Knitted structural design of MXene/Cu₂O based strain sensor for smart wear

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Abstract Electronic textiles present an enticing prospect for personal health assessment and physical monitoring, owing to their strong stretchability, high flexibility, mechanical robustness and high capacity in sensing small deformations in human motions. Herein, a multifunctional robust flexible knitting-shaped strain sensor based on the functional heterostructure composed of the conductive MXene (Ti₃C₂Tx) nanosheet and the antimicrobial Cu₂O nanoparticles is prepared via a solution-processable dip-dry coating approach. The textile-based strain sensor exhibits a highly stable and immediate response over a wide range, which shows great advantages in detecting and monitoring human activities, such as smiling, swallowing, and wrist/finger/joint bending. Significantly, these prepared strain sensors present a promising application in smart wear, which was typically employed as the smart sensing gloves in barrier-free communication for hearing-impaired people. Interestingly, the different resistance evolutions of the knitted sensor under both low and high strain were carried out to study the sensing mechanism for the first time. Notably, the strain sensor displays a reliable antibacterial efficiency of ~99.1% for Escherichia coli and outstanding breathability as high as 190 mm/s. This developed MXene/Cu₂O hybrid materials supplies a new insight for the rational design and synthesis of multifunctional nanomaterials, as well as the achievement of the flexible wearable sensor with high performance.

Yuan-Ming Cao and Yi-Fei Li have contributed equally to this work.

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Introduction

Flexible and wearable electronic devices have drawn considerable research attention in both fundamental research and practical applications of smart wear and artificial intelligence (Dong et al. 2020; Li et al. 2017; Shi et al. 2021; Wang et al. 2018; Xu et al. 2021). Fiber-based strain sensors are interfaced with conductive fibers or battery fibers show great potential in the integrated-circuit textile for smart wear (Taylor et al. 2021; Yang et al. 2021), robotics (Gao et al. 2020b), safety clothing (Lin et al. 2020), and programmable and computational textiles (Wang et al. 2020a). Immense efforts have been devoted to developing an expansive range of the flexible and wearable strain sensors by different sensing mechanisms of piezoelectric (Cheng et al. 2020), piezocapacitive (Wei et al. 2021), triboelectric (He et al. 2020) and strain-resistance effect (Wang et al. 2014). Notably, metal nanoparticles/nanowires (Li et al. 2016; Zou et al. 2021), carbon black (Wu et al. 2016), carbon nanotubes (CNTs) (Zhang et al. 2019), graphene (Luo et al. 2020), and conductive polymers (He et al. 2018), have been employed as the building blocks for the knitted strain sensor textiles, which is attributed to their high sensitivity, excellent reproducibility, and simple manufacturing process. For example, the thermoplastic polyurethane strain sensing network based on the CNT bridged Ag nanoparticles shows an excellent gauge factor of 250 upon stretching to 100% and an ultra-high stretching of more than 550% (Huang et al. 2019). However, their practical applications is still limited by the inherent impermeability, the possible allergic reaction, and the bacterial attack caused by contact with the skin (Miyamoto et al. 2017). Currently, immense efforts have been devoted to developing fabric-based sensing devices for the realization of widespread human sensing (Liu et al. 2017b; Gao et al. 2020a). The corresponding sensing mechanism of fabric-based sensors is rarely explored, which greatly hinders the development of flexible sensing.

The two-dimensional (2D) conductive materials with unique atomic-level structures exhibit exceptional biocompatibility (Pang et al. 2020), high stretchability (Jang et al. 2016), large specific surface area (Cao et al. 2021), and mechanically compliant (Yun et al. 2021), making them promising building blocks for the knitted strain sensor textiles. As the pioneer example, the MXene with an excellent electrical conductivity of ~10$^4$ S/cm (Zhang et al. 2017) demonstrates the potential applications in catalysis (Wang et al. 2019), energy storage (Ghidiu et al. 2014), biochemical/strain sensors (Yu et al. 2015) and electromagnetic wave shielding (Liu et al. 2017a). The MXene-based strain sensor achieved a sensitivity of ~363, a wide working strain range from 0 to 100%, as well as excellent gas permeability, which shows great potential in the synthesis of desired strain sensor (Wang et al. 2021). Notably, the intermolecular forces and electrostatic interactions of MXene is favorable for producing MXene nanocomposites with semiconductor nanoparticles (Wang et al. 2020b), metal nanoparticles (Wang et al. 2019), organic materials (Chen et al. 2018), and polymer (Liu et al. 2018). The poor air permeability and the discomfort of the wearable devices for close skin contact will pose a health risk of allergic reactions and potential bacterial infections, limiting their practical applications in smart wear (Schwartz et al. 2013). In this context, one way in meeting such requirements of lightweight, softness and breathability is to make the sensor in the form of conformable textiles. Furthermore, the pure MXene displays a low efficiency of bacteriostatic activity, whose bacterial biofilm inhibition activity against Staphylococcus aureus biofilm was 18% (Zheng et al. 2020). Interestingly, as a result of its promising economic applicability, biocompatible Cu$_2$O has been widely used in antibacterial materials (Tao et al. 2019). The copper-based nanomaterials can regulate intracellular oxidative stress and help bacterial cell lysis with nearly 100% antibacterial efficiency for Staphylococcus aureus (Qiao et al. 2020). Directed by these successes, the MXene nanocomposite fabric with desired sensing performance is coordinated with textile materials, which provides a valuable strategy for the wearable design of flexible devices.

