Fast Sheath-driven Electrothermal Artificial Muscles with High Power Densities

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Abstract

Electrothermal carbon nanotube (CNT) yarn muscles can provide large strokes during heating-cooling cycles. However, the slow cooling rate of thermal muscles limit their applications, since large diameter prior-art thermal muscles cannot be rapidly cycled. We here report an ultrafast thermally powered sheath-driven yarn muscle that uses a hybrid CNT sheath and an inexpensive polymer core. Our coiled muscle contracts 14.3% at 1 Hz and 7.3% at 8 Hz in air when powered by a square-wave electrical voltage input. The 70-mm-diameter actuated muscle cools in air to 16°C from 150°C within 0.5 s, compared with 6 s for a 65-mm-diameter sheath-run muscle that uses an electrothermally heated CNT core and 9 s for a 78-mm-diameter muscle that uses the sheath material for the entire muscle. An average power density of 12 kW/kg was obtained for a sheath-driven muscle, which is 42 times that for human skeletal muscle. This high performance results since the heating that drives fast actuation cycles is largely restricted to the muscle sheath, and this sheath is in direct contact with ambient temperature air.

Introduction

Artificial muscles that convert external energy to mechanical energy are of great interest because of their potential applications in devices like exoskeletons, prostheses, and bionic robots. Many functional materials have been used as artificial muscles, such as shape memory polymers (SMPs)^{1,2}, shape memory alloys (SMAs)³, dielectric elastomers (DEs)⁴⁻⁸, polymer fibers⁹⁻¹¹, ionic polymer metal composites (IPMCs)^{12,13}, graphene based fibers¹⁴⁻¹⁶, and carbon nanotubes (CNTs)¹⁷⁻²¹. CNT yarns are especially promising candidates due to their high strokes, electrical conductivity, thermal conductivity, and mechanical strength^{22,23}. When powered electrochemically²⁴⁻²⁵, photonicall²⁶, thermall²⁶, or electrothermall²⁷, twisted and coiled CNT muscles exhibit exceptional torsional and tensile actuation. Electrothermall²⁷ powered CNT muscles have the advantage that they are easy to operate. Filled with volume expanding guest, hybrid CNT muscles can provide large tensile strokes²⁸⁻³⁰. For example, hybrid CNT yarn muscle infiltrated with a thermoplastic polyurethane generated a tensile stroke of 13.8%²⁹. Jeong and co-workers reported a silicone-infiltrated CNT yarn muscle that provided a tensile stroke of 30.5%³⁰. Nevertheless, even moderate-diameter versions of these hybrid yarn muscles cannot actuate at high frequencies, which restricts their applications as fast response actuators.

Electrothermall²⁷ powered artificial muscles with the same handedness of yarn twist as yarn coiling, which are called homochiral, contract when electricall²⁷ heated and expand when the electrical power is off. Both heating and cooling processes affect actuation frequency. The heating process can be shortened by increasing input power, while the cooling process is largely uncontrollable in ambient air. Thus, the actuation frequency for electrothermall²⁷ powered artificial muscles is limited by the cooling time.

For torsionall²⁷ y tethered twisted and coiled hybrid muscles, thermal volume expansion of yarn guest causes yarn untwist and transfer of this twist to yarn coiling produces muscle contraction if the muscle is

homochiral. The contribution of guest expansion to yarn untwist depends on the yarn's bias angle (the angle between the yarn length and the CNT alignment direction). This angle decreases to zero in going from yarn surface to yarn center, which means that the material near yarn center consumes energy without making much contribution to muscle stroke. The weight of needed CNTs can be reduced by fabricating sheath-run muscles (SRAMs)³¹, which deploy a twisted CNT yarn as the core, and a polymer guest as the sheath. When these SRAMs are powered electrothermally by electrically heating the yarn core, the thermal path that produces actuation goes from yarn core to yarn sheath. Since the volume expansion of the sheath contributes most to muscle stroke, the heating and cooling processes are limited by the separation between the heating element and both the actuating sheath and the surrounding ambient air.

