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Moisture-sensitive torsional cotton artificial muscle and textile*

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Developing moisture-sensitive artificial muscles from industrialized natural fibers with large abundance is highly desired for smart textiles that can respond to humidity or temperature change. However, currently most of fiber artificial muscles are based on non-common industrial textile materials or of a small portion of global textile fiber market. In this paper, we developed moisture-sensitive torsional artificial muscles and textiles based on cotton yarns. It was prepared by twisting the cotton yarn followed by folding in the middle point to form a self-balanced structure. The cotton yarn muscle showed a torsional stroke of 42.55 °/mm and a rotational speed of 720 rpm upon exposure to water moisture. Good reversibility and retention of stroke during cyclic exposure and removal of water moisture were obtained. A moisture-sensitive smart window that can close when it rains was demonstrated based on the torsional cotton yarn muscles. This twist-based technique combining natural textile fibers provides a new insight for construction of smart textile materials.

Keywords: artificial muscle, smart textile, cotton yarn

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1. Introduction

Developing moisture-sensitive artificial muscles from industrialized natural fibers with large abundance is highly desired for smart textiles. Textiles have been an indispensable part in human life for thousands of years. The basic function of traditional textiles is for blocking the body and providing warmth by isolating air from the environment to decrease the heat transfer.[1] Nowadays, with advances in textile technologies, multi-functional textiles that can sense, respond, communicate, or adapt with environmental change are highly desired.[2] Successful examples have been realized for smart textiles that show color change, lighting, actuating, and sensing, when interacting with environmental changes.[3]

Among these advances in smart textiles, the incorporation of traditional textile technology and fiber artificial muscle can provide tensile and torsional responses triggered by electricity, moisture, heat, light, etc.[4] In recent years, twist-based fiber artificial muscles have been designed based on a volume expansion mechanism, which showed large actuation strokes and high work capacity.[5] Different fiber materials were designed for twist-based fiber muscles, including graphene[6] and carbon nanotube fibers,[5] polymer fibers,[7] shape memory alloy,[8] elastomers,[9] and their composites.[10] In the material's point of view, natural textile materials are more attractive for smart textiles due to their merits of comfortability, large availability, and low cost. Artificial muscles based on pure natural textile fibers that can respond to environmental changes (e.g., moisture, temperature, etc.) show extraordinary applicability for industrialization, because there is no need for additional material design and biocompatibility investigations.

Recently we demonstrated moisture sensitive twist-based torsional artificial muscles and smart textiles from silkworm silk.[11] However, silkworm silk only has a miniscule percentage of global textile fiber market (less than 0.20%),[12] possibly due to its limitation of productivity and relative high price. Moreover, the silk is a type of protein fiber,[13] it is highly suggested to develop artificial muscles based on more wide range of natural products. Except for comfortability, a combination of wearable requirements such as softness by absorption of water moisture, high porosity for keeping warm, high

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temperature tolerance is also required for smart textiles that can be used in scenarios other than silkworm silk. Therefore, it is highly desired to identify other more widely used natural fibers as artificial muscles for smart textiles.

Cotton is an important raw material in textile industry, which accounts for $\sim 39.50\%$ of the world's textiles in 2018.[14] The cotton yarn exhibits high strength, excellent hygroscopic properties, and biocompatibility with human body, which boosted its demand in textile industry. Furthermore, cotton shows softening on absorption of moisture, good cold-proof properties, good temperature tolerance, and alkaline resistance. Cotton yarn is mainly composed of cellulose, which is hydrophilic and shows good air permeability.[15] It absorbs the moisture from human body and evaporates water into the environment to keep a humidity balance. This makes it a good candidate for moisture-responsive smart textiles. So far, cotton-based humidity-driven torsional artificial muscles and smart fabrics have not been developed.

In this work, we demonstrate humidity driven torsional artificial muscles from twisted and plied cotton yarns. To enable reversible actuation without the need for torsional tethering, we exploit torque-balanced fiber structures that are obtained by folding a twisted fiber onto itself to form fiber plying. When exposed to water fog, the torsional muscle provided a fully reversible torsional stroke of 42.55 °/mm and normalized value of 3.00°, which were close to the water-absorption-driven coiled carbon-nanotube fiber (61.30 °/mm) and normalized value of 1.20°.[16] A humidity sensitive intelligent window was demonstrated for the cotton artificial muscle.

