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ADVANCED MATERIALS

Supporting Information

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Electromechanical Actuator Ribbons Driven by Electrically Conducting Spring-Like Fibers

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Electromechanical actuator ribbons driven by electrically conducting spring-like fibers

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The first two authors contributed equally to this work.

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Captions for supporting movies

Movie S1. Slow-motion video of an electromechanically anticlockwise rotation generated by a left-handed SLF that was assembled from 20 left-handed CNT yarns upon passing through a pulse current (40 mA and 2.5 Hz).

Movie S2. Slow-motion video of an electromechanical contraction generated by a slack SLF (the same to Movie S1) upon passing through a current of 40 mA.

Movie S3. Electromechanical contraction and relaxation of an SLF (the same to Movie S1) that was loaded with an object (70 mg in weight) upon pass of a pulse current (40 mA and 2 Hz). The length of the SLF was 3.5 cm.

Movie S4. Electromechanically bending motions generated by a *Kapton* ribbon woven from SLFs upon applying a pulse current (240 mA and 0.25 Hz).

Movie S5. Fast-motion video of a crawling motion generated by an electric walker robot upon application of a pulse current of 240 mA and 0.25 Hz.

Movie S6. Electromechanical contraction motion generated by a left-handed *Kapton* helix ribbon woven from a left handed SLF.

Movie S7. Electromechanical elongation motion generated by a right-handed *Kapton* helix ribbon woven from a left handed SLF.

Experimental section

The CNT fibers were dry-spun from spinnable CNT arrays with a thickness of ~250 μm synthesized by chemical vapor deposition and reported elsewhere.[S1, S2] One end of CNT sheet was attached on a collecting drum (3 rpm) during fabrication. CNT fibers with a helical angle of 30^{o} were prepared at a twisting speed of 2000 rpm for the motor shaft. The diameters of the CNT fibers were controlled by varying the widths of CNT sheets, and the CNT fibers here shared diameters of 15-17 μm at the CNT sheet width of 1 cm. The chirality of the CNT fibers depended on the twisting direction, i.e., left- and right-handed CNT fibers were prepared by twisting in counterclockwise and clockwise directions, respectively.

Multi-plied CNT fibers were bundled together with one end fixed on a motor shaft and the other at a movable block. The bundled CNT fibers were over-twisted by operating the motor with a constant rotary speed of 300 rpm. During the over-twisting process, the bundle was maintained to be horizontal and stretched by moving the block toward the twisting motor. The twisting operation was shut down until the whole bundle was transferred to coiled loops. A freestanding SLF with a length of ~5 cm was obtained from bundled CNT fibers with the same length of 20 cm. The left-handed (or right-handed) SLF was prepared by over-twisting a bundle of left-handed (or right-handed) CNT fibers in an anticlockwise (or clockwise) direction.

Three continuous SLFs were woven into a commercial *Kapton* film in parallel by using a sewing needle (length of ~3 mm for the needle gage). The ends of the three SLFs were stabilized on the *Kapton* ribbon and connected with ultrafine aluminum wires by silver paste. Slender *Kapton* fabric ribbons with the same width of 2.5 mm were further transformed to left- or right-handed structures through a heat-setting method. The generated electromechanical actuations were recorded by a digital camera (Nikon J1).

The structures were characterized by Hitachi FE-SEM S-4800. For mechanical measurements, two ends of a fiber were fixed to a paper hole with a gauge length of 5 mm and tested by a HY0350 Table-top Universal Testing Instrument with a tensile rate of 1 mm/min. To measure the contractive actuation, the two ends of the fiber were connected to two conductive wires by silver paste and fixed on the paper hole with a gauge length of 5 mm. The electromechanically contractive forces generated by the fiber were traced in situ. For the measurements on electromechanically rotary actuations (Figure S10), a paddle with a weight of 70 mg was fixed at one end of a 2-cm-long SLF and recorded by a high-speed camera. The generated revelations were obtained through a frame-by-frame analysis. The electric current was provided by Keithley Model 2400 Source Meter.

The initial torsional torque

The paddle acceleration (α) in the initial 65 ms (Figure S11) was calculated as 1,094 rad/s^2 (62,677 °/s^2). The moment of inertia (J) of the paddle was 1.22×10^{-10} kg·m^2 for an SLF with the mass of 120 μg. Therefore, the initial torsional torque (τ) provided by the SLF may be calculated by $\tau = J\alpha = 1.33 \times 10^{-7}$ N·m, i.e., 1.11 N·m/Kg

References

[S1] L. Qiu, X. Sun, Z. Yang, W. Guo, H. Peng, *Acta Chim. Sinica* **2012**, *70*, 1523.
[S2] W. Guo, C. Liu, F. Zhao, X. Sun, Z. Yang, T. Chen, X. Chen, L. Qiu, X. Hu, H. Peng, *Adv. Mater.* **2012**, *24*, 5379.

