their operation on human subjects.

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