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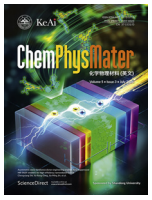

Research Article

Performance evaluation of CNT-COOH coated dual-intertwined yarn for wearable resistive strain sensing

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ABSTRACT

Stretchable resistive strain sensors are generating significant interest in wearable electronics due to their exceptional stretchability, rapid response, and ability to detect complex human movements. While yarn-based strain sensors show enormous potential for textile integration, they typically suffer from low sensitivity, poor interfacial adhesion between conductive materials and yarn surfaces, and limited mechanical durability under repeated strain, undermining their long-term applicability and fruitful use. This study presents a novel high-performance yarn strain sensor created by depositing multi-walled carboxyl-functionalized carbon nanotubes (MWCNT-COOH) onto a dual-intertwined yarn (DIY) substrate, consisting of a spandex core wrapped with nylon monofilaments using a scalable, cost-effective layer-by-layer (LBL) assembly without surfactants, followed by encapsulation with Ecoflex to enhance mechanical resilience and environmental endurance. The CNT-COOH dispersion exhibited excellent coverage and adsorption on the yarn surface, resulting in a reliable and conductive sensing layer. The CNT-COOH/DIY sensor demonstrated exceptional strain responsiveness, achieving a gauge factor (GF) of 11.40 for 10%–40% strain and 8.75 for 40%–60% strain. It also exhibited a response time of 263 ms and an electrical conductivity of 6.03×10^{-3} S/m. The Ecoflex/CNT-COH/DIY sensor retained stable sensing performance across 2000 stretching cycles at 30% strain. Real-time assessments on the finger, wrist, elbow, and knee confirmed its practical viability for wearable motion sensors and smart textiles.

1. Introduction

The rapid development of wearable electronics has revolutionized healthcare, sports, and human-computer interaction, creating a demand for flexible, elastic strain sensors seamlessly integrated into textiles for real-time motion monitoring [1–3]. Yarn-based resistive strain sensors, which are lightweight, adaptable, and compatible with fabric manufacturing, are ideal for smart textiles, enabling potential applications in physiological monitoring, rehabilitation, and gesture management systems [4–7]. However, their broad use is hampered by challenges such as low sensitivity, poor interfacial adhesion between conductive nanoparticles and textile substrates, and inadequate mechanical resilience under cyclic load. Achieving a high GF for small deformations remains challenging, as many sensors exhibit low GF values that are unsatisfactory for precise motion detection. Furthermore, poor adhesion frequently results in delamination of conductive layers, while repeated stretching creates microcracks, reducing long-term stability [8–10]. Compounding these challenges, the use of surfactants to disperse conductive nanomaterials, such as carbon nanotubes (CNTs), undermines conductivity, biocompatibility, and environmental sustainability. These constraints further highlight the critical need for novel yarn-based sensors that incorporate high sensitivity, strong adhesion, exceptional durability, and affordable fabrication to satisfy the stringent requirements for next-generation wearable electronics. Recent efforts to overcome the limits of yarn-based strain sensors have investigated a variety of conductive materials, including CNTs, carbon black (CB), graphene, copper nanoparticles, gold nanoparticles, silver nanoparticles [11–22], and conductive polymers such as poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) [23], which are among the most prominent alternative conductive materials used as active sensing materials. Substrates for flexible and stretchable sensors are commonly made from materials like polydimethylsiloxane (PDMS), latex rubber, Ecoflex, and polyurethane (PU) [4], but significant gaps remain.

Building on these materials and methods, numerous researchers have exerted considerable effort. For example, Ma et al. [24] developed a light-strain sensor by partially coating CNT yarn with an epoxy

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resin/acetone polymer solution by a rapid coating technique, resulting in a core-sheath configuration of the CNT/epoxy composite yarn. Despite the sensor's remarkable flexibility, its strain sensitivity was insufficient, with a GF as low as around 8.65, inadequate for detecting subtle deformations. In their study, Seo et al. [25] reported a CNT-coated spandex fiber that had a high stretchability but a limited cyclic stability (1000 cycles at 30% strain). On the other hand, using polydopamine-enhanced adhesive interfaces and a hydrophobic protective layer, Lu et al. [26] created a durable yarn-based strain sensor. Although durable, the sensor had low GF, 3.2 between 0–10% strain and 7.3 between 20%–30%, indicating low sensitivity. By incorporating MWCNT-COOH into PEDOT:PSS-coated fabrics, Cui et al. [27] were able to achieve a high GF of 17.5 at low strains. However, the sensitivity dropped significantly to 1.5 at 10% strain, and the operational lifespan was restricted to 500 cycles. These investigations underscore prevalent challenges: insufficient adhesion between CNTs and yarn substrates, resulting in conductive network breakdown, and dependence on intricate or surfactant-based methods that impede scaling and biocompatibility. Furthermore, the majority of sensors are tailored for particular strain ranges or joints, lacking adaptability for multi-joint monitoring, which is essential for thorough motion tracking.

Herein, a novel high-performance yarn-based strain sensor is developed that exhibits excellent sensitivity, durability, and mechanical resilience simultaneously by utilizing a dual-intertwined yarn (DIY) structure, involving a spandex core helically wrapped in nylon monofilaments. This structure is coated with multi-walled carboxyl-functionalized carbon nanotubes (MWCNT-COOH) through a scalable, cost-effective, surfactant-free LBL assembly. Then, the sensor is encapsulated in Ecoflex for improved longevity. Unlike conventional yarn substrates, the DIY structure provides enhanced mechanical integrity and flexibility, facilitating exceptional strain sensing even at significant deformations. The surfactant-free MWCNT-COOH dispersion ensures enhanced interfacial adhesion along with conductivity, whereas the LBL assembly's compatibility with automated coating methods facilitates economical, large-scale manufacturing.

Furthermore, the Ecoflex encapsulation layer notably improves environmental resilience and mechanical durability, maintaining consistent performance throughout 2000 stretching cycles at 30% strain. The Ecoflex/CNT-COOH/DIY sensor exhibits a high GF of 11.40 (10%–40% strain) and a response time of 263 ms, demonstrating superior electromechanical behavior and versatility, as confirmed by real-time tracking of finger, wrist, elbow, and knee movements. This interdisciplinary fusion of materials science, textile engineering, and wearable electronics places the sensor as a viable option for next-generation smart textiles, healthcare monitoring, and human-machine interactions, intersecting with the need for soft, bio-integrated systems.

