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ElboSense: A Novel Capacitive Strain Sensor for Textile-Based Elbow Movement Monitoring

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***Abstract*—The field of wearable sensors has witnessed remarkable progress in recent years, enabling real-time monitoring of musculoskeletal biomechanics. Musculoskeletal injuries require long-term management through medications and physical therapy to ensure a smooth recovery. Assessment of a patient's range of motion (ROM) is an essential component of physical therapy. However, existing methods for measuring ROM are either analog or require expensive equipment. In this work, we present ElboSense, a smart textile-based sensing solution to monitor elbow motion precisely. ElboSense is embedded with a novel yarn-like capacitive strain sensor made with braided composite structures of multiple filament strands in a helical pattern. We seamlessly integrated the sensor into an elbow brace and developed an embedded system for data acquisition. The work conducted a study with eight healthy adult participants who performed a regulated elbow movement exercise (flexion and extension) 10 times. We validated the sensor measurements against a reliable optical motion-capture system. The average cross-correlation was found to be 0.91. Pearson's correlation coefficient analysis showed 0.95 for peak-to-peak and 0.98 for valley-to-valley. All the preliminary results indicate a good agreement and reliability as a potential sensing solution to monitor the range of motion during elbow exercises.**

***Index Terms*—Smart Textile, Elbow Brace, Flexion-Extension, Musculoskeletal injuries, Capacitive Strain Sensor, Composite Braided Filament.**

I. INTRODUCTION

Musculoskeletal injuries encompass a wide range of conditions affecting the muscles, bones, ligaments, and other structures crucial for body movement [1], [2]. These injuries often require long-term management involving medication and physical therapy to ensure adequate recovery. Within the realm of physical therapy, a key aspect is assessing a patient's range of motion (ROM) in synovial joints, which plays a vital role in progress monitoring and devising appropriate treatment plans [3]. Restricted or abnormal ROM in flexion and extension can serve as an indicator of various musculoskeletal conditions, including joint stiffness, ligament injuries, arthritis, or joint degeneration. The existing solution includes Goniometers [4], [5], Optical tracking [6], and Inertial wearable devices [7] that are often used to evaluate the flexion and extension performance of the elbow after injury. Table I shows the advantages and limitations associated with each solution. Flexion involves bending the elbow joint, reducing the angle between the forearm and upper arm. Conversely, extension refers to straightening the elbow joint, moving the forearm away from the upper arm.

In recent years, researchers have been exploring various methods to incorporate soft sensors into textiles to monitor joint movement. Textiles offer several advantages, as they are commonly used in rehabilitation applications such as elbow braces, pads, and cuffs. Previous studies have focused on integrating fiber optic sensors [8] and inertial measurement sensors [9], [10] into elbow pads. These systems require additional components, wiring, and support structures, which can be cumbersome. An alternative approach involves using conductive knit fabric structures that exhibit changes in resistance during joint extension [11], [12]. Conversely, these sensors have limited repeatability and significant hysteresis effects. To overcome these limitations, researchers have explored the combination of piezoresistive materials and composite materials, resulting in improved scalability and sensitivity of the sensors [13]. However, integrating these sensors into textiles requires a complex integration process.

In this research paper, we presented the integration of a novel yarn-like capacitive strain sensor into textiles and conducted an elbow range of motion test involving eight healthy participants. The sensor was seamlessly integrated into the textile material, ensuring a cohesive and comfortable interface. We developed our bio-instrumentation and embedded system for data acquisition to measure the capacitance changes. Furthermore, we compared our integrated sensor system with the widely recognized motion-capturing module, OptiTrack, as a gold standard.

TABLE I
EXISTING SOLUTIONS TO MEASURE THE RANGE OF MOTIONS.

Method	***Advantages***	***Limitations***
Goniometer	-Inexpensive -Analog	-No logging/wireless. -Discrete measurements. -Hard to use for patients.
Optical Tracking	-Accurate -3d pose -High resolution -Continuous	-Expensive. -Accurate marker placement. -Unavailable for personal use.
Inertial Wearables	-High resolution -Continuous -In-home logging	-Pose models need processing. -Rigid body reduces the comfort.

