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Inductive Textile Sensing for Movement Monitoring

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Abstract—Textile-based wearable technologies have significant potential for monitoring movements in fitness and health applications. Inductive sensing is a promising modality due to the ease of sensors fabrication and the quality of sensors' response. This letter initially focused on designing individual textile inductive sensors. Then, selected parameters were used to create a textile-based garment with inductive sensors capable of monitoring back movements in three directions. This letter successfully demonstrated that the developed garment can monitor back movements in three directions.

Index Terms—Sensor systems, textile wearable for motion capture, motion capture, smart clothing, strain sensing, textile sensor, wearable technology.

I. INTRODUCTION

With recent advancements in wearable technologies, it has become feasible to record various physiological parameters in a nonintrusive manner, making it practical for everyday use. The ability to monitor detailed movements is highly sought after in the fields of health and fitness. For instance, wearable technologies provide the means for the monitoring of the movements of the back in real world to provide data that can be employed in the selection of treatment preventing or aiding the rehabilitation of low back pain, which is a prevalent musculoskeletal issue associated with occupational activities [1], [2], [3], [4].

Despite the evident demand for such monitoring, comprehensive movement tracking remains challenging. Traditional options like inertial measurement unit suits come with significant costs and intrusiveness, while location-restricted solutions, such as camera-based optical motion capture (OMC) systems, are limited to specific setups. Textile-based wearable technologies offer great promise in addressing this challenge because of their comfortable nature and familiar form-factor. Several textile-based sensing methods have been investigated for movement monitoring, including piezoresistive, capacitive, and inductive sensors [5], [6], [7], [8], [9]. Piezoresistive [10] and optical [11] sensors have been used for the monitoring of back movement. Each modality has its own advantages and limitations. For instance, resistive sensors are easy to fabricate and acquire signals from, but they are susceptible to extensive drift and hysteresis [12]. Optical sensing has shown promising results, but is sensitive to temperature which can cause limitations in specific applications of the wearable technologies [11]. Inductive sensors can be seamlessly integrated into textiles using standard sewing or embroidery machines, ensuring consistent results [9]. This sensing modality has been employed in various ways within textile-based wearable technologies. For instance, Garcia et al. demonstrated the use of stitched inductors to monitor strain by measuring changes in the inductor's area. This information was then used to infer body movements [9]. Another example is the work by Wijesiriwardana [13], who implemented textile-based sensing by monitoring voltage changes induced by the movements of coils in relation to each other.

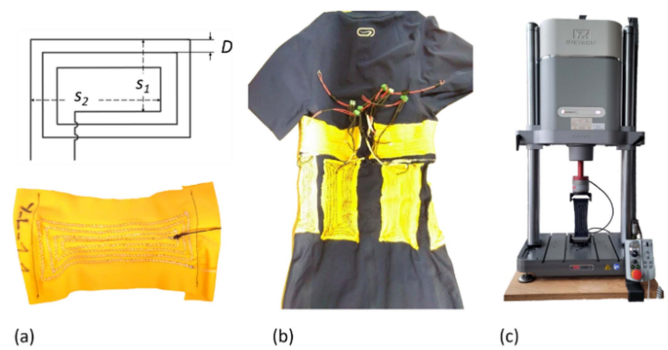

Fig. 1. (a) Sensor shape and parameters, (b) garment with integrated sensors, and (c) test setup for characterization.

Patiño and Menon [8] explored the impact of design parameters, like size, number of loops, and material on the inductance of textile planar spiral inductors. Expanding upon their research, we delved into the theoretical and experimental examination of additional factors, such as dimensions and number of loops. Moreover, we conducted a thorough characterization of the sensors to assess their drift and hysteresis. Last, we integrated them into a garment to monitor back movements in three planes.

II. MATERIALS AND METHODS

A. Sensor Design and Characterization

The inductive sensors consisted of flat rectangular spiral coils, which were made by stitching conductive thread/wire onto textile materials [9]. The sensor's shape is illustrated in Fig. 1(a).

This letter explored design parameters concerning the sensor dimensions and compared two types of conductive threads for sensor fabrication: metal-based (enameled copper wire, diameter 0.1 mm, Adafruit

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Industries) and fabric-based threads (silver coated vectran “Liberator,” Syscom Adv. Materials). Dimension parameters [the schematic in Fig. 1(a)] were investigated both theoretically and experimentally.