2. Experimental

2.1. Materials

The water-soluble polymer polyvinyl alcohol (PVA-1788) was sourced from Aladdin, Ltd. Functional nanomaterials, MWCNT-COOH (purity: 99 wt%, diameter: <8 nm, length: 0.5–2 μm) were acquired from Nanjing Xianfeng Nanomaterials Technology Co., Ltd. (China). Nylon monofilament (diameter: 0.10 mm) was purchased from Wujiang Mingdi Trade Co., Ltd. The elastomer Ecoflex was purchased from Beijing Chengxing Industrial Co., Ltd, and the stretchable spandex yarn (1680D) was sourced from Fuzhou Tianfang Textile Co., Ltd.

2.2. Fabrication of DIY

DIY, composed of nylon monofilaments wrapped around a spandex core, is fabricated using an automated wrapping machine. The nylon monofilaments are helically wound around the spandex core using a spindle-driven mechanism at a controlled angle during the initial stage of manufacturing. The first layer of wrapping provides subsequent reinforcement by providing basic mechanical support and elasticity. A second spindle is used to wind an extra layer of nylon monofilaments with the same winding and twist parameters as the first one, allowing the partially wrapped yarn to achieve the double-wrapped structure. The wrapping velocity is 2000 RPM (spindle speed), while the wrapping turns are 500 turns per meter for the complete yarn construction. The characteristic helical structure of the yarn can only be achieved by meticulously controlling the winding and twist angles, set at 45°, at both phases. The precise wrapping technique improves the DIY's mechanical properties, including its tensile strength, structural integrity, and overall flexibility, by distributing the tension evenly.

2.3. Fabrication of CNT-COOH/DIY

Deionized (DI) water was used to disperse MWCNT-COOH at a concentration of 1 wt% to create a uniform aqueous dispersion. The carboxyl functional groups provided effective dispersion without the need for surfactants or other agents [28]. The suspension was treated with ultrasonication for 60 min to achieve complete deagglomeration and even distribution. Simultaneously, a 0.5 wt% PVA solution was prepared by dissolving PVA in DI water with continuous agitation at 90 °C for 50 min, following established methods [16]. After a 10-min cleaning with ethanol and DI water, the DIYs were dried in an oven at 60 °C to eliminate surface impurities. Cleaned DIYs were immersed in PVA for 5 min to improve interfacial adhesion during surface treatment. The PVA adheres to the yarn surface through non-covalent interactions, including hydrogen bonding, van der Waals forces, and hydrophobic attraction. After washing with DI water, the yarns were dried at 60 °C. The yarns were subsequently submerged in the CNT-COOH dispersion for 10 min in an ultrasonic bath to enhance penetration into the yarn structure. Six LBL cycles were adjusted to balance conductivity and coating thickness, ensuring strong adherence while preserving the flexibility of the CNT-COOH layer on the DIY surface. This specific cycle count promotes percolating conductive network development while maintaining yarn flexibility for wearable applications. Each cycle progressively deposits a thin CNT-COOH layer; six cycles provide adequate coverage for reliable conductivity through continuous electron transport channels, as fewer cycles resulted in discontinuous networks with reduced conductivity. Simultaneously, six cycles inhibit excessive coating thickness that could compromise flexibility. Finally, conductive yarn segments 50 mm in length were fabricated for sensor construction. Copper wires were carefully wound at both ends to guarantee safe electrical connections and minimal contact resistance, secured with silver-filled conductive paste; the sensing area measured 40 mm of the yarn length.

2.4. Ecoflex/CNT-COOH/DIY sensor fabrication

The Ecoflex components A and B were meticulously combined in a 1:1 mass ratio to manufacture the elastomeric encapsulant. The mixture was mechanically agitated at ambient temperature for 5 min to ensure a uniform texture. The CNT-COOH/DIY sensor yarn, previously fitted with copper wire electrodes, was meticulously submerged in the prepared Ecoflex solution for 15 s to ensure a homogeneous coating. After immersion, the coated sensor underwent vacuum drying at 80 °C for 1 h to ensure thorough curing of the encapsulating layer. This protective Ecoflex sheathing encased the yarn to prevent CNT coating flaking. The effect of different encapsulating thicknesses on sensitivity and durability has not been studied, but will be investigated in future experiments, along with the effects of Ecoflex thickness and curing duration. The conformal Ecoflex layer prevents CNT coating delamination, improves surface smoothness, and enhances long-term electromechanical reliability under cyclic strain, making the sensor suitable for wearable applications.

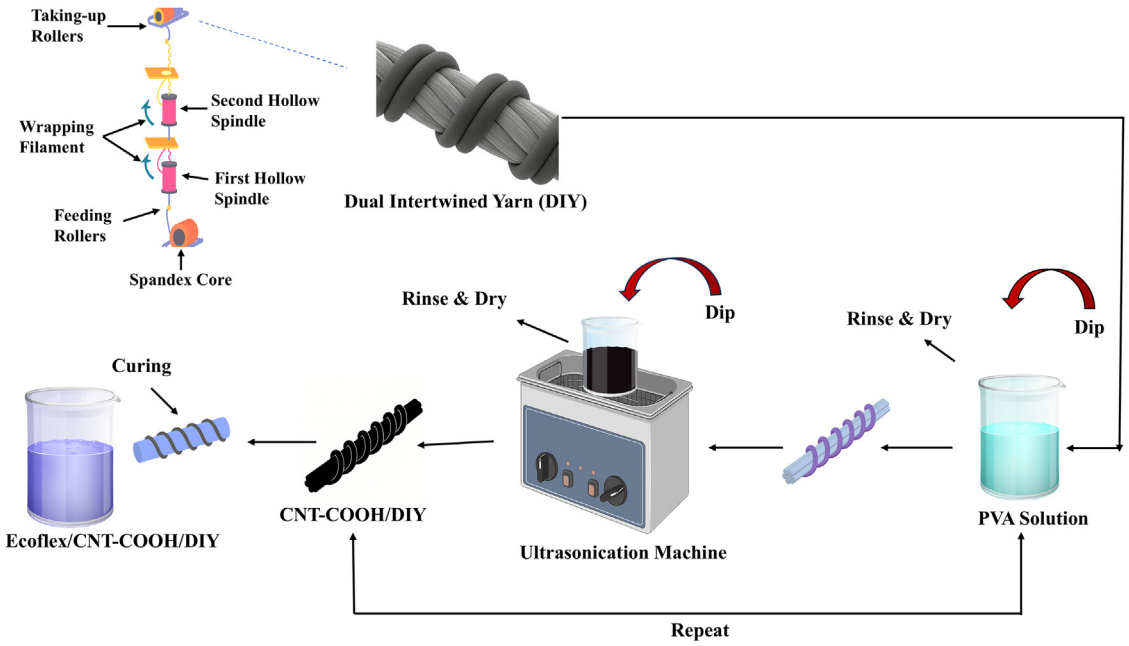

Fig. 1. Schematic representation of the fabrication process for CNT-COOH/DIY and Ecoflex/CNT-COOH/DIY strain sensors, including sequential preparation of the DIY structure and sensor assembly.