II. MATERIALS AND METHODS

A. Capacitive Strain Sensor Structure

We used a new yarn-like capacitive strain sensor developed by Nautilus Defense [14] and characterized by our lab. The sensor is a braided composite structure made with polyamide coated Copper wire, Kevlar, and Spandex filament (Figure 1). Braided is a weaving technique that involves interlacing multiple strands of yarn strips in a diagonal or helical pattern. The straight Spandex filament introduces stretchability, and the

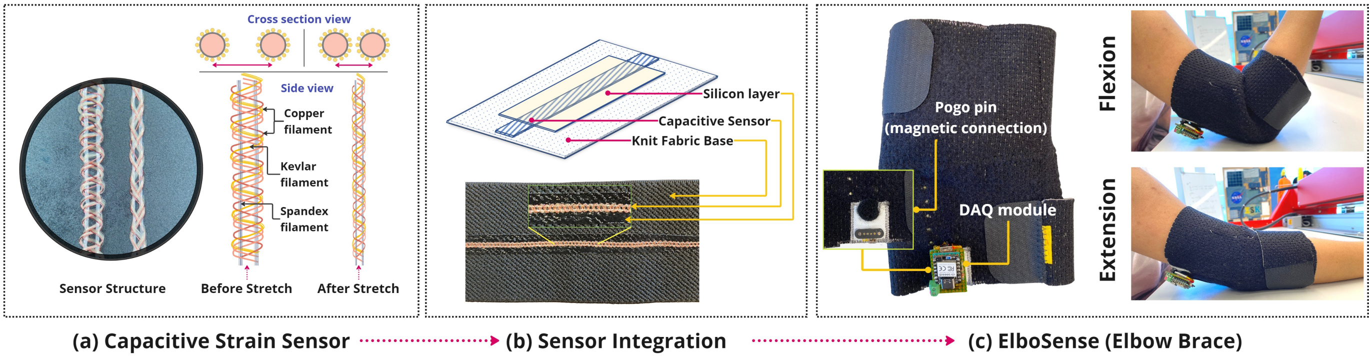

Fig. 1. Development process of ElboSense (sensor structure, integration).

helical Kevlar filament maintains the strength of the sensor by adjusting similar expansion of copper wire during the stretch. The sensor works with the same principle as a parallel plate capacitor, where the capacitance changes with the variation in the distance between its two electrodes (Equation 1). In this sensor, we assume the dielectric value (ε_0) and area (A) as constants.

$$C = \frac{\varepsilon_0 \cdot A}{d} \tag{1}$$

The mutual capacitance between any two conductors in these yarns increases linearly as the yarn undergoes axial tension and resultant elongation or through-thickness compression (Figure 2). As the yarn is relaxed, the mutual capacitance between conductor pairs decreases back to the baseline mutual capacitance. The sensor integration process consists of two

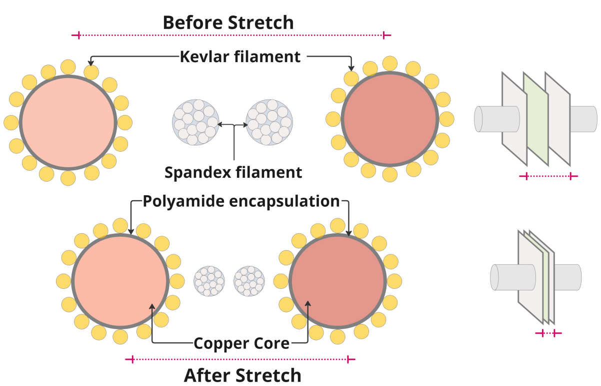

Fig. 2. Capacitive strain sensor's working principle as a parallel plate capacitor.

steps: first, integrating the sensor with the base fabric, and second, insulating the sensor layer to avoid any mechanical abrasion (Figure 1). We used polyvinyl acetate (PVA) based fabric glue to place the sensor. After drying, we applied a silicon rubber [15] layer (1mm) on top of the sensor.