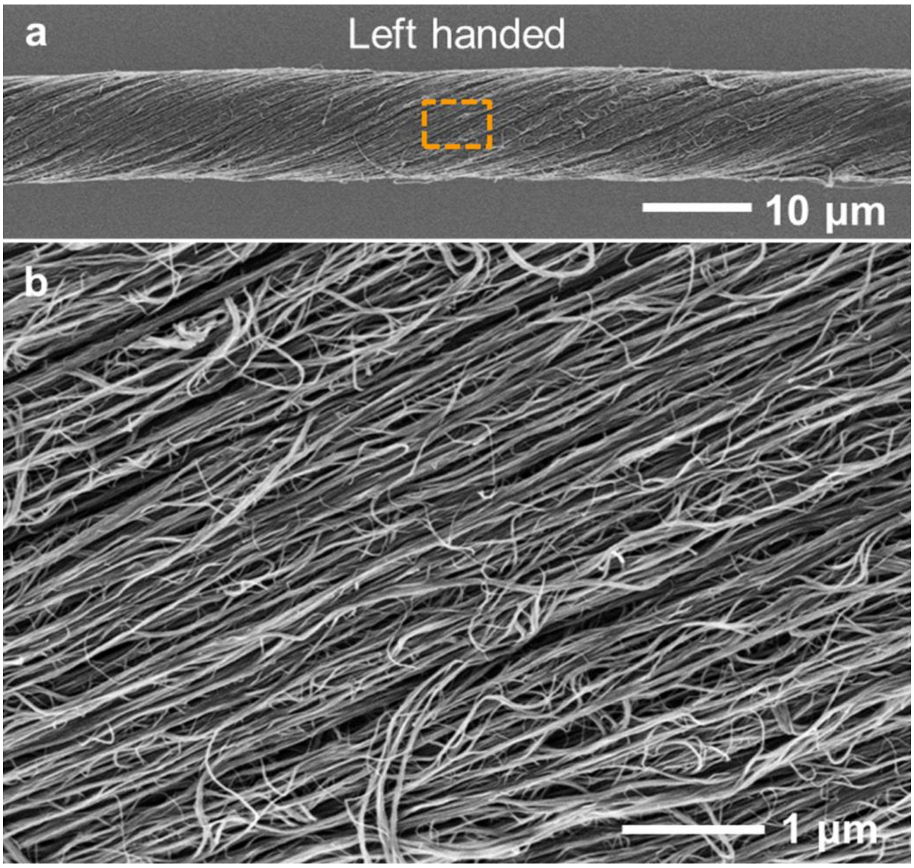

Figure S1. SEM images of a left-handed primary fiber assembled from aligned multi-walled carbon nanotubes (MWCNTs) with a helical angle of approximately 30º.

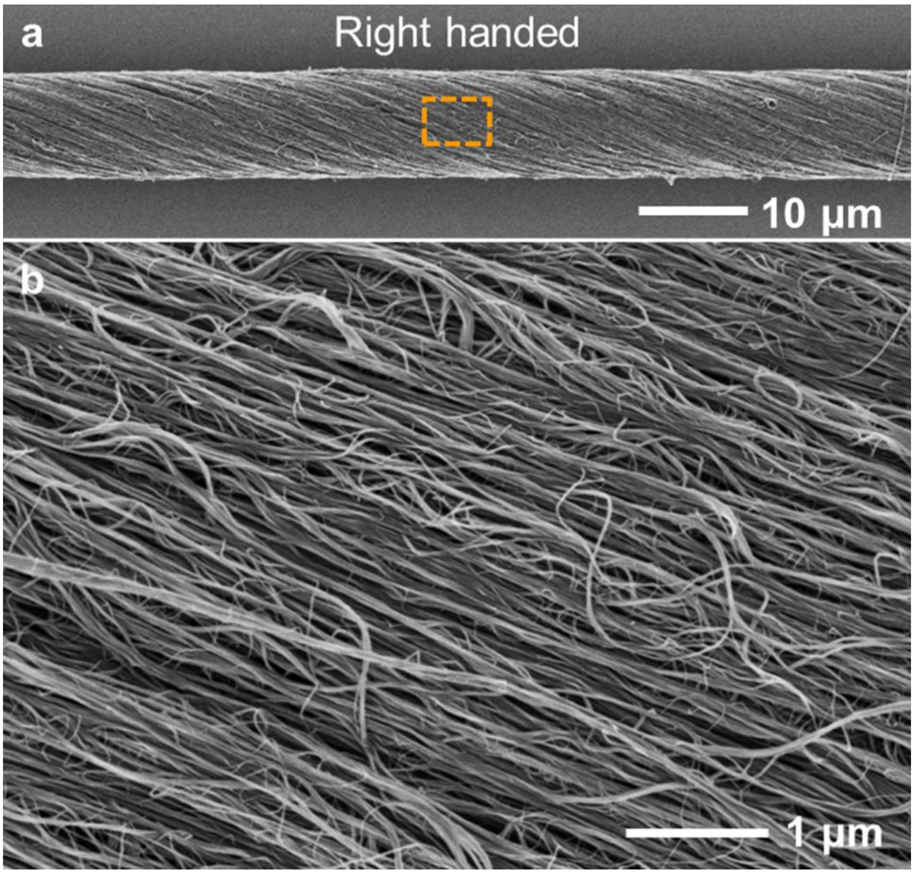

Figure S2. SEM images of a right-handed primary fiber assembled from aligned MWCNTs with a helical angle of approximately 30º.

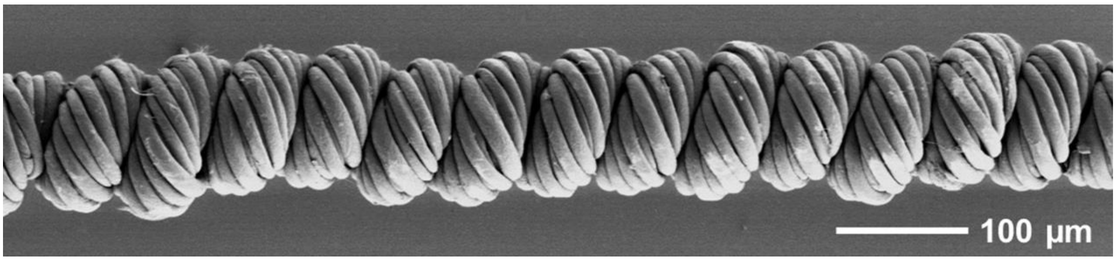

Figure S3. SEM image of a left-handed SLF assembled from 20 left-handed primary fibers as shown in Figure S1.

