



Axially decoupled multidirectional stretchable strain sensor based on plain-woven carbon nanotube-infiltrated rubber nanocomposites

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Abstract

Accurately sensing the direction and magnitude of strain is essential for decoding complex mechanical deformations, particularly in human-centered wearable technologies. However, conventional technologies based on orthogonally arranged strain sensors fixed on soft substrates inevitably suffer from mechano-electrical coupling between sensing axes, which complicates signal interpretation. In this study, we developed a plain-woven strain sensor composed of piezoresistive rubber nanocomposite strips that achieves exceptionally low axial crosstalk while maintaining high sensitivity and stretchability. The orthogonally interlaced structure enabled mechanical decoupling between sensing axes, resulting in an on-to-off-axis sensitivity ratio of 1446.8. The nanocomposite forming the woven sensing architecture was prepared by infiltrating a swollen rubber matrix with multiwalled carbon nanotubes, resulting in a percolation network beneath the rubber surface while preserving the inherent mechanical properties of natural rubber, including its low elastic modulus and high stretchability. As a result, plain-woven nanocomposite bands exhibited gauge factors of 3.9, 13.4, and 30.5 in the strain ranges of 0–150%, 150–300%, and 300–500%, respectively, with stable cycling performance. The utility of the multidirectional strain sensor was evaluated through glove-based finger gesture recognition and sleeve-based knee joint monitoring. The sensor exhibited accurate decoupling of the strain magnitude and direction, demonstrating its suitability for next-generation wearable bio-mechanical feedback systems.

Keywords Nanocomposite · Carbon nanotubes · Stretchable sensor · Multidirectional strain sensing · Low crosstalk

1 Introduction

Strain sensors, which convert mechanical deformation into electrical signals, are widely used in various industrial applications. However, conventional strain sensors exhibit low sensitivities and narrow detection ranges owing to the intrinsic rigidity of the constituent materials. In recent decades, advancements in nanoscale materials and structures have enabled the development of highly sensitive strain sensors,

characterized by high gauge factors (GFs) [1–6]. Soft strain sensors have been developed by integrating nanomaterials with flexible or stretchable elastomers, enabling precise strain measurements over a broad deformation range [2, 5, 7–9]. As a result, soft strain sensors have become indispensable components of wearable electronics, enabling the accurate detection of diverse human motions, from subtle physiological activities (e.g., pulse monitoring, speech recognition, and respiration) to large-scale movements (e.g., joint motions) [6–10]. These demands highlight the need for strain sensors that combine high sensitivity, a broad sensing range, low detection limits, and long-term durability.

Conductive polymer composites have been extensively investigated for resistive-type stretchable strain sensors owing to their exceptional elasticity and high mechanical compliance [11–18]. These sensors operate based on a percolation network of conductive materials, which are either deposited onto or embedded within a polymer matrix, resulting in measurable changes in electrical resistance in response to mechanical deformation. Typical integration

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methods involve the solution-based coating of functional materials or the transfer of structured films onto polymer substrates [12–15, 19]. These approaches are favored for their compatibility with various functional materials and ability to produce sensors with high GF. However, typical sensors suffer from poor stability and a limited sensing range, primarily due to mechanical mismatches at the interfaces (e.g., significant differences in elastic modulus), resulting in weak adhesion between the conductive materials and the polymeric substrate [14, 20–23]. Another approach is to uniformly disperse conductive fillers within the polymer matrix to enhance miscibility [16–18]. This method ensures homogeneous electrical conductivity throughout the composite. However, the incorporation of conductive fillers often compromises the mechanical properties of the elastomer substrate, leading to increased stiffness and reduced elongation [18, 24, 25]. Therefore, the development of conductive composites with strong interfacial adhesion between the fillers and polymer matrix is crucial for achieving high strain sensitivity and stability while preserving the low modulus and high stretchability of the polymer matrix.

For biomedical applications, such as healthcare monitoring and daily motion tracking, stretchable strain sensors must exhibit multi-axial sensing capabilities while minimizing off-axis interference, as human body movements generate multidirectional strain stimuli [26–30]. The conventional method for obtaining multi-axial strain data, including direction and magnitude, uses rosette strain gauges, in which two or more strain sensors are arranged in predefined orientations [31, 32]. However, the small separation between individual sensors in the in-plane configuration limits the sensor to localized strain measurements. An alternative structure is an out-of-plane stacked architecture, in which multiple strain-sensing layers are vertically assembled to detect multi-axial strain at a specific point [26, 29, 33–36]. However, this structure imparts unavoidable mechanical coupling between the layers, resulting in significant signal interference between the integrated strain sensors. Moreover, both in-plane and out-of-plane sensor designs are typically affixed to the skin or rigid accessories such as wristbands, which could be uncomfortable for the user [26, 29, 30].

For practical strain sensing in daily life, integrating strain sensors into highly elastic textiles is of great interest, as they can be comfortably worn to various body parts [8, 37]. These sensors can be seamlessly incorporated into wearable electronics by being woven into fabrics or used as a liner in clothing, ensuring user comfort. In this study, we fabricated a multidirectional strain sensor with minimal axial cross-talk using plain-woven rubber nanocomposites. To enhance sensing performance and ensure the stability of the nanocomposites, carbon nanotubes (CNTs) were infiltrated into natural rubber (commercial rubber bands) using a solution-based process optimized using Hansen Solubility Parameters

(HSP). The CNTs infiltrated only a few tens of micrometers below the rubber surface, forming a percolation network that endowed high strain sensitivity while preserving the intrinsically low modulus and high stretchability of the rubber. Consequently, the rubber nanocomposites exhibited a stable and monotonic response, achieving a GF of 30.5 over a wide strain range (up to 500%) without noticeable degradation. Furthermore, multidirectional strain sensors were developed by plain weaving CNT–rubber nanocomposite, which achieved an exceptional on-axis to off-axis GF ratio of up to 1446.8 over a wide strain range of 400%, significantly outperforming previously reported multidirectional sensors. The woven nanocomposites were integrated with textiles, including gloves for detecting subtle finger flexion and athletic knee sleeves for detecting large joint movements, thereby demonstrating the biaxial sensing of human bodily motions without off-axial signal interference.

2 Experimental section

2.1 Materials

Natural rubber bands were purchased from Dongyang Gomu Corporation, Republic of Korea. Toluene and dimethylformamide (DMF) were obtained from SK Chemical Daejeong Corporation, Republic of Korea. Multiwalled CNTs with a diameter of ~8 nm and length of ~10–30 μm were purchased from Beijing Ding Sheng Xiong Di Technology Corporation, People's Republic of China. All materials and chemicals were used as received without further purification.

2.2 Preparation of nanocomposites

We prepared the CNT dispersions by mixing dimethylformamide (DMF) and deionized (DI) water at volume ratios of 1:0, 1:1, 1:2, 1:3, and 1:4, followed by magnetic stirring at 500 rpm for 2 h. CNT powders of 40 and 200 mg (corresponding to 0.2 and 1.0 mg/mL, respectively) were then added and dispersed by ultrasonication with an energy density of 1 kJ/mL.

