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Highly Sensitive Detection of Subtle Movement using a Flexible Strain Sensor from Helical Wrapping Carbon Yarns

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Electronic Supplementary Information

Table S1 Summary of flexible strain sensors with outstanding comprehensive performance.

Materials	Elastic materials for encapsulation	Methods	Strain (%)#	Gauge factor	Cycle number	Ref.
MWCNT / TPU (homogeneous composite)	---	3D printing using fused deposition modeling	50	18.2	10	[4]
Graphene / TPU yarn (as core yarn)	---	A layer-by-layer assembly method	50	86.9	100	[12]
CNT paper	PDMS	Embedding	20	10^6	10000	[15]
laser-engraved CNT paper	PDMS	Embedding	80	1.2×10^6	5000	[16]
Carbon nanofibers	TPU	Embedding	100	12	8000	[18]
reduced graphene oxide)/ deionized water	Ecoflex	Embedding	40	1.25	10000	[28]
$Ti_3C_2T_x$ MXene/ CNT	---	a layer-by- layer spray coating technique	20	64.6	1000	[29]
Graphene / CNT / TPU (homogeneous composite)	---	Compression molding	30	35.78	20	[30]
Silver nanowire /polyurethane yarn	TPU	Coating	10	~60	10000	[41]
Graphite / silk fiber	Ecoflex	Coating / Embedding	15	14.5	3000	[45]
CNT / PDMS (homogeneous composite)	---	Curing	25	15	--	[47]
Fragmentized graphene foam	PDMS	CVD	50	15	10000	[48]
Graphene woven fabrics	PDMS	CVD / sandwich	13.68	~400	500	[49]
CNT	PDMS	Spraying / sandwich	50	35.75	1000	[50]
Graphene / nature rubber (homogeneous composite)	---	Hot compression	100	82.5	300	[52]
Helical carbon nanofiber yarn as sheath / cotton yarn as core	TPU	Embedding	20	14.2	>1,000	This work

#The strain range here is determined according to the fatigue test for repeatability.

* CVD: an abbreviation for chemical vapor deposition.

Table S2 Summary of flexible strain sensors capable of detecting small strains

Materials	Elastic materials for encapsulation	Methods	Strain (%)[#]	Gauge factor	Cycle number	Ref.
Carbon black / natural rubber (composite) / TPU yarn (as core yarn)	---	A layer-by-layer assembly method	1	43.2	10,000	[9]
Carbon nanofiber yarn	TPU	Embedding	2	403	300	[22]
Carbon nanofiber fabric	TPU	Embedding	5	30	1,000	[25]
Graphene woven fabrics	PDMS	CVD/casting film	3	223	1,000	[26]
reduced graphene oxide/ deionized water	Ecoflex	Embedding	0.1	2.5	---	[28]
$Ti_3C_2T_x$ MXene/ CNT	---	a layer-by- layer spray coating technique	0.1	3.4	---	[29]
Glass fiber fabric / GO	---	Dip-coating	1	480	---	[35]
Graphene mesh fabric	---	Dry spinning	5	20	500	[37]
Molybdenum disulfide/ porous graphene	PDMS	laser/ Embedding	4	83.25	12000	[38]
CNT / polyvinylpyrrolidone (homogeneous composite)	---	Meniscus-guided printing	2	13.07	1,500	[39]
Graphene / polyester fabric (as the elastic matrix)	---	Dipping / Drying	5	12	500	[40]
Silver nanowire /polyurethane yarn	TPU	Coating	0.1	<10	12	[41]
Graphene woven fabrics	PDMS	CVD / sandwich	0.3	~320	---	[49]
Helical carbon nanofiber yarn as sheath / cotton yarn as core	TPU	Embedding	0.1	37.3	>1,000	This work

[#]The strain range here is determined according to the fatigue test for repeatability.

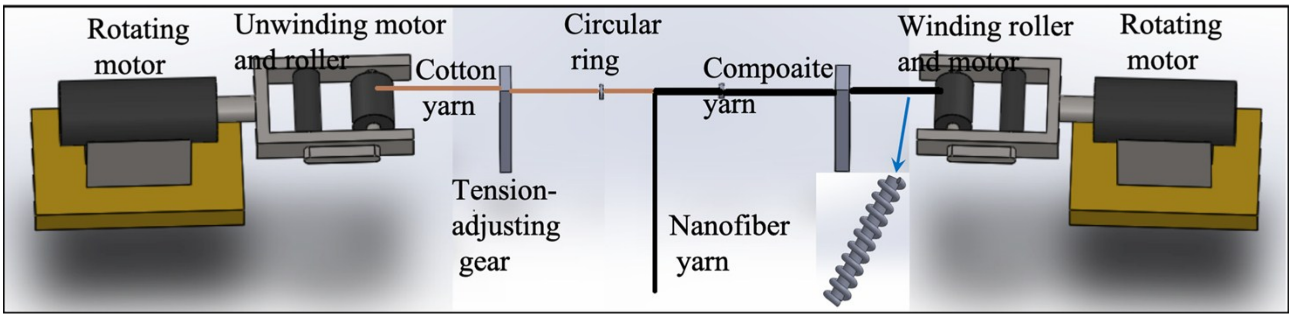

Figure S1. The process for making composite yarns.