2.5. Characterization

A scanning electron microscope (SEM), Hitachi S-4800, was deployed to gather information regarding the surface morphologies of the DIY strain sensors. A digital voltage meter was used to measure the initial electrical resistance (R_n) of the CNT-COOH/DIY strain sensor before performing mechanical tests at ambient conditions. According to the results of the five samples, the sensors had a consistent baseline electrical performance with an average initial resistance of around 5000 kΩ. The electrical signals from the tensile strain sensors were recorded on an Agilent 34970A (Agilent Technologies, Inc., USA). The strain sensors were mounted on a universal material testing equipment (Zwick, Z050) to apply strain. The cyclic tensile trials were carried out at a speed of 500 mm/min. The selected speed of 500 mm/min ensures performance stability while also allowing for minimum sensor relaxation.

3. Results and discussion

Fig. 1 illustrates the fabrication of the CNT-COOH/DIY strain sensor, which combines a dual-intertwined yarn structure with a substantially conductive CNT network to provide mechanical flexibility and reliable electrical pathways. This architecture, combined with elastomeric encapsulation, enables a durable electromechanical connection during tensile deformation.

The SEM characteristics and dispersion arrangement of CNT-COOH and their composite with Ecoflex elastomer are illustrated in Fig. 2. Figs. 2(a)(b) show the CNT-COOH coating on the DIY surface at the provided magnification, revealing a continuous layer with no visible large-scale aggregates. The absence of surfactants in the dispersion process is facilitated by the carboxyl (-COOH) groups on the surface of the CNTs. These polar functional groups augment the hydrophilicity of CNTs and induce electrostatic repulsion, effectively counteracting the intrinsic van der Waals attraction forces between individual nanotubes [29]. Consequently, CNT-COOH exists in a dependable, well-dispersed colloidal state, which is essential for further composite fabrication. Figs. 2(c)(d) depict the cross-sectional morphologies of pristine CNT-COOH and Ecoflex/CNT-COOH composite, respectively, with insets showing internal microstructures. In Fig. 2(c), CNT-COOH reveals an entangled, porous network characterized by a loosely bonded structure with open channels, typical of dried CNT films. Conversely, Fig. 2(d) illustrates the cross-sectional morphology of Ecoflex/CNT-COOH, wherein the CNTs appear well-integrated within the dense elastomer matrix without observable phase separation at this magnification. While the magnification of these SEM images is insufficient to detect individual CNTs, the reported microscale features confirm the formation of a continuous conducting network without visible aggregation, which is required for reliable piezoresistive performance. This integration suggests compatibility between functionalized CNTs and polymer chains. The carboxylated CNTs establish percolating conductive networks throughout the structure of the DIY due to their elevated aspect ratio and consistent dispersion. When applied to the yarn surface or included in a polymeric matrix such as Ecoflex, these CNTs create continuous routes for efficient electron conduction. The elastomeric matrix maintains network shape during mechanical deformation. Interfacial contact between CNTs and yarn fibers enhances conductive junction density and electron hopping sites, thereby improving conductivity, mechanical strength, and strain sensitivity. This configuration underscores the promise of CNT-COOH/Ecoflex composites for wearable electronic textiles.

The dynamic electromechanical response of the CNT-COOH/DIY strain sensor to cyclic tensile strain ranging from 10% to 60% is repeatedly demonstrated in Fig. 3. The sensor exhibits consistent and discrete resistance changes across 10%–60% strain, demonstrating reliable piezoresistive functionality. The sensor shows a gradual and sharp rise in resistance with each stretching cycle in the low-to-moderate strain range of 10%–40%. This is because the CNT-COOH conductive networks distributed on the DIY surface gradually form microcracks, reorient, and partially disconnect. The electron transport channels are modulated by these structural disruptions, which cause a high sensitivity to mechanical deformation by increasing tunneling resistance and varying the inter-tube gap. A calculated GF of 11.40 reflects this tendency, suggesting a significant strain-sensing response. The investigated CNT-COOH/DIY-based sensor shows much improved sensitivity and strain response relative to other reported sensors [30]. The formula for GF= $\frac{\Delta R/R_0}{\epsilon}$, where ΔR is the change in resistance under strain, R_0 is the initial resistance of the sensor, and ϵ is the applied tensile strain. For applications requiring high levels of precision in sensing, a higher GF indicates a more responsive material to strain. As the strain increases from 40% to 60%,