In parallel, natural rubber bands were swollen in 50 mL of toluene and treated with bath sonication for 10 min in order to sufficiently expand the rubber matrix and create free spaces for CNT infiltration. The swollen rubber bands were then immersed in the CNT dispersions and subjected to overnight bath sonication for 9 h to facilitate CNT infiltration into the rubber. Finally, the CNT-infiltrated rubber bands were dried in an oven at 60 $^{\circ}\text{C}$ for 6 h, rinsed with isopropyl alcohol, and dried again. Upon drying, the rubber contracted and confined the CNTs within the matrix, forming a stable conductive layer near the surface. To fabricate multidirectional strain sensors, individual nanocomposites—prepared

by cutting CNT-infiltrated rubber—were manually plain-woven to form a mesh of interlaced horizontal and vertical bands with a typical warp/weft structure. Each nanocomposite strip, with dimensions of 50 mm in length and 1 mm × 1 mm in cross-sectional area, was fixed at both ends together with electrodes to ensure stable electrical connection and mechanical anchoring, yielding an effective sensing length of 40 mm defined by the electrode gap. In the woven sensor structure, individual strips were interlaced with a spacing of 2 mm, resulting in an overall sensor dimension of 50 mm × 50 mm.

2.3 Characterization

The morphology of the rubber nanocomposites was examined using field emission scanning electron microscopy (FE-SEM; Hitachi S-4800). Thermogravimetric analysis (TGA) was performed from 30 to 600 °C under a nitrogen atmosphere at a heating rate of 10 °C/min using an SDT Q600 system (TA Instruments). Raman spectra were collected by confocal Raman spectroscopy (NOST HEDA) measurements using a 532-nm laser at room temperature. X-ray photoelectron spectroscopy (XPS) spectra were recorded using a K-Alpha spectrometer (Thermo Fisher Scientific). The elemental composition of the nanocomposites was analyzed using energy dispersive spectroscopy (EDS; Oxford Instruments). The mechanical properties of the rubber nanocomposites were evaluated using a universal testing machine (Instron 3400) under uniaxial force at a stretching speed of

50 mm/min. Electromechanical properties and strain-sensing responses of the rubber nanocomposites were characterized by measuring resistance changes with a sourcemeter (Keithley 2634B) while applying tensile strain via the universal testing machine.

3 Results and discussion

Stretchable rubber nanocomposites were fabricated by swelling pristine natural rubber (polyisoprene) upon immersion in toluene, followed by infiltration of the swollen rubber matrix with CNTs from a DMF–water solution (Fig. 1a and b). This resulted in the formation of a percolation-network layer of CNTs with a thickness of ~35 µm beneath the rubber surface (Fig. 1c). Photographs at each processing step confirm the successful formation of CNT-based nanocomposites through rubber swelling, CNT infiltration, and drying (Fig. S1, Supplementary Information). To optimize the nanocomposite preparation process, HSPs were considered [38, 39]. The HSP values of the materials, listed in Table S1 (Supplementary Information), were used to calculate the energy–density distance (R_a) between the components using the following equation:

$$(R_a)^2 = 4(\delta_{D1} - \delta_{D2})^2 + (\delta_{P1} - \delta_{P2})^2 + (\delta_{H1} - \delta_{H2})^2$$

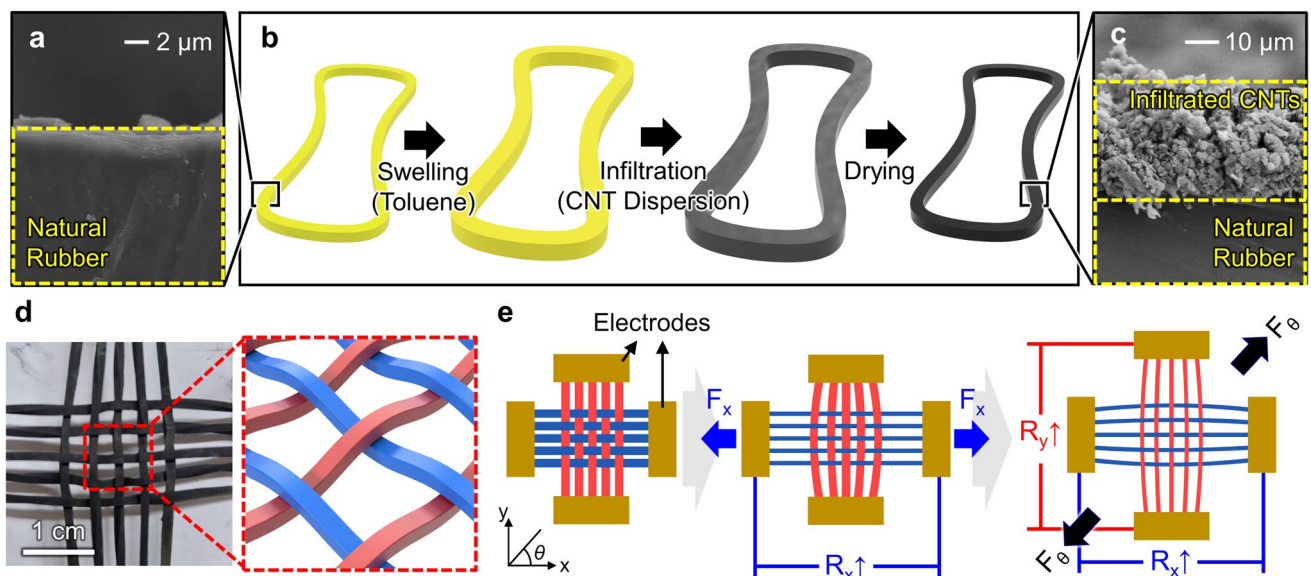


Fig. 1 Fabrication and structure of CNT-infiltrated rubber nanocomposites for multidirectional strain sensing. **a** Cross-sectional SEM image of pristine natural rubber. **b** Schematic of the fabrication process for CNT–rubber nanocomposite. **c** Cross-sectional SEM image of CNT-infiltrated rubber, showing CNTs localized underneath the

rubber surface with a thickness of ~35 µm. **d** Photograph and schematic of a plain-woven nanocomposite sensor. False colors are used to distinguish the weft and warp nanocomposite bands. **e** Concept of axially independent multidirectional strain sensing using the woven nanocomposites

Here, δ_D , δ_P , and δ_H are the dispersion, polar, and hydrogen-bond contributions to the cohesive energy density, respectively, and subscripts 1 and 2 refer to the different components. The low R_a value of $\sim 3.84 \text{ MPa}^{1/2}$ between toluene and natural rubber confirms the strong solubility of toluene in rubber, leading to an ~ 8.3 -fold volume expansion. This swelling creates abundant free spaces within the cross-linked rubber matrix, which is crucial for the subsequent infiltration of CNTs and the formation of a conductive network. A control experiment using non-swollen rubber further validates the necessity of this swelling step, as demonstrated by insufficient CNT infiltration into the rubber matrix (Fig. S2, Supplementary Information).