B. Embedded System

Measurements from the capacitive sensing thread are acquired using a 28-bit Capacitive to Digital convertor (FDC2212), which utilizes an LC (inductor-capacitor) resonator to register the frequency shifts associated with capacitance change in comparison to a 40MHz reference crystal clock. The module connects using the magnetic Pogo pin with the sensor interface. The FDC2212 capacitance converter interfaces over I2C to a miniature wireless data acquisition system based on the XIAO BLE nRF52840 board powered by a rechargeable 400mAh lipo battery. In order to synchronize the start of the OptiTrack system with our sensing brace, the SYNC trigger from the OptiTrack system is connected to a digital interrupt pin on the nRF52840 board (Figure 3).

The change in logic level (High-Low) of the SYNC trigger, when measured by the DAQ board, initiates data transmission over Bluetooth Low Energy (BLE) simultaneously. The Nordic UART BLE GATT profile is utilized to transmit sensor payloads to a receiving computer. In the test environment, the receiver computer connects to the elbow brace before data collection and listens to incoming BLE messages (sampling rate- 100 Hz) using the BLE-serial command-line tool, which bridges BLE UART payloads to a local serial port. The data is logged using the CoolTerm serial manager tool to CSV files.

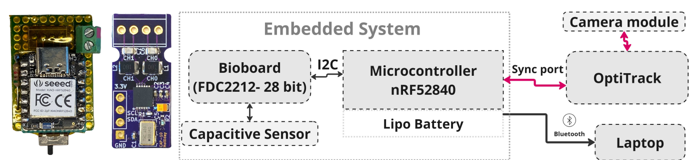

Fig. 3. Data acquisition module of ElboSense.

C. Testing Protocol

A human study was conducted involving eight healthy participants. Before testing, the OptiTrack cameras were calibrated to eliminate external vibrations or interference that could bias the data. The testing protocol involved instructing participants to wear the Elbow brace and adjust it according to their comfort. The subject inclusion criteria were based on the ease of right elbow-joint movement. A demonstration was given to illustrate the desired movement, which involved flexing the elbow from a 0° position (lying straight on the table) to approximately a 120° angle (as shown in Figure 4). Each participant performed ten repetitions of the flexion and extension movement. It is important to note that the testing protocol was not time-sensitive, resulting in variations in the total time taken by each participant. Data acquisition was carried out simultaneously using both the OptiTrack system and ElboSense. The study was approved by Institutional Review Board at the University of Rhode Island (1785106-7), and all participants provided signed consent to participate.

III. RESULTS AND DISCUSSIONS

We have collected capacitance data from ElboSense and distance from OptiTrack data. For analyzing the data, we have re-sampled both the signals to the same sampling rate and converted them to the same time scale. Both data were collected in a time-synchronized manner with the help of the embedded system.

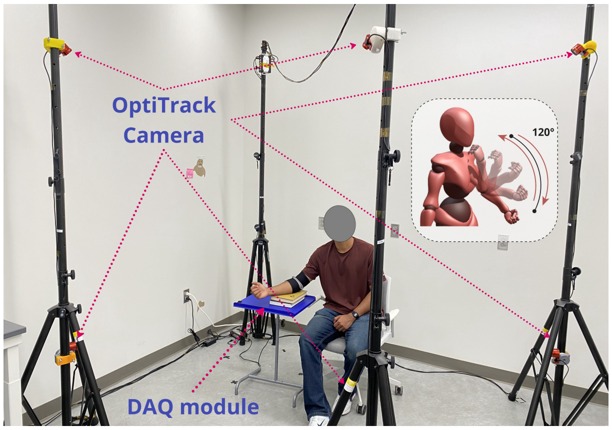

Fig. 4. Healthy adult human testing protocol.

A. Elbow Flexion-Extension Test

The integrated sensor undergoes changes in capacitance when subjected to external axial tension or compression. During elbow flexion, the elbow brace applies longitudinal stress externally, leading to an increase in capacitance. Conversely, during elbow extension, the sensor relaxes, resulting in a decrease in capacitance. During the test, the elbow moves between 0° (extension) to the maximum angle of 120° (flexion). We measured the angular changes using the three-point motion-imaging techniques of OptiTrack. The measured capacitance (pF) value was plotted together against the joint angle variations. Figure 5 shows the comparison of performance characteristics of ElboSense and OptiTrack (Participant-8). Both data show similar peaks and valleys, which indicate a consistent pattern in the range of motion measurements. The consistent alignment of the data highlights the reliability and consistency of the measurements obtained from both systems. This reinforces the accuracy and precision of the measurement techniques employed in capturing the joint angle change and capacitance values.