The goal is to increase cycle rate by shortening the thermal transport path for both heating and cooling. In contrast to previous thermally powered SRAMs, which were core driven by electrothermally heating the CNT core of the muscle, our present sheath-core muscles are sheath driven by directly electrothermally heating a guest-containing CNT sheath. Hence, they are called sheath-driven artificial muscles, since they are sheath run by directly electrothermally heating the sheath of a SRAM. Results show that our approximately 70-mm-diameter sheath-driven muscles can provide a tensile contraction of up to 23% and generate an average gravimetric mechanical work density of 2.6 kJ/kg, which is 65 times that for human skeletal muscle³². An average contractile power density of 12 kW/kg was obtained, which is 42 times that of human skeletal muscle³².

Results And Discussion

Fabrication and Structure. Sheath-driven yarn muscles consist of two parts, a high mechanical strength polymer core and a CNT-layer sheath that is infiltrated with silicone elastomer. Actuator performance varies when using different polymer fibers, such as a polyimide (PI), nylon 6,6, and Kevlar. The nylon 6,6 polymer is a monofilament fiber and the PI and Kevlar are yarns which contain three and one-hundred 10-micron-diameter fibers, respectively. The mechanical properties of these polymer fibers are listed in Table S1. The fabrication of a sheath-driven electrothermal muscle is schematically illustrated in Fig. 1. Except for the polymer coating step that results in polymer infiltration into the CNT sheath, in going from Fig. 1c to 1d, this process is analogous to that previously used to make sheath-run electrochemically powered artificial muscles³¹. As an example of a typical fabrication method, which was used unless otherwise indicated, a highly aligned 20-mm-diameter PI yarn was first twisted with 7 turns/cm under an isobaric mechanical load of 14 MPa (Fig. 1a). Then the twisted polymer yarn was transferred to a vertical stage with opposite yarn ends fixed (Fig. 1b). Thereafter, a 5-layer, 20-cm-long, 5-cm-wide CNT sheet was wrapped around the polymer yarn as a cylinder, so that the CNT alignment direction was parallel to the polymer fiber direction. By inserting twist into this forest-drawn CNT sheet stack from opposite cylinder ends, two opposite cones were formed until the CNT sheet cylinder was twisted onto the polymer yarn (Fig. 1c). After the wrapping process, silicone elastomer resin was uniformly coated on the CNT sheet (so as to infiltrate the resin into the CNT sheath), which is shown in Fig. 1d. After curing the silicone

elastomer resin at 60°C for 12 h and inserting twist into the sheath-core yarn to obtain complete coiling, using the same tensile load as used for yarn twist, a coiled sheath-driven electrothermal artificial muscle was obtained (Fig. 1e). SEM images for sheath-driven muscles are shown in figs. S1&S2. Hybrid yarn muscles were made using a previous described method^{19,20,33}. A CNT yarn fully infiltrated with PDMS, which is called a hybrid yarn, is noted as PDMS@CNT, a sheath driven muscle with PDMS-infiltrated CNT as sheath and PI polymer as core is expressed as PI_PDMS@CNT.

An additional process is needed for making a sheath-driven muscle that has a twisted CNT yarn core. In order to avoid infiltration of the silicone elastomer into the CNT core, paraffin wax was used as sacrificial material to fill the twisted CNT yarn³⁴. Due to the incompatibility of silicone and paraffin wax, the silicone resin fully infiltrated into the sheath, without penetrating into the twisted CNT core. Since silicone has a high melting temperature of 450°C (fig. S3), we can remove the paraffin wax without melting the silicone by heating the muscle at 180°C in vacuum to volatilize the paraffin wax.

The twist density is defined as the number of inserted twisted turns divided by the original fiber length. The applied tensile stress was obtained by dividing the applied force by the cross-sectional area of the non-loaded, non-actuated, fully-twisted muscle, as measured immediately before the onset of coiling. The spring index is defined for the non-actuated muscle as the ratio of the average coil diameter to the total muscle diameter. The sheath-core ratio (SCR), which is defined as the sheath thickness divided by the core diameter, is about 0.37 unless otherwise indicated. Contractile stroke is defined as the change of the length of the loaded muscle divided by the non-actuated length of the loaded muscle. Stroke rate is contractile stroke divided by the cycle time. The applied input power density is the input power divided by the total muscle weight. Work capacity is the contractile work divided by the total muscle weight. Contractile power density means the contractile mechanical work divided by the contraction time.