To facilitate CNT infiltration, the solvent composition for CNT dispersion was optimized. The CNTs (1.0 mg/mL) were dispersed in DMF–water mixtures with volume ratios of 1:0, 1:1, 1:2, and 1:3, followed by the immersion of swollen rubber samples in each dispersion overnight. After drying, it was observed that higher water fractions in the DMF–water mixture resulted in enhanced CNT infiltration into the rubber, despite the identical CNT concentrations in all dispersions (Fig. S3, Supplementary Information). This trend is further supported by HSP calculations. The high R_a value of $\sim 33.77 \text{ MPa}^{1/2}$ between the CNTs and 1:3 DMF–water mixture indicates poor dispersion stability. Conversely, the lower R_a value of $\sim 4.24 \text{ MPa}^{1/2}$ between the CNTs and natural rubber suggests strong compatibility, facilitating the homogeneous infiltration of CNTs into the rubber matrix. Based on these findings, a 1:3 DMF–water mixture was selected as the dispersion medium for CNTs in all subsequent experiments. Notably, increasing the water ratio to 1:4 resulted in an unstable dispersion exhibiting CNT aggregation (Fig. S4, Supplementary Information).

Figure 1d shows a multidirectional stretchable strain sensor fabricated by plain weaving rubber nanocomposite bands. The weaving process involved interlacing weft (horizontal) and warp (vertical) bands in a cross-axial pattern, forming a robust, free-standing structure. The spacing between individual rubber nanocomposite bands was $\sim 2 \text{ mm}$. As depicted in Fig. 1e, when uniaxial strain is applied along the horizontal axis ($\theta = 0^\circ$), the nanocomposites aligned in this direction undergo tensile deformation, leading to an increase in the electrical resistance. Importantly, the interlaced structure effectively minimizes cross-sensitivity in the off-axis direction owing to the slip between weft and warp strips [40, 41]. As a result, even under substantial deformation along the horizontal axis, the nanocomposites on orthogonal vertical axis experience only slight bending, which is insufficient to induce notable resistance changes in this direction. Unlike conventional strain sensors that suffer from inevitable cross-axis interference, the plain-woven nanocomposite bands can function as a multidirectional in-plane strain sensor, capable of quantitatively measuring

strain applied at arbitrary angles by analyzing the resistance changes along two orthogonal axes.

To determine the weight fraction of CNTs in the rubber nanocomposites, TGA was performed on two nanocomposite specimens prepared using CNT dispersions with concentrations of 0.2 and 1.0 mg/mL. Natural rubber was also measured as the control, prepared by swelling in toluene and immersion in the 1:3 DMF–water mixture without CNTs. Figure 2a presents the weight loss profiles of all three rubbers as a function of temperature. Since the CNTs are primarily localized beneath the rubber surface, the nanocomposites exhibit thermal degradation behavior similar to that of pristine rubber, with significant weight loss starting at $\sim 377^\circ\text{C}$. At temperatures above 450°C , where rubber chains undergo decomposition [42, 43], differences in residual weight were observed depending on the CNT dispersion concentration, as shown in Fig. 2b. These differences are attributed to the different CNT concentrations, given the high thermal stability of CNTs in the measured temperature range under a nitrogen atmosphere [44, 45]. Based on the TGA results, the estimated CNT weight fractions in the rubber matrix after immersion in 0.2 and 1.0 mg/mL CNT dispersions were 0.37 and 0.93 wt%, respectively. Since the CNTs are predominantly located beneath the rubber surface, a percolation network is effectively formed, even at CNT concentrations below 1 wt%, while preserving the inherent mechanical properties of natural rubber and endowing strain sensitivity.

Furthermore, we investigated the effect of infiltration time on CNT penetration depth. As shown in Fig. S5a (Supplementary Information), the resistance per unit length of the nanocomposites decreased with increasing infiltration time in the 0.2 mg/mL CNT dispersion, indicating greater CNT loading. Beyond 15 min, the resistance no longer decreased, suggesting saturation of the percolation network. Cross-sectional SEM images (Figs. S5b and S5c, Supplementary Information) confirmed this trend, showing penetration depths of $\sim 12 \mu\text{m}$ and $\sim 32 \mu\text{m}$ after 1 and 20 min of infiltration, respectively, which are consistent with the observed reduction in resistance.

We also examined the influence of rubber dimensions on CNT penetration. As shown in Fig. S6 (Supplementary Information), CNT–rubber composites with different cross-sectional areas ($1 \text{ mm} \times 1 \text{ mm}$ and $3.8 \text{ mm} \times 0.78 \text{ mm}$) exhibited similar CNT penetration depths of $\sim 32 \mu\text{m}$. These results indicate that CNT penetration depth is primarily governed by infiltration time rather than rubber dimensions. Therefore, adjusting the infiltration time provides a potential means of tuning sensing performance by regulating CNT penetration depth. Nevertheless, we found that combining an optimized CNT concentration (0.2–1.0 mg/mL) with sufficient infiltration time until saturation offers a more reproducible strategy for achieving stable CNT infiltration.