Herein, the MXene/Cu$_2$O nanocomposites were rationally designed and successfully prepared by in-situ growth process, which were further applied to fabricate the conductive fabric sensors with high sensing and antibacterial peculiarities via a facile and scalable dip-drying method. The conductive fabric with a low loading of 0.51–1.4 wt%
demonstrates desirable electrical conductivity (up to 600 Ω/sq, equivalent to 5×10^{-2} S/cm), which achieves novel functions including wide sensing range (up to 100%, the sensitivity up to 16.8), high stability (> 3000 cycles over 100% strain), excellent bacteriostasis (99.1% and 96.3% against *E. coli* and *S. aureus*, respectively), and satisfactory breathability (> 190 mm/s). Furthermore, a sensing mechanism of the knitted fabric sensor was proposed, resistance increases under low-stretch conditions (<10%), and decreases under high-stretch conditions (>10%). The conductive fabric strain sensors demonstrate significant superiority in detecting and monitoring both small and large human motions such as smiling, swallowing, wrist/finger/leg bending, as well as perceiving different bending amplitudes of the joint motions. Interestingly, an intelligent sensing gloves system for human motion monitoring is designed and demonstrated, which is based on integrated strain sensors. This study supplies a new strategy into the design and synthesis of MXene/Cu$_2$O nanocomposites, and presents a novel insight into the textiles-based strain sensors with tailorable structures and compositions for various smart wearable devices.

**Experimental method**

**Materials**

The materials required for the experiment are shown in Table 1.

| Materials       | Specification                                      | Manufacturer                                      |
|-----------------|----------------------------------------------------|---------------------------------------------------|
| Knitted fabrics | 155 g/m^2, 95% cotton, 5% spandex                  | Shaoxing Runiu Knitwear Co., Ltd, China           |
| LiF             | 99.9%                                              | Shanghai Aladdin Biochemical Technology Co., Ltd, China |
| HCl             | 36–38%                                             | Jiangsu Qiangsheng Functional Chemical Co., Ltd, China |
| Ti$_3$AlC$_2$   | Mass fraction: 98%                                 | Beijing Huawei Ruike Chemical Co., Ltd, China     |
| C$_2$H$_5$OH    | AR                                                 | Jiangsu Qiangsheng Functional Chemical Co., Ltd, China |
| Cu(AC)$_2$·H$_2$O | 99%                                               | Shanghai Aladdin Biochemical Technology Co., Ltd, China |
| NH$_4$HCO$_3$   | 99%                                                | Jiangsu Qiangsheng Functional Chemical Co., Ltd, China |
| PVP             | AR                                                 | Shanghai Aladdin Biochemical Technology Co., Ltd, China |
| ethylene glycol | AR                                                 | Jiangsu Qiangsheng Functional Chemical Co., Ltd, China |

More textile information is listed in Table S1 in Supporting Information.

**Synthesis of MXene**

MXene was prepared by etching Ti$_3$AlC$_2$ through LiF/HCl. Briefly, 1.5 g of LiF was added to 20 mL of HCl (9 M), stirred in a Teflon beaker for 10 min until the salt was dissolved, and 1 g of Ti$_3$AlC$_2$ powder (400 mesh) was slowly added to the above solution within 10 min. After magnetic stirring in a water bath at 40 °C for 24 h. The obtained product was washed with deionized water for 5 times until pH > 5, and then the mixture was dispersed in 100 mL of absolute ethanol followed by sonication for 1 h in an ice bath. After centrifugation, the precipitate was dispersed in 100 mL of deionized water and sonicated for 30 min (KQ-50E, ultrasonic power: 50 W). Finally, the product was centrifuged at 3500 rpm for 10 min to obtain MXene supernatant with an average concentration of 1.225 g/L.