2. Results and discussion

2.1. Cotton yarn structure and properties

Cotton yarn is formed by lengthening and thickening epidermal cells of fertilized ovule, which is around the seeds of the cotton plants and will increase dispersal of the seeds.[17] The main components of the cotton yarn are cellulose, which is a natural polymer that contains a large number of hydrocarbon groups ($[C_8H_{10}O_5]_n$) and forms both crystalline and amorphous regions.[18]

Scanning electron microscope (SEM) images show that a cotton fiber is $\sim$ 10–20 μm in diameter, which is composed of a fiber core formed with aligned nanometer-scale fibers and a thin porous surface layer (Fig. S1). Different from silkworm silk that is a meters-long, single filament, the cotton fibers are short fibers with length ranging from 1 cm to 4 cm. These short cotton fibers are spun into long yarns for further knitting into textiles (Fig. 1(b)). Cotton fibers contain a large amount of hydroxyl groups, which can form hydrogen bonds with water molecules. Fully absorption of water droplet by a cotton yarn results in anisotropic expansion of the yarn (12.50% increase in yarn radius and negligible change ($< 1\%$ increase) in yarn length (Fig. 4(a))), corresponding to 12.50% volume increase.

We then tested the water absorption/desorption kinetics of a cotton yarn. When a dry cotton yarn is exposed to air with a relative humidity of 90%, a 10-mg cotton yarn uptakes $\sim$ 20 mg of water in 15 min. There is a linear relationship between the water absorption rate and time (see Fig. 1(f)). Then the cotton yarn is exposed to a 30%-humidity air, and the weight returns back in 18 min. This fast water absorption and desorption kinetics should be ascribed to the hierarchical fiber structure of the cotton yarn.

The microstructural change of the cotton yarn for water absorption/desorption processes was also investigated using x-ray diffraction (XRD). The dried cotton yarns show crystallites embedded in the amorphous region.[19] The XRD peaks at 2θ angles of 15.30°, 17.50°, 22.50°, and 34.50° correspond to 101, 10$\bar{1}$, 002, and 040 reflections of the cellulose, respectively.[20] The 101 plane (2θ angle of 15.30°) corresponds to densely packed hydroxyl groups in the crystalline region, whose intensity dramatically decreases upon absorption of water moisture. The new broad peak observed at $\sim$ 28.50° corresponds to a combination of 130, 131,221, 22$\bar{1}$, 230, and 310 reflections upon yarn exposure to water moisture, which was also observed for the immature cotton fiber.[21] This indicates that the fiber exposure to water moisture induces crystal lattice distortion and increased amorphous scattering. Removing water moisture fully reverses the XRD patterns of the dried cotton yarn, indicating good reversibility of the water absorption/desorption processes.

The above results about large radial expansion, fast absorption/desorption kinetics, and reversible structural changes upon fiber exposure to water moisture indicate that the cotton yarn is an ideal candidate for fabrication of fiber artificial muscles.

2.2. Fabrication of torsional cotton muscles

Torsional muscles were fabricated from the cotton yarns using a twist-based technique, as shown in Fig. 1(a). The cotton yarn investigated in this paper was obtained by taking out one 35-tex single yarn from a commercial 17-plies 35-tex yarn. To make the muscle, the cotton yarn was connected to a load at the bottom, and the top end was connected to a 42-step servo motor. Twist was inserted into the yarn at an isobaric stress of 3.25 MPa (constant load) using the motor at the top end (at a twist speed of 50 turns/min). The load was torsionally tethered using a pin to avoid release of the inserted twist. Because during the twist insertion, the length of the cotton yarn decreases, this isobaric loading is important to avoid cotton yarn breaking, rather than an isometric (constant length) tethering. Directly removing the pin results in twist release of the cotton yarn. Therefore, the twisted cotton yarn was folded in the middle and a paddle was loaded in this middle point to produce a 3.25 MPa stress. This cotton yarn will untwist and ply together to form a self-balanced torsional muscle (Fig. 1(d)). Because a torsional stress still preserves in this self-balanced 2-ply yarn, on exposure to water moisture, the volume expansion of the yarn produces further untwisting of each single yarn and uptwist of plying. Removing water moisture reverses this process.

The measurement of torsional actuation was in an open circulating environment with 40% relative humidity (RH) at the room temperature of 25 ℃. The cotton yarn muscle was exposed to ultrasonically generated water fog to produce torsion rotation. If not specified, a self-balanced 2-ply muscle prepared from a single filament cotton yarn was used for measurements. For multiply muscle measurements, self-balanced 4-ply muscle from two filament cotton yarns, and self-balanced 6-plymuscle from three-filament cotton yarns were also prepared. The torsional rotation was recorded by using a fast-speed camera and the data was obtained from the video by counting the rotations.