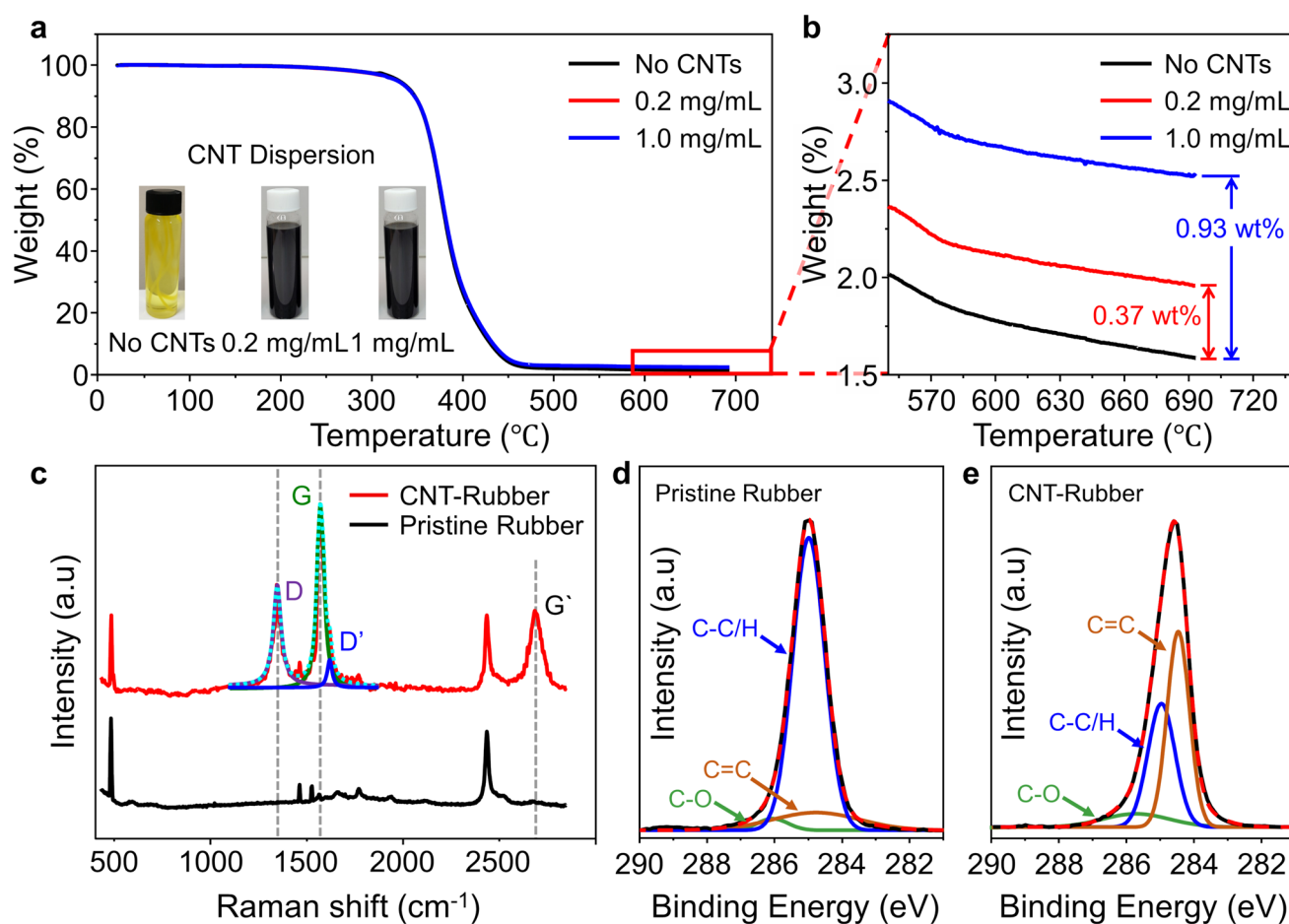


Fig. 2 Characterization of CNT-infiltrated rubber nanocomposites. **a** TGA of the CNT–rubber nanocomposites prepared with dispersions containing different CNT concentrations (0, 0.2, and 1.0 mg/mL). Inset photographs show swollen rubber immersed in each dispersion. **b** Enlarged TGA curves within the decomposition temperature range

of rubber used to estimate the weight fraction of CNTs infiltrated into the rubber matrix. **c** Raman spectra of pristine rubber and a CNT–rubber nanocomposite. XPS C1s spectra of **d** pristine rubber and **e** CNT–rubber nanocomposite

Raman spectroscopy was conducted to confirm the presence of CNTs within the rubber matrix. As shown in Fig. 2c, the Raman spectrum of the CNT–rubber nanocomposite exhibits characteristic CNT signatures, including D-, G-, D'-, and G'-bands at 1345, 1584, 1619, and 2695 cm^{-1} , respectively, which are not observed in the spectrum of pristine natural rubber. The I_G/I_D ratio of ~ 1.18 , originating from the sp^2 bonding of carbon atoms and associated defects, further indicates the incorporation of CNTs [46, 47]. Additionally, as shown in Fig. 2d, the Gaussian fits of the deconvoluted C1s XPS peaks of pristine rubber reveal three peaks centered at 284.7, 285, and 286 eV, corresponding to C–C/H (sp^3), C=C (sp^2), and C–O bonds, respectively. A similar XPS spectrum is obtained from the CNT–rubber nanocomposite (Fig. 2e); however, the relative intensity of the C=C (sp^2) peak is significantly enhanced owing to the presence of infiltrated CNTs, as confirmed by EDS elemental analysis (Table S2, Supplementary Information).

The tensile mechanical properties of pristine rubber and CNT–rubber nanocomposites containing 0.37 and 0.93 wt% CNTs were evaluated, as shown in the stress–strain curves in Fig. 3a. The elongation at break slightly decreases with increasing CNT concentration. However, the elastic modulus (~ 325 kPa) and tensile strength (~ 4 MPa) of the CNT–rubber nanocomposites are similar to those of pristine rubber. This mechanical behavior is attributed to the localized distribution of CNTs beneath the rubber surface enabled by the swelling–infiltration process. In this structure, the rubber matrix predominantly governs the mechanical properties, while the infiltrated CNTs form a percolation network that provides electrical conductivity. In conventional nanocomposites, the homogeneous incorporation of CNTs typically enhances the mechanical strength but simultaneously reduces the stretchability owing to increased stiffness [18, 24, 25]. In contrast, our nanocomposite preserves the intrinsic elasticity and stretchability of natural rubber while

