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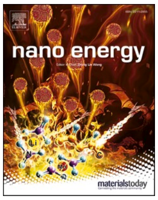

Self-powered stretchable strain sensors for motion monitoring and wireless control

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ABSTRACT

Smart skins and smart textiles equipped with strain sensors for motion detection are of prime significance for personalized health monitoring, lifestyle and fitness applications. Yet, the dependence of these devices on wired power supplies and rigid batteries limits their use in everyday settings. Here, we report self-powered and highly elastic strain sensors withstanding stretching to 200% for monitoring the human motion. The sensor is based on a torsional-spring-shaped coil of liquid metal wound around an elastomeric tubing and equipped with a tiny piece of a magnetic ring. The energy is harvested from the body motion relying on the Faraday's law of electromagnetic induction when the coil is exposed to a time-varying magnetic field of the magnetic ring upon the mechanical deformation of the strain sensor. The max short-circuit current is 2 mA, which is much higher than previous work, and the peak power of our device is 20 μW, sufficiently high to drive conventional low-power electronics. We demonstrate the application potential of our sensor for wearable electronics for monitoring the motion of arms and legs during fitness workout and riding bicycle. The sensor can measure motion of fingers and wrist for health applications and establish wireless control of robotic hands.

1. Introduction

Wearable electronics have made tremendous progress owing to their great application potential in personalized health-monitoring, intelligent robotics, smart displays, energy harvesting and storage [1–9]. In particular, health monitoring relies on the logging and analysis of physiological indicators and has already proven to be beneficial to supervise and guide rehabilitation treatment, e.g. of finger joints [10], or curing of diseases, e.g. Parkinson's diseases [11–14]. This success stimulated a broad use of health monitoring devices in portable gadgets like smartphones and smartwatches.

Flexible electronic technologies for health monitoring [15–18] address key shortcomings of the state-of-the-art portables in terms of bulkiness, motion constraint due to rigidity, and energy inefficiency. Soft, stretchable, and skin-compliant electronics offer the highest degree of personalization and comfort upon continuous use in everyday activities [19–22]. There are different families of stretchable functional elements, which are developed for monitoring of physiological indicators

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including temperature [23], biopotential signals [24], heart rate [25], blood pressure [26], oxygen level [27], sweat [28].

Stretchable strain sensors [29,30] emerged as the key functional element of skin compliant health monitoring systems due to their broad applicability for human motion monitoring [31], cardiology [32], neurology [33], and hematology [34]. Current laboratory demonstrations of stretchable strain sensors rely on wired power supplies, which is hardly acceptable for skin-compliant portable electronics [35]. A typical approach to realize autonomous yet limited in time operation of strain sensing devices is based on the integration of the sensor with a battery [36–38]. However, the use of batteries increases not only bulkiness but also the overall complexity of the device and manufacturing process. Energy harvesting from body motion is considered the most promising technology to realize self-powered stretchable electronics and in particular strain sensors. Indeed, human motion activities contain vibration energy in abundance, which can be harvested by various transduction mechanisms [39–41] (Table S1). In this respect, there are demonstrations of wearable piezoelectric triboelectric nanogenerators (TENG) based on the coupling effect of contact electrification (CE) and electrostatic induction. Ultrathin ZnO p–n homojunction films can convert flexor tendon's movement into distinguishable electrical signals that can be further used to recognize gestures [42]. Patterned Ag-nanofiber electrodes [43] and polytetrafluoro-ethylene nanocomposite membrane [44] are applied for detecting and spatially mapping trajectory profiles and enable water wave energy harvesting and subtle motion monitoring in water. Still, the high output impedance of TENG and low output current makes them hardly usable in low impedance sensor applications including strain sensors, which are typically based on current-driven stretchable conductors [45–50]. Recently, stretchable inductive coils started to gain attention for the realization of self-powered mechanically flexible and even elastic resistive sensor devices due to the appealing possibility to provide current for powering the sensors [51,52]. The most promising strategy to realize long-term stable highly stretchable strain sensors relies on the use of liquid metals. Liquid metals are broadly used for smart wearable applications and already include exciting demonstrations of stretchable circuits [53], antennas [54], strain and stress sensors [55] to name just a few.