Actuator performance

Twisted muscles and homochiral coiled muscles contract when input power is on, and expand when input power is off. For a homochiral thermally-powered coiled hybrid yarn muscle (Fig. 2a), comprising a volume changing guest infiltrated throughout the muscles volume, thermal expansion of the muscle on increasing temperature transfers some of the yarn twist to the twist of yarn coiling, which causes the muscle to contract. For a sheath-driven muscle with hybrid sheath (Fig. 2b), volume expansion of the hybrid sheath is driven by electrothermally heating the yarn sheath, which causes the yarn to untwist by transferring yarn twist to an increased twist of coiling.

Figure 2c shows the time dependence of contractile stroke for a coiled neat CNT muscle, a coiled hybrid PDMS@CNT muscle, and a coiled sheath-driven PI_PDMS@CNT muscle when a 0.05 Hz, 10.4 kW/g square-wave power input is used to drive actuation. At this low frequency, a PI_PDMS@CNT muscle provides a 23.2% contractile stroke, which is 1.2 times that for a thermal PDMS@CNT muscle (20.1%) and 23 times that for a thermal neat CNT muscle (1.0%, fig. S4a). The spring indices for these muscles are 1.55, 1.56, and 1.6, respectively. The nearly identical spring indices are important for this comparison,

since muscle stroke increases with increasing spring index. The yarn diameter for sheath-driven muscle, hybrid muscle, and CNT muscle were 68 mm, 78 mm, and 68 mm, respectively. Hence, the yarn surface area that is available for environmental cooling is similar. Nevertheless, the cooling time needed to reduce the contractile stroke by 90% for the PI_PDMS@CNT muscle (1.9 s) is much shorter than for the PDMS@CNT muscle (9.0 s). When the frequency increased to 1 Hz, the stroke (5.4%) for the hybrid PDMS@CNT muscle was much lower than the stroke for 0.05 Hz actuation, while the stroke for 1 Hz actuation (14.3%) (Fig. 2d, fig. S5a, Movie. S1) for the PI_PDMS@CNT muscle was close to the stroke for 0.05 Hz actuation.

The frequency dependencies of contractile stroke and contractile power density for the above sheath-driven muscle and hybrid muscle are shown in Fig. 2e. These results are for an applied power that is constant (10.4 kW/g) during muscle actuation. The contractile stroke decreases with increasing frequency for both muscles, since the input energy per cycle is inversely proportional to frequency. For both muscles (fig. S6), the contractile efficiency, calculated by dividing the contractile work per cycle by the input energy per cycle, increases with increasing frequency and increasing isobaric tensile stress. For an 8 Hz square-wave power, the PI_PDMS@CNT muscle can provide a contractile stroke of 7.3% (fig. S5b, Movie. S2), which is 7 times that for the hybrid PDMS@CNT muscle (Fig. 2e, fig. S7d, 1.04%). Because of the decreased cooling time for the sheath-driven muscle, the contractile power density dramatically increases with increasing frequency. A maximum power density of 12.1 kW/kg was obtained at 8 Hz, which is 10 times the maximum power density for the hybrid PDMS@CNT muscle (1.2 kW/kg at 2 Hz). The corresponding maximum stroke rate, defined as contractile stroke divided by the cycle time, is 57.6%/s at 8 Hz (fig. S5c) for the sheath-driven muscle, which is 8.7 times the maximum stroke rate for the hybrid muscle (6.6%/s at 2 Hz, fig. S5c).