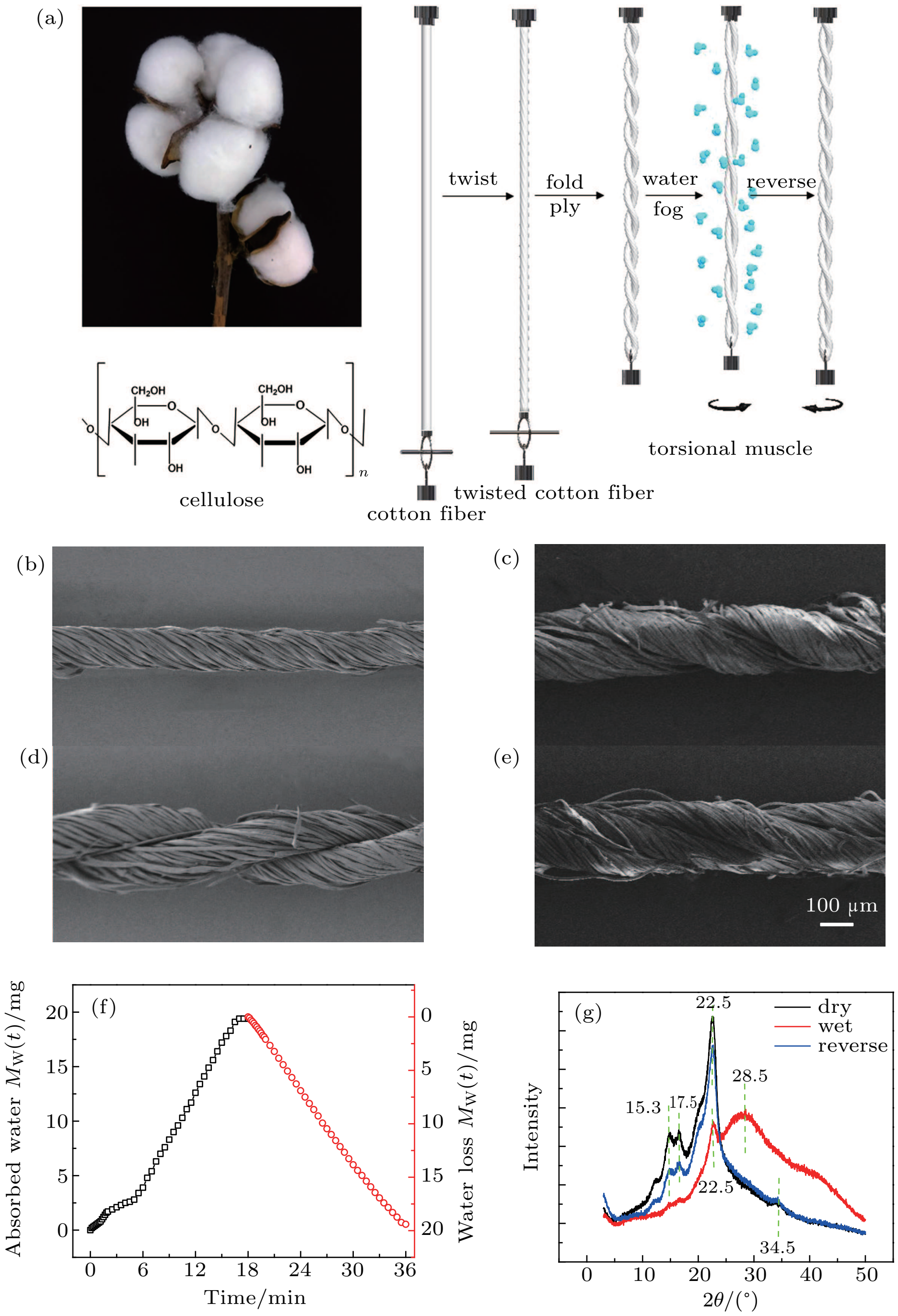

Fig. 1. (a) Schematic demonstration of fabrication of torsional cotton yarn artificial muscle. (b)–(e) SEM images for (b) single, (c) two-ply, (d) two-ply self-balanced, and (e) three-ply cotton yarns. The twist densities for (b)–(e) are 1400, 1000, 1400, and 800 turns/m, respectively, when normalized to the non-twisted length, the scale bars are the same in (b)–(e). (f) Kinetics of the water absorption/desorption by a cotton yarn. (g) XRD (Cu $K\alpha$ radiation) of cotton yarn before, after water absorption, and after water desorption, on exposure to a humidity of 100%.