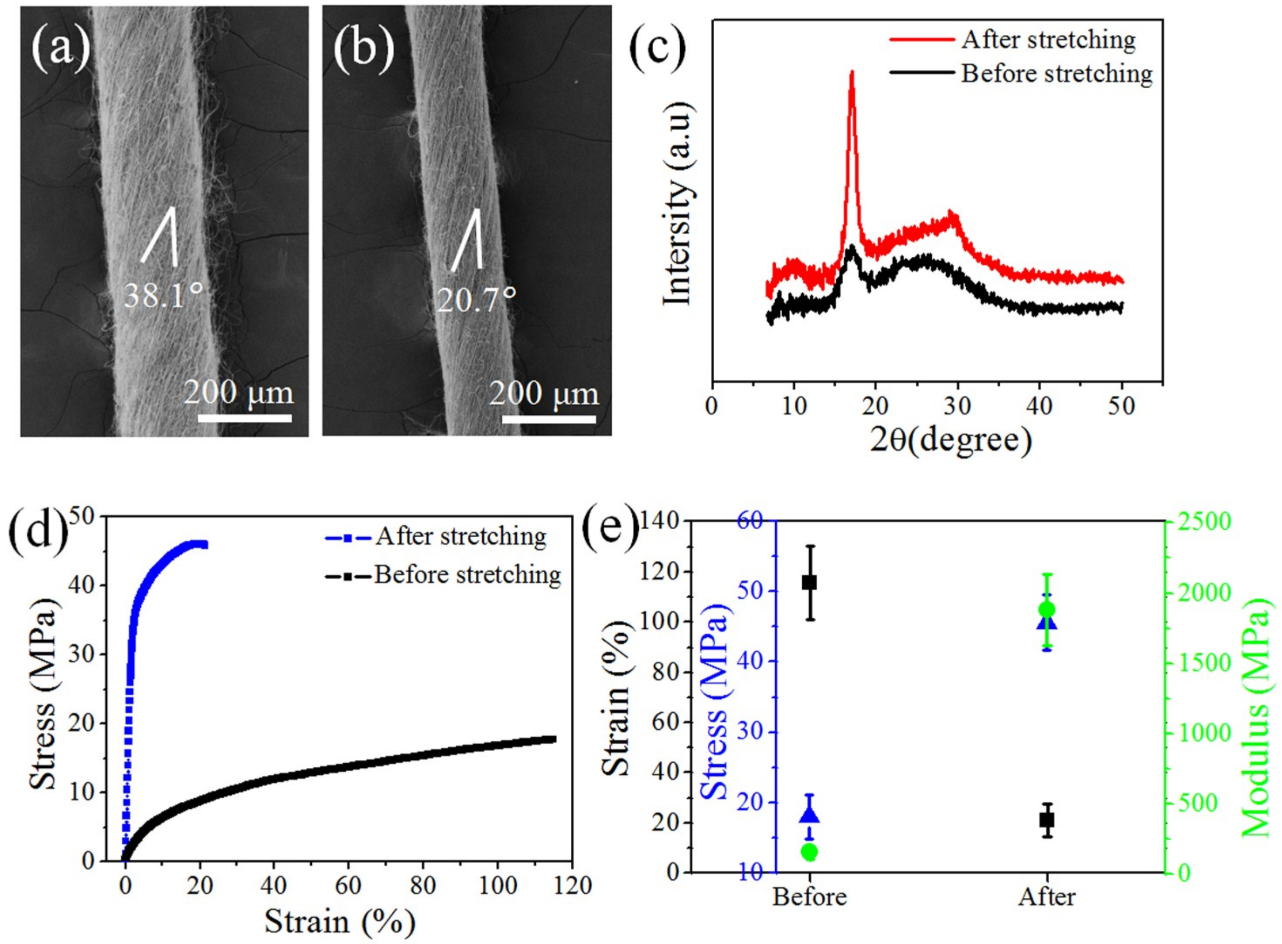

Figure S2. SEM images of nanofiber yarn (a) before stretching, (b) after stretching; (c) XRD diffraction spectra, (d) stress-strain curves, and (e) tensile properties of nanofiber yarns.