Herein, we report a self-powered stretchable strain sensor equipped with a spiral coil based on liquid metal (LM). Being exposed to a magnetic field of a permanent magnetic ring in its proximity, the coil harvests electrical energy for the strain sensor relying on the Faraday's law of electromagnetic induction. LM spiral coil is fabricated on a twisted thermoplastic elastomeric tube (TPE). The sensor exhibits stretchability of 200% and the LM coil retains its adherence with the TPE tube even at this extreme stretch condition. Energy conversion takes place when the LM spiral coils is mechanically deformed in the time varying magnetic field. We experimentally address the effect of the magnetic field (direction and gradient) on the performance of the sensor. The energy harvesting performance is significantly enhanced when operating in gradient magnetic fields reaching remarkable output of 2 mA short-circuit current (I_{SC}), which is sufficient to supply low-power electronics. The use of a cobalt-based amorphous wire (CoAW), inserted inside the TPE tube, allows to further boost the energy conversion efficiency by 33%. The sensor offers high output in response to a human motion, such as finger or wrist bending and hand trembling. With the magnetic field provided by a small permanent magnetic ring, the sensor system is portable and fully autonomous. We demonstrate the application potential of our self-powered strain sensor for wearable electronics including smart textiles and electronic skins for monitoring the motion of fingers, arms, and legs. The high short-circuit current enables the device to transmit signals wirelessly to control a robotic hand. The wearable sensor can be readily used for lifestyle, fitness and health applications including remote operation, rehabilitation workout and monitoring of the Parkinson disease.

2. Results and discussions

2.1. Preparation of self-powered stretchable strain sensors

The self-powered stretchable strain sensor consists of a hollow TPE tube with an outer diameter of 1 mm, LM spiral coil, and Co-based amorphous wire (CoAW; CoFeSiCr alloy). The TPE tube possesses excellent stretchability and serves as a stretchable substrate for the sensor. To fabricate spiral patterns, the TPE tube was twisted along its longitudinal axis (Fig. 1). The LM stripe made of Galinstan, a eutectic alloy composed of gallium, indium, and tin with 1.5 Ω/cm resistivity was coated on the top side of the twisted TPE tube. Upon releasing the twisted TPE tube, the LM layer adopted the shape of a spiral coil wound along the tube axis (**Video S1**). The thickness and width of the LM coil depends on the number of turns of the TPE tube (Fig. S1). Furthermore, the hollow TPE tube can accommodate in its interior a CoAW with a diameter of 30 μm.

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Due to its high magnetic permeability, the CoAW allows to enhance the sensor signal output. As the final fabrication step, the entire sensor assembly was encapsulated using polydimethylsiloxane (PDMS) elastomer. The entire sensor is mechanically soft; it can be bent (Fig. 2**a**), twisted (Fig. 2**b**) and stretched (Fig. 2**(c, d)**). This allows to use these stretchable strain sensors as a functional element of skin compliant electronics (Fig. 2**e**). In an external magnetic field, the change of the coil geometry while stretching or bending results in the change of the magnetic flux density in the coil leading to the induced electrical voltage according to the Faraday's law of electromagnetic induction.

2.2. Characterization of self-powered stretchable strain sensors

We estimate the Young's modulus of the TPE tube to be at the level of 0.8 MPa (Fig. S2). The low Young's modulus of the material allows us to achieve rather large elongation at low force as required for on-skin and wearable electronics applications. The sensor's performance depends on the number of windings of the LM spiral coil per unit length, which can be tailored by varying the number of turns applied upon the initial twisting of the TPE tube (Fig. S3). Instead of operating with the number of windings, it is more convenient to perform analysis of the device performance by considering the angle α, which is formed by the LM stripe with respect to the long axis of the TPE tube (Fig. 2**f**). If α is big, then the number of turns per unit length will be small and vice versa. As shown in Fig. 2**f**, for $\alpha < 100^\circ$, the sensors' resistance changed minutely even when stretched up to 200%, which is beyond the typical stretching of less than 100% of the human skin [56]. When the angle α is increased beyond 100°, the sensor reveals a more significant resistance change upon stretching. We note that for all the samples, the resistance initially decreases but after reaching a certain critical strain value it starts increasing. For the sensor with $\alpha < 100^\circ$, the critical strain value is about 100%. This value gradually decreases to 0 with the increase of α to 120°. Qualitatively, the behavior can be understood in terms of the deformation of the liquid metal layer. During the stretching process, when the angle α is close to 90°, the main deformation of the liquid metal is the increase of its cross-sectional area. Thus, the resistance decreases. As the angle α increases, the main deformation of the liquid metal becomes the length increment, resulting in the resistance increase.

If α approaches 90°, the sensor's resistance becomes stable and the largest number of windings in the spiral coil can be achieved (Fig. 2**f**). The latter is of major relevance for the energy harvesting relying on electromagnetic induction processes. Therefore, this sensor geometry is used in the further experiments. Fig. 2**g** shows the optical microscopy images of the LM spiral coil with $\alpha = 92^\circ$ (see also Fig. S4a and Fig. S4b revealing the coil before and after stretching to 200%). The LM coil adheres well to the TPE tube even under these extreme stretch conditions (Fig. S4b), which confirms the extended operating range of