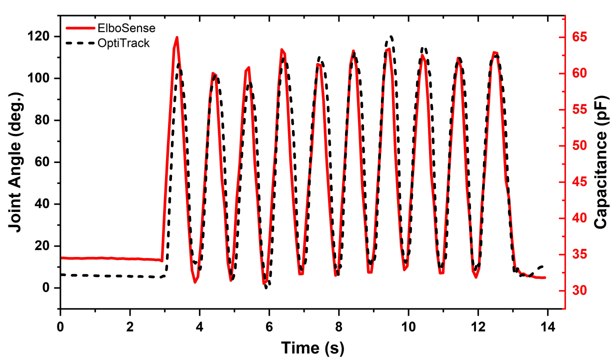

Fig. 5. Comparison of Joint angle change (OptiTrack) and Capacitance variation (ElboSense).

B. Feature Analysis

For feature extraction, ElboSense and OptiTrack data are normalized, peaks and valleys are identified using the find peaks algorithm, and the average peak to peak, valley to-valley distances are calculated. This analysis measures the total variation signal distance. It helps determine the difference between the peaks and the valley in a waveform, which can be useful in characterizing the overall magnitude of a signal or identifying any irregularities or anomalies. Both variations were calculated for time-synchronized data. Figure 6 shows the peak-to-peak (top) and valley-to-valley (bottom) analyses. For peak-to-peak (P2P) and valley-to-valley (V2V) analysis, we normalized both the ElboSense and OptiTrack data sets. For P2P, we measured the average time-based distance between two successive peaks, and for V2V, we calculated the sample distance between two consecutive valleys. Sample distance is mapped to time series data. Both analyses show a clean

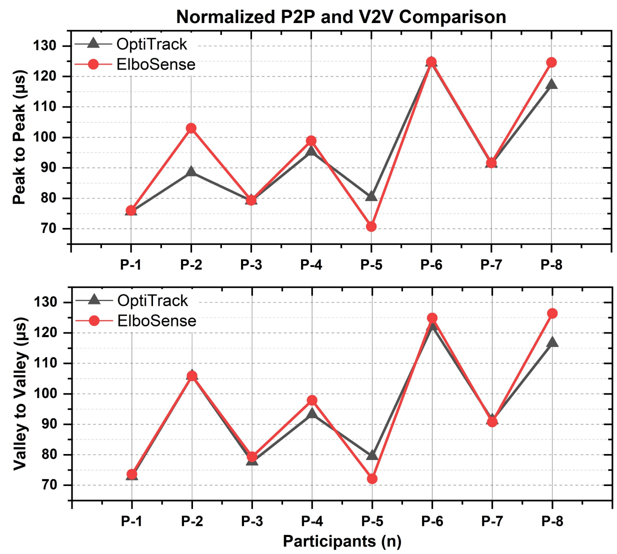

Fig. 6. Normalized P2P (top) and V2V (bottom) analysis.

cohesiveness of both signals. Although participants 2 and 5 showed a negligible amount of discrepancy for both P2P and V2V analysis. It can happen for multiple reasons, for instance, loose fit or irregular flexion distance. We performed Pearson's correlation coefficient analysis, which ranges from -1 to 1, where 1 represents a perfect positive correlation, -1 represents a perfect negative correlation, and 0 represents no correlation. In our case, Pearson's correlation coefficient analysis revealed a coefficient of 0.95 for P2P (Point-to-Point) and 0.98 for V2V (Vehicle-to-Vehicle). These coefficients indicate a very strong positive correlation between the respective variables.

C. Capacitance Variation During Human Test

Figure 7 displays the average capacitance variation of all eight participants during the flexion-extension test. The capacitance range during flexion was found to be 45-55 pF; for extension, it was 30-35 pF, which shows reliable repeatability of the sensor performance. The mean capacitance during flexion (52.83) pF is higher than during extension (33.53) pF, indicating that there is an overall increase in capacitance during flexion and a decrease during extension. The paired t-test shows a highly significant difference between the flexion and extension measurements (p ¡ 0.001). The average difference between flexion and extension of the capacitive sensor is 18.59, and the standard deviation is 3.13. Major capacitance difference and SD signifies that the capacitive sensor performs effective differences to classify the major events in the elbow movement test. This indicates that as the capacitance increases during flexion, it tends to decrease during extension and vice versa.