**Synthesis of MXene/Cu$_2$O nanocomposite**

5 mL of MXene supernatant (1.2 g/L) and 2 mL Cu(AC)$_2$ (0.1 M) solution was added into 50 mL Ethylene Glycol (EG) which contain 0.4 g PVP under vigorous stirring. Subsequently, 1 mL N$_2$H$_4$·H$_2$O (1 M) was slowly added in to the mixture solution dropwise. After 30 min of stirring in room temperature, the product was centrifuged, and rinsed in deionized water and absolute ethanol for serval times to remove the byproducts. Finally, the sediment was collected and vacuum dried at 60 °C for 4 h.
Preparation of conductive fabric

The strain sensor-based smart-textile was fabricated through commonly used dip-dry method. 0.4 g MXene/Cu2O was dispersed into 50 mL distilled water and sonicated for 1 h. The acidic-fluoride-containing solutions result in the presence of numerous surface termination groups (such as -OH, -O, and -F), which is favorable for the easy adsorption of Cu2+ on these termination group sites via electrostatic interactions. Cu2O nanoparticles could form in situ on the surface of the Ti3C2Tx nanosheets via a coprecipitation reaction. The fabrics were impregnated in the dispersion for 10 min, and then the excess liquid is removed from the fabric by a special automatic roll dip coater. The weight of the wet-fabric is 1 times the weight of the original fabric in this process. The obtained strain sensor was dried in electric heating air-blowing drier at 80 °C for 5 min, followed by 3 min of curing at 150 °C. The dip-dry procedure was repeated 1–5 times to achieve better conductivity and antibacterial property. The MXene/Cu2O content of strain sensor ranges from 0.51 to 1.4 wt%. The prepared sensor was stored in a glove box to reduce oxidation effects.

Preparation of smart sensing glove

Cut the conductive fabric into strips of 10 × 70 mm according to the warp direction, and paste the copper foil on both ends of the strip with silver paste as electrodes, and keep the distance between the copper foil electrodes at 50 mm. After drying, the stretch sensor is obtained, and 5 sensors are integrated on the sports glove to test the signal response from the 5 finger joints. Since the recording of the signals of the five finger joints in the test must ensure synchronization, we use the multi-channel acquisition function of the data acquisition card to collect the voltage signals at both ends of the fixed-value resistor. Since the sensor will move when it follows the gesture, we collect the voltage signal of the fixed fixed-value resistor, eliminate the unstable factors when collecting the sensor voltage signal, and then convert it into the voltage across the sensor according to the formula of $V_{sensor} = U - V_R$. Where the $V_{sensor}$ is the voltage of the sensor, $V_R$ is the voltage of the fixed-value resistor, and U is the power supply voltage.

Characterization

X-ray diffraction (XRD) patterns of MXene powder, MAX powder, Cu2O powder, and MXene/Cu2O composite powder (All samples were not ground and were directly pressed) were recorded with a X-ray diffraction analyzer (D/max-IIIC, Japan). Cu-Kα radiation (K-Alphal wavelength = 0.15418 nm) at a generator current of 100 mA was used as the radiation source and the generator voltage was set as 40 kV with a scan step size of 0.02°, 2θ rotates 4° min

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where $R$ is the resistance of the sensor under strain, $U$ is the supply voltage and its value is constant at 9 V, $V_R$ is voltage value of constant resistance $R_1$ (10 kΩ). Antibacterial Property of pristine fabric, pure MXene and MXene/Cu$_2$O loaded fabric against Escherichia coli and Staphylococcus aureus was tested using shaking flask method according to AATCC100-2004. 1 ml of bacterial suspension (1–2 × 10$^5$ CFU) was added on to the samples with a diameter of 4.8 cm in the flasks. Then add 100 ml of neutralizing solution into the flasks until each specimen has completely absorbed the bacterial suspension. After incubation at 37 ± 2 °C for 24 h under continuous shake, plate cultivation method was utilized to census the bacterial colonies. The images of culture dishes were captured and the bacteriostatic rates were calculated according to Eq. (2)

$$Bacteriostatic\ rates = \frac{A_0-A}{A_0} \times 100\%$$ (2)

where $A_0$ is the bacterial colonies of blank sample and $A$ is the bacterial colonies of samples’ dish. The mechanical properties of the original fabric and NMCF sensor were measured using universal material testing machine (Instron 3365) while the size of each specimen was 5 cm×30 cm (gauge length 20 cm), and the loading rate was 100 mm/min. Before testing, all the samples were conditioned for 24 h at a temperature of (20 ± 2) °C and a humidity of (65 ± 2)% according to the ASTM D1776-04.