2.3. Torsional actuation performance of cotton yarn muscles

Figure 2(a) shows the first example of torsional actuation of a 10-cm-long, self-balanced 2-ply, 140-μm-diameter single filament cotton yarn muscle (5 mg). The rotation angle of the muscle increases to 32.73 °/mm in 3 s on delivering 0.25 $\mathrm{g \cdot s^{-1} \cdot m^{-2}}$ flux of water fog, corresponding to a peak rotation speed of 400 rpm. On removing the water fog, the yarn muscle returns back to the initial state in 200 s. This cotton yarn muscle showed high reversibility and recyclability for rotation angle and speed during the investigated 500 times of actuation cycles (Figs. 2(b) and 2(c)). The difference in forward and reverse rotation speeds is likely due to the difference in water absorption/desorption kinetics of the cotton yarn (Fig. 1(f)). The torsional actuation of the cotton yarn muscle highly depends on the isobaric stress, because the rotation of the paddle highly depends on its inertia.

Figure 2(d) shows the stress dependence of the maximum rotation angle and the maximum rotational speed for the cotton yarn muscle. With increase in the isobaric stress, the maximum rotation angle increases to a peak value of 42.55 °/mm at an isobaric stress of 25 kPa and then decreases. Similarly, the maximum rotation speed increases to a peak value of 720 rpm at an isobaric stress of 35 kPa. The mass of the paddle (230 mg) is 46 times that of the yarn muscle (5 mg), which gives the moment of inertia of 1.42×10^{-9} $\mathrm{kg \cdot m^2}$, and the muscle generates a torque per muscle mass of 17.80 $\mathrm{mN \cdot m \cdot kg^{-1}}$. Too small applied stress results in both small rotation angle and low rotation speed, which is likely because the internal stress is too small to generate efficient untwisting upon volume expansion by water-fog uptake. During water-fog induced torsional rotation, we also observed a slight tensile contraction ($< 1\%$). Such contractile actuation also consumes part of the muscle power from moisture uptake.

