Feasibility of Bilateral Joint Flexion Monitoring Using a Wearable Loop Sensor

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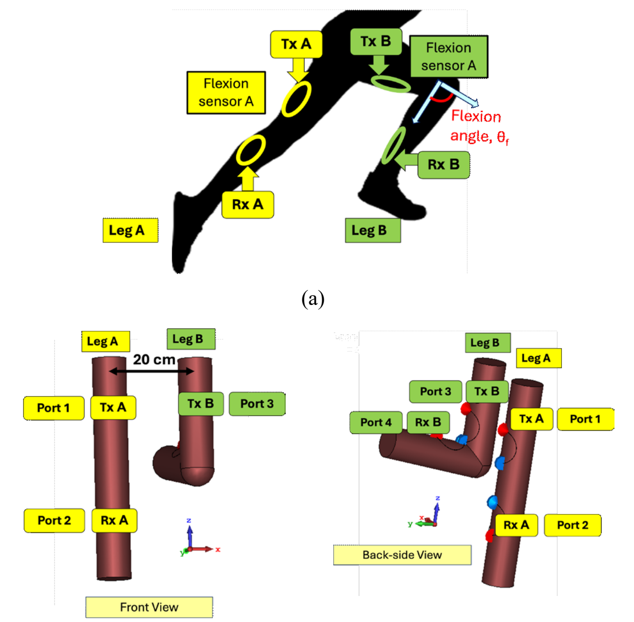
***Abstract*—Monitoring human movement is relevant to several crucial sectors, including healthcare, sports, and beyond. Recently, we introduced a new class of wearable loop sensors for monitoring joint flexion that overcomes shortcomings in the state-of-the-art and allows seamless motion capture in real-time without restricting natural movement. The sensor consists of transmit and receive loops coupled via magnetic field. This sensor has been demonstrated for monitoring one joint on one leg at a time. Monitoring knee joint movement on both legs simultaneously can allow monitoring of crucial gait parameters. However, placement of two sensors in close vicinity can lead to interference between the two due to coupling from the transmitter of one sensor to the receiver of another. In this work, we study the condition for non-interference and demonstrate the feasibility of bilateral knee flexion monitoring. Guidelines to improve the non-interference performance are also laid out. This feasibility study opens doors for full-body motion capture using our wearable loop sensors.**

I. Introduction

Monitoring human movement has plethora of advantages in several crucial sectors such as healthcare (e.g. rehabilitation, biomedical research), sports (training and injury prevention), gesture recognition, and others [1]. There are several state-of-the-art technologies for motion capture. For instance, gold-standard motion capture labs utilize camera-based systems. These are quite accurate, but are restricted to contrived settings, line of sight, and high cost [1]. Another popular technology in this area entails inertial measurement units (IMUs) that can operate outside the confined environment. However, these have inherent drift issues and are not injury safe [1]. Several electromagnetics-based systems have also been reported, including radar-, Wi-Fi-, and RFID-based methods. However, these are also either restricted to contrived settings or are limited by line-of-sight issues, among others. Last but not least, bending sensors that are worn directly on the joint and use strain mechanisms for monitoring movement restrict natural movement and have limited cycles of use [1].

Recently, we introduced a class of wearable loop sensors for seamless monitoring of joint flexion and rotation which overcome limitations in the state-of-the-art [2][3][4]. These can be integrated on garments using conductive threads (e-threads) and allow seamless motion capture. The most basic form of sensor consists of a pair of transmit and receive loops placed across the joint and coupled in the near field via magnetic field [see Fig. 1(a)]. With changes in flexion angle, the transmission between the transmitter (Tx) and receiver (Rx) changes due to Faraday's law of induction which is, in-turn, used to monitor joint flexion. To date, this sensor has only been explored for knee joint movement of only one leg. For monitoring several crucial gait parameters, it is important to extend the operation of this sensor to both legs. Ultimately, the goal is to build a full-body motion capture system using this sensor. However, extension to both legs is not trivial, as the sensors operate using near-field magnetic field coupling. Such field can get coupled to the sensor located on the other leg, leading to interference.



(a)

(b) (c)

Fig. 1. (a) Schematic depicting knee joint flexion sensors on both legs with corresponding transmitters (Tx) and receivers (Rx). Simulation models depicting (b) front, and (c) back-side views.

In this work, we report: (a) results from conformal loops to confirm the wearability of the sensor, (b) the condition to be met by sensors worn on both legs to reliably monitor joint flexion without interference, (c) corresponding results demonstrating the feasibility for the same, and (d) guidelines that can help build better systems. To do so, we utilize the sensor presented in [3] [see Fig. 1(a)].

