KMUTT | ภูมิปัญญา 65 ปี สู่วิถีความยั่งยืน | คณะวิศวกรรมศาสตร์ Faculty of Engineering | PROJECT DAY 2026 FACULTY OF ENGINEERING

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Development of Natural Rubber-Based Dielectric Elastomer for Human Motion Tracking Applications

CONTROL SYSTEMS AND INSTRUMENTATION ENGINEERING

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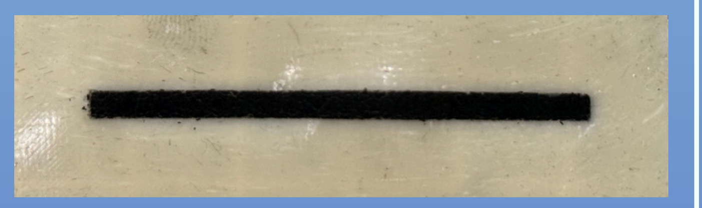

ABSTRACT

Wearable sensors for human motion tracking have gained significant attention in applications such as rehabilitation, sports performance monitoring, and human–machine interaction, where accurate and reliable sensing is essential for improving safety, performance analysis, and real-time feedback. However, conventional strain sensors often suffer from limited flexibility, high material cost, poor environmental sustainability, and signal instability under repeated mechanical deformation, which limits their long-term wearable applications.To address these limitations, this study develops a natural rubber-based dielectric elastomer sensor using carbon nanotubes (CNTs) as compliant electrodes, which enable high stretchability and electrical conductivity. The fabrication process involves preparing natural rubber films with different compositions and coating them with CNTs, and the sensors are evaluated under cyclic stretching to assess sensitivity, stability, and repeatability. The results show that the E50 s0.4 formulation provides the best balance between sensitivity and signal stability, while the E50 s0.2 formulation exhibitshigher sensitivity but greater signal drift.For practical validation, the sensor is integrated into a wearable knee device consisting of an ESP32-C3 microcontroller, a BNO055 inertial measurement unit, and a voltage divider circuit, and the system demonstrates stable, consistent, and repeatable performance. The measured coefficient of variation (CV) of 3.42% confirms good reliability under cyclic operation.
In addition, the sensor successfully detects knee joint motion and enables real-time monitoring.Overall, the developed sensor shows strong potential for flexible, sustainable, and reliable wearable motion tracking applications.

METHODS

A carbon nanotube (CNT) solution (0.2 wt%) was prepared by dispersing CNTs in isopropyl alcohol (IPA) using ultrasonic sonication was performed for 60 minutes, divided into three cycles, to ensure uniform dispersion,and the solution was applied onto natural rubber to form a conductive layer. The sensor was fabricated as a rectangular film (2 × 6 cm) and was coated with CNTs to create a strain-sensitive conductive network, The sample was subsequently encapsulated with a thin silicone layer to prevent CNT detachment, followed by the attachment of copper electrodes at both ends for resistance measurement.Mechanical and electromechanical properties were evaluated by stretching the sensor under controlled conditions, and the initial resistance (R_0) and strained resistance (R) calculated using Eq.**(1)** were recorded to calculate strain (ε), relative resistance change ($\Delta R/R_0$), gauge factor (GF), and hysteresis.

$$R = \rho \frac{L}{A} \quad (1)$$

When the sensor is stretched, the length (L) increases and the cross-sectional area (A) decreases, which causes the resistance (R) to increase. Cyclic tests were performed to assess stability and repeatability. A voltage divider circuit was used for signal acquisition, and the sensor output was read by an ESP32-C3 microcontroller, while the data were transmitted to a web-based interface via Wi-Fi for real-time motion tracking and recording, and the sensor was mounted on the knee joint to evaluate its performance in wearable applications.