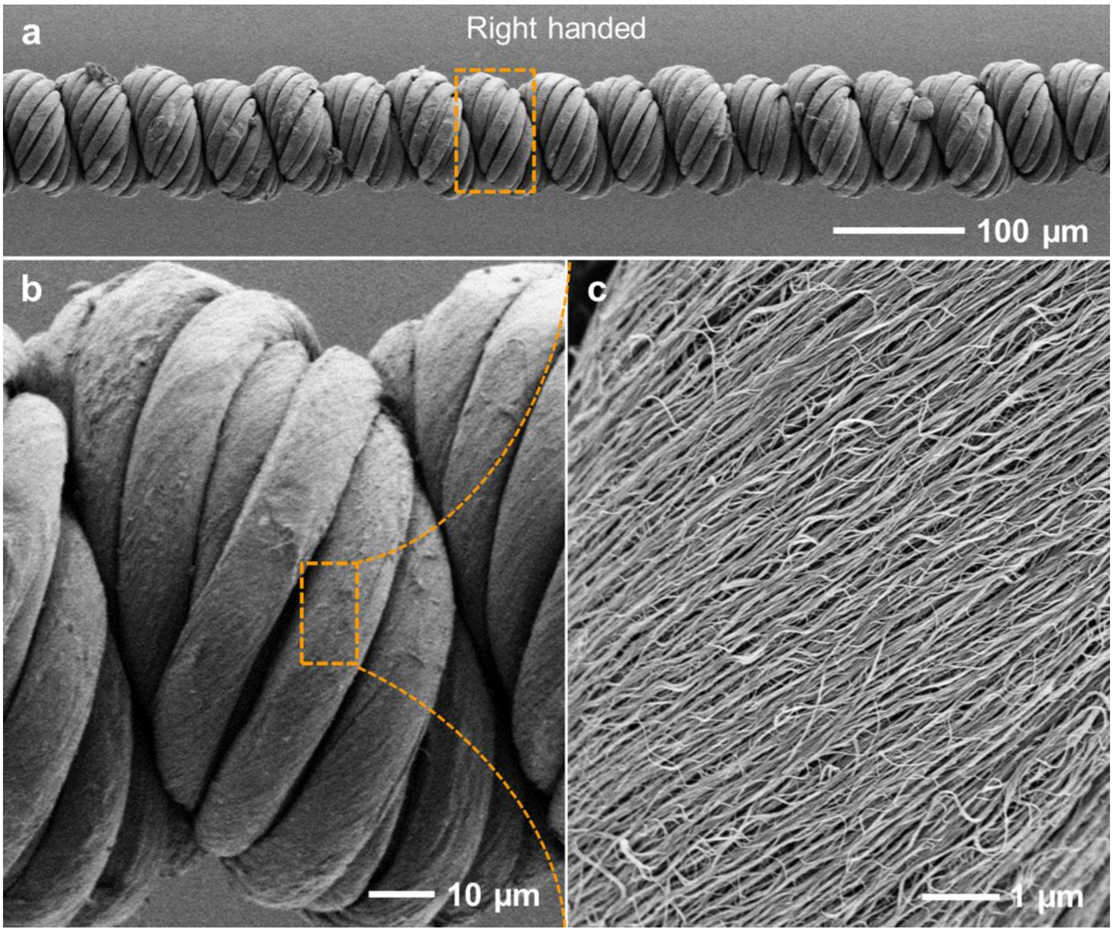

Figure S4. SEM images of a right-handed SLF assembled from 20 right-handed primary fibers as shown in Figure S2.

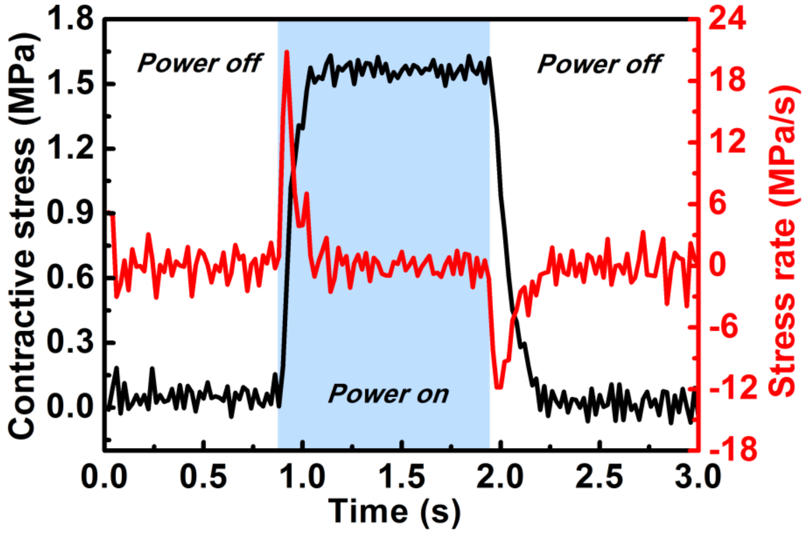

Figure S5. Dependence of the contractive stress and stress rate on the time upon application of a pulse current (40 mA and 0.5 Hz) for an SLF.