II. Bilateral Joint Flexion System

A. Model and Non-interference Condition

For demonstration, we choose a longitudinal configuration sensor [3] made using transmit and receive wearable electrically small resonant loops placed across the knee joint on both legs as shown in Fig. 1(a). Transmitters (Tx), receivers (Rx), and

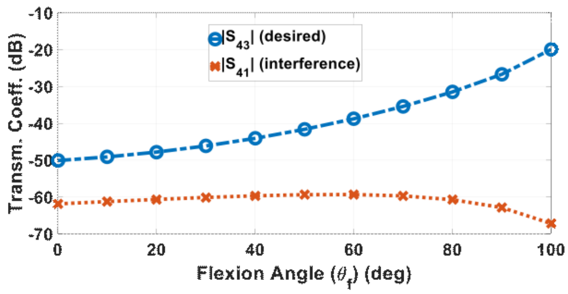


Fig. 2. Results for transmission coefficient for desired and interfering signals, demonstrating feasibility of bilateral joint flexion monitoring.

flexion sensors are named corresponding to each leg as ‘A’ and ‘B’. The corresponding simulation model is depicted in Fig. 1(b) and (c). This model is an extension of the model for one leg demonstrated in [3]. Particularly, each leg is modeled using a cylinder of radius 3.9 cm with loops of radius 4 cm placed conformally [see Fig. 1(c)]. The transmitter and receiver on each leg are separated by a gap of 10 cm, while 2/3 muscle properties are used to emulate the average human tissue properties [3]. Legs are separated by 20 cm from center to center to approximate a typical distance between legs [Fig. 1(b)]. Loops are made resonant around 32 MHz. Simulations are performed with leg B performing flexion, while leg A is stationary. This simulates different human postures and covers different positions of flexion sensor B with respect to A, as required for our study. Also, for simulation purposes and as depicted in Fig. 1(b) and (c), Tx A represents port 1, Rx A port 2, Tx B port 3, and Rx B port 4.

Next, we present the condition for non-interference between flexion sensors A and B. Referring to Fig. 1, maximum signal received by the receiver of sensor B (Rx B) from the transmitter of sensor A (Tx A) represents the maximum value of the interfering signal. This signal should be much less than the minimum desired signal. The desired signal is the signal received by the receiver of sensor B (Rx B) from the transmitter of sensor B (Tx B). In other words, max (Tx A → Rx B) << min (Tx B → Rx B). Referring to port numbers in Fig. 1(b) and (c), the above condition can be summarized as $\max(|S_{41}|) \ll \min(|S_{43}|)$.

B. Results and Guidelines

Simulations are performed in CST® Microwave studio [5] using the frequency domain solver [3]. The results obtained are depicted in Fig. 2 [6]. As observed, the maximum value obtained for $|S_{41}|$ (interference signal) is at least 10 times lower than $|S_{43}|$ (desired signal). This demonstrates the feasibility to monitor joint flexion using both sensors simultaneously. Furthermore, the above difference between interference and desired signals can be increased using the following guidelines. Note that this can be done either by shifting the desired signal up or by shifting the interference signal down, or by performing both at the same time. To achieve this, we can utilize three different design methods: (a) changing size of one/both flexion sensors, (b) changing shape of one/both sensors, and (c) changing the operating frequency of both sensors. In both (a) and (b), the area intercepting the magnetic flux from transmitter to receiver is varied which can cause change in transmission coefficient and, hence, lead to shifting of the curves. For (c), the curves can be shifted by changing the frequency. This happens because the loops are resonant and, hence, have peak value of transmission coefficient at the given frequency. The value of transmission coefficients away from the resonant frequency falls sharply and, hence, if the loops of the sensor on the other leg are resonant at a different frequency, the transmission coefficient for this sensor will be considerably lower at the operating frequency of the first sensor. Thus, by using any one or combination of the abovementioned techniques, the bilateral joint flexion system can be designed for desired level of non-interference.

III. Conclusion

In this work, we demonstrated bilateral joint flexion feasibility using our previously reported longitudinal configuration sensor. Although one variant of the sensor was used for demonstration, the conclusions are valid for other variants as well. We presented the condition that ensures non-interference between sensors leading to reliable operation. To test the condition, we devised a two-leg model and used one flexion sensor on each leg. Flexion simulation was carried out on one leg while the other leg was stationary. Usage of conformal loops confirmed the wearability aspect. The results showed that the interference signal was at least 10 times lower than the minimum desired signal. This proved the feasibility of monitoring joint flexion of both legs using our sensors. Furthermore, we also laid down guidelines that can be utilized to further improve the performance by increasing the gap between the desired and interfering signal.

In the future, these guidelines can be used to design the system for both legs and eventually to empower a full-body motion capture system.

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