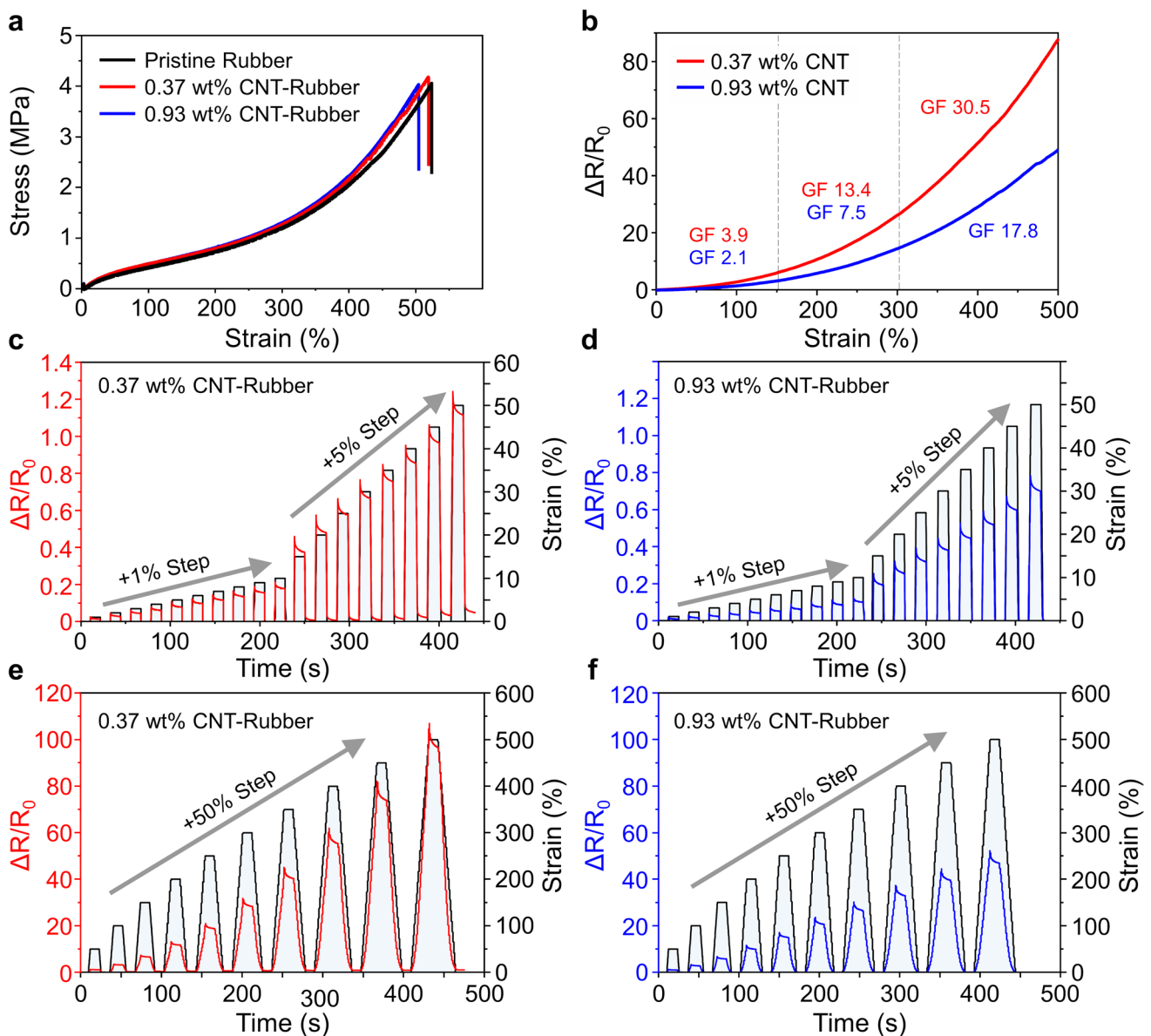


Fig. 3 Mechanical and electromechanical performance of CNT-rubber nanocomposites. **a** Tensile stress-strain curves of pristine rubber and CNT-rubber nanocomposites with CNT concentrations of 0.37 and 0.93 wt%. **b** Relative resistance changes as a function of tensile strain for CNT-rubber nanocomposites with 0.37 and 0.93 wt%

CNTs. **c, d** Transient strain-sensing responses of CNT-rubber nanocomposites with different CNT concentrations under small tensile strains of 1–50%. **e, f** Transient strain-sensing responses under large deformations of 50–500%

endowing electrical functionality, making it suitable for stretchable sensors.

The strain-sensing performance of the CNT-rubber nanocomposites was evaluated by measuring relative resistance changes under applied tensile strain up to 500%. The GF, a key performance metric for resistive strain sensors, is defined as $GF = (\Delta R/R_0)/\Delta \epsilon$, where ΔR , R_0 , and $\Delta \epsilon$ are the resistance change, initial resistance, and applied strain, respectively. As shown in Fig. 3b, the resistance of the CNT-rubber nanocomposites gradually increases with

increasing applied strain until the percolation network of CNTs is disrupted by mechanical fracture, demonstrating a wide detection range up to 500%. The nanocomposite with a lower CNT concentration (0.37 wt%) exhibits a higher response to strain compared to the 0.93 wt% CNT nanocomposite with a denser network. This is attributed to the easier breakdown of the percolation network in the rubber matrix with fewer CNTs during elongation. The GF was determined for three distinct linear sensing regions ($R^2 = 0.95$ – 0.99): 0–150%, 150–300%, and 300–500% strain. Detailed GF

values for the nanocomposites with 0.37 and 0.93 wt% CNTs are summarized in Table S3 (Supplementary Information). During initial stretching up to 150%, randomly entangled CNTs realign along the direction of applied strain, leading to an increase in resistance owing to dimensional changes, with a GF of 3.9 for the 0.37 wt% nanocomposite. Notably, the high aspect ratio of CNTs enables stable electrical connectivity across a broad strain range. Accordingly, the CNT–rubber nanocomposite can measure strains up to 150–300% with a high GF of 13.4, which is attributed to the sliding and increasing distance between individual CNTs [48]. As the strain further increases above 300%, the number of electrical paths in the percolation network are reduced because of the separation of the CNTs, resulting in a further increase in resistance with a high GF of 30.5.

In addition to the GF and sensing range, the sensing resolution is a crucial factor in evaluating strain sensor performance. To assess this, transient responses of the rubber nanocomposites were examined under cyclic loading and unloading strains with increments from 0 to 10% (1% steps) and 10% to 50% (5% steps). As shown in Fig. 3c and d, the nanocomposites clearly distinguish between 1 and 5% strain steps, with the 0.37 wt% CNT–rubber composite exhibiting a higher response than the 0.93 wt% CNT–rubber composite, as expected. Therefore, nanocomposite sensors can detect subtle strain variations with high sensitivity. In addition, the transient responses exhibited slightly larger changes compared with those measured under continuously increasing strain (Fig. 3b). This higher response under the stepwise loading–unloading cycles is attributed to the viscoelastic properties of natural rubber, which causes a characteristic “shoulder peak,” as shown in Fig. S7 (Supplementary Information) and commonly observed in elastomer-based strain sensors. During strain loading, the resistance initially increases sharply and then gradually decreases under sustained strain. This behavior leads to a time-dependent rearrangement of conductive fillers within the matrix of rubber composites [12, 49]. Moreover, the resistance change with tensile strain was not linear but increased progressively at higher strain levels, consistent with the strain-dependent increase of the GF. The nanocomposites also demonstrated fast response and recovery times, below 100 ms at 1% strain (Fig. S7, Supplementary Information). Furthermore, the nanocomposites maintained stable and distinct responses under large strains ranging from 50 to 500%, in 50% increments (Fig. 3e and f). These results demonstrate that our nanocomposites can accurately detect both subtle strain variations and large deformations, making them well-suited for diverse strain-sensing applications that require high sensitivity and stretchability.

Nanomaterial-based strain sensors with surface-exposed conductive layers are typically susceptible to water and frictional detachment. To address this, previous studies

have proposed unconventional yet simple strategies, such as intermolecularly bonded networks, encapsulation layers, and core–shell structural designs, which enhance mechanical stability and waterproofing [50–54]. These approaches effectively suppress detachment, provide waterproof functionality, and prevent electrical crosstalk, thereby enabling reliable use in applications such as body motion monitoring and human–machine interaction.

To verify stability of the sensor under various environmental conditions, we evaluated the strain responses after washing and tape peeling tests. Figure S8a (Supplementary Information) presents strain responses before and after water washing, showing negligible variation under identical strain input. Because the CNTs are mostly confined beneath the rubber surface, the conductive network was not directly exposed. Although a small portion of surface-exposed CNTs may be removed, the inherent hydrophobicity of CNTs and rubber preserved stable performance [55], as confirmed by water contact angle observations (Fig. S8b, Supplementary Information). Furthermore, we also examined CNT detachment under repeated peel-off tests with commercial tape. In the first trial, a small amount of CNTs were transferred to the tape (Fig. S9a, Supplementary Information), but detachment decreased significantly in subsequent peelings, indicating that infiltrated CNTs were stably confined. The transient response after four peel-off cycles (Fig. S9b, Supplementary Information) showed only a minor decrease in amplitude, and the sensing performance was largely preserved. These results confirm that frictional detachment does not critically affect sensor stability in practical use.