The washable property of fabric sensors were carried out according to the 7A procedure in the standard ISO6330: 2000 "TEXTILES. DOMESTIC WASHING AND DRYING PROCEDURES FOR TEXTILE TESTING". Every 5 min was recorded as an effective washing. The surface resistance of the dried fabrics was tested using a four-pointer square resistance tester. The dip-dry procedure was repeated 1, 3, and 5 times to obtain the fabric sensor for testing washable property.

**Results and discussion**

Synthesis and characterization of MXene/Cu$_2$O nanocomposite

$\text{Ti}_3\text{C}_2\text{Tx}$ MXene nanosheets were prepared via HCl/LiF etching method, which was further applied to synthesize MXene/Cu$_2$O nanocomposite (NMC) through liquid reduction method at room temperature (Fig. 1a) (detailed experiment in Supporting Information). As shown in the transmission electron microscope (TEM) image (Fig. 1b), the high transparency indicates the small thickness and the slightly stacked of the prepared MXene nanosheets with a 2D structure. The atomic force microscopy (AFM) image showed that the thickness of individual flakes was around 2.4 nm (Fig. 1c). The higher measured thickness of Ti$_3$C$_2$Tx compared to its theoretical thickness ~0.98 nm is conductive to result from the confinement of water molecules (Lipatov et al. 2018), which confirms the monolayer feature (Yun et al. 2020). The substantial active sites and the high specific surface area on the surface of MXene nanosheets is favorable for the in-situ growth of Cu$_2$O nanoparticles. The Cu$_2$O nanoparticles with a diameter of 50–100 nm were successfully introduced on the surface of the MXene nanosheet, constructing the MXene/Cu$_2$O nanocomposite as verified by the TEM image (Fig. 1d). Furthermore, the typical high-resolution TEM images show that clear lattice fringes of 0.246 and 0.214 nm respectively corresponding to (111) and (200) facets of Cu$_2$O (Fig. S1a). The MXene/Cu$_2$O nanocomposite has been coated onto the fabrics (NMCF) to form the conductive textile via a hot-blast dip-dry method. Typically, the weaving structure of the fabric (the content of MXene/Cu$_2$O is 1.4 wt%) is clearly visible as presented in the scanning electron microscope (SEM) image (Fig. 1e), suggesting the successful preparation of MXene/Cu$_2$O nanocomposite-based fabric. As shown in Fig. 1f, MXene/Cu$_2$O uniformly forms a film on the surface of cotton fiber via dip-drying and baking at 150 °C for 3 min process. The corresponding EDS mapping images (Fig. S2) show that MXene/Cu$_2$O have nearly a homogeneous distribution across the conductive surface. The 2D MXene nanosheets and Cu$_2$O nanoparticles are clearly observed in high-resolution SEM (Fig. 1g), indicating that the MXene/Cu$_2$O nanocomposite is uniformly deposited on the cotton fiber.
The crystal structure of MXene/Cu₂O composite was further analyzed by X-ray diffraction (XRD) patterns (Fig. 1h). The characteristic peak (104) at 39° of Ti₃AlC₂ disappeared (green curve) after the etching process by HCl/LiF solution and sonication treatment, confirming complete movement of the Al atoms. Meanwhile, the (002) peak of Ti₃AlC₂ at 2θ=9.6° shifts to around 6.2° due to the expansion of the 2D MXene-basal plane, further confirming the formation of Ti₃C₂Tx (Liu et al. 2017a). Moreover, the diffraction peaks at 29.7°, 36.5°, 42.3°, 61.5° and 73.9° can be indexed to the cubic phase of Cu₂O (JCPDS-05-0667) (Azimi et al. 2014), suggesting the formation of the MXene/Cu₂O nanocomposite, which is consistent with XRD results. The corresponding elemental mapping images (Fig. S1b) confirm the high-density distribution of Cu and O elements on the surface of Ti elements, indicating the successful introduction of Cu₂O on the surface of MXene. The high-resolution XPS spectrum of Ti 2p (Fig. 1j) demonstrates two dominant peaks of C-Ti-Tₓ 2p₃/2 at 457.5 eV and C-Ti-Tₓ 2p₁/2 at 463.2 eV, indicating the presence of terminal groups on MXene nanosheets (Wang et al. 2016). The fitted peaks of Ti 2p located at 455.7 (460.3), 457.6 (463.1) and 458.3 (464.2) eV correspond to Ti-C, Ti²⁺ and Ti³⁺ (Liu et al. 2018). Compared with
The pure MXene nanosheets, the two main peaks at 463.3 (Ti 2p\(\text{\textsubscript{1/2}}\)) and 457.5 (Ti 2p\(\text{\textsubscript{3/2}}\)) display a positive shift in the XPS spectrum of the MXene/Cu\(_2\)O nanocomposite (Fig. S4), which confirms the formation of the strong interaction network between Cu\(_2\)O and MXene. The primary peaks at 932.2 and 951.9 eV, as shown in Fig. 1k, correspond to Cu 2p\(\text{\textsubscript{3/2}}\) and Cu 2p\(\text{\textsubscript{1/2}}\), respectively, and are attributed to Cu\(_2\)O (Tian et al. 2014). Moreover, the two extra weak peaks at 933.4 eV and 953.5 eV are attributed to the Cu\(^{2+}\) of Cu 2p\(\text{\textsubscript{3/2}}\) and Cu 2p\(\text{\textsubscript{1/2}}\) in the material, indicating the slight oxidation of Cu\(_2\)O during the liquid reduction process (Li et al. 2018). For a short conclusion, the MXene/Cu\(_2\)O nanocomposite was finely prepared and successfully introduced into the cotton fabric to form the conductive fibers.