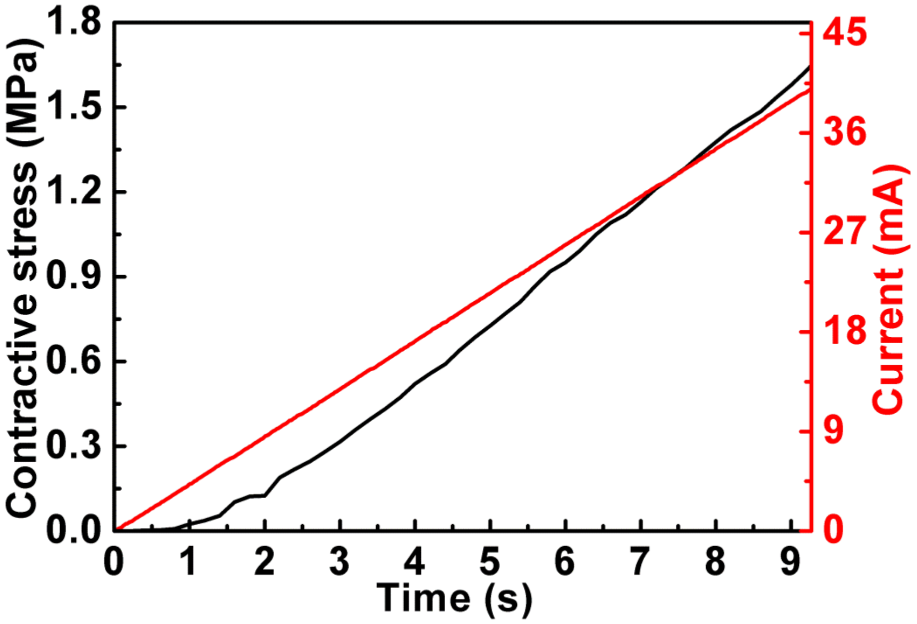

Figure S6. Dependence of contractive stress generated by a SLF on the time upon application of a linear current with a scan rate of 4.3 mA/s. The corresponding SLF was showed in Figure S2.

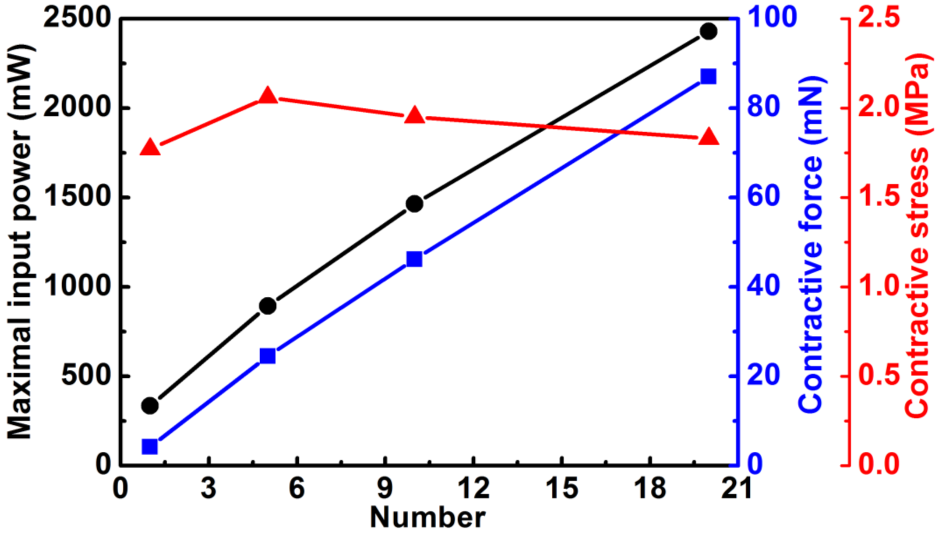

Figure S7. Maximal input power and corresponding electromechanically contractive force and stress of SLFs with increasing numbers of primary fibers.

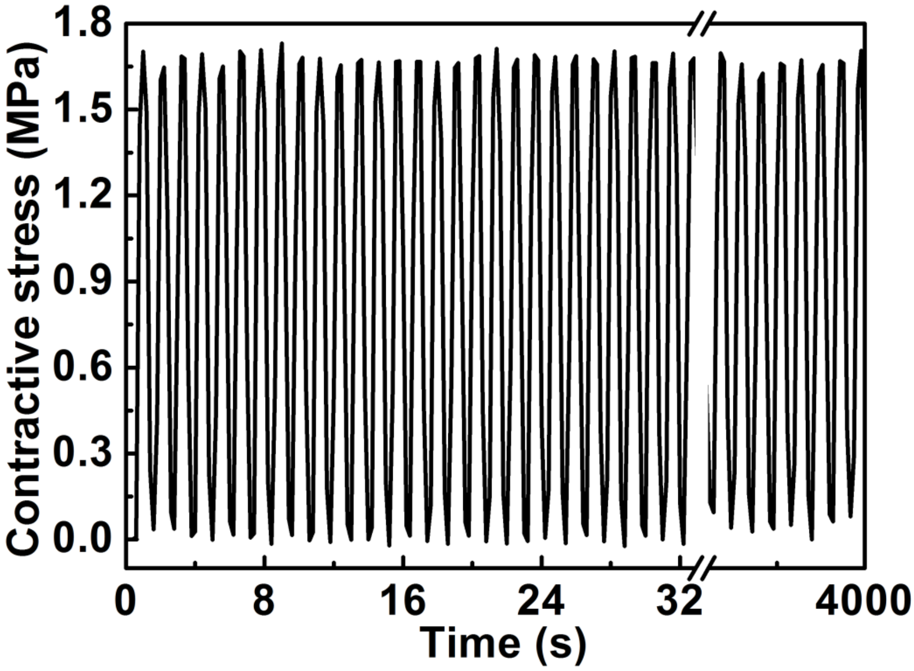

Figure S8. Contractive stresses in 4000 cycles upon applying a pulse current (40 mA and 0.5 Hz).