Since strain stimuli generated by bodily motions are inherently multidirectional, in-plane multidirectional strain sensing is essential for wearable applications, enabling the detection of both the magnitude and direction of applied strain [26–28]. We investigated the bidirectional strain sensing capability of plain-woven rubber nanocomposites prepared with 0.37 wt% CNTs. Figure 4a shows the linear current–voltage (I – V) curves obtained using sensors with an increasing number of parallel weft bands (1–5). The measured electrical resistance of a sensor with five parallel weft bands, without any warp bands, was 5.09 k Ω . As shown in Fig. S10 (Supplementary Information), the strain response of five parallel nanocomposite bands was nearly identical to that of a single nanocomposite band. This indicates that the fabrication process is reproducible and that increasing the number of bands enhances structural stability without compromising strain sensitivity. Furthermore, weaving additional nanocomposite bands in the warp direction did not significantly change the resistance. This confirms that the weft and warp bands maintain electrical orthogonality after plain weaving, a key feature for effective bidirectional strain sensing.

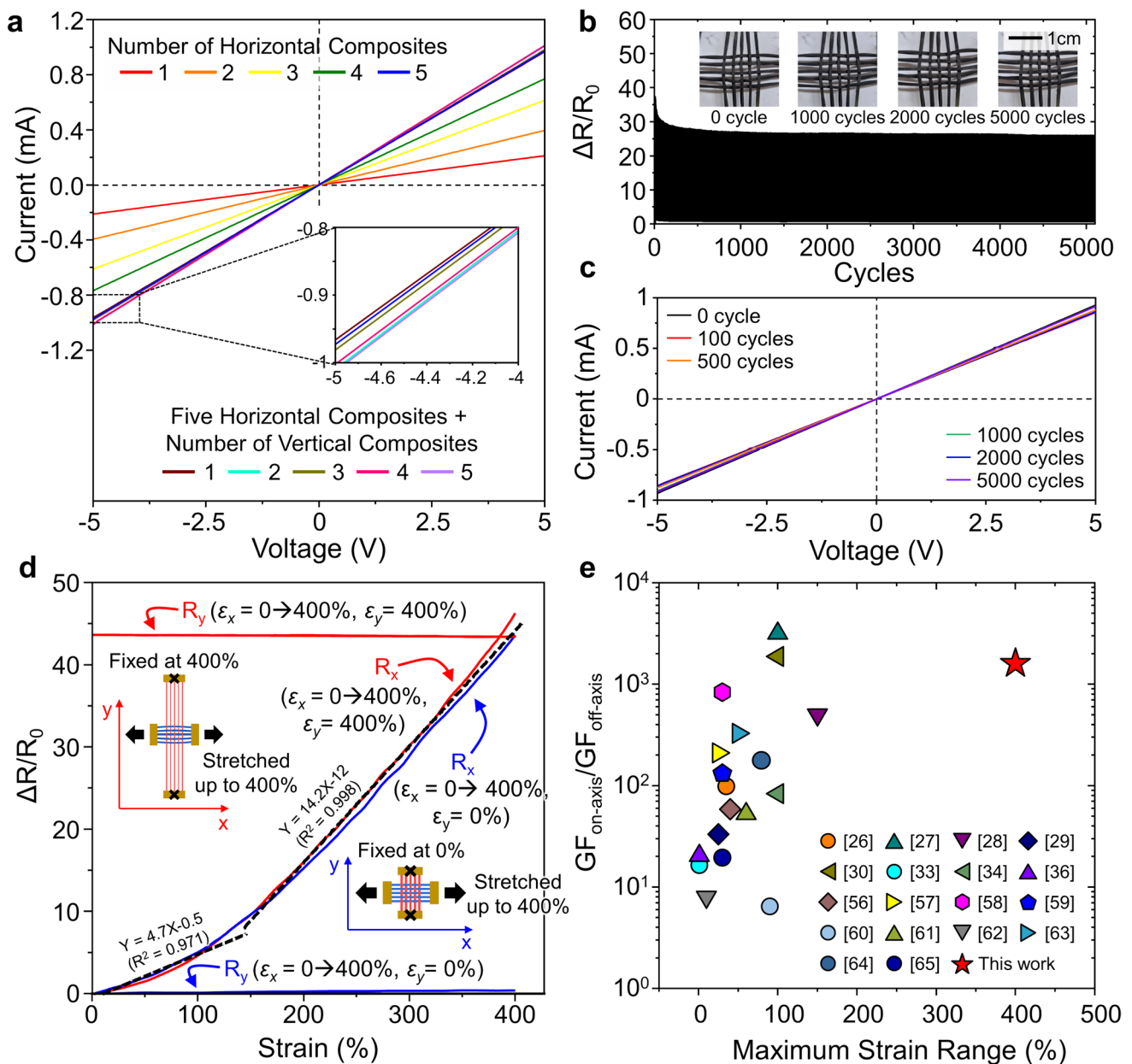


Fig. 4 Characterization of plain-woven CNT–rubber nanocomposites for bidirectional strain sensing. **a** I – V curves of woven nanocomposites with various numbers of weft and warp strips (up to five), measured along the horizontal axis. **b** Transient response of woven nanocomposites under 400% unidirectional tensile strain for 5000 cycles, measured along the horizontal axis. **c** I – V curves measured at different intervals during the 5000 cycles of 400% unidirectional tensile strain presented in **b**. **d** Strain responses of woven nanocomposites

in the horizontal (x -axis) direction (R_x) and vertical (y -axis) direction (R_y). The blue solid lines are R_x and R_y measured when the strain along the y -axis was fixed at 0%, while the strain along the x -axis increased from 0 to 400%. The red solid lines are R_x and R_y measured when the strain along the y -axis was fixed at 400%, while the strain along the x -axis increased from 0 to 400%. **e** Comparison of the on-axis to off-axis GF ratio and sensing range of our sensor with those of previously reported bidirectional strain sensors

The long-term durability of the bidirectional strain sensor was evaluated under repeated uniaxial stretching of 400% strain for 5000 cycles by monitoring resistance changes. As shown in Fig. 4b, the sensor exhibits a gradual signal drift during the initial 600 cycles, followed by stable and repeatable responses over the remaining cycles. This initial drift is

likely due to stress softening of the polymer matrix and rearrangement of CNTs under repeated cycles of high strain [17, 18, 56]. The insets in Fig. 4b show that the woven structure of the sensor remains nearly unchanged throughout cyclic loading. This mechanical stability is further supported by the I – V curves recorded at selected intervals throughout the

5000 cycles, which show no significant differences. These results confirm the mechanical and electrical durability of both the rubber nanocomposite and woven architecture, demonstrating their suitability for reliable and stable strain sensing in dynamic environments.