Conductivity of conductive textile

The amount of the prepared MXene/Cu\(_2\)O nanocomposite on the conductive textile could be modulated via the dip-dry times in the scalable dip-dry method (Fig. S5a). The amount of MXene/Cu\(_2\)O nanocomposite on the surface of the conductive textile enhances from 0.51 to 1.4 wt% through 1 to 5 dip-dry times in a scalable dip-dry process. Accordingly, the corresponding surface resistance of the conductive textile decreases from 3.9 to 0.6 kΩ/sq (Fig. S5b). The larger surface resistance value of the conductive textile with the lower load amount of the MXene/Cu\(_2\)O nanocomposite indicates the inhomogeneous conductivity of the fabric, which is caused by a discontinuous conductive layer on the fiber after one single dip-dry process. After 5 times dip-drying process, the fabrics still have the best washable property. As well as the surface resistance is still lower than 5 kΩ/sq after 20 washings (Table S2), suggesting the attractive robustness as a fabric sensor. The GF of the sensor was −1.1, −0.92 and −0.70 after 5, 10 and 20 washings, respectively. The decrease of the sensor sensitivity is attributed to the reduction of the loaded MXene/Cu\(_2\)O nanocomposite during the washing process. Furthermore, the GF curve still exhibits good linearity at 0–100% strain, which guarantees working stability in the whole sensing range (Fig. S6). The MXene/Cu\(_2\)O nanocomposite-based fabric sensor is integrated into a closed circuit as a stretchable conductor. During the increasing amount of MXene/Cu\(_2\)O nanocomposite from 0.51 to 1.4 wt%, the LED lamps become more bright (Fig. S7a). Correspondingly, the color of the conductive fabric changed from gray to black (Fig. S7b), the softness and flexibility of the prepared conductive cotton fabric show almost no change after the dip-dry process.

Sensing performances of the conductive fabric

The conductive features of these prepared conductive fabrics were evaluated depending on the homemade test circuit, and the sensor is pre-stretched by 10% before testing (Fig. S8a and S8b), which is beneficial for the further investigation of the corresponding sensing performances. The relationships between the relative resistance value (R−R\(\text{\textsubscript{0}}\)/R\(\text{\textsubscript{0}}\)) of the conductive fabric and the dynamic strain were demonstrated in Fig. 2, where R and R\(\text{\textsubscript{0}}\) are the resistance of conductive fabric with or without the external stress, respectively. As shown in Fig. 2a, the relative resistance value of these prepared conductive fabrics with 0.51 wt% MXene/Cu\(_2\)O nanocomposite increased dramatically under strain range from 0 to 100%, illustrating the sensitive electrical response. With 1.16 wt% MXene/Cu\(_2\)O nanocomposite loading, the conductive fabric presents a smaller change in relative resistance value under strain, which is clarified the better conductive stability. For a higher loading ratio of 1.40 wt%, the MXene/Cu\(_2\)O nanocomposite coating on the fiber is thicker and leads to the formation of the denser network for a better conductive. Furthermore, the gauge factor (GF) of the conductive fabric is calculated via the equation: \(\text{GF} = \Delta R/(R_\text{0}\varepsilon)\times 100\%\), where \(\varepsilon\) is the strain (expressed as a percentage) (Liu et al. 2015).