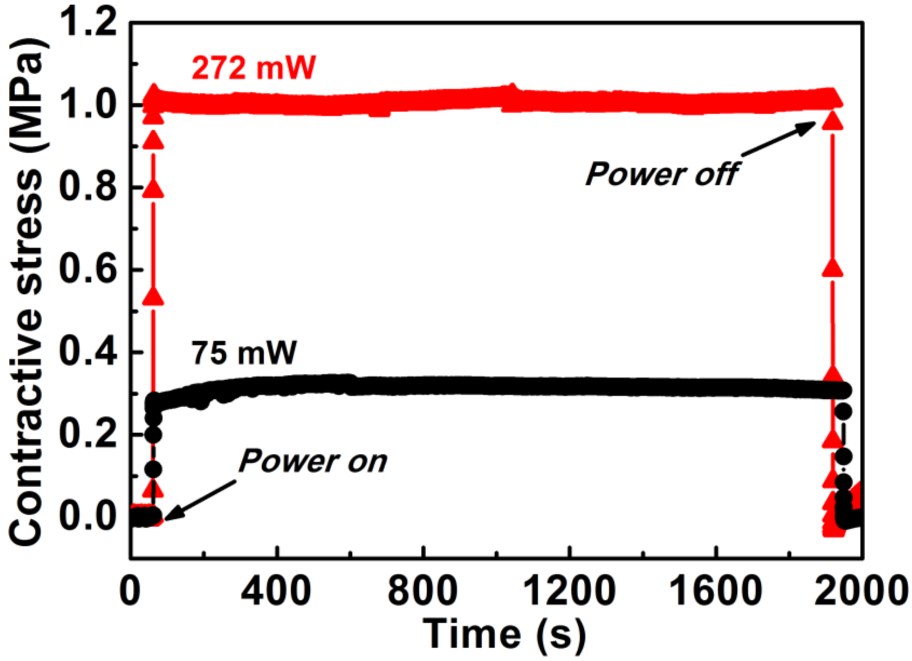

Figure S9. Contractive stress generated by a large yarn twisted from 20 SLFs upon the application of electric powers of 75 and 272 mW for more than half an hour, respectively.

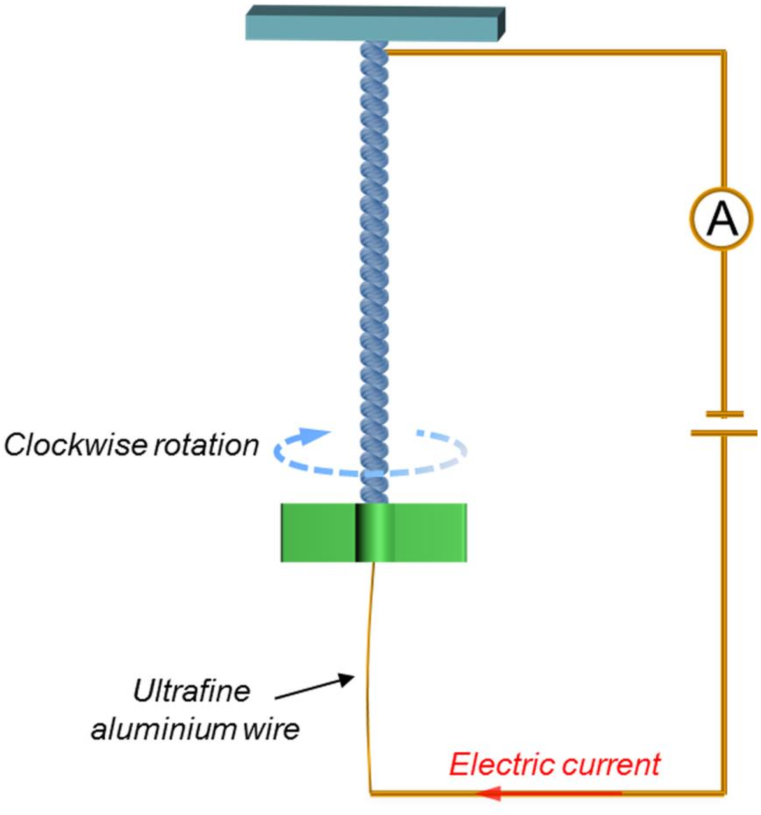

Figure S10. Schematic illustration to the electromechanically rotary actuation generated by a left-handed SLF. A clockwise rotation was generated upon the pass of an electric current through the fiber.

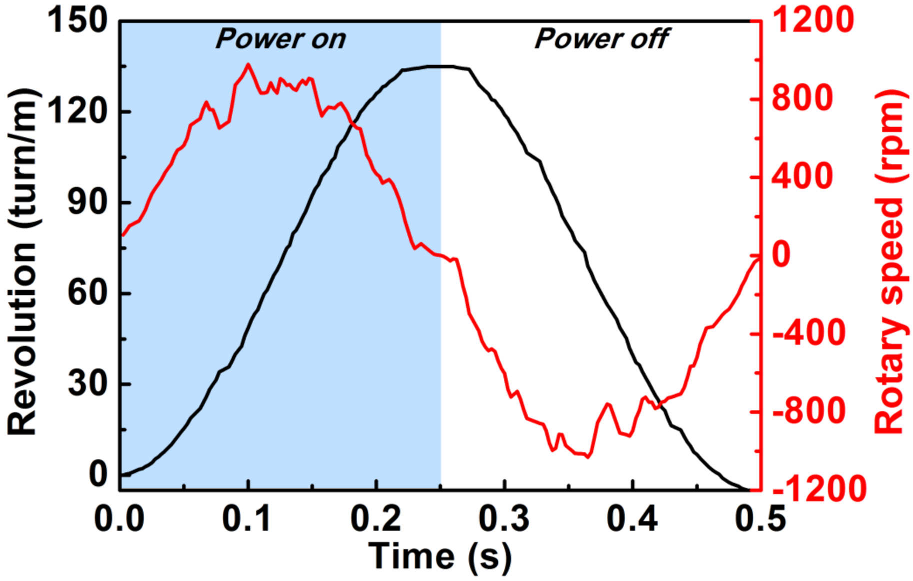

Figure S11. Dependence of the revolution and rotary speed (revolutions per minute) on the time upon applying a pulse current (40 mA and 2 Hz) on an SLF.