The gauge factor (GF), measure of sensor’s sensitivity to strain, [14], served as the outcome measure for the comparisons. GF is calculated as shown in (1). Here, L_{base} represents the inductance of the sensor when it is not stretched, while S_{base} denotes the length of the sensor in its unstretched state. ΔL and ΔS refer to the differences between the stretched and unstretched values. For this letter, GFs at 20% and 25% were considered, as it has been determined that this range is sufficient for capturing strain in clothing resulting from back movements, based on our preliminary tests

$$\text{GF} = \frac{\Delta L / L_{\text{base}}}{\Delta S / S_{\text{base}}}. \tag{1}$$

1) Theoretical Evaluation: The choice of a rectangular shape for the sensor was based on various factors. First, a rectangular shape facilitates fabrication using a standard sewing machine compared with curved patterns. In addition, it offers higher sensitivity in a specific direction by adjusting the height and the width, which is important for distinguishing between different body movements.

The inductance of a planar spiral rectangular inductor can be calculated using (2) and (3) [15]. These equations provide insights into the parameters that influence the resulting inductance of the sensor, and consequently, the GF

$$\begin{aligned} L \approx\ & 0.02339n^2 \left[(s_1 + s_2) \log_{10} \frac{2 s_1 s_2}{nD} - s_1 \log 10\,(s_1 + g) \right. \\ & \left. - s_2 \log 10\,(s_2 + g) \right] + 0.01016n^2 (2g - \frac{s_1 + s_2}{2} \\ & + \& \, 0.442nD - 0.01016n\,(s_1 + s_1)\,(A + B) \end{aligned} \tag{2}$$

$$g = \sqrt{s_1^2 + s_2^2} \tag{3}$$

where s_1 represents the length of the inductor, s_2 denotes the width, D is the distance between loops, and n represents the number of loops. The values of constants A and B are dependent on the material and diameter of the conductive thread/wire used to construct the coil [8].

The theoretical evaluation involved the analysis of the effects of s_1, s_2, and n on the sensor’s GF at 25% strain. Each parameter was investigated one at a time, as other parameters remained constant.

2) Experimental Evaluation: Theoretical findings on sensor behavior were experimentally validated to address simplifications made in the theoretical evaluation (e.g., not accounting for zig-zag stitch). The sensors were manufactured following a similar approach as described in [8]: Briefly, conductive thread/wire were sewn on stretchable spandex fabric; zig-zag stitch patterns were used to allow stretchability [Fig. 1(a)].

For experimental tests, a universal testing machine (Instron ElectroPuls E3000) was employed to strain the sensors in a controlled manner. Simultaneously, the inductance of the sensor was continuously measured using a precision LCR meter (Hioki IM3536), with ∼1% error as per manufacturer’s specifications.

During the validation process, each sensor underwent 25% stretching along the s_1 direction for 10 s. This stretching and relaxation cycle was repeated 10 times for each sensor. The inductance of the sensor was recorded and averaged in both the relaxed and strained states. The validation was performed on five sensors of each design to account for potential variations among sensors.

The initial parameters of the baseline sensor were determined through preliminary tests ($s_1 = 120$ mm, $s_2 = 50$ mm, $n = 3$, and

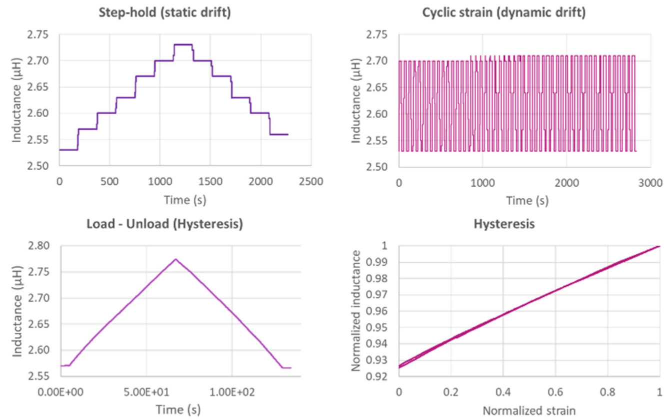

Fig. 2. Sensor characterization test protocol using the Instron machine for the investigation of hysteresis, static and dynamic drift, and linearity.