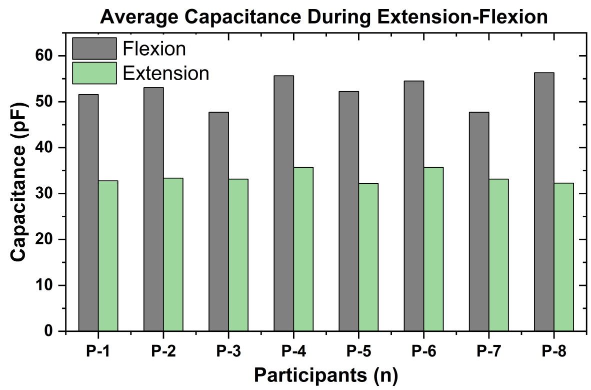

Fig. 7. Average capacitance changes due to the Extension-Flexion test.

D. Cross-Correlation and Lag Analysis

Figure 8 displays a graphical representation of cross correlation (CC) and lag across eight participants. CC is a measure of similarity between two waveforms as a function of the time lag applied to one of them. The lag in this context refers to the time delay in sample index numbers between the two signals being compared. The change of the trigger pin (to change logic level- high,low) maintains the data synchronization and generates the minimum lag. The high value of mean cross-correlation 0.907 implies that there is a strong correlation between the elbow tracking and OptiTrack measurements, further confirming the consistency and reliability of ElboSense for tracking elbow flexion-extension movements.

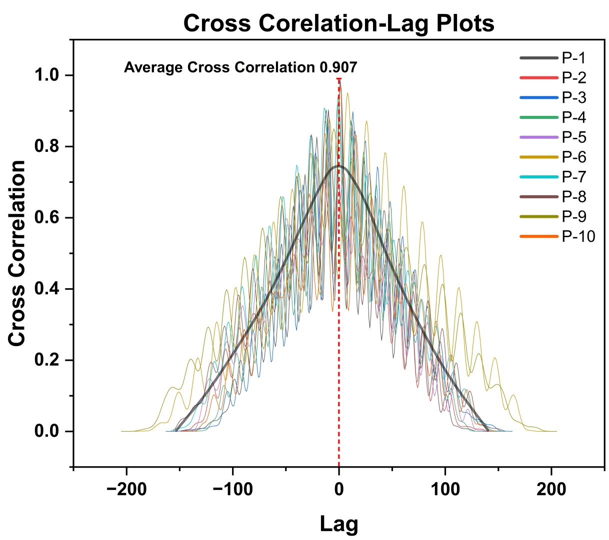

Fig. 8. Cross-Correlation and Lag plot analysis.

IV. Conclusions and Future Work

This work introduced ElboSense, where we demonstrated the structure and integration process of a novel capacitive strain sensor to measure elbows' flexion and extension. The work conducted a human test consisting of ten healthy participants. For verification, we utilized the motion-capturing module OptiTrack as a reference. We used our own data acquisition module to measure capacitance changes in the sensor. Number The findings from the study indicate that capacitance sensors can detect elbow flexion-extension angles similar to optical markers. Cross-correlation analysis between raw capacitance signals and OptiTrack indicates that they are highly correlated (Average CC: 0.91). This data consistency reinforces the ElboSense system's potential as a viable alternative for measuring the elbow's range of motion.

However, this work has some limitations; we evaluated only one type of motion analysis. Future work will expand on this by integrating IMU data and capacitive stretch sensors to construct multiple angular motion models. Another possible research prospect is to check the external interference on the sensor, for instance, motion artifacts, humidity, and perspiration. The directional dependencies (stretch) and ESD (electrostatic discharge) phenomenon also need to be evaluated to get the overall characteristics of the sensor.

Future iterations will incorporate a single modular design that enables plug-and-play functionality. The wireless system will intuitively measure and facilitate the range of motion exercises for patients with musculoskeletal injuries.

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