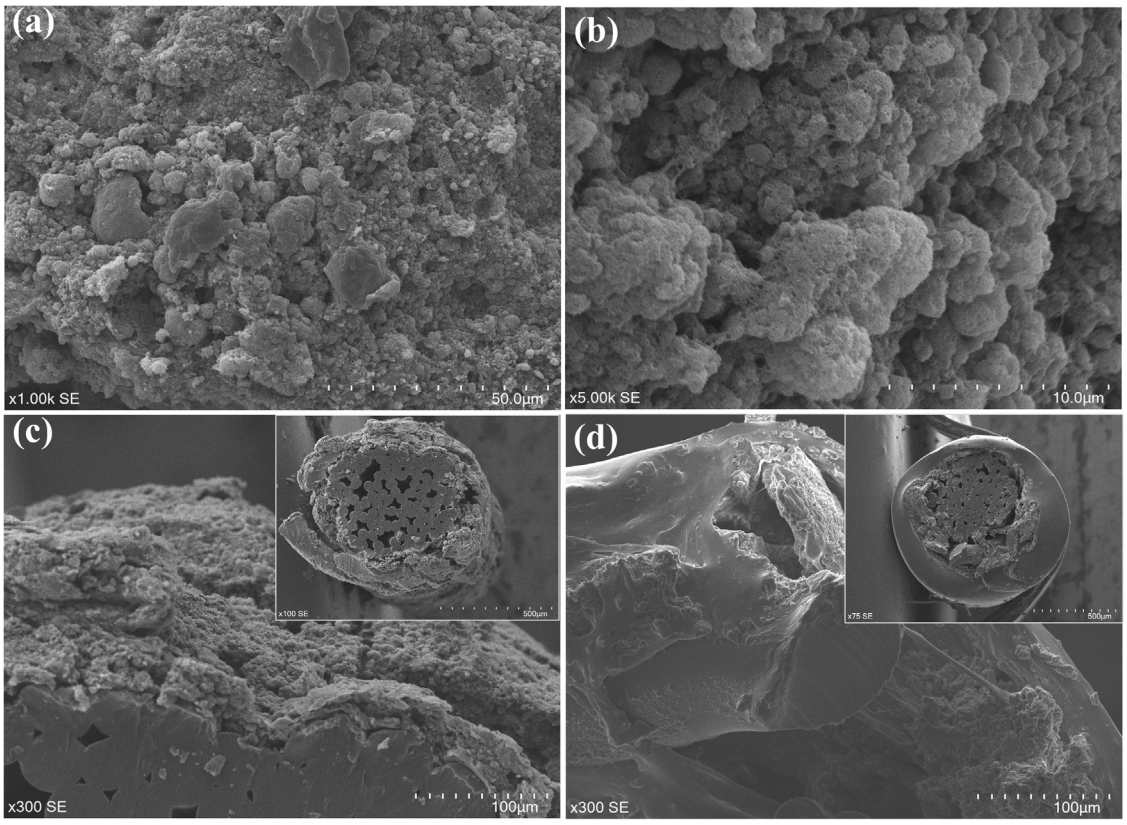

Fig. 2. SEM images of the sensors. (a)(b) CNT-COOH coating on the DIY surface at the provided magnification, revealing a continuous layer with no visible large-scale aggregates. (c) Cross-sectional image of CNT-COOH. (d) Cross-sectional image of Ecoflex/CNT-COOH composite showing CNT incorporation within the elastomer matrix; insets in (c) and (d) show internal microstructures.

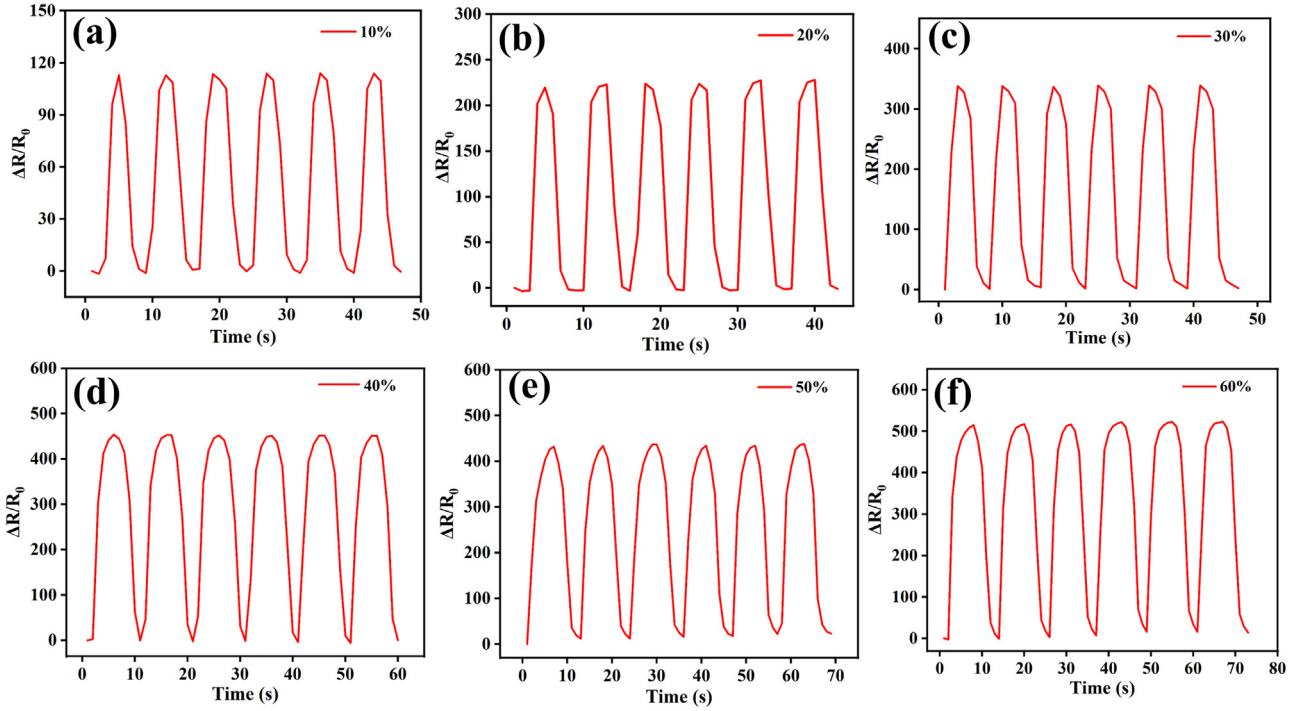

Fig. 3. CNT-COOH/DIY strain sensor's dynamic response behavior to repeated stretching and releasing at different strain levels. Real-time resistance variations show the sensor's repeatability, mechanical integrity, and piezoresistive performance over a strain range of 10% to 60%.