Thread Type = enameled copper wire). In addition to the baseline sensor, experimental tests included parameter values of 65 and 92.5 mm for s_1, 90 mm for s_2, 4 and 6 for n, and Liberator as an alternative thread type. The dimensions of the sensor are constrained by the measurement setup and fabrication. Importantly, the sensor design also considers constraints related to integration in a garment (limitation on size and positioning).

3) Sensor Characterization: Once the shape and material of the sensor were determined, the following properties were characterized for the sensor: GF over the strain range, drift, and hysteresis. The test protocols are depicted in Fig. 2.

B. Sensorized Garment for Back Movement Monitoring

To ensure accurate and repeatable measurements, a tight-fitting one-piece athletic suit was used to prevent sensor sliding. The sensors were sewn onto the garment in a prestretched configuration, utilizing a zig-zag stitching pattern in the stretch direction to minimize undesired deformation. The final garment design, depicted in Fig. 1(b), showcases these sensor integration techniques. The inductance of the sensors was read using a portable *LDC1614* evaluation board (Texas Instruments) connected to an Arduino Nano via I^2C, with data transmission enabled by a Bluetooth module (HC06). Sensors are read sequentially by the *LDC1614* module with a final total sampling frequency of approximately 15 Hz for all sensors. The inductance signals were filtered with moving average to remove high-frequency noise. The garment was worn by a user who performed three repetitions of forward flexion, right and left lateral flexion, and right and left rotations. Sensor signals were recorded during these motions to evaluate the garment’s capability of capturing back movements.

III. RESULTS AND DISCUSSION

A. Sensor Design

The theoretical and experimental evaluations of the sensor are summarized in Fig. 3. We observed that increasing the length of s_1 leads to a higher GF, suggesting that maximizing s_1 within manufacturing and design constraints is advantageous. In addition, maximizing the number of turns n and using Liberator thread instead of copper wire improves performance.

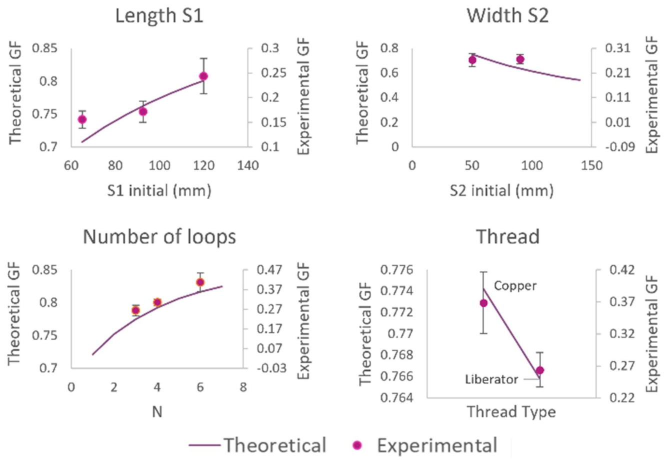

Fig. 3. Results of the theoretical analysis of the effect of the length (s_1), the width (s_2), the number of loops (n), and thread type on the gauge factor. Experimental results are shown on the same plot for comparison.

The positioning of the sensors on the garment was determined based on prior article [16] and the specific movements to monitor: forward flexion, lateral flexion, and rotation. The arrangement of the sensors was designed to enable the differentiation of these movements by comparing the sensors responses. Considering manufacturability, limited area for sensor placement, and the desired movements to monitor, the final sensor design was established. In this design, the length s_1 was approximately 155 mm. By reducing s_2 while increasing n and considering practical manufacturing considerations, the optimal sensor design was found to be $s_2 =$ 65 mm and $n = 4$.