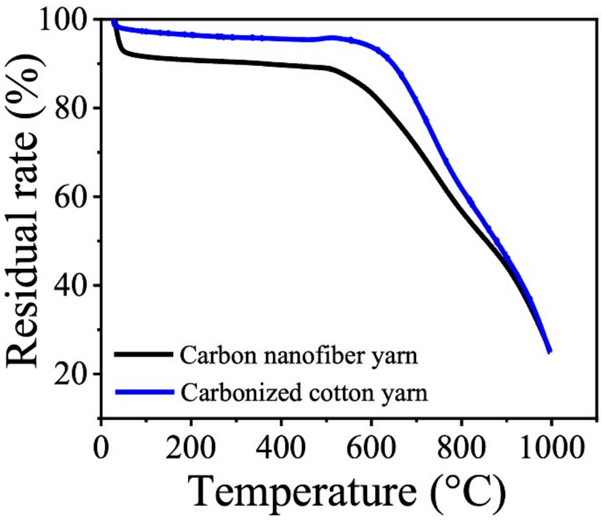

Figure S3. TG curves of carbon nanofiber yarns and carbonized cotton yarn.

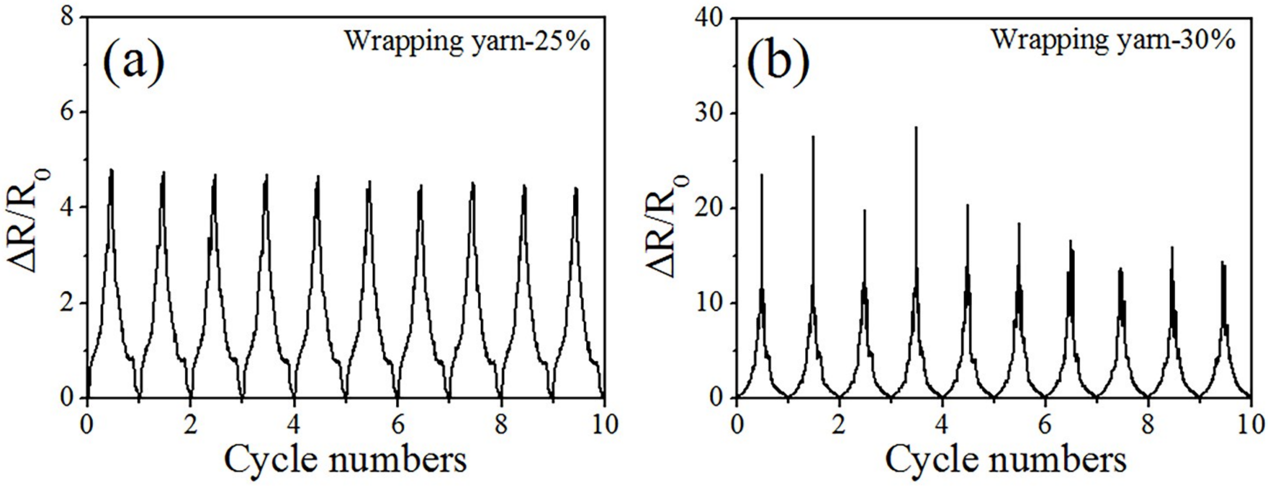

Figure S4. The strain response for the sensor device made of the helical wrapping yarn at strain (a) 25%, and (b) 30%. (Stretching rate 72 mm/min)

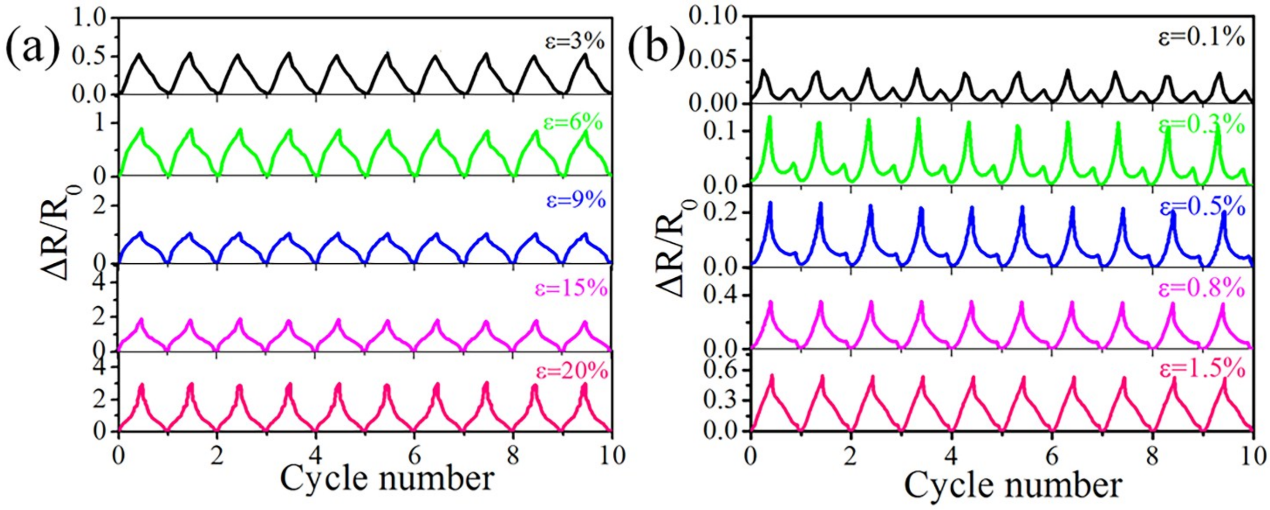

Figure S5. Strain response for the wrapping yarn device in strain range of 3%-20% (stretching rate 72 mm/min) and strain range of 0.1%-1.5% (stretching rate 3 mm/min).

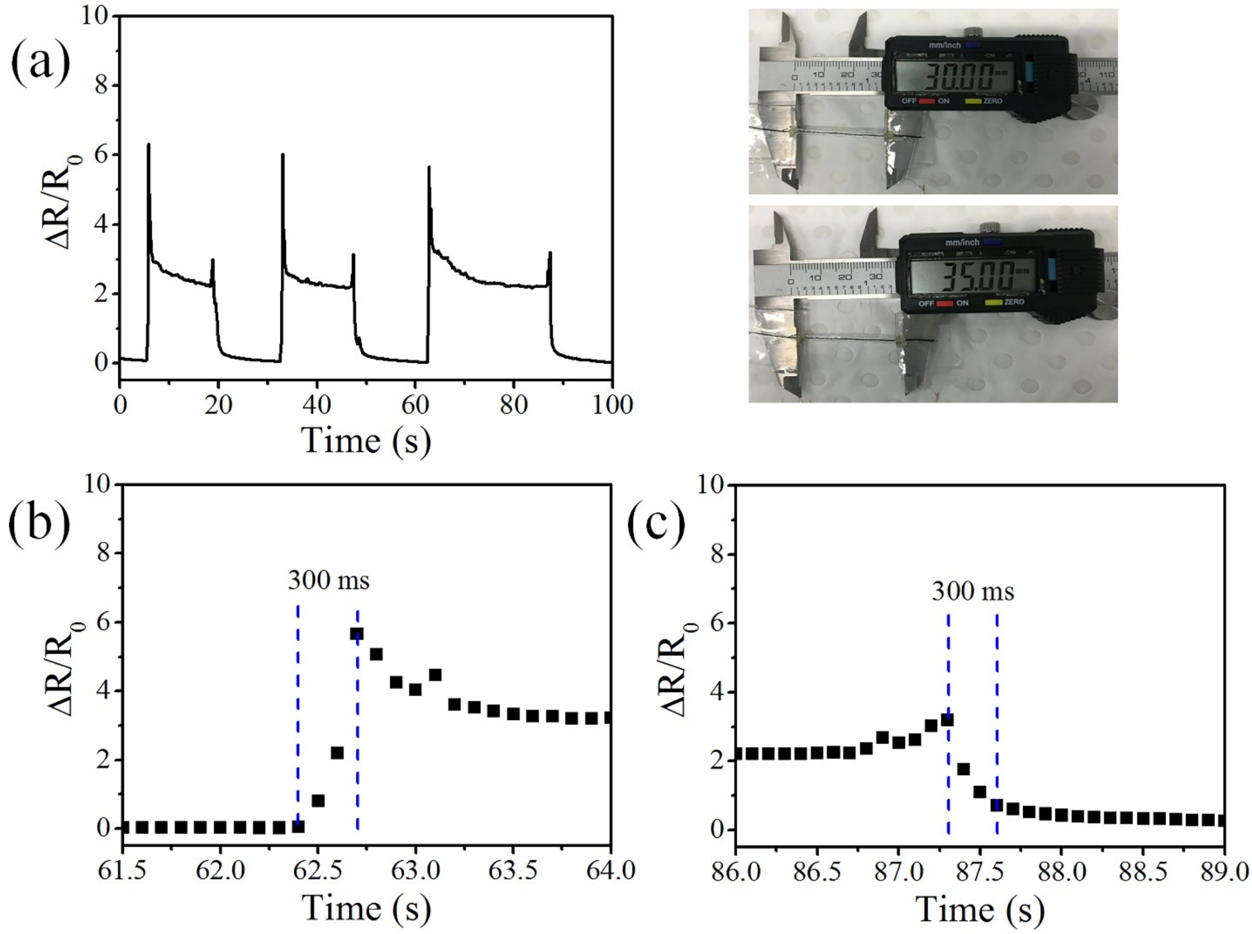

Figure S6. (a) Static detection for the helical wrapping yarn device using a digital micrometer, (b) response time for the wrapping yarn device, (c) recovery time for the wrapping yarn device.

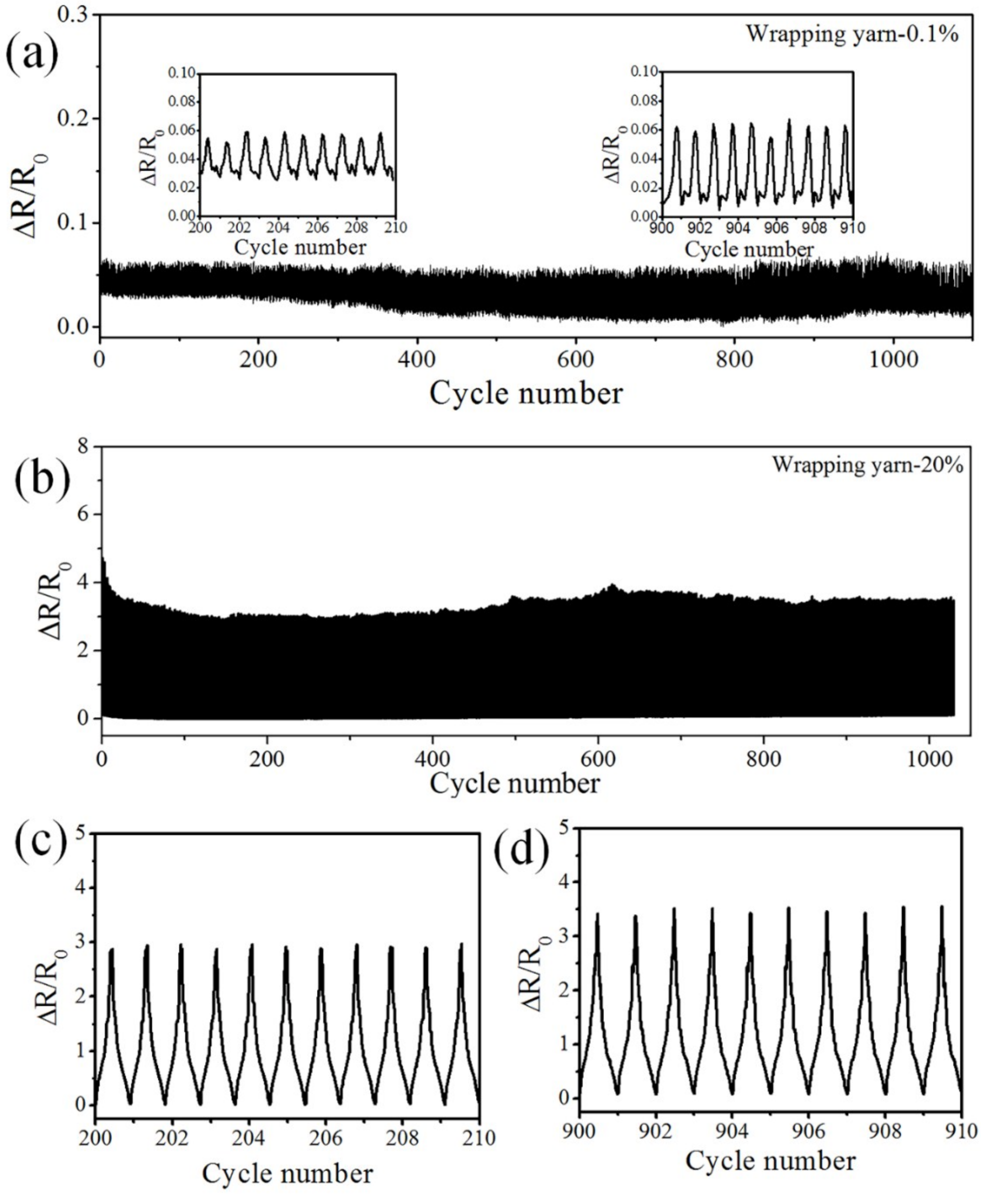

Figure S7. Repeat loading-and-unloading of wrapping yarn device for 1000 cycles, (a) strain 0.1%, 3 mm/min, (b) strain 20%, 72 mm/min, (c,d) different stages of (b).

For stretching at 0.1% strain (Figure S7a), the variation in response could be due to the slippage of carbon nanofibers within core yarn. The response did not return to zero. This might come from the errors of instrument. When the strain was 20%, the response changed at a much smaller level. This could be explained by the slight shift of the carbon fibers in the core yarn, which changed the resistance.

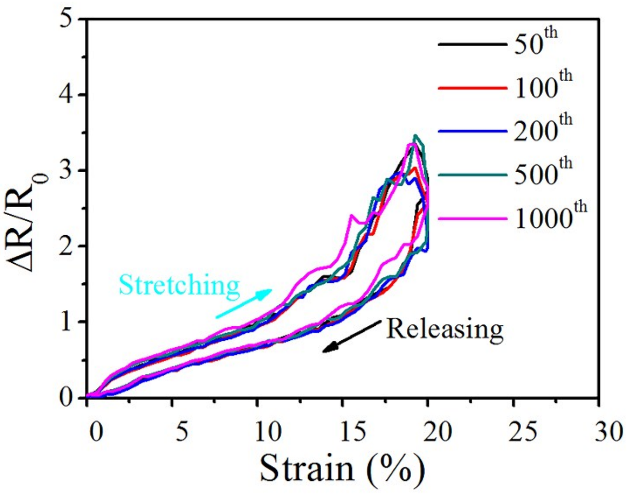

Figure S8. The hysteresis and stability of the repeat loading-and-unloading of wrapping yarn device (stretching rate 72 mm/min).

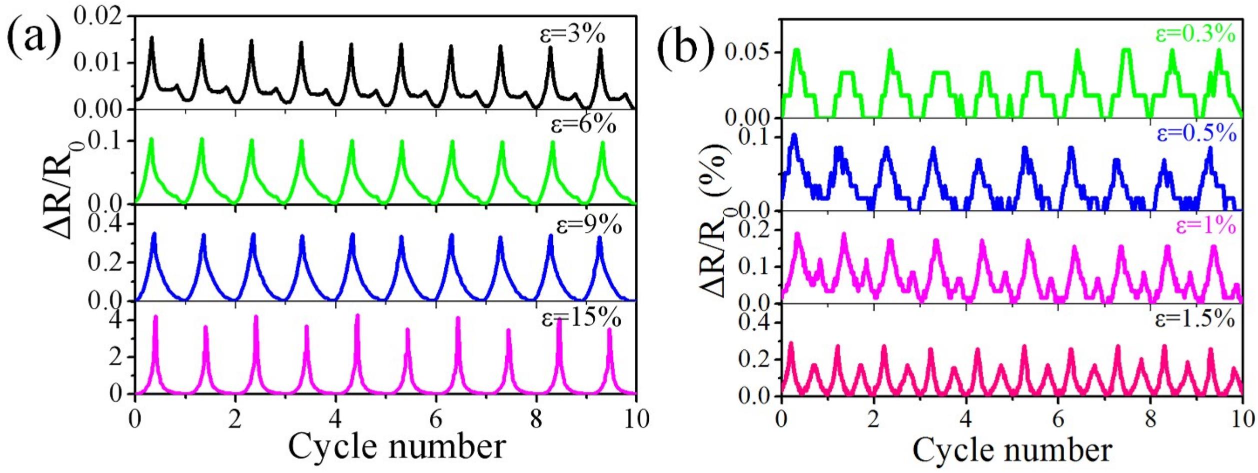

Figure S9. Strain response for the spring yarn device in large strain range of 3%-15% (stretching rate 72 mm/min) and strain range of 0.3%-1.5% (stretching rate 6 mm/min).

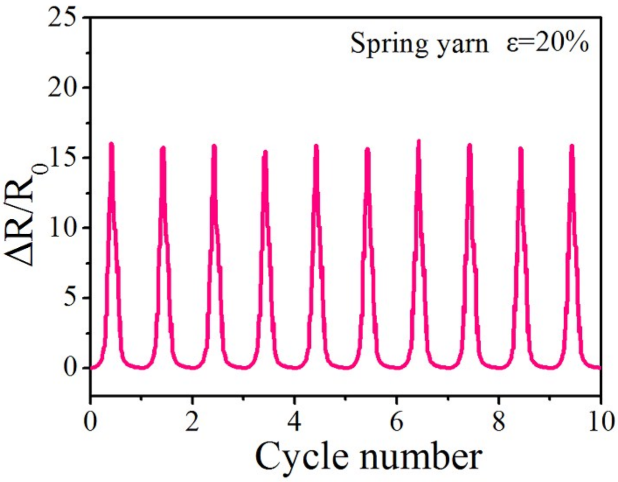

Figure S10. The sensitivity of the spring yarn device at strain 20% (stretching rate of 72 mm/min).

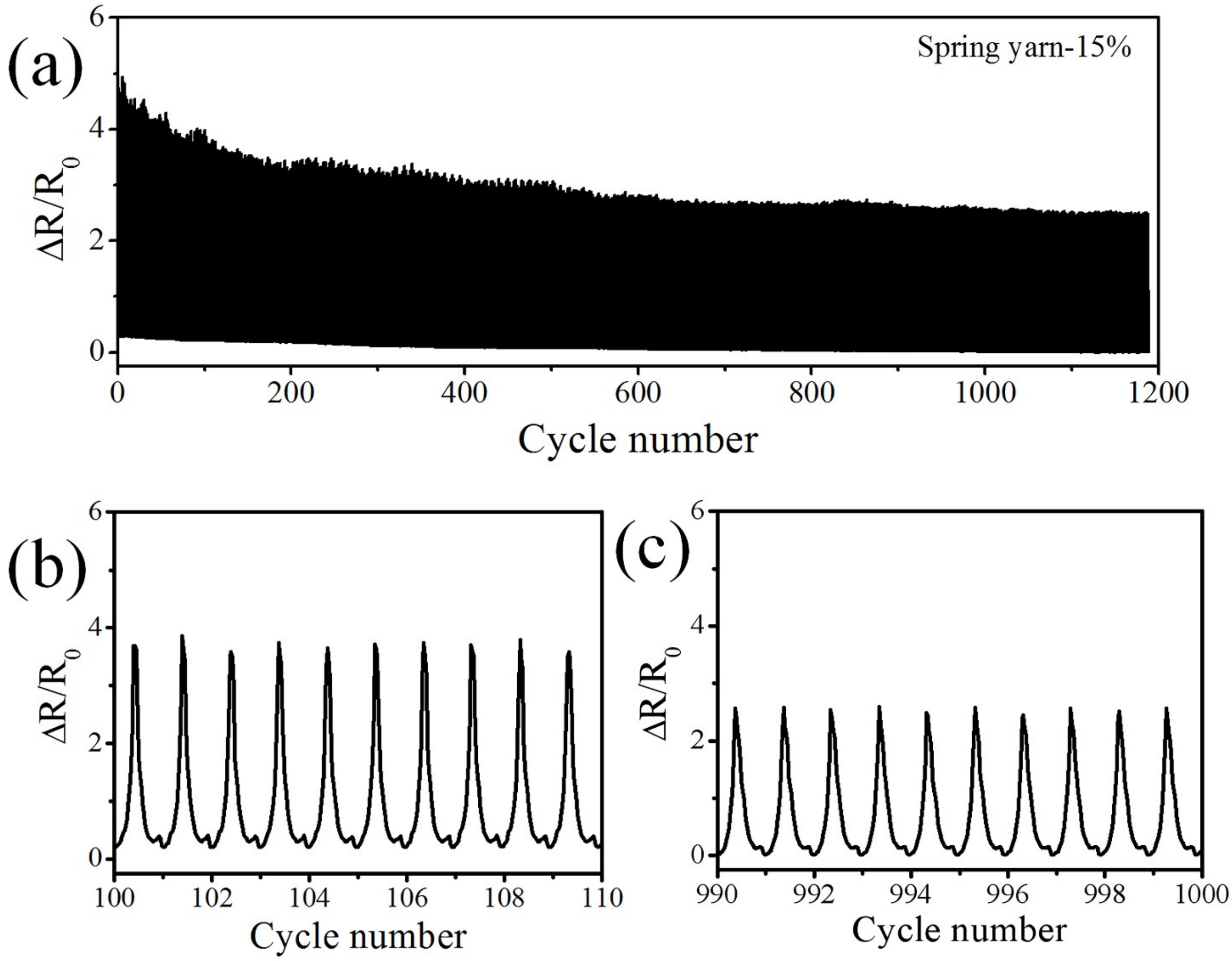

Figure S11. Repeat loading-and-unloading of spring yarn device for 1000 cycles, (a) strain 15%, 72 mm/min, (b,c) different stages of (a).

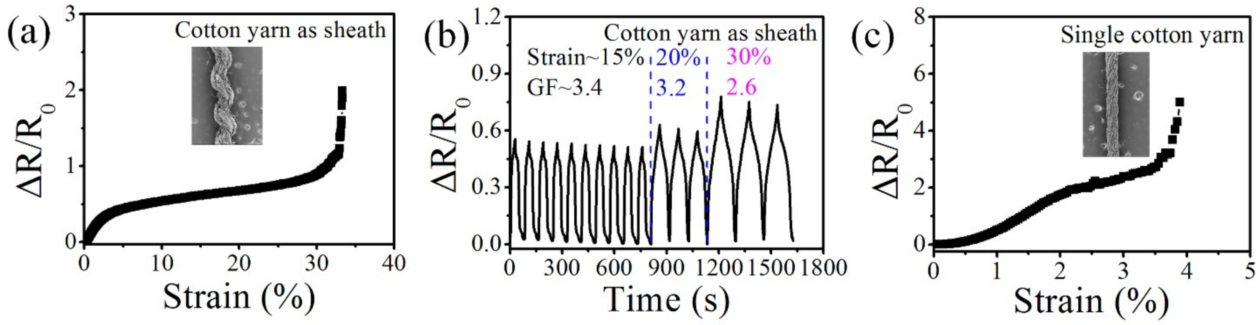

Figure S12. (a) Resistance-strain curve (b) strain response and gauge factors of the sensor device made of wrapping yarn from both cotton yarn core and cotton yarn sheath; (c) resistance-strain curve of the sensor made of the single carbonized cotton yarn without sheath.

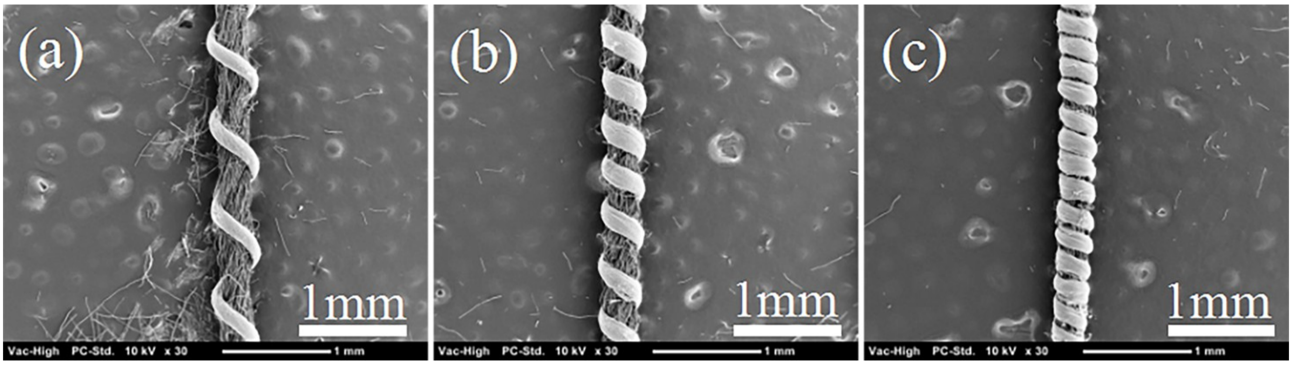

Figure S13. SEM images of the helical wrapping yarns with different coil pitches after carbonization.

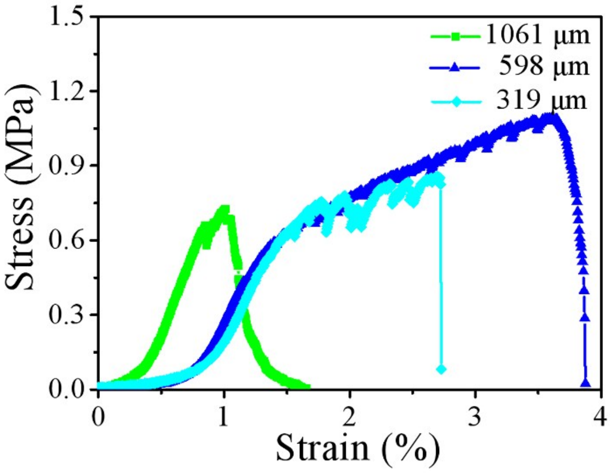

Figure S14. Stress-strain curves for the carbonized wrapping yarns with different coil pitches.

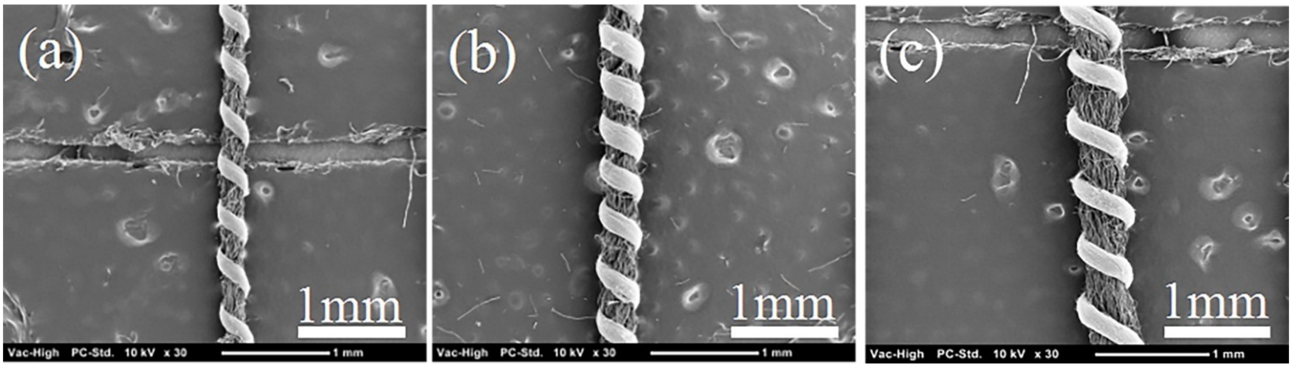

Figure S15. SEM images of the helical wrapping yarns made of cotton core yarn with different diameters after carbonization.