For a 78-mm-fiber-diameter PDMS@CNT muscle and a 68-mm-fiber-diameter PI_PDMS@CNT muscle, Fig. 2f shows the contractile stroke and work capacity as a function of applied tensile stress for these muscles for a 1 Hz square-wave power input. These results show that the load lifting capability of the sheath-driven muscle is higher than for the hybrid muscle. At this frequency, a maximum output work capacity of 1.63 kJ/kg was obtained for the PI_PDMS@CNT muscle, which is 2.9 times that for the PDMS@CNT muscle (0.56 kJ/kg). The work capacity for the PI_PDMS@CNT muscle increased to 2.73 kJ/kg for a 0.3 Hz square-wave power input (fig. S5d). Although the sheath-driven yarn muscle shows much higher performance than the hybrid muscle, the weight percent (20 wt %) of PDMS to the CNT is approximately the same for the PDMS@CNT muscle and for the PI_PDMS@CNT muscle, and the spring index for these yarn muscles were both about 1.55.

As shown in fig. S8, the sheath-driven muscle shows a similar contractile stroke (23.2%) as a hybrid muscle (21%) when a 0.05 Hz, 10.7 kW/g square-wave voltage is applied, where the input power is normalized to total muscle weight. However, when using a 1 Hz, 10.7 kW/g square-wave power input, the contractile stroke for a sheath-driven muscle (15.1%) is about 3.1 times that for a hybrid muscle (Fig. 3a).

The value of the sheath-core ratio (SCR) is important. Too low a SCR means that the sheath is not thick enough to affect the dimensions of the muscle core. Too high a SCR increases the electrothermal energy needed to power actuation and increases the time required to cool the sheath, which degrades high frequency actuation. The effect of SCR on actuation for a PI_PDMS@CNT muscle is shown in Fig. 3b. While the SCR little affects stroke for a frequency of 0.1 Hz, increasing the SCR produces a larger stroke decrease at higher frequencies. Figure 3c shows the effect of SCR on the tensile stress dependence of contractile stroke and work capacity for an actuation frequency of 0.1 Hz. These results show that the highest contractile work capacity for this low actuation frequency was obtained for an intermediate SCR of 0.37.

Since muscle stress generation is also important for powering soft robotics, we also measured isometric stress generation, using the apparatus in Fig. 3d. The isometric stress first increases and then decreases with increasing applied pre-strain (fig. S9a). The maximum generated isometric stress during actuation for a PI_PDMS@CNT muscle was 11 MPa for a pre-strain of 25%. The frequency dependence of the generated stress is shown in Fig. 3e for an isometric pre-strain of 25%. Actuation was driven by a 15 V/cm square-wave voltage. These results show that the generated stress decreases with increasing frequency, which is a consequence of the decreased heating time at increased actuation frequency (fig. S9b). For 1 Hz actuation, the sheath-driven muscle generated a stress of 3.5 MPa, which is 5.9 times that for a hybrid muscle (0.6 MPa, Fig. 3e). The diameters for the sheath-driven and hybrid muscles were 45 and 51 mm, respectively.

Our sheath-driven muscles exhibit good cyclability. Figure 3f shows results obtained when a PI_PDMS@CNT muscle was cycled 1000 times by applying a 1 Hz square-wave voltage, while a mechanical load of 15.6 MPa was applied. The inset shows the time dependence of contractile stroke for the first three cycles and for the last ten cycles. After 1000 cycles, the stroke of 14.3% decreased by only 5.6% of that for the first cycle, which demonstrates that the sheath-driven muscle has excellent cyclability.

Fast actuation mechanism

In order to more deeply understand why the sheath-driven muscle shows much faster actuation than a hybrid muscle having the same diameter, the time dependence of temperature changes for sheath-driven muscle and hybrid muscle were measured using a thermal infrared camera. For these comparative measurements, the peak surface temperature for these muscles was regulated to be the same (150°C), by using a different constant voltage for the square-wave voltage input for the sheath-driven muscle and the hybrid muscle. When cycled using a 1 Hz square-wave voltage, the sheath-driven muscle cools faster and provides a larger contractile stroke than the hybrid muscle (Fig. 4a and Fig. 4b). Although the sheath-driven muscle and hybrid muscle have the same diameter of 65 mm, the sheath-driven muscle cools to ambient temperature (16°C) within 0.5 s, which is to a lower temperature than for the hybrid muscle (30°C) with the same cooling time. The sheath-driven muscle provides a contractile stroke that is 1.4 times that obtained for a hybrid muscle (9%).