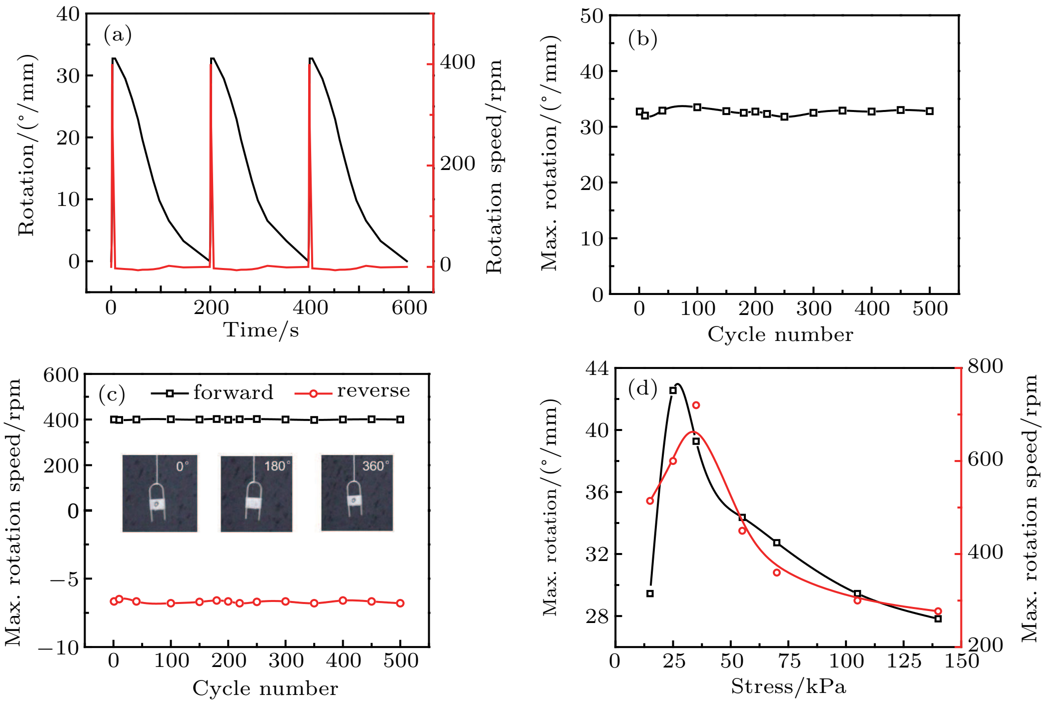

Fig. 2. Torsional actuation performance of a self-balanced, 2-ply cotton yarn muscle. (a) Rotation angle and rotation speed as a function of time for three cycles of delivering/removing water fog. (b) Maximum rotation angle for 500 cycles of water-fog induced torsional actuation. (c) Forward and reverse maximum rotation speeds for 500 cycles of water-fog induced torsional actuation. (d) Maximum rotation angle and maximum rotation speed as a function of isobaric stress. The ambient relative humidity was 40%, and room temperature was 25 ℃. The water fog flux was 0.25 $\mathrm{g \cdot s^{-1} \cdot m^{-2}}$. The initial inserted twist was 1200 turns/m. The paddle weight in (a)–(c) was 0.47 g. The initial non-twisted cotton yarn was 25 cm in length and 140 μm in diameter.

This moisture-driven torsional actuation of the cotton yarn muscle largely depends on the internal stress change of the twisted yarn upon volume expansion. By inserting twist, the cotton yarn showed a bias angle (α) with the fiber length direction. For a cotton yarn with radius r and inserted twist density T (number of inserted twist divided by the fiber length), this bias angle α for the surface layer of the yarn can be calculated as $\alpha = \tan^{-1}(2\pi rT)$.[22] Figure 3(a) shows that the measured surface bias angle linearly increases with increase in inserted twist, which agrees well with the calculated value. Because larger diameter yarn normally contains less inserted twist, resulting in lower rotation angle. We then normalized the rotation angle of the cotton yarn muscle by multiplying the muscle radius. Because the muscle is a self-balanced, multi-ply structure, an equivalent radius r' is defined for a n-plied yarn ($r' = n^{0.5}r$). After this normalization, the rotation angle (42.55 °/mm) corresponds to 3.00° of rotation. This is comparable to the carbon nanotube yarn muscles (1.20°), graphene fiber muscle (14.70°), and silk yarn muscle (5.20°).

Twist insertion is generally used in yarn spinning to assemble loose short fibers into a high-strength, long yarn. We further investigated the dependence of the mechanical properties of the cotton yarn on the twist insertion (Fig. 3(b)). With increasing the twist density in a 140-μm-diameter cotton yarn from 400 turns/m to 1200 turns/m, the breaking strength decreases from 156 MPa to 117 MPa, and the failure strain increases from 13.60% to 18%. We also investigated the change in mechanical strength of a twisted cotton yarn exposure to water moisture. A 140-μm-diameter cotton yarn with inserted twist of 800 turns/m showed a breaking strength of 140 MPa and 132 MPa, and failure strain of 16% and 27.50% before and after exposure to 100% water humidity.

The dependence of the torsional actuation behavior on the inserted twist density for cotton yarn muscles was then investigated, as shown in Fig. 3(e). A 10-cm-long, 2-ply self-balanced cotton yarn muscle (5 mg) with single yarn diameter of 140 μm was isobarically loaded with a 470-mg paddle (94 times the muscle weight). By increasing the twist density from 400 turns/m to 1200 turns/m, the maximum rotation angle monotonically increases from 14.12° to 32.73°, and the maximum rotational speed monotonically increases from 150 rpm to 400 rpm. Interestingly, with increase in twist density, the ratio of the rotational speed for the forward process to that of the reverse process increases from 19 (for 400 turns/m) to a maximum value of 81 (for 800 turns/m), and then decreases to 60 (for 1200 turns/m).