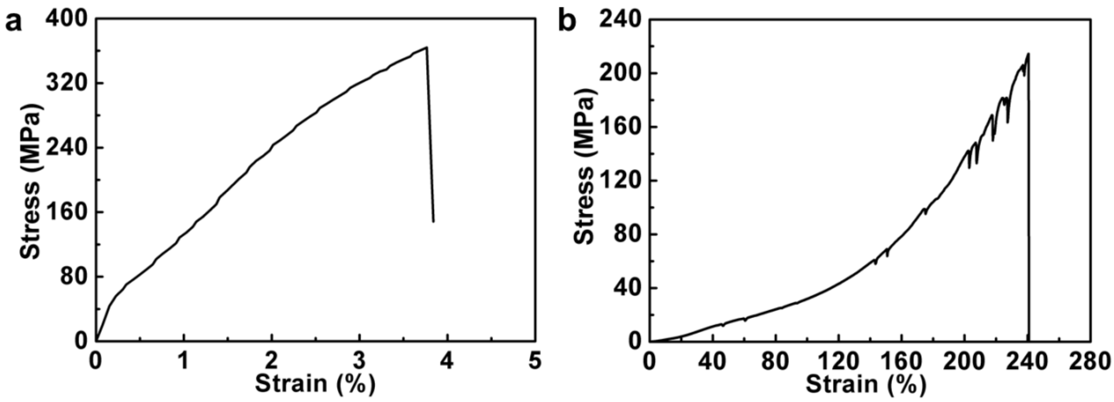

Figure S12. Stress-strain curves of a left-handed primary fiber (**a**) and corresponding SLF (**b**) in Figure S1.

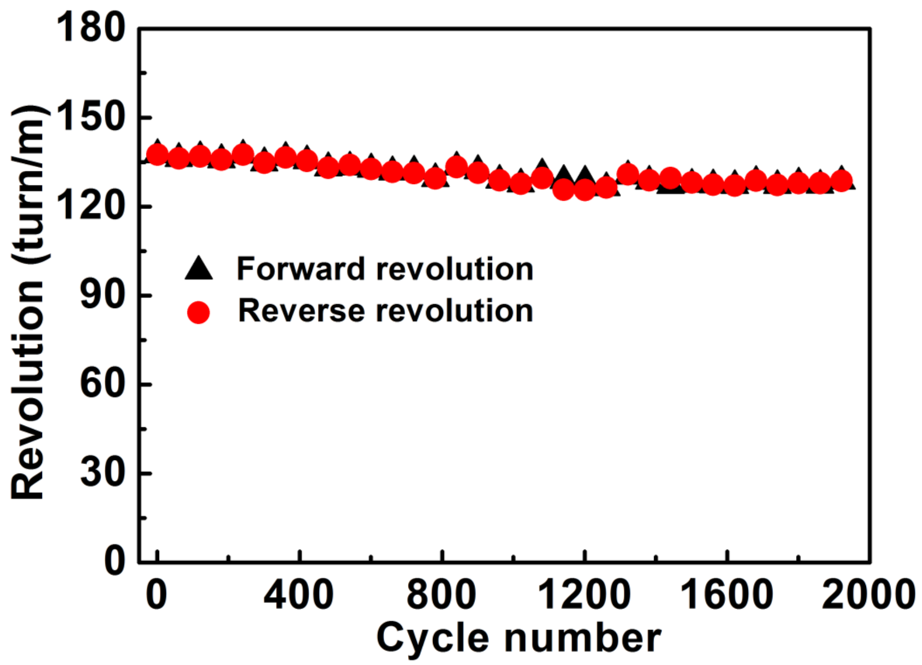

Figure S13. Forward and reverse revolutions produced by the SLF over 2000 cycles.

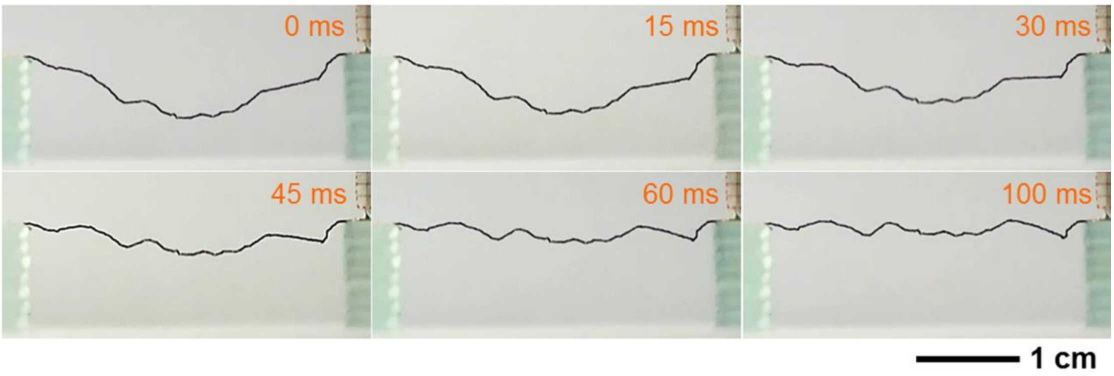

Figure S14. Photographs of the rapid contracting process of a slack SLF upon applying a current of 80 mA.