Since temperature measurements using a thermal infrared camera only provides information on the muscle surface, the temperature distribution along the muscle radius is needed. Theoretical modeling was used to predict the temperature profile along the radial direction. For a fully-infiltrated hybrid muscle, the input electrical energy is uniformly delivered to the whole muscle, and therefore the initial temperature from muscle surface to center is nearly the same (fig. S10). As shown in Fig. 4d and 4e, the sheath temperature varies between 286°C and 60°C during 1 Hz continuous square-wave actuation cycles, while the muscle core temperature fluctuates only between 180°C and 150°C (Movie. S3). This indicates that the high actuation rate for the sheath-driven muscle results since temperature changes during cycling are largely localized on the sheath, which drives the actuation. The temperature profile for sheath-driven muscle can be optimized by changing the sheath-core ratio (fig. S11).

By using the infrared-camera-measured surface temperatures, we calculated the heat transfer coefficients for sheath-driven muscles and hybrid muscles by applying Newton's cooling law:

$$t = -(T_1 - T_2) / (dT/dt), \quad (1)$$

where t is the heat transfer coefficient³⁵. T_1 and T_2 are the surface temperatures of actuated and non-actuated states, respectively. For the same diameter sheath-driven and hybrid muscle (70 mm), the heat transfer coefficient for the sheath-driven muscle and hybrid muscle were 0.151 and 0.207, indicating that the sheath-driven muscle cools faster than the same diameter hybrid muscle.

Thus, there are two reasons that sheath-driven muscle can operate at high frequencies. Firstly, the hybrid CNT sheath delivers thermal energy to itself, which improves the heating process. During cooling process, the CNT network in the sheath accelerates thermal transport rate between hybrid sheath and ambient air, which enables fast cooling. On the other hand, due to the big difference of thermal conductivity between hybrid sheath and polymer core^{36,37}, the thermal energy delivered to the polymer core in first few cycles is mostly trapped in the polymer core during next heating-cooling cycles. Hence, the exchange of thermal energy is largely restricted in the hybrid sheath.

Demonstration of crawling robot

A robot that crawls in a pipe was designed and implemented to demonstrate the use of the high frequency actuation of our sheath-driven artificial muscles. The robot was made of silicone elastomer (SYLGARD 184, Dow Inc.) and actuated by Kevlar_PDMS@CNT muscles with yarn diameter of 287 μm and spring index of 1.63. The robot has a total length of 55 mm and can crawl inside a 10-mm-diameter pipe. As shown in Fig. 5a, the robot consists of four rhombic modules made of silicone struts, and powered by muscles that are along a rhombic diagonal. The two end modules are larger in diameter, so they can clamp on the pipe surface, while the smaller diagonal inner modules provide actuation but no clamping. Upon electrothermal heating, the artificial muscles contract, causing the module to shrink in the muscle length direction and expand in the perpendicular direction. The four modules are connected in series along the diagonal direction and can be electrically heated individually. The working principle of the robot imitates the inchworm mechanism. First, the anterior clamping module is heated to clamp

against the pipe, then the middle modules are heated to pull the posterior forward. Afterwards the posterior clamping module is heated and the other modules are afterwards allowed to cool to complete a cycle. Figure 5b shows the robot crawling between two parallel walls. When operated using a 0.25 Hz, 1 V square-wave voltage input, the robot has a crawling speed of 7.5 mm/min (Movie. S4).

Conclusion

Fast sheath-driven artificial muscles with a high-mechanical-strength polymer core and a hybrid CNT sheath were demonstrated. The polymer core enables high load capability, and electrothermally powering the hybrid CNT sheath increases actuator cycle rate. Results show that our muscle contracts 14.3% at 1 Hz and 7.3% at 8 Hz in air, and it cools to 16°C from 150°C within 0.5 s. A average power density of 12 kW/kg was obtained, which is 42 times that for human skeletal muscle. Theoretical modeling confirms that the heat flux is largely localized in the sheath layer. A series-connected muscle crawler that climb inside a glass tube was demonstrated.