As presented in Fig. 2b, the GF curves exhibit good linearity under 0–100% strain, which is guaranteed work stability under the whole sensing range. As well as the GF values of sensing range corresponding to the strain range of 0–20%, 20–80%, and 80–100% are −1.12, −1.42, and −0.94, respectively, suggesting the sensitive response for both the low and high-level strain. It is noteworthy that the conductive sensitivity of the functional fabric also could be influenced by tensile speed (Fig. S9). Typically, all curves have the same sensitivity value with an increasing strain rate from 0.1 to 2.0 mm/s at 0–20% strain. With a strain of 20–50%, the GF value expands from −1.18 to −1.45 as the strain rate increases from 0.1 to 2.0 mm/s. As shown in Fig. 2c, the relative resistance variation of the conductive fabric under 20% strain with the strain
rates of 0.005–1 Hz (the strain rates of 0.1–20 mm/s corresponding to the stretching frequencies from 0.005 to 1 Hz) displays no frequency dependence. The cyclic response of conductive fabric presents the uniform and repeatable signal output during tuning the strain rates. Remarkably, the corresponding response stability of electrical signals is of vital importance for their practical application of wearable devices (Shi et al. 2018). The relative resistance values of conductive fabric exhibit a uniform and continuous response over the strain range from 10 to 70% as verified in Fig. 2d. Importantly, the symmetric curves during loading and unloading steps imply that the quick resistance recovers as the strain changes, which is a desired property for in situ tests of the strain. The relative resistance value of the conductive fabric during the bending or compression process is detected by the test system of Fig. S10a and b. The bending angle of the conductive fabric is recorded as $\alpha$, which is a positive value when bent and a negative value when compressed. From Fig. S10c, the $\Delta R/R_0$ of bending deformation increases by 32% in the range of chord length of 50–36 mm, as well as 14% of compression deformation. It is suggested that the sensitivity of the bending model of the sensors is higher than that of the compression model, and both of them depict great linearity between relative resistance value and chord lengths. From Fig. S10d and e, the conductive fabric has a resistance change in the range of $-90^\circ$ to $90^\circ$, and the response within $0^\circ$–$90^\circ$ is obviously stronger.
than −90° to 0°, the resistance response of the conductive fabric exhibits good repeatability and stability in each cycle during periodic bending or compression. There is a slight friction at the interface in the textile constructure under sliding conditions. Thus, the conductive fabric shows desirable maintenance after 3000 cyclic tests under the 40% strain, except for a small attenuation of the signal (Fig. 2e). In addition, the sensor was also performed under a high stretch cycle in the range of 80–110% as shown in Fig. S11. The $\Delta R/R_0$ decreases rapidly in the first 3000 cycles, while the corresponding value is relatively stable after 3000 cycles, which deeply demonstrates that the device could maintain a certain sensing ability even in the high stretching range. Compared with the pure fabric, the coated MXene/Cu$_2$O layers play a key effect in increasing the mechanical strength of the conductive fabric (Fig. S7c). Hence, the efficient conductive network and the enhanced mechanical strength were successfully achieved via loading MXene/Cu$_2$O onto the textile substrate. The real-time strain response was assessed based on the intensity relationship between the relative resistance value and the response time through offering a rapid response in a quick stretching and release process. As shown in Fig. 2f, the response time of the stretching and release process are 110 and 80 ms, respectively. The low latency for signal acquisition is critical for monitoring human motion monitoring. The stretch of the conductive fabric is maintained at 10%, 30%, and 50% (Fig. S12a), the resistance value of the conductive fabric remains constant. It shows that the resistance of the conductive fabric has good stability under creep conditions. As shown in Fig. S12b, the sensor is suspended vertically with an attached weight, which provides a constant pull of 2 N for 600 s. The resistance sharply reduced from 22 to 8 kΩ as soon as the pulling force was applied, and then the resistance remained nearly unchanged when the pulling force was kept constant. The above results clarify that the resistance of the sensor is basically not affected by stress relaxation, which could ensure the stability of the sensing signal output. Therefore, the prepared conductive fabric has excellent strain sensing properties, which is a promising building block for the wearable device.