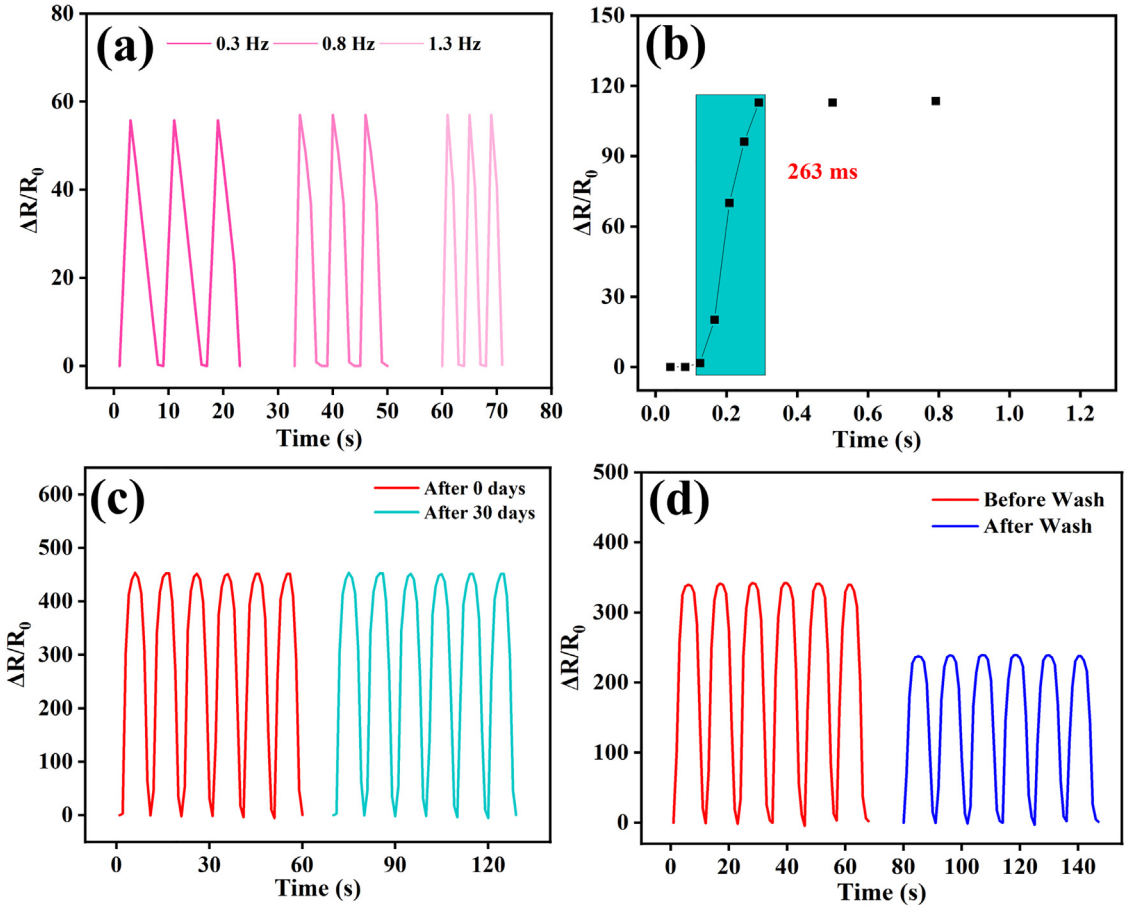

Fig. 4. Strain sensors' performance characterization. (a) Show the frequency-dependent resistance change of the CNT-COOH/DIY sensor under 5% strain at various stretching frequencies. (b) The sensor's response time under 10% strain. (c) environmental stability test of the CNT-COOH/DIY strain sensor under 30 days of storage at 40% strain (d) Washability testing of the Ecoflex/CNT-COOH/DIY sensor after 10 ultrasonic washing cycles.

the sensor still shows consistent and reversible resistance variations, but the relative resistance fluctuation is less steep, yielding a lower GF of 8.75. This GF reduction stems from partial stabilization and saturation of the conductive CNT network, where most substantial conductive disconnections have already occurred at lower strains. Additional stretching primarily causes elastic deformation or rearrangement of the already-stretched network, with new conductive gap formation contributing less to sensitivity changes. Nevertheless, the sensor remains highly resilient, demonstrating excellent mechanical integrity and dependable performance across a wide deformation spectrum. The CNT-COOH/DIY sensor's electrical conductivity (σ) was determined to be 6.03×10^{-3} S/m by applying the equation $\sigma = \frac{L}{R_0 A}$ where, L is the effective length of the conductive path, R_0 is the measured resistance, and A is the cross-sectional area of the sensing region. The reported electrical conductivity 6.03×10^{-3} S/m is less than that of highly conductive CNT-based yarns for electrical transmission, yet this range is optimal for piezoresistive strain sensing. In such sensors, signal generation is driven by deformation-related changes in conductive pathways, such as changes in tunneling resistance and microcrack evolution, rather than by high charge-transport efficiency. Excessive conductivity can reduce $\Delta R/R_n$, reducing GF and sensitivity [31]. Thus, the measured conductivity indicates a balanced conductive network that enables steady signal transmission while preserving high strain sensitivity. This electromechanical transition enables strain detection, as resistance changes reflect applied mechanical deformation in real time. The conductivity remains intact even after repeated stretching due to the CNT-COOH coating's excellent conformability and adhesion to the DIY surface, and strain accommodation is made possible by the DIY structure, which is both flexible and supportive. Overall, it shows that the sensor suits next-generation wearable electronics and motion monitoring due to its high sensitivity, durability, and reliable signal output across a wide strain range.

The CNT-COOH/DIY strain sensor's washability, response characteristics, and dynamic performance under various mechanical scenarios that are essential for wearable sensing platforms are comprehensively examined in Fig. 4. In order to test the sensor in deformation scenarios typical of wearable devices, we purposefully chose a range of strain values. The sensitivity to minor human motions was tested with a 5% strain, whereas response-time measurement was done with a 10% strain to ensure consistent step loading. The cyclic durability and washing stability tests were conducted with a normal working strain of 30% to mimic real-world joint movements. In contrast, the environmental stability evaluation was conducted under more rigorous deformation conditions with a significantly larger strain of 40%. Under a 5% strain, Fig. 4(a) shows the sensor's real-time resistance response at three separate frequencies: 0.3, 0.8, and 1.3 Hz. The sensor produces clear, periodic, repeatable resistance signals across all frequencies without baseline drift or distortion, demonstrating excellent frequency responsiveness and signal fidelity. This reproducible performance across different actuation speeds confirms the sensor's capacity to capture both slow and fast human motions for physiological monitoring and dynamic body motion tracking. The sensor's response time, a critical characteristic for real-time sensing capability, was determined through sudden 10% strain application, as shown in Fig. 4(b). Response time was measured from the resistance-time curve by quantitatively extracting the interval between strain application and when resistance reached 90% of the peak value (ΔR). This widely employed technique accurately por-

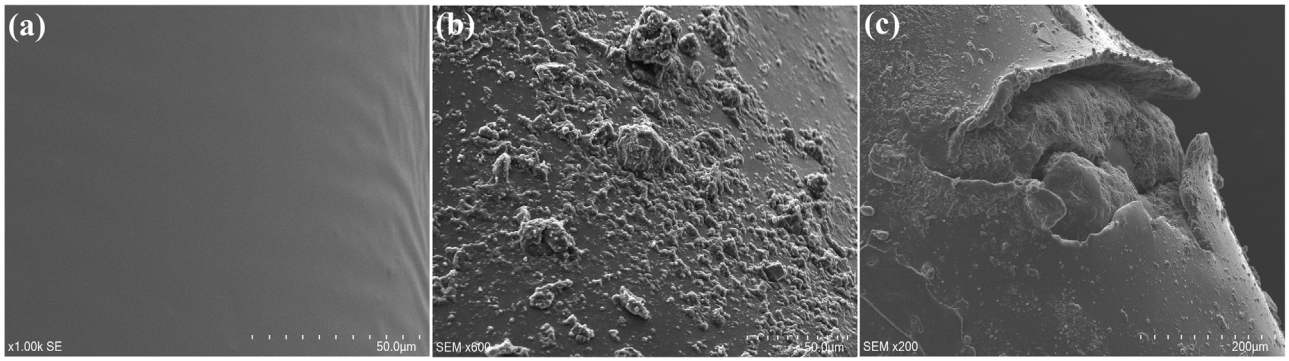

Fig. 5. The surface morphology of the Ecoflex/CNT-COOH/DIY sensor was examined using SEM (a) before washing, showing a uniform and smooth Ecoflex coating; (b) after washing, showing surface roughening and partial disruption; and (c) Ecoflex/CNT-COOH/DIY sensor following washing, showing scattered conductive regions and minor breakdown to the network.