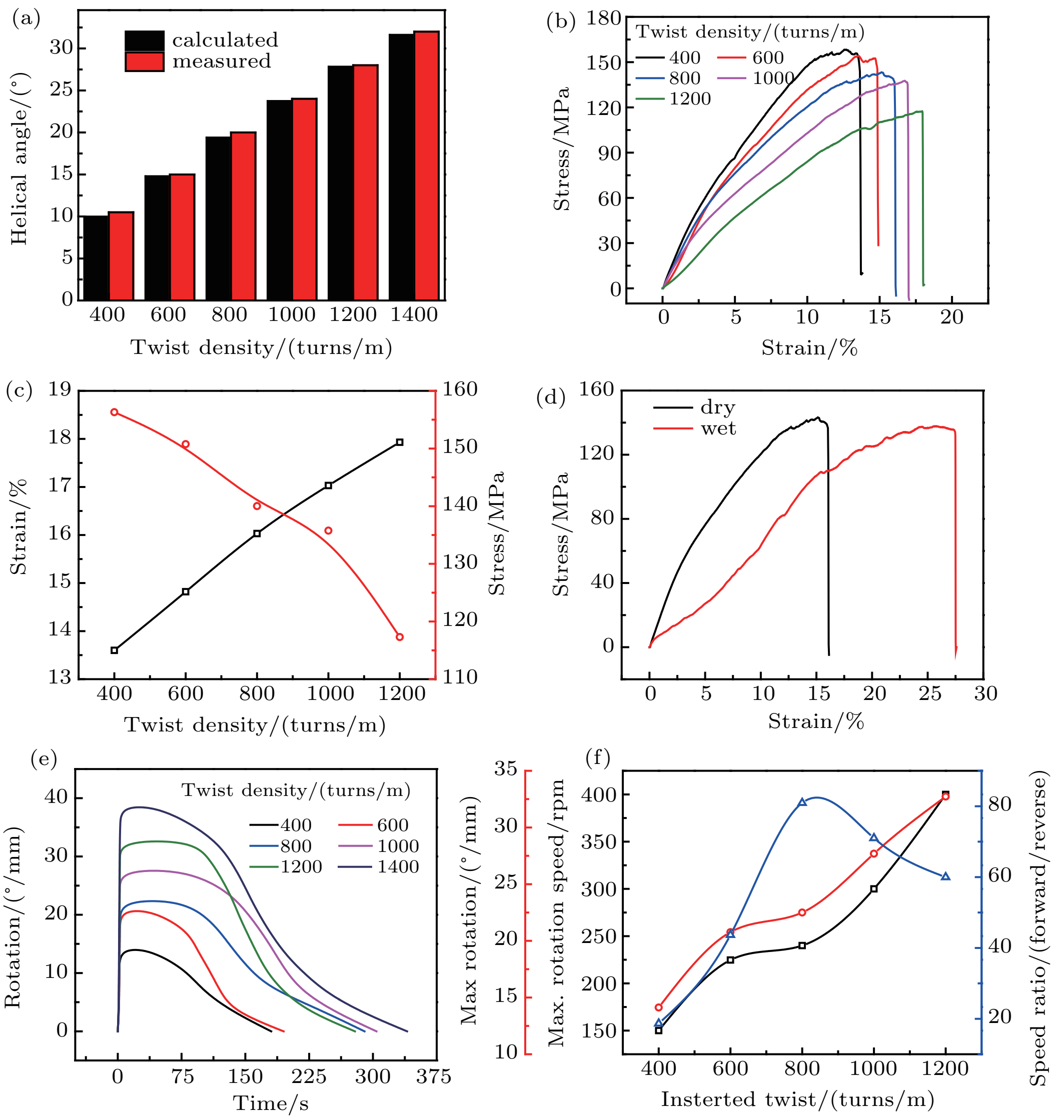

Fig. 3. Structure, mechanical, and actuation properties of yarns with different twist density. (a) Measured and calculated surface bias angles of a 140-μm-diameter cotton yarn as a function of inserted twist density. (b) Stress–strain curves of a 140-μm-diameter cotton yarn at different inserted twist. (c) Breaking stress and failure strain obtained from (b). (d) Stress–strain curves of a 140-μm-diameter cotton yarn with 800 turns/m of inserted twist before and after exposure to 100% relative humidity. (e) Torsional rotation angle as a function of time for a self-balanced, 2-ply, single filament cotton yarn muscle with different inserted twist on exposure and removing the water fog. (f) Maximum rotation angle, maximum rotational speed, and the ratio of the maximum rotational speed in the forward process to that in the reverse process for a self-balanced, 2-ply, single filament cotton yarn muscle with different inserted twist on exposure to water fog. The ambient relative humidity is 40%, and room temperature is 25 ℃. The loaded paddle during torsional actuation for (e) and (f) is 0.47 g. The flux of water fog in (e) and (f) is 0.25 g·s^{-1}·m^{-2}.

The origin of torsional actuation in this twisted yarn is stress change due to the moisture-induced volume expansion. So we investigated the volume expansion ratio of the cotton yarn with different twist density upon water absorption. When exposed to 100% relative humidity, the yarn length (l) shows negligible change (Δl <1%) for different inserted twist, while the yarn diameter (d) shows dramatic increase. The change in yarn diameter (Δd) monotonically decreases from 12.50% to 7% when the inserted twist increases from 0 to 1200 turns/m (Fig. 4(a)). For a torsional balanced muscle by twisting yarn with number of inserted twist n and surface bias angle α, the change in number of inserted twist (Δn) can be calculated as[8,21] $\Delta n/n = (\Delta\lambda/\lambda)\cos^2\alpha - \Delta d/d - (\Delta l/l)\tan^2\alpha$, where λ and $\Delta\lambda$ are the length of the helical yarn after twist insertion and its change after exposure to moisture, respectively. As both the relative change in helical length of the yarn ($\Delta\lambda/\lambda$) and the relative change in yarn length ($\Delta l/l$) are negligibly changed on humidity exposure, this equation can be approximated as $\Delta n/n = -\Delta d/d$. Therefore, the torsional actuation stroke (the change in twist density, ΔT) for a yarn with inserted twist of T can be calculated as $\Delta T = -T(\Delta d/d)$. Figure 4(b) shows that the measured torsional stroke quasi-linearly increases with the increase in inserted twist, which agrees well with the calculated values.