The alternating current impedance analysis result of the conductive fabric is shown in Fig. S13. The phase angle is maintained at 0° in the mid-low frequency range from 1 to $10^3$ Hz, indicating that the conductive fabric maintains the characteristics of pure resistance without capacitance and inductance effects (Fig. S13a and S13b) (Sharma et al. 2021). Numerical fluctuations appear in the high-frequency range, which is caused by the scan time being too short when scanning in the high-frequency range. The impedance $Z'$ of the conductive fabric remains basically unchanged, showing a straight line (Fig. S13c). The introduction of Cu$_2$O in MXene/Cu$_2$O only reduces the resistance of MXene/Cu$_2$O conductive fabrics, has not changed their properties as pure resistive elements. Which is due to reducing the specific gravity of MXene nanosheets under the same loading conditions. Correspondingly, when the content of MXene/Cu$_2$O is increased from 0.48 to 1.36 wt% (Fig. S13d), the resistance of the conductive fabric decreases, and the characteristic of the pure resistance element of the conductive fabric is not will change. Therefore, it can be considered that the work of the prepared MXene-based conductive fabric is mainly based on the principle of resistive sensing. Furthermore, the relationship between the microstructural change of the conductive fabric and external tensile force is useful to further study the sensing mechanism. The micrograph and a diagrammatic sketch of the conductive fabric in Fig. 2g (I) show that the yarn loops are close to each other when not stretched. There are a large number of contact points in the fabric structure with the strain of zero. As shown in Fig. 2g (II), a tensile force ($F$) is applied in the weft direction. The adjacent loops are disengaged under a slight strain. At this time, intertwined yarns generate the contact points, forming a conductive network. It could be seen from the microscopic images that the diameter of the yarns is basically unchanged during the stretching process. After the above process, the conductive network of the fabric loses abundant contact points, which results in the raised resistance. The resistance evolution (Fig. S14a and S14b) exhibits a small increase (<10%, not 10% pre-stretching) under the low stretch range in both warp and weft directions. Therefore, in the low stretch stage, the reduction of contact points at the collective scale of the three-dimensional (3D) yarn is the dominant factor leading to the change of sensor resistance. From the micrograph in Fig. 2g (III), there is a certain void between the yarns in the initial stage. It means that the conduction mechanism of the sensor no longer relies...
on the direct contact of the yarn coils. At 100% strain (not 10% pre-stretching) (Fig. 2g (IV)), the voids between the yarns loops were obviously found. As well, the contact points of the yarns nested with each other were subjected to greater pressure, inducing the increased contact area (yellow area in Fig. 2g (IV)). At the same time, the diameter of the yarn has been significantly reduced, and the deformation model of a single yarn was supplied (Fig. 2h). The yarn stretches in the direction of the central axis and becomes thinner. The tighter contacts between the cotton fibers contribute to the increased contact points area. Furthermore, the increase of the contact points favors the formation of a better conductive network, resulting in a decrease in resistance (Fig. S14a and S14b). From the above description, it could be concluded that the resistance change under high tension is mainly caused by the number change of contact points in the two-dimensional (2D) yarn network and one-dimensional (1D) fiber aggregates. Two modes of resistance change are corresponding to the working mechanism of textile-based sensors. In contrast to the warp stretching, the resistance changes of the weft direction in the range of low stretch (0–10%) and high stretch (10–100%) show better linearity, and the detection range of stretch is also larger (Fig. S14a and S14b).

The sensitivity of the sensor with 1.36% MXene (Fig. S14c) exhibited a trend of increasing first, and then decreasing with the rising of strain. The sensor sensitivity is 9.18 in the first 2% strain range, which further increases to 16.8 in the 2–6% strain range with better linearity. Finally, the sensitivity will reduce to 7.16 at the stage of 6–10%. In addition, the resistance curve exhibits a special “M” shape in a single cyclic stretching under cyclic stretching, and shrinking process spans the two-mode range as shown in Fig. S14d. It is well known that the resistance of the sensor does not maintain a uniform upward or downward trend in the entire stretching range, which may bring difficulties to the identification of subsequent sensing signals. Therefore, choosing weft stretch as the force direction of the sensor and using 10% pre-stretching are more consistent with the needs of sensor development. The conductive fabric serves as a textile-based efficient conductive network with pretty sensing ability, natural comfort, which can well satisfy the practical demands of the flexible and stretchable sensors. Inspiring the excellent strain sensing properties of the conductive fabric based on MXene/Cu$_2$O nanocomposite, a strain sensor is assembled on an elastic fabric substrate, the copper electrode and conductive fabric are bonded with silver paste, and the contact points are fixed with elastic fabric (Fig. 2i). Based on the strain sensor module, the integrated and portable strain sensors were constructed as shown on the right of Fig. 2i. The manufactured strain sensors are predicted to capture and analyze the detailed process of various human activities due to their desired strain detecting behavior.

As a proof-of-concept, the prepared strain sensor was attached to the corners of the mouth and throat to monitor small-scale human physiological activities of the facial expression and the muscle motions near the throat via a tester to noninvasively. As presented in Fig. 3a and b, the sensor-generated two discernable characteristic current patterns according to the smiling and swallowing actions. This is an attribute to each action caused specific form of movement of corners muscle at the mouth and throat, resulting in a distinguishable resistance change signal. The significant characteristic difference between these resistance change signals indicates that the strain sensor has the potential as a voice and expression recognition device. The electrical signals are almost identical during each smiling and swallowing cycle, manifesting the sensitivity and stability of the strain sensor. Aside from detecting small-scale physiological activity, the strain sensor also could be employed to monitor the joint action of bending wrist, finger, elbow, and leg due to their good stretchability. As shown in Fig. 3c, the strain sensor-generated two characteristic current signals for the response of the wrist bending and straightening activities. Similarly, the relevant characteristic signals for the bending/straightening activities of the finger and leg could also be obtained as verified in Fig. 3d and e. Furthermore, for responding to repeated motion, essentially invariable resistance change patterns were obtained, demonstrating that strain sensors for wearable devices had outstanding repeatability and reliability in practical applications. Notably, the bending/straightening activities of the arm, such as keeping the bending angles of 0°, 30°, 45°, 90°, 120° and 150° for a few seconds, also could be fine tested (Fig. 3f). This elucidates that the strain sensor could perceive different motion amplitudes.
Smart sensing glove detect and recognize gesture signals