The sensor characterization revealed that the sensor's GF did not exhibit linearity across the entire range of strain, with average values varying between approximately 0.38 and 0.42. During a stepwise test with constant strain, the sensor showed negligible static drift, with an average change in inductance of −1.28E−14 H, significantly smaller than the baseline inductance. When subjected to cyclic strain (50 cycles), the sensor exhibited an average dynamic drift of 2.14E−11 H/s, indicating a small but measurable change in inductance over time (still order of magnitudes lower than the baseline inductance). The sensor demonstrated low hysteresis, with an average area of the hysteresis loop being 0.07% of the entire area under the curve. The mismatch between the end and starting points of the loop was approximately 2.53 nH.

Other design factors such as the type of the base fabric (e.g., kinesiotape) on which the sensor was sewn or using two sensors in paralell were tested for their effect on sensor's sensitivity. It was determined that these options were either not practical, e.g., because of high stiffness, or did not improve the sensitivity of the sensor.

B. Sensorized Garment for Back Movement Monitoring

Initial tests with the garment showed promising results in detecting forward and lateral flexion using only two sensors (2 and 3, Fig. 4). The signals captured by these sensors were sufficiently large and had distinct patterns, allowing for the distinction between these movements. During forward flexion, the inductance rose to approximately four times the baseline value (inductance of upright standing)—from 0.05 to 0.20 normalized inductance, while during lateral flexion, the inductance doubled—from 0.05 to 0.1. Distinguishing between lateral and forward flexion was possible because in forward flexion the sensors on both the right and the left sides of the back stretch (increase in inductance), whereas in lateral flexion the sensors on the two sides of the back behave in opposite ways. For example, side bending to the right causes sensor 2 to stretch and sensor 3 to compress. Based on these observations, using only sensors 2 and 3, forward and lateral flexions can be distinguished.

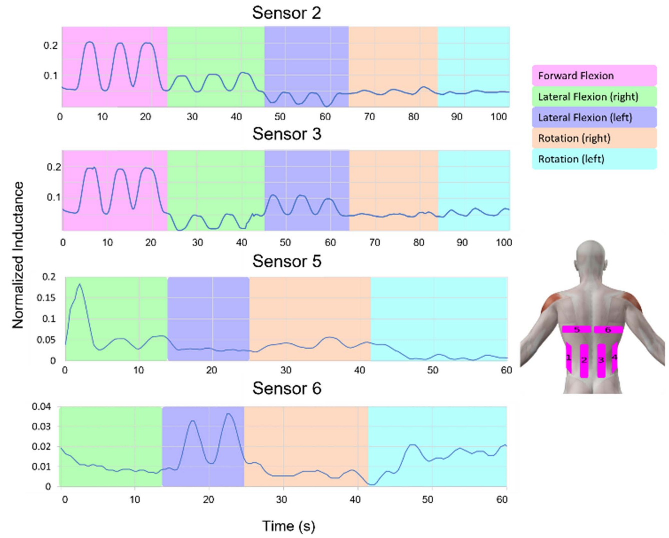

Fig. 4. Filtered signals from sensors 2, 3, 5, and 6 of the garment during different movements of the back. Location of sensors is shown in the image.

However, detecting back rotation proved to be more challenging, as the signals associated with rotations had relatively smaller amplitude (Fig. 4, it should be noted that signals from sensors 5 and 6 only have two repetitions of lateral flexion to left because of experiment errors). This can be expected given the lower stretch of the garment in these movements, as compared to flexion. Nonetheless, by leveraging data from additional sensors (sensors 5 and 6), it was still possible to detect the two rotation movements.

Future article should focus on studying sensor signals with a quantitative measurement of the angles of the back (e.g., with simultaneous OMC). In addition, artificial intelligence techniques can be used to quantitively evaluate the garment's capabilities for accurate prediction of back movement angles.

IV. CONCLUSION

Inductive textile sensing has potential for wearable technologies. In this letter, we conducted theoretical and experimental investigations to explore the design parameters of a textile-based inductive sensor that is simple to manufacture. We identified suitable sensor design for our intended wearable application through experimental and theoretical analysis and fully characterized the sensor with selected parameters. Subsequently, we incorporated six sensors with the selected parameters into a garment to monitor movements of the back in three planes. Notably, our findings demonstrated that by utilizing four sensors (two located in the lower back and two in the upper back), forward flexion, lateral flexion, and back rotation can be discerned. This highlights the potential of these types of sensors for movement monitoring. Further investigation is required for validation with a larger number of participants and more complex movements.

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