We then investigated the torsional actuation performance for multiply cotton yarns. Figure 4(c) shows the time dependence of rotation angle for self-balanced muscles made from one to five cotton yarns upon exposure to and removal from 100% relative humidity air. These fibers were twist-inserted to form the same surface bias angle, which was calculated from $\alpha = \tan^{-1}(2\pi r' T)$, where r' is the equivalent radius for the n-plied yarn ($r' = n^{0.5}r$). With increasing the number of cotton yarns from one to five, the maximum rotation angle decreases from 32.73 °/mm to 9.47 °/mm, and the maximum rotational speed decreases from 400 rpm to 70.56 rpm. This is likely due to the decreased water uptake for increased diameter for multiply yarns.

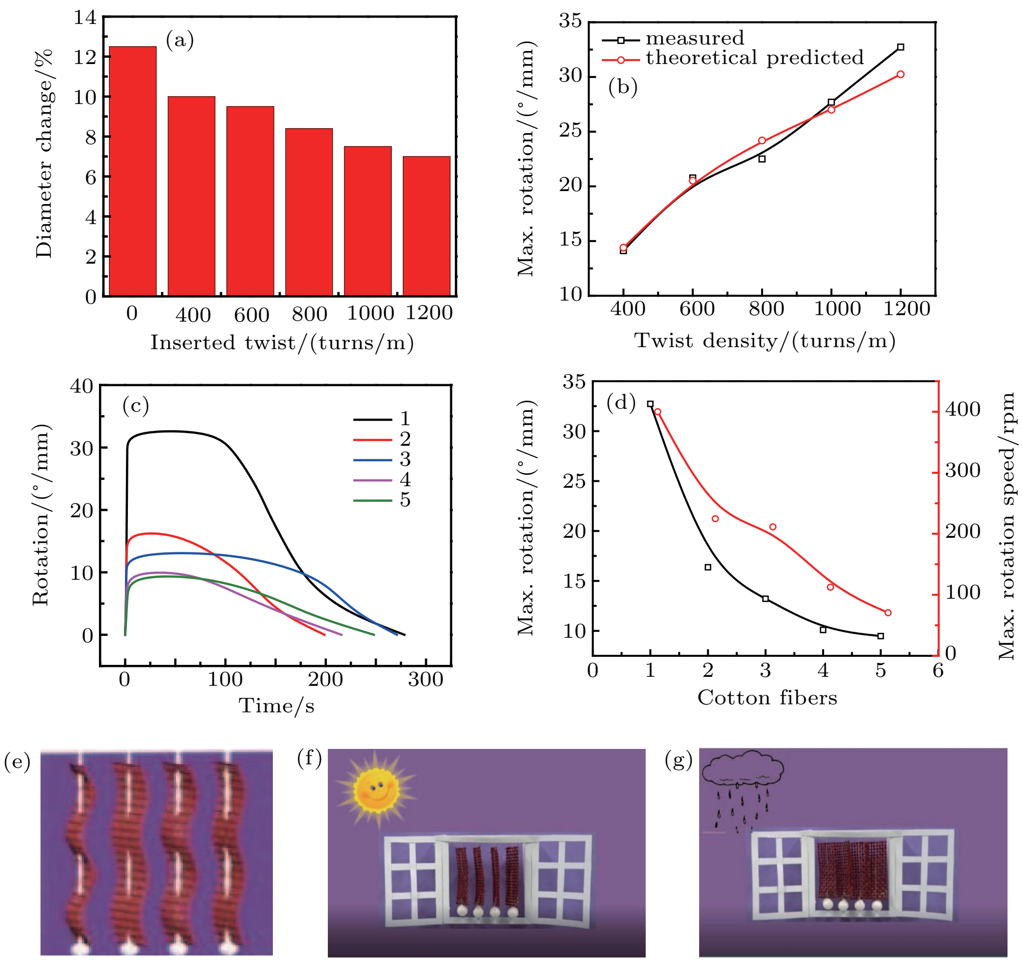

Fig. 4. Torsional actuation for different inserted twist and number of plies. (a) Diameter change of a cotton yarn with different inserted twist on exposure to 100% humidity. (b) Experimentally measured and theoretically calculated maximum rotation angles for cotton yarn muscle with different inserted twist. (c) Time dependence of rotation angle for torsional muscle prepared from different number of plies of cotton yarns, 1, 2, 3, 4, 5 are the number of the cotton yarns. (d) Maximum rotation angle and maximum rotational speed obtained from (c). The cotton yarns used for fabricating yarn muscles are 140 μm in diameter and 25 cm in length. The environmental relative humidity is 40%, and the room temperature is 25 ℃. The isobarically loaded paddle weighs 0.47 g. (e) Schematic demonstration and (f), (g) sequential photos of a smart window by knitting a cotton yarn muscle through a textile. The muscles rotate and close the window on exposure to high humidity. Sequential photos show that the smart window can automatically close when moisture increases.

2.4. Demonstration of the cotton yarn muscle as smart window

These cotton yarn muscles can be delicately designed to obtain tunable torsional actuation performance by adjusting the internal parameters (such as inserted twist and number of plies) and the external parameters (such as isobaric load). The full reversibility and highly retention of the torsional actuation angle on repeated exposure or removal of water moisture enable the cotton yarn muscle as an ideal candidate for smart textiles. We then investigated the applicability of this torsional cotton yarn muscle as a moisture-driven smart window.

Based on the torsional rotation of the cotton yarn muscle on exposure to water humidity, a smart window was schematically demonstrated, which can close when it rains and open when rain stops (Fig. 4(e), movie S1). A 5-cm-long, self-balanced, 2-ply, single filament cotton yarn muscle (with yarn diameter of 140 μm and weight of 2.50 mg) was knitted through the center of a 5-cm-long, 2-cm-wide textile (weight of 0.14 g). A 25-mg load was connected