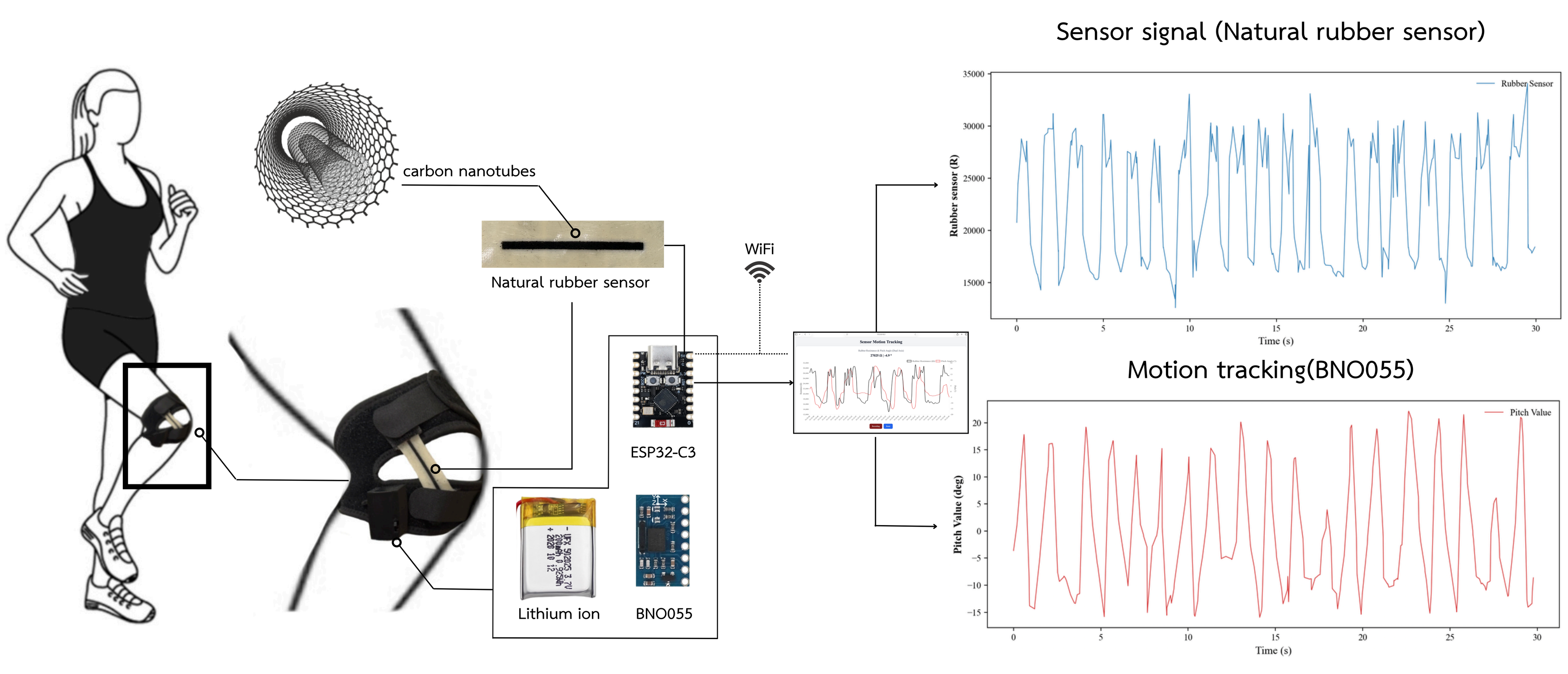

Figure 1 : System Operation Steps

RESULTS

The performance of the developed materials and sensors was evaluated by systematically investigating their sensitivity, stability, and repeatability at both the material and device levels.For material performance, the E50-S0.2 sample exhibited the highest gauge factor and sensitivity, indicating strong responsiveness to strain. however, it showed significant signal drift, which reduced stability.
In contrast, the E50-S0.4 sample demonstrated good sensitivity with significantly lower drift, resulting in more stable behavior. Therefore, the E50-S0.4 formulation was selected as the optimal formulation because it provided the best balance between sensitivity and stability.