trays piezoresistive sensor response velocity [32,33]. Indicative of its ability to effectively convert mechanical input into a discernible electrical output, the CNT-COOH/DIY sensor had a response time of only 263 ms. A variety of interrelated physical mechanisms lead to this reaction time. To start with, the piezoresistive sensing method is based on the dynamic rebuilding of the CNT percolation network. This process involves a finite amount of time for the conductive junctions and tunneling gaps to re-establish electrical contacts after strain release [34]. Additionally, the mechanical hysteresis and interfacial friction between the textile substrate and CNT coating further hinder structural recovery. Finally, the response time is limited to 263 ms due to the effective reorganization of the CNT-COOH conductive network and strong interfacial adhesion between the nanotubes and the DIY substrate, which reduces extra mechanical lag and hysteresis [35]. These combined effects determine the overall temporal response. Due to this moderate response speed, the sensor is well suited for monitoring typical human joint movements but may be limited in detecting high-frequency mechanical vibrations or extremely rapid motions. The environmental stability of the CNT-COOH/DIY strain sensor over a long-term storage trial is displayed in Fig. 4(c). After 0 days, the sensor was tested at 40% strain, and 30 days later, it was checked once more. There was no discernible decline in sensing performance, as evidenced by the constant resistance change profiles. This outcome demonstrates long-term environmental durability, making the sensor appropriate for extended wearable applications. Fig. 4(d) shows the Ecoflex/CNT-COOH/DIY sensor's washability with an elastomeric encapsulating layer to protect the conducting network. The washing test involved putting the Ecoflex/CNT-COOH/DIY sensor through 10 ultrasonic rinse cycles in a Jac 4020 ultrasonic bath to simulate severe cleaning conditions. Each cycle entailed submerging the sensor in DI water at 30 °C, employing ultrasonic high-frequency and power for 10 min. After cycles, the sensor was cleaned with DI water and subsequently dried in an oven at 60 °C. The selected parameters were chosen to replicate authentic laundry procedures while maintaining reproducibility, with frequency, power, and temperature regulated to optimize cleaning efficacy and sensor integrity. While ultrasonic washing can be used to quickly and accurately assess coating stability in the presence of cavitation and strong agitation, it is not yet capable of fully simulating the complex mechanical stresses found in typical home washing machines. These stresses include tumbling, twisting, abrasion, and load-dependent deformation. These multi-directional stresses may affect the sensor's longevity in real-world washing processes, particularly in top- and front-loading machines. Since actual washing circumstances cannot be fully replicated in this study, the results are mostly indicative of the conductive coating's inherent adhesive strength. Further evaluation of wearable performance in actual usage scenarios will be carried out in future research through comprehensive validation in washing machines.

To analyze the changes in surface morphology, Fig. 5 displays SEM taken before and after ultrasonic cleaning of the Ecoflex/CNT-COOH/DIY sensor. In Fig. 5(a), the sensor is shown before washing. Its Ecoflex surface is smooth and uniform, showing that the elastomeric coating is well-formed and continuous, completely encasing the conductive yarn. After 10 cycles of ultrasonic washing, the Ecoflex surface becomes visibly rough and uneven as a result of micro-scale abrasion and surface deformation caused by repeated ultrasonic cavitation and mechanical agitation shows in Fig. 5(b). Following washing, Fig. 5(c) shows scattered and locally disrupted Ecoflex patches, which may indicate microstructural disturbance and partial redistribution of the elastomer due to sustained ultrasonic stress. There is a decrease in sensing performance after washing because these surface degradations compromise the encapsulating conductive network, which in turn increases contact resistance. Despite this, the sensor retained fundamental functionality after washing; however, its relative resistance response decreased, indicating partial sensing layer deterioration [36]. This loss is attributed to microstructural fatigue, weakly bound CNT separation, and mechanical strain at the sensor-yarn interface. The reduction in GF after repeated washing may result from damage to CNT percolation pathways and loss of uniform electrical contact. These findings emphasize the importance of careful washing techniques even with encapsulation. Although Ecoflex provides protection, extreme or prolonged mechanical agitation, such as ultrasonic washing, can still compromise sensor performance and sensitivity. Therefore, to minimize mechanical stress and preserve functionality, the Ecoflex/CNT-COOH/DIY sensor should be cleaned gently. Future research will explore multilayer Ecoflex coatings via dip-coating to enhance washability while maintaining scalability.

The cyclic durability of the CNT-COOH/DIY sensor over the long term is shown in Fig. 6. The CNT-COOH/DIY sensor shown in Fig. 6(a) and the Ecoflex/CNT-COOH/DIY sensor shown in Fig. 6(b) strain sensors were tested for long-term durability to see how well they withstand repeated deformation over an extended period. Both sensors were tested for cyclic performance by putting them through 2000 cycles of stretching and releasing at 30% strain and a constant loading rate of 500 mm/min. To improve mechanical support and reduce fatigue-related degradation during high-cycle operation, Ecoflex encapsulation was employed. At the beginning of the cyclic test, the relative resistance change ($\Delta R/R_0$) exhibited a minimal decrease with increasing cycle count, indicating that the conductive network within the sensor yarn remains highly stable. The cyclic durability of the sensor was further assessed quantitatively by comparing the peak resistance variation between the first and last cycles. Over 2000 continuous stretching-releasing cycles at 30% strain, the sensor's peak resistance increased by approximately 25%, indicating moderate fatigue of the conductive network caused by repeated mechanical loading. The key causes of this attenuation include the slow development of microcracks, partial slippage between the yarn substrate and conductive nanotubes, and the incremental destruction of conductive pathways carried on by cyclic tension [37–39]. Over time, these microstructural alterations raise