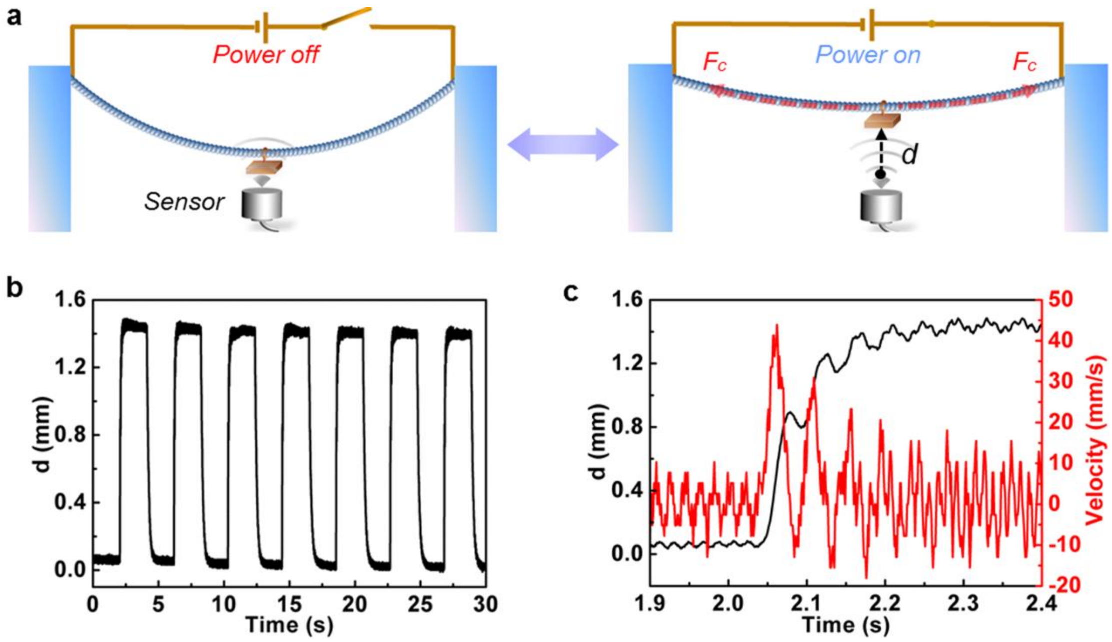

Figure S15. a) Schematic illustration to the electromechanical contraction process where a metal block was hung at the midpoint of the SLF. **b**) Dependence of the ascending distance (*d*) of the metal block on the time upon applying a pulse current (40 mA and 0.25 Hz). **c**) Enlarged view of the ascending curve in (**b**).

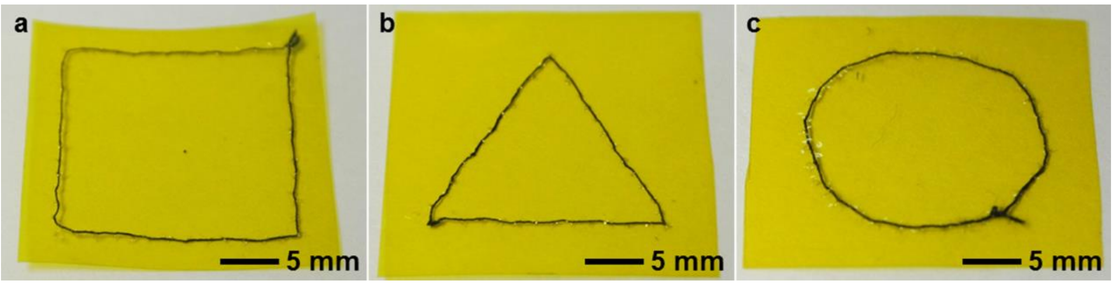

Figure S16. Fabric films woven from SLFs with various sewing patterns including square (**a**), triangle (**b**) and circle (**c**).

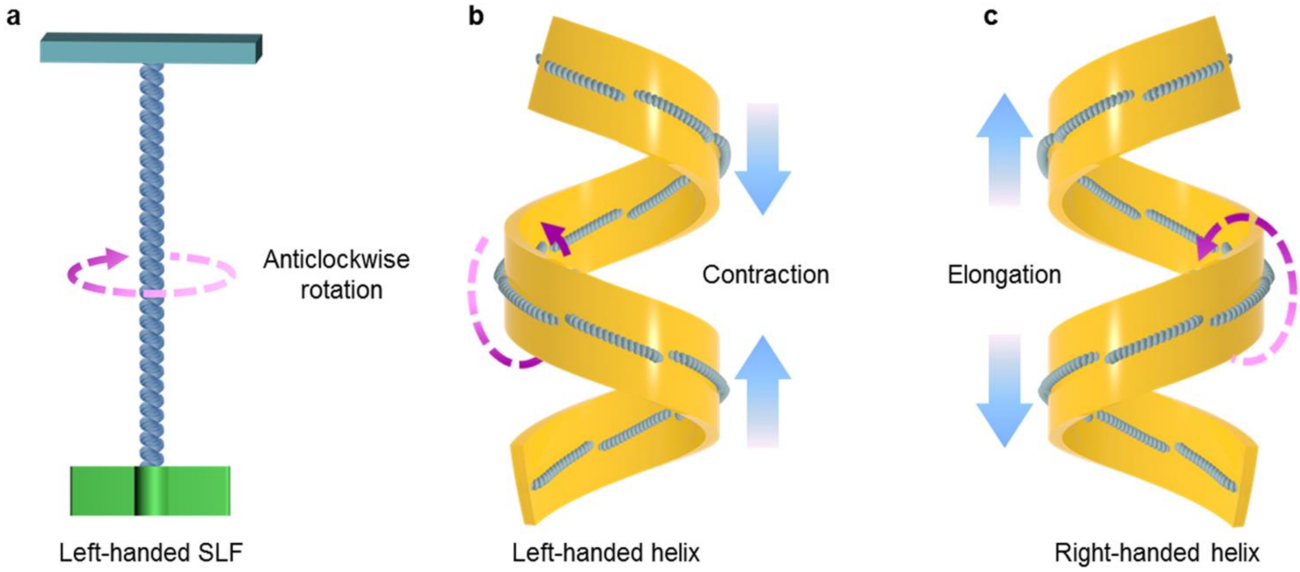

Figure S17. **Mechanism analysis of the electromechanical actuation for the fabric ribbon helix**. **a**) An anticlockwise rotation (looking upward from the bottom) is generated by a SLF upon pass of an electric current. **b** and **c**) Electromechanical contraction and elongation generated by left- and right-handed fabric ribbon helices, respectively. The SLFs woven in the helices share the chirality of left-handedness.