Formulation	GF	Sensitivity	Drift(%)	Hysteresis (%)
E50-S0.2	**1.32**	**55.7**	38	4.25
E50-S0.4	7.60	21.7	**2.60**	**4**

Figure 2 : Summary of Sensor Performance

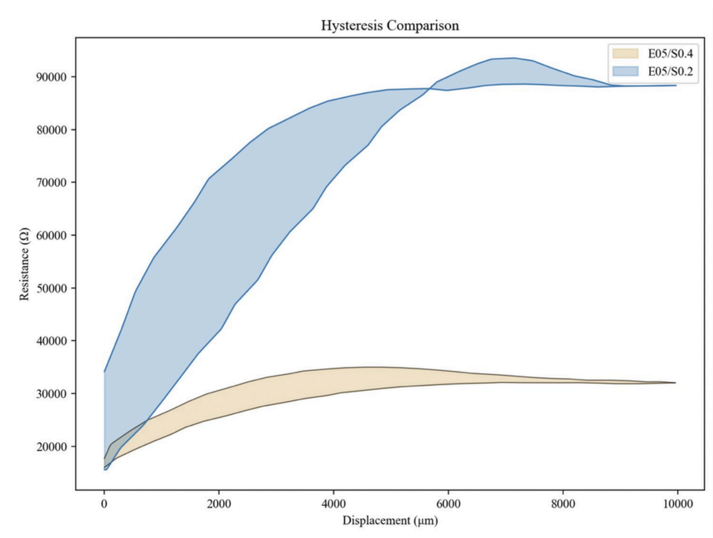

Figure 3 : Comparison of Hysteresis Behavior between Formulations E50-S0.2 and E50-S0.4

For device performance, the integrated sensor exhibited a clear and consistent response during cyclic testing, and similar resistance patterns were observed across all cycles. The narrow mean ± SD indicated low variation, while the low coefficient of variation of 3.42% confirmed high stability and excellent repeatability. These results demonstratereliable sensor performance for practical wearable applications.

Mean Peak (Ω)	STD Peak (Ω)	CV (%)
29,137.59	997.13	**3.42**

Figure 4: Summary of Peak Response and Stability Metrics

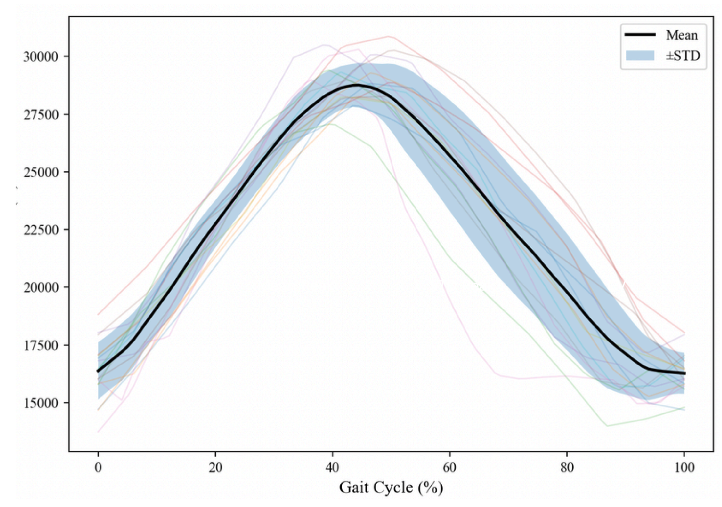

Figure 5 : Repeatability Analysis of Sensor Response (Mean ± SD)

CONCLUSION

This work presents the development of a CNT-coated natural rubber sensor for piezoresistive strain sensing, in which the E50-S0.4 formulation provided a better balance between sensitivity and stability compared to the E50-S0.2 formulation, which showed higher sensitivity but exhibited significant signal drift. The selected sensor demonstrated stable and repeatable performance (CV = 3.42%) and showed a consistent electromechanical response, and these results highlightits potential for practical wearable sensing applications.

REFERENCES

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