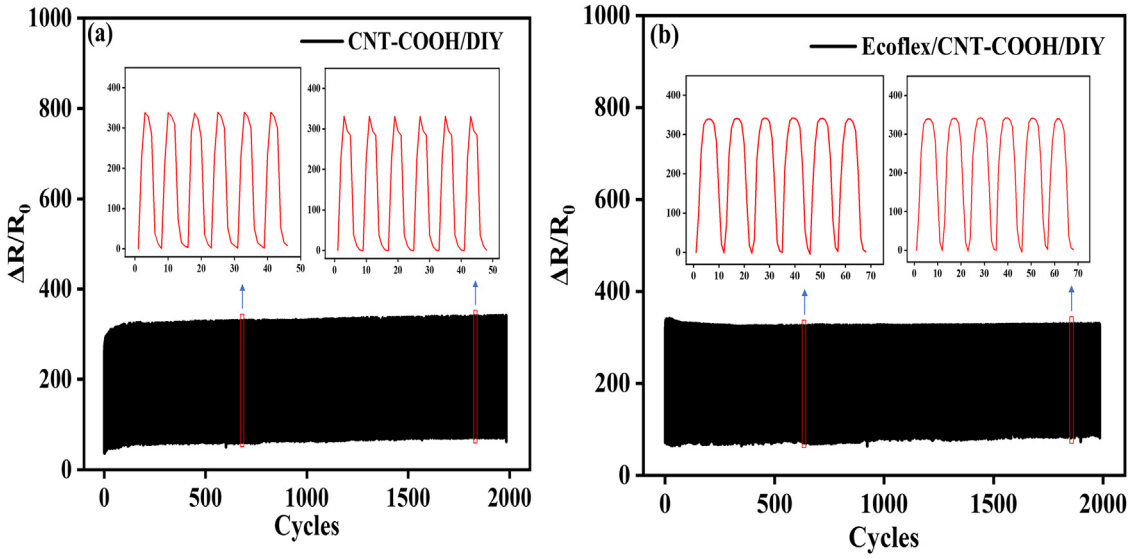

Fig. 6. Long-term cycle durability testing. (a) CNT-COOH/DIY sensors under continuous mechanical loading over 2000 stretching/releasing cycles at 30% strain, (b) Ecoflex/CNT-COOH/DIY under continuous mechanical loading over 2000 stretching/releasing cycles at 30% strain.

Table 1
Performance comparison of recently reported yarn-based strain sensors with the proposed Ecoflex/CNT-COOH/DIY sensor.

Sensitive materials	Strain range (%)	GF	Response time (ms)	Durability (cycles)	References
AgNPs/DCY	50	10.00	24	500	[42]
Liquid metal/elastomer fiber	50	1.90	124	500	[43]
LM/CNT-coated polyester yarn	300	6.73	N/A	1000	[44]
CNF/Ecoflex	130	307.00	<400	1000	[45]
CNT-COOH/Ecoflex	60	11.40	263	2000	This work

contact resistance and lower charge transport efficiency. Despite this variation, the sensor maintained steady and reproducible signal patterns throughout the test, confirming its preserved sensing performance and mechanical robustness. In Contrast, the Ecoflex/CNT-COOH/DIY strain sensor showed minimal variation in baseline or peak resistance values throughout 2000 cycles. Encasing the sensor yarn in Ecoflex improved its durability and repeatability under cyclic loading and decreased peak deterioration. The enlarged view of cycles 1500–2000, Fig. 6(b), reveals consistent resistance fluctuations without noticeable degradation, indicating stable strain-sensing capability over the entire test duration. These results demonstrate that Ecoflex encapsulation significantly enhances the durability and reliability of the CNT-COOH/DIY strain sensor. Previous research on yarn-based strain sensors found that they were not as resilient or durable as the Ecoflex/CNT-COOH/DIY sensor when subjected to long-term cyclic loading [40,41]. The Ecoflex layer improves mechanical integrity and long-term performance by serving as a soft, elastic matrix that evenly distributes mechanical stress while reducing localized strain on the conducting network. Its superior adherence to the yarn substrate and conductive materials prevents delamination or fracture after repetitive deformation. As a result, over 2000 stretching cycles at 30% strain, the Ecoflex/CNT-COOH/DIY sensor shows negligible signal degradation, indicating stable electrical performance over time. These findings support its suitability for wearable, flexible strain-sensing systems that require resistance to repetitive mechanical stress while maintaining structural reliability.

Table 1 presents a detailed comparison of the CNT-COOH/DIY sensor with other yarn-based strain sensors reported in the past five years, highlighting key performance characteristics and differences. The AgNPs/DCY sensor exhibits a fast response time of 24 ms and a GF of 10; however, its durability is limited to 500 cycles. Similarly, the liquid metal-based yarn sensor shows a low GF of 1.9 and a response time of 124 ms, but also suffers from low cyclic stability. Although its temporal reaction was not reported, the LM/CNT-coated polyester yarn sensor offers a wide strain range of 300% and stable operation over 1000 cycles only. The CNF/Ecoflex sensor features a large strain range of 130%, exceptionally high sensitivity, and a prolonged response rate below 400 ms. In comparison, the CNT-COOH/DIY sensor achieves a superior balance of sensitivity (GF of 11.4 within 10%–40% strain), response time (263 ms), and robust durability after Ecoflex encapsulation (2000 cycles). This combination of sensitivity, responsiveness, and mechanical stability makes it a promising candidate for wearable strain-sensing applications.

The final manufactured sensor was enclosed in Ecoflex, which preserved its small profile and high flexibility, enabling it to be directly contacted by the skin. Ecoflex's great flexibility, skin-like softness, and biological compatibility make it effective for long-term use. Validating its suitability for skin-close wearable applications, the sensor adhered well to curved surfaces through practical demonstrations on parts such as the wrist, elbow, and knee, without restricting mobility or causing irritation. The Ecoflex/CNT-COOH/DIY strain sensor is used to measure joint motion on various body parts, as seen in Fig. 7. The objective here was to test how the sensor signals fared under actual dynamic conditions in terms of their stability, adaptability, and conformability. The Ecoflex encapsulation provides mechanical support without compromising sensor stretchiness or skin adherence; as a result, it is safe to apply directly to human joints without limiting movement. Figs. 7(a)(b) depict the Ecoflex/CNT-COOH/DIY sensor positioning on various body joints, showcasing its integration versatility for smart textile applications. Fig. 7(c) shows the sensor attached to the finger joint, which accurately measures the changing resistance during repeated bending and stretching. The reproducible and clear resistance changes demonstrate high sensitivity to very small finger movements. The wrist-mounted sensor, shown in Fig. 7(d), observes small angular movements with a big output signal. Its application for low-strain monitoring is made possi-