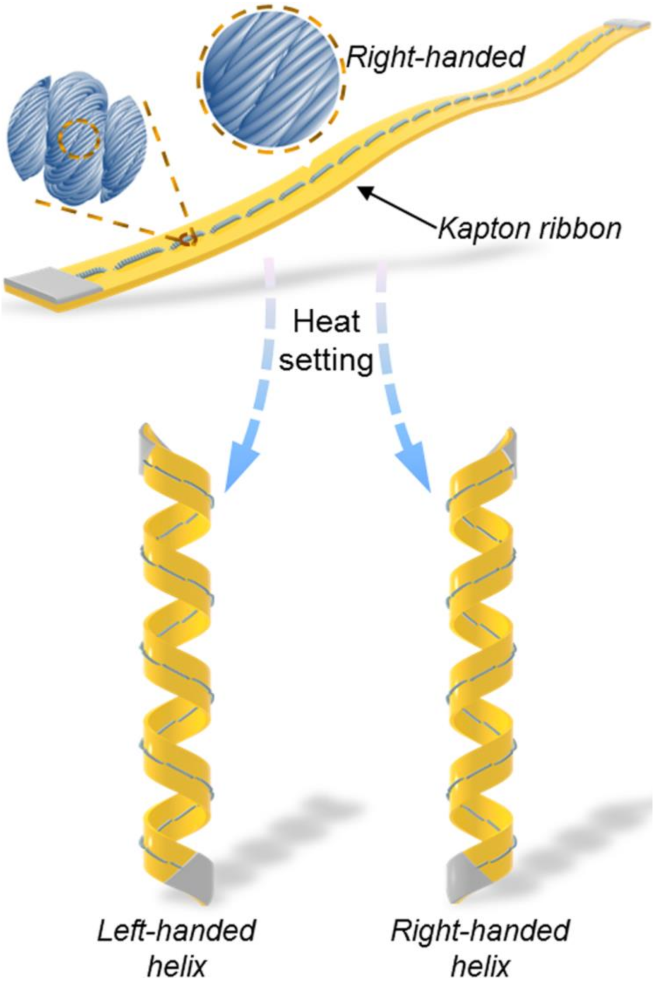

Figure S18. Schematic illustration to the preparation of helical *Kapton* fabric ribbons in an opposite helical chirality. Here the used SLFs were right-handed.

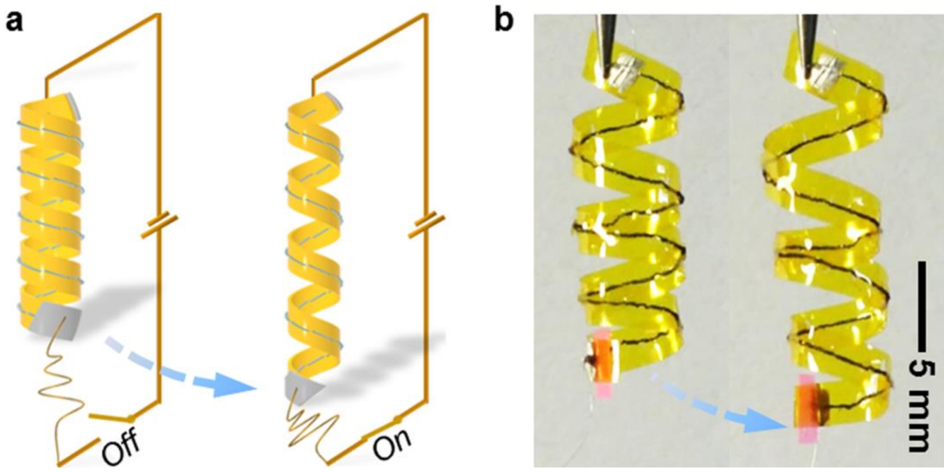

Figure S19. Schematic illustration (**a**) and photographs (**b**) of the electromechanical elongation motion generated by a left-handed *Kapton* fabric ribbon in Figure S17.

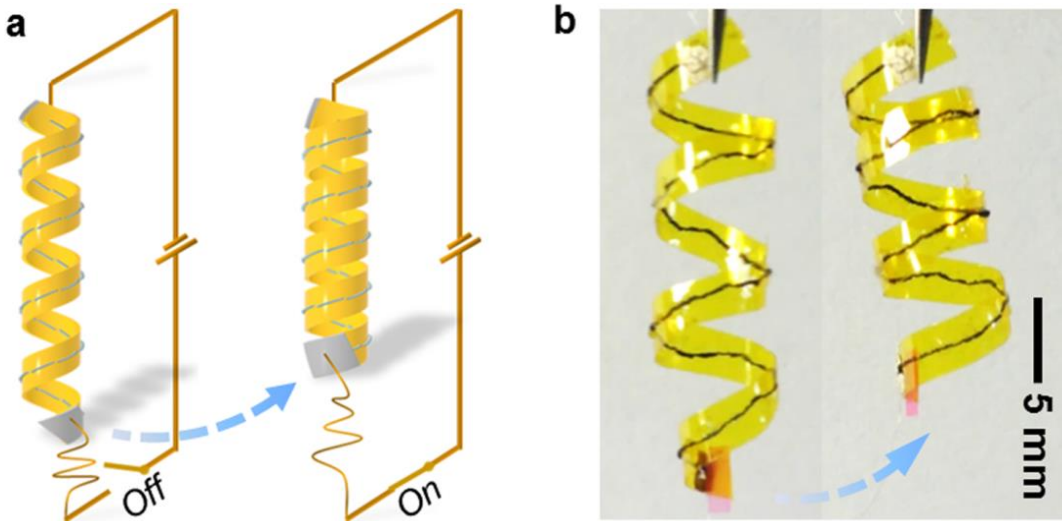

Figure S20. Schematic illustration (**a**) and photographs (**b**) of the electromechanical contraction motion generated by a right-handed *Kapton* fabric ribbon in Figure S17.