to the bottom end of the cotton yarn muscle to provide isobaric stress. In dried ambient air, the window is set to be open to allow sunshine goes into the room (Fig. 4(f)). When it rains, the cotton yarn muscle absorbs water moisture and rotates to close the window (Fig. 4(g)). For such a smart window, the cotton yarn can rotate 5.6-times its own weight to 90° in 15 s on exposure to water fog of flux of 0.25 $g\cdot s^{-1}\cdot m^{-2}$.

3. Conclusions

In summary, moisture-sensitive torsional artificial muscles and textiles were prepared from cotton yarns. The cotton yarn was twisted and folded in the middle point to form a self-balanced structure. Upon water moisture absorption, the cotton yarn showed volume expansion and the muscle showed fast rotation with torsional stroke of 42.55 °/mm and a rotational speed of 720 rpm. The cotton yarn muscle showed good reversibility and stable actuation during applying/removing water moisture. Based on the cotton yarn torsional muscle, a smart window was designed that can spontaneously close when it is wet and open when it dries. This work provides a new opportunity for smart textiles based on natural fiber materials.

4. Experimental section

4.1. Preparation of cotton muscles

The cotton thread (35 tex) was purchased from China cotton group Co. Ltd. The as-received cotton thread contains 17-plies of single cotton yarns (140-μm-diameter, 35 tex). A single cotton yarn was split out from the as-obtained cotton thread for preparing the cotton muscle. The fabrication of the torsional muscle is briefly described as follows. The top end of the cotton yarn was connected to a 42-step servo motor, and the bottom of end of the cotton yarn was isobarically loaded with a weight, which was torsionally tethered. Twist was inserted by rotating of the servo motor. After twist insertion, the cotton yarn was folded in the middle, each twisted yarn untwisted to ply the yarns together to form a self-balanced torsional muscle.

4.2. Characterizations

The stress–strain curves of the cotton yarns were measured on an Instron mechanical tester modeled 3365. For mechanical testing, the samples were attached to paper frames using double-sided adhesive tape. The gauge length was 20.00 mm. The frames were mounted onto the Instron tester equipped with a calibrated 5 N load cell. The extension rate was 10.00 mm/min. The cotton yarn diameter was measured using SEM, which can obtain the cross-sectional area of the samples. SEM characterization was carried out using an MERLIN Compact. The x-ray diffraction results were obtained using Cu $K\alpha$ radiation on an Ultima IV x-ray diffractometer. The data were collected from 5° to 50°. Ambient temperature and relative humidity were measured by a hygrometer (CEM DT-615).

Supplementary data

Supplementary data associated with this article can be found online.

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