Unlike previously reported strain sensors that exhibit inherently coupled responses between orthogonal axes [26, 27, 29], the woven structure of our strain sensor effectively suppresses cross-axis interference, enabling accurate detection of the magnitude and direction of in-plane strains. To verify the biaxial sensing capability of the sensor, its responses ($\Delta R/R_0$) along the horizontal and vertical directions, denoted as R_x and R_y , respectively, were measured simultaneously. When uniaxial strain up to 400% was applied along the x-axis, R_x increased monotonically to 43.646 ($R^2=0.998$ in the 150–400% strain), while the off-axis R_y values remained nearly unchanged, with a maximum of only 0.396, as shown by the blue solid lines of Fig. 4d. After releasing the x-axis strain, y-axis strain was applied and held at 400%, while the x-axis strain was again increased up to 400%. As shown by the red solid lines in Fig. 4d, R_x increases similarly to the previous case, reaching 46.297, while R_y exhibits only a minimal variation of 0.032 (from 43.639 to 43.671). This low axial crosstalk demonstrates that the developed sensor can independently detect bidirectional strain components. Notably, the sensor achieved a high average on-axis to off-axis GF ratio of 1446.8 over a large strain range of 400%, outperforming the performance of previously reported bidirectional strain sensors [26–30, 33, 34, 36, 56–65], as summarized in Fig. 4e (see Table S4 for detailed values). These results confirm that the developed sensor can detect large in-plane strains with high selectivity.

We further investigated the low off-axis interference observed in the woven sensor to clarify its underlying mechanism. The low axial crosstalk of the woven structure can be explained by two factors. First, the high contact resistance at the junctions ($\sim 1\text{ M}\Omega$), which is substantially larger than the intrinsic resistance of each strip ($\sim 5\text{ k}\Omega/\text{cm}$), suppresses current leakage and thereby minimizes electrical crosstalk. Second, the slip at the intersections reduces mechanical interference. Specifically, when an on-axis tensile load is applied, static friction at the junctions induces a slight lateral deflection of the off-axis strip. Once the applied force exceeds the maximum static friction, slip occurs, and no further deflection is observed in the off-axis strip (Fig. S11a,b, Supplementary Information). This phenomenon was experimentally verified (Fig. S11c, Supplementary Information), and cross-axis interference was found to be negligible when bidirectional strains were applied simultaneously (Fig. S11d, Supplementary Information). As a result, the combined effects of large contact resistance and slip transition effectively minimize both electrical and mechanical crosstalk between orthogonal nanocomposites, allowing the

woven sensor to distinguish multidirectional strains with high accuracy and stability.

In addition to its low off-axis interference, stability against environmental variables such as temperature or humidity is another critical factor for reliable strain sensing. The measured temperature coefficient of resistance (TCR) of the CNT–rubber nanocomposite is $-0.398\%/K$ (Fig. S12, Supplementary Information). The corresponding temperature compensation constant, defined as TCR/GF , is -130.5 ppm/K , which is similar to those of previously reported strain gauges [66, 67]. Figure S13 (Supplementary Information) presents the relative resistance changes of CNT–rubber nanocomposites (0.37 wt% CNTs) under tensile strain at 65% RH and 25 °C, 90% RH and 25 °C, and 65% RH and 42 °C. No noticeable difference in strain response was observed between 25 and 42 °C (both at 65% RH), although the resistance at 0% strain decreased slightly from 5.02 k Ω/cm to 4.82 k Ω/cm with increasing temperature. Similarly, no significant difference in strain responses was found at relative humidity levels of 65% and 90% at 25 °C. This stability can be attributed to the fact that only a small fraction of CNTs is exposed at the surface, while the bulk conductive network remains embedded in the rubber; additionally, the hydrophobicity of both CNTs and rubber further suppresses humidity effects [55]. Nevertheless, environmental variations may introduce minor signal errors in strain sensors. Conventional strain gauges address such issues by employing half- or full-Wheatstone bridge configurations to compensate for environmental effects and ensure accurate measurements [68]. Adopting similar compensation schemes in CNT–rubber sensors could further enhance their stability under varying environmental conditions.

To demonstrate the potential of the bidirectional strain sensor for wearable applications, the woven nanocomposite sensor was integrated into a textile glove to monitor finger movements. As shown in Fig. 5a, five vertical nanocomposite bands were attached along the length of each finger, while five horizontal nanocomposite bands, woven with the vertical ones, were positioned laterally across the fingers. In the initial open-hand posture, no strain responses were observed. When forming an O-shape with the thumb and index finger, a large response was detected by vertical band #4 and horizontal bands #1 and #2 (Fig. 5b). Additionally, minor bending of the ring, middle, and thumb fingers was captured by vertical bands #2, #3, and #5, respectively. The sensor also independently detected finger-specific deformation during fist clenching (Fig. 5c) and selective bending of the middle and ring fingers (Fig. 5d) via changes in the resistance response of the vertical and horizontal nanocomposite bands. Furthermore, to ensure experimental reliability, repeated measurements of the bending gestures of the middle and ring fingers were conducted, and the sensor exhibited stable and reproducible responses (Fig. S14, Supplementary