Experimental Section

Core materials and CNT forest. Aerogel carbon nanotube sheets were drawn from a CNT forest that was grown using a floating catalytic chemical vapor deposition method³⁸. High strength polymer fibers (such as Kevlar, polyimide fiber) were used as the core materials. Kevlar[®] 29, which contains a hundred 10-micron-diameter fibers, was purchased from DuPont[™] company. Polyimide fiber (P84[®]), which is a co-polyimide of 3,3',4,4'-benzophenone tetracarboxylic dianhydride and 80% methyl phenylene-diamine + 20% methylene diamine, was purchased from EVONIK company. Paraffin wax, which has a melting point of 52~56 °C, was purchased from MACKLIN company.

Fabrication of sheath-driven muscles and hybrid muscles. As shown in Fig. 1a, a highly aligned 20-mm-diameter PI fiber was first twisted under an isobaric mechanical load of 14 MPa. Then the twisted polymer fiber was transferred to a vertical stage in which opposite fiber ends were fixed. Thereafter, a 5-layer, 20-cm-long, 5-cm-wide CNT sheet was wrapped around the polymer fiber to form a cylinder. By inserting twist into this cylindrical CNT sheet from both ends, two opposite cones were formed until the CNT sheets began to adhere to the polymer fiber and transfer torque to it.

The CNT@PI was then dip-coated with the precursor resin for polydimethylsiloxane (PDMS), which was SYLGARD 184 purchased from Dow Inc. To decrease the viscosity to enable uniform infiltration of the precursor resin into the CNT sheath, the precursor resin (comprising a 1/10 weight ratio of curing agent to resin) was diluted with ethyl acetate to obtain a resin to solvent weight ratio of 1:6. This liquid did not infiltrate into the PI yarn because of sizing (polyurethane resin) on the component fibers.

After PDMS infiltration into the sheath and thermal annealing at 60°C for 12 h to fully cure the PDMS, the resulting product is called PI_PDMS@CNT. After curing, the PI_PDMS@CNT was twisted to form a coiled structure. The twist density is described as the twist turns per initial length of the PI_PDMS@CNT yarn.

Methods for characterization. Tensile actuation was recorded using a contactless inductive proximity sensor (OMEGA LD701) and a USB_6009 data acquisition card. Electrothermal measurements were made by using the carbon-nanotube-containing structural element for heating. Thermal tensile actuation was characterized using a TA Instrument (TMA Q400EM) at heating and cooling rates of 5°C/minute.

The structure and morphology of sheath-driven muscle, hybrid muscle and neat CNT muscle were characterized using a field emission scanning electron microscope (JSM-7800F, JEOL). The temperatures of the yarn muscles were measured using an infrared temperature measurement microscope system (FLIR T540, USA).

Temperature Modeling. The temperature changes for the sheath-driven muscle and the hybrid muscle were analyzed by using the finite element method (ANSYS 14.0). The temperature of ambient air was set as 25°C and the calculations for these muscles were for a 1 Hz, 2 W/mm³ square-wave power input.

Declarations

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Author Contributions

The project was conceived and designed by X.H. H., J.J. J., and R.H. B. The yarn muscles were prepared and characterized by X.H. H., J.J. J., Y.M. W, and X.T. T. Thermal mechanical analysis measurements and thermal field modeling were conducted and analyzed by X.H. H and X.T. T. The schematic illustrations for sheath-driven muscles were prepared by Y.L. W. J.J. J and Y.M. W performed SEM characterizations for the muscles, and X.T. T. designed and made the soft robots by using sheath-driven muscles. X.H. H. and R.H. B. prepared the manuscript. All authors commented on the manuscript.

Competing interests

The authors declare no competing interests.

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Figures

Figure 1

Schematic illustration of the fabrication of a sheath-driven electrothermal artificial muscle. (a) Polymer yarn; (b) Twisted polymer yarn; (c) Twisted polymer yarn being wrapped with CNT sheets by twisting a CNT cylinder to produce two cones that eventually merge with the polymer yarn surface to conformally coat the polymer yarn as a sheath; (d) Silicone elastomer resin infiltrated into a CNT sheet sheath during the fabrication of a hybrid sheath. (e) Coiled structure of a sheath-driven artificial muscle.