Considered their outstanding sensitivity, reproducibility and durability, the strain sensors were further made into wearable sensors and integrated into a versatile strain-sensing platform, such as the smart sensing glove (Fig. 4a). The smart sensing glove is useful to detect and recognize gesture signals for the communication needs of hearing-impaired people to realize barrier-free communication. Through wearing the prepared sensing glove, the strain sensors were attached to the joints of the thumb, index finger, middle finger, ring finger and little finger, which is applied to read the sign language via a more convenient method. Its circuit diagram is shown in Fig. 4b by which the voltage variation is measured. As given in Fig. 4c, the smart sensing glove generates different characteristic current patterns associated with the gesture signals of "1", "2", "3", "4", and "5". The simple letters of "C", "S", "L", "O", and "Y" also could be translated and presented (Fig. 4d). Importantly, these sign languages could be quickly cached in a continuous test-time, indicating good sensitivity. Furthermore, the combination of sensor array and glove can realize more accurate gesture recognition, further supporting the application prospects of MXene/Cu$_2$O nanocomposite-based conductive fabric strain sensor on electronics and biomedical devices.

Breathability and antibacterial properties of the MXene/Cu$_2$O nanocomposite-based fabric sensor

In addition to sensing performance, the strain sensor also exhibits great wearability including breathability and antibacterial properties. The bactericidal activity of the MXene/Cu$_2$O nanocomposite-based fabric sensor was evaluated via 24 h shake flask test. The bacteria colonies showed that samples with pure MXene have no obvious antibacterial activity against Escherichia coli (E. coli) and Staphylococcus aureus (S. aureus) in comparison with MXene/Cu$_2$O nanocomposite-based fabric (Fig. 5a and b). While the bacteriostatic rates of E. coli and S. aureus were 96.3% and 81.3% respectively with the MXene/Cu$_2$O content of 1.16 wt%. Samples with loaded MXene/Cu$_2$O of 1.4 wt% show the highest bacteriostatic rates, which were 99.1% to E. coli, and 96.3% to S. aureus (Fig. 5c). The strain sensor exhibits a stronger inhibitory activity against E. coli than S. aureus. The
introduction of Cu$_2$O has substantially improved the antibacterial ability of the strain sensor. More interestingly, the treated fabric remains an excellent air permeability of 233.75 mm/s with a margin drop from 297.5 mm/s (Fig. 5d) after one dip-dry process, even after being treated 5 times, the fabric remains desirable breathability (190 mm/s). The results have revealed that MXene/Cu$_2$O nanocomposite-based fabric sensor possesses a great advantage in smart sensing while creating a skin-friendly and sterile environment on the skin-sensor interface, ensuring favorable wearability as a wearable sensor.

**Conclusion**

In summary, the strain sensing MXene/Cu$_2$O nanocomposite-based cotton fabric with a low surface electrical resistance of 600 Ω/sq was successfully fabricated by adopting a facial dip-dry strategy. The sensor resistance increased with the rising strain from 0 to 10%, which exhibited an excellent sensing sensitivity of 16.8. Meanwhile, the resistance decreased with the rising strain in the > 10% range, which exhibited a −1.42 sensing sensitivity. After pre-stretching, these prepared stretch sensors not only demonstrates good tensile linear sensitivity, but also effectively monitors bending responses from −90° to 90°. The prepared stretch sensor presents great advantages in detecting and monitoring of small and large human activities (such as smiling, swallowing, wrist/finger/leg bending), sensing different bending amplitudes of joint movements and was further developed for gesture language recognition gloves. The strain sensor exhibits high stability over 3000 cycles over 100%, low response delay of 80 ms, and the synergy of hybrid materials successfully enhances the antibacterial ability, safety and comfort (breathability reaches...
190 mm/s) of the sensor. This study offers a reasonable design strategy for high-performant strain sensors, and provides new insight reference for smart e-textiles in wearable electronics fields.

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Declarations

Competing interests The authors declare that they have no competing interests.

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