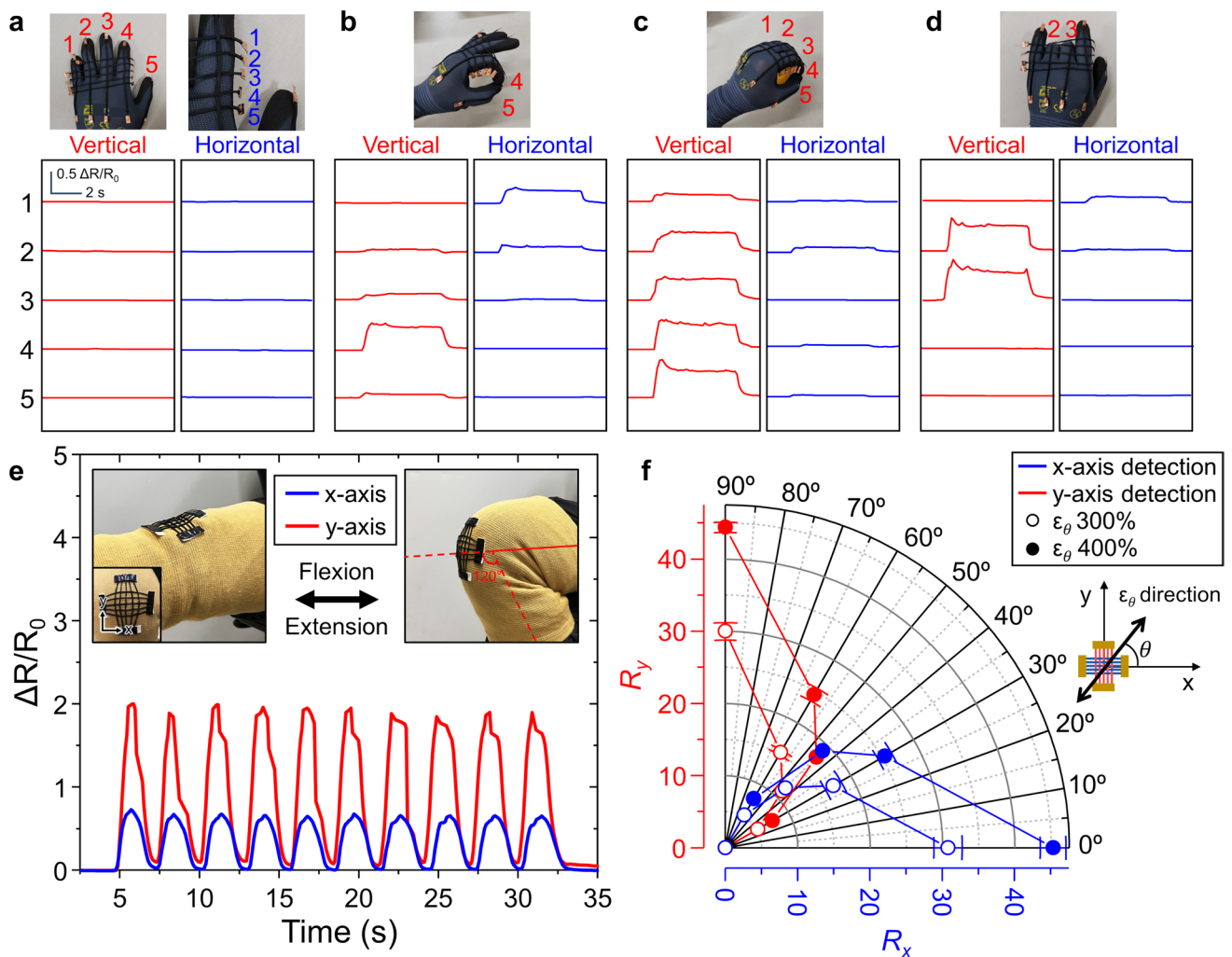


Fig. 5 Wearable applications of bidirectional strain sensors. **a–d** Strain responses of the CNT–rubber nanocomposite sensor integrated into gloves, measured along the vertical (red lines) and horizontal (blue lines) axes during various hand gestures: **a** open-hand posture, **b** forming an O with the thumb and index finger, **c** fist clenching, and **d** bending the middle and ring fingers. The sensor clearly distinguishes directional strain corresponding to each finger movement.

Information). These results confirm the bidirectional sensitivity of the woven nanocomposite sensor for complex finger motions. Moreover, the customizable arrangement of woven bands allows for location-specific strain sensing, enabling versatile configurations for various wearable applications.

The knee joint exhibits one of the largest ranges of motion in the human body. The broad detection range of the rubber nanocomposite sensor enables the quantitative measurement of bidirectional strains generated during knee bending. As shown in Fig. 5e, transient responses were recorded from a sensor embedded in the knee region of a sportswear garment during repeated flexion ($\sim 120^\circ$ from the initial straight-leg position) and extension. The vertical and horizontal nanocomposite bands exhibited R_x and R_y values of ~ 0.7

e Transient response of a sensor embedded on the knee sleeve during repeated bending and unbending cycles. **f** Polar plot of sensing responses corresponding to various strain directions (0° , 30° , 45° , 60° , and 90°) at 300% strain (open symbols) and 400% strain (solid symbols), demonstrating the capability of the sensor to detect both the direction and magnitude of applied in-plane strain

and ~ 2.0 , respectively. The corresponding strains on the skin surface were $\sim 37\%$ along the x-axis (perpendicular to the leg direction) and $\sim 71\%$ along the y-axis (parallel to the leg), which are comparable to previously reported strains measured during human knee motion [26, 30, 60]. These results highlight the bidirectional sensitivity and wide detection range of the sensor and its suitability as a wearable sensor for joint motion monitoring.

Furthermore, the woven sensor was embedded in a wristband to evaluate its capability for multidirectional joint monitoring. As shown in Fig. S15 (Supplementary Information), during wrist bending (15–20% strain), the vertical nanocomposite band exhibited a clear increase in R_y (~ 0.73), whereas the horizontal band showed only a

negligible change (~ 0.02), indicating that the deformation occurred primarily along the y-axis. In contrast, during wrist rotation, R_y decreased to ~ 0.11 , while R_x remained at ~ 0.02 , changing the R_y -to- R_x ratio from $\sim 36:1$ (bending) to $\sim 5.5:1$ (rotation). These distinct response patterns highlight the inherent multidirectional sensing capability of woven sensor, enabling reliable discrimination of complex wrist motions with clear and stable output.

To determine the magnitude and direction of applied in-plane strain, the anisotropic sensitivity of the sensor along orthogonal directions was evaluated under 300% and 400% strain applied at various angles ($\theta = 0^\circ, 30^\circ, 45^\circ, 60^\circ$, and 90°), while measuring the R_x and R_y responses. The representative strain–response curves at angles of $30^\circ, 45^\circ$, and 60° are presented in Fig. S16 (Supplementary Information). As shown in Fig. 5f, for equivalent strains applied at angles of 0° – 45° , R_x is larger than R_y . Conversely, for angles of 45° – 90° , where dominant strain component is aligned along the y-axis, R_y exceeds R_x . Furthermore, repeated measurements with error bars (standard deviation, $n = 3$) confirmed that the largest deviation occurred at 300% strain, corresponding to an error of only $\sim \pm 4.6\%$ (Table S5, Supplementary Information). These results demonstrate that the woven sensor can decouple strain magnitude and direction with sufficient quantitative accuracy for practical use. In addition to in-plane sensing, the woven structure of the CNT–rubber nanocomposite sensor enabled out-of-plane pressure sensing by measuring contact resistance changes between the weft and warp strips (Fig. S17, Supplementary Information). The sensor exhibited a pressure detection range of 310 kPa–1.38 MPa, with a sensitivity of $\sim 0.018 \text{ MPa}^{-1}$, demonstrating its potential for multidirectional force sensing applications.

4 Conclusions

We developed a multidirectional stretchable strain sensor composed of CNT-infiltrated rubber nanocomposites for axially decoupled strain sensing. The plain-woven configuration of rubber nanocomposite bands effectively minimizes cross-axis interference, achieving a high on-to-off-axis GF ratio of 1446.8 across a strain range of 400%, which outperforms conventional multidirectional strain sensors. The nanocomposite rubber bands were fabricated using an optimized CNT infiltration process, which preserved the elastic modulus and tensile strength of the natural rubber while imparting piezoresistive functionality. The CNT–rubber nanocomposite bands exhibited a GF of 30.5 and stable performance over 5000 cycles of 400% strain, even after integration into a woven structure. Wearable applications, including integration into gloves and knee sleeves for gesture recognition and

joint tracking, respectively, were demonstrated to highlight that the developed sensor is suitable for accurate, low-interference strain sensing in next-generation soft electronics and robotics.

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Data availability No datasets were generated or analyzed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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