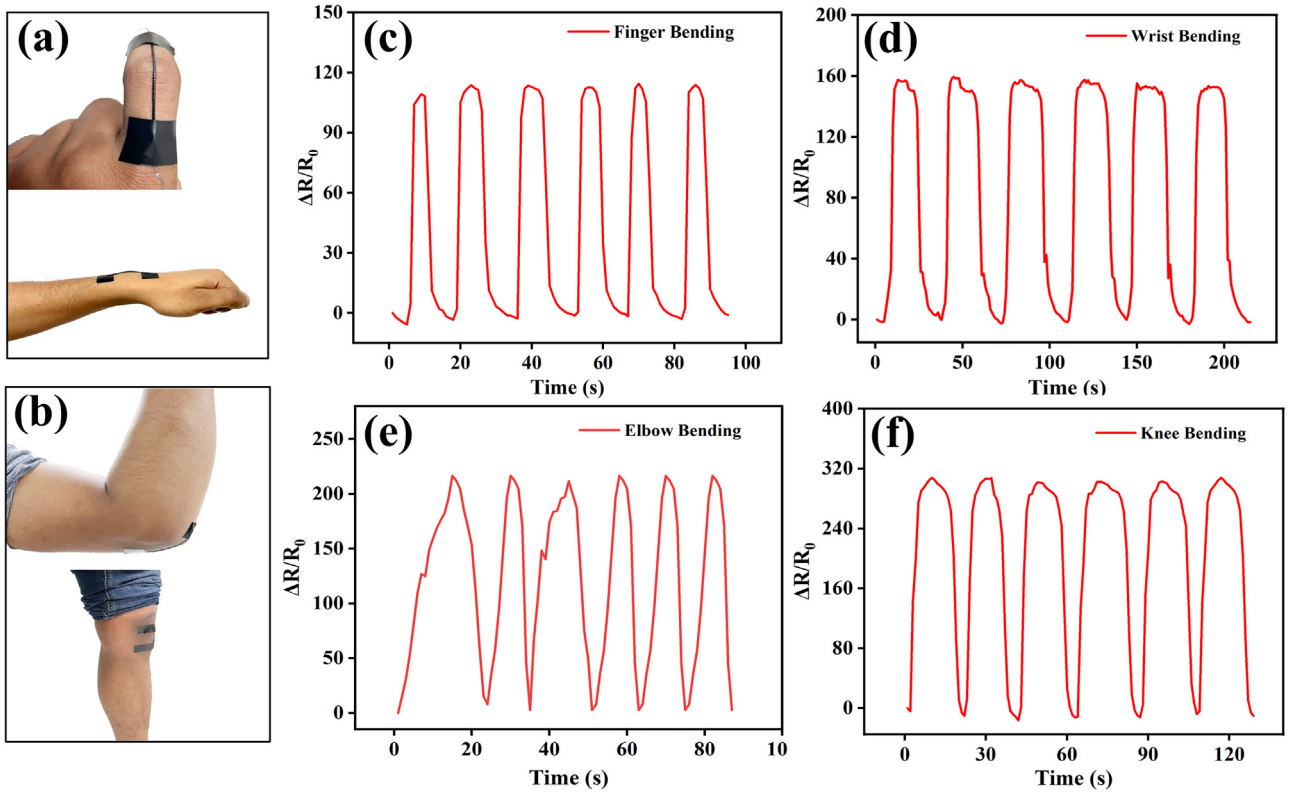

Fig. 7. Ecoflex/CNT-COOH/DIY strain sensor performance in real-time human motion monitoring. (a)(b) Images showing sensor placement on the finger, wrist, elbow, and knee. (c) Finger motion detection, demonstrating sensitivity to low-strain deformations. (d) Wrist motion monitoring, verifying consistent signal response to mild joint movement. (e) Elbow motion monitoring, showing steady resistance changes during continuous bending. (f) Knee motion detection, reliably measuring lower limb movements.

ble by its sticky conformation on curved skin surfaces and sensitivity to low-amplitude deformations. Fig. 7(e) shows the sensor positioned at the elbow, allowing it to go through cycles of moderate-range flexion and extension. Showing that the sensor is sensitive to modest strain, the resistance response to elbow motion is continuous and quick. However, a minor asymmetry is detected in the third cycle. This occurrence can be ascribed to the viscoelastic characteristics of the Ecoflex encapsulation, which generate varying relaxation rates during the stretching and releasing phases [46]. The dynamic reconfiguration of the CNT conductive network may not be entirely reversible during the cycle period, resulting in some fluctuations in peak resistance values. The mechanical hysteresis at the interface between the CNT coating and the DIY substrate may potentially contribute to this asymmetrical behavior [47]. Although this little asymmetry, the sensor exhibits reliable overall performance across multiple cycles, validating its appropriateness for continuous human motion monitoring. Fig. 7(f) shows the sensor in action at the knee joint, which is a high-strain, high-flexion area. The sensor detects substantial deformations as a result of knee flexion, and there is no trace of mechanical failure, delamination, or considerable signal drift after multiple cycles. Across all four uses, the Ecoflex/CNT-COOH/DIY sensor shows outstanding mechanical compliance, signal stability, and sensitivity to small and large joint movements. These combined attributes position it as a promising candidate for gesture control systems, wearable health monitoring, rehabilitation tracking, and real-time movement detection.

4. Conclusion

In summary, we developed a new, flexible, and wearable yarn-based strain sensor utilizing a DIY configuration, wherein a spandex core is helically double-wrapped with nylon monofilaments through a scalable, automated process. This distinctive structure was functionalized using a cost-effective, surfactant-free layer-by-layer assembly of MWCNT-COOH, ensuring excellent dispersion and mighty interfacial bonding, resulting in a highly conductive network with a conductivity of 6.03×10^{-3} S/m. The sensor exhibited outstanding strain-responsive behavior, with a GF of 11.40 (10%–40% strain) and 8.75 (40%–60% strain), a response time of 263 ms. Ecoflex encapsulation layer enhanced the DIY structure's mechanical strength and resilience. Long-term durability testing of the Ecoflex/CNT-COOH/DIY sensor confirmed consistent performance over 2000 cycles at 30% strain, demonstrating long-term robustness. Finally, real-time human motion monitoring showed consistent signal output and versatile motion detection, promising applications in smart textiles and healthcare. Future efforts will focus on enhancing washability through cost-effective encapsulating strategies, incorporating wireless capabilities, and creating multi-sensor configurations to track complex motion and physiological signals, while maximizing scalability for industrial use.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Rezaul Karim Khan Alave: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Mahin Ahmed Shishir: Visualization, Investigation, Formal analysis, Data curation. **Sheikh Mohammad Rahat:** Visualization, Data curation. **Fazle Rabbe:** Visualization, Data curation. **Gazi Farhan Ishraque Toki:** Writing – review & editing, Formal analysis. **Jiyong Hu:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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