Figure 2

Actuation of sheath-driven electrothermal artificial muscles. (a) Illustration of the actuation of a sheath-driven electrothermal artificial muscle. (b) Illustration of the actuation mechanism for a sheath-driven artificial muscle, wherein electrothermal heating of the sheath causes the sheath expansion and resulting yarn untwist that produces tensile contraction of the coiled yarn. (c) The time dependence of contractile stroke for a PI_PDMS@CNT muscle, a hybrid PDMS@CNT muscle, and a neat CNT muscle that are

coiled. The applied electrical input was a 0.05 Hz, 10.4 kW/g square-wave power. (d) The time dependence of contractile stroke for a PI_PDMS@CNT muscle, a hybrid PDMS@CNT muscle, and a neat CNT muscle. The insets in (c) and (d) are illustrations of the cross-sections of these muscles. (e) The frequency dependence of contractile stroke and contractile power density for a PI_PDMS@CNT muscle and a hybrid PDMS@CNT muscle having a 10.4 kW/g square-wave power input. (f) The contractile stroke and work capacity as a function of the applied tensile stress for a PI_PDMS@CNT muscle and a hybrid PDMS@CNT muscle for a 1 Hz, 10.4 kW/g square-wave power input. The spring indices for these coiled muscles are 1.55 and 1.56, respectively. The weight percent of PDMS to CNT is 20 wt % for hybrid and sheath-driven muscles. The yarn diameter for sheath-driven muscle, hybrid muscle, and CNT muscle were 68 μm , 78 μm , and 68 μm , respectively. The applied load was 15.6 MPa for the sheath-driven muscle and 14.7 MPa for the hybrid muscle for (c), (d), and (e).

Figure 3

Sheath-driven artificial muscles electrothermally actuated by a square-wave applied power input. (a) Contractile stroke as a function of input power for PI_PDMS@CNT, PDMS@CNT, and neat CNT muscles that are coiled. The applied frequency was 1 Hz. The applied load was 15.6 MPa for the sheath-driven muscle and 14.7 MPa for the hybrid muscle. (b) The frequency dependence of contractile stroke and contractile power density for PI_PDMS@CNT muscle having different SCRs. The applied tensile stresses for these muscles are about 9.7 MPa and the applied power was 0.26 W/cm. (c) The tensile stress dependence of contractile stroke and contractile work capacity for sheath-driven muscle having different SCRs. The applied power was 1.12 kW/g. (d) Illustration of the configuration used for isometric stress generation measurements. (e) The frequency dependence of isometric generated stress for

PI/PDMS@CNT and PDMS@CNT muscles during 15 V/cm square-wave electrothermal actuation when the applied pre-strain was 25%. (f) The contractile stroke as a function of cycle number for a PI/PDMS@CNT muscle and a 10.7 kW/g applied power. The initial contractile stroke of 14.3% decreased by 5.6% after 1000 cycles. The inset shows the time scale dependence of contractile stroke for a PI/PDMS@CNT muscle, which indicates high reversibility during cycling.

Figure 4

Mechanisms for fast-response, sheath-driven muscles. (a) Surface temperature as a function of time for a coiled sheath-driven muscle and a coiled hybrid muscle when applying a 1 Hz square-wave voltage of 9.4 V/cm and 7.5 V/cm, respectively. (b) The corresponding contractile stroke changes with time for these muscles for an isobaric applied load of 12.6 MPa. (c) Thermal camera images of non-actuated and actuated states for the sheath-driven muscle used in (a). (d) Modeling results showing the time dependence of the temperature for the sheath and the core of a sheath-driven muscle with a sheath-core ratio of 0.33. (e) Calculated temperature profiles for a sheath-driven muscle in actuated and non-actuated states. (f) The calculated peak temperature of sheath and core for sheath-driven muscle with different sheath-core ratios of 0.1, 0.25, 0.5, 0.6, 0.9.

Figure 5

Demonstration of crawling robot based on sheath-driven muscles. (a) Working principle for crawling robot. The robot consists of four independent modules actuated by sheath-driven muscles. The modules work in sequence to move the robot forward. (b) Photographs showing the robot crawling at a speed of 7.5 mm/min when actuated by a 0.25 Hz, 1 V square-wave voltage.

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