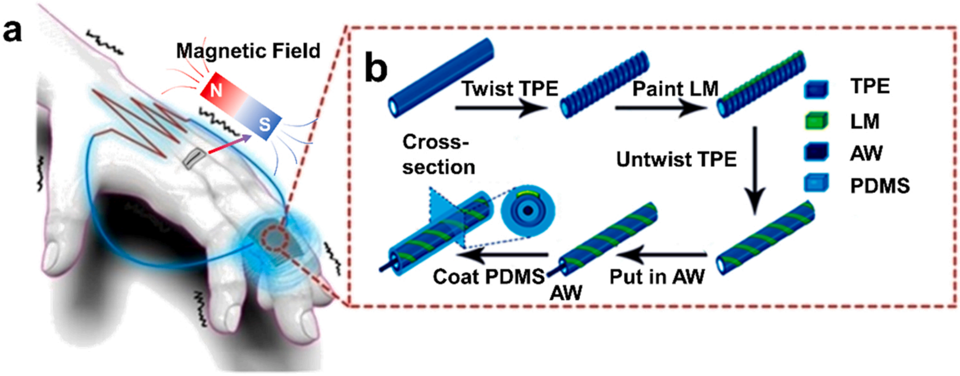

Fig. 1. Self-powered stretchable strain sensor based on LM spiral coil. a) Identify the hand tremor by a self-powered stretchable strain sensor for health monitoring. b) Schematics of the fabrication steps to realize stretchable strain sensor based on LM spiral coil. First, the TPE tube is twisted and then coated with a LM stripe. After releasing the twisted TPE tube, LM stripe adopts a spiral shape. Optionally, CoAW can be inserted in the hollow TPE tube to further enhance the energy conversion performance. Finally, the whole sensor assembly is encapsulated in PDMS elastomer.

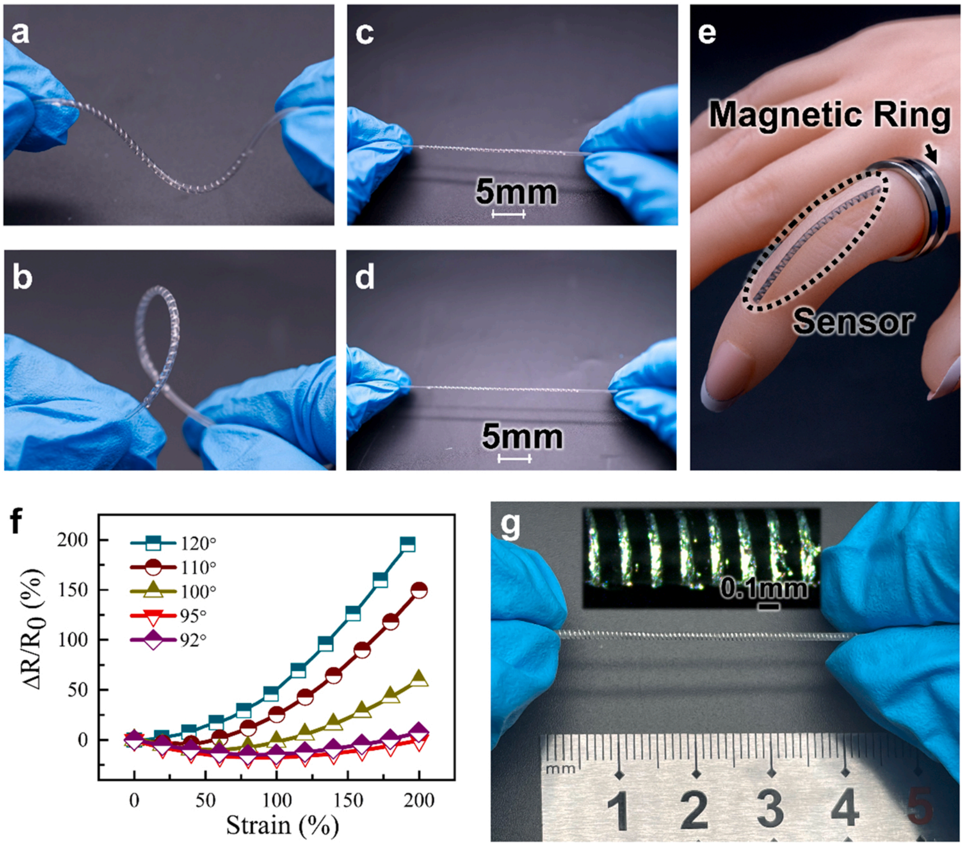

Fig. 2. Self-powered stretchable strain sensor based on LM spiral coil. Motion monitoring by the self-powered stretchable strain sensor. a–d) The sensor is soft and elastic. It can be easily a) bent, b) twisted or stretched (compare panels c) and d)). e) Photograph showing the sensor applied to the finger. Permanent magnetic ring is indicated as well. f) Normalized resistance change of the sensors having various coil angles α as a function of the applied tensile strain. g) Optical and magnified images at a coil angle of 92 degrees.

mechanical loading for our sensor device.

2.3. *Energy conversion efficiency of stretchable LM spiral coils*

According to the Faraday's law of electromagnetic induction, when the spiral coil is stretched in an external magnetic field, a corresponding voltage will be generated in the LM spiral coil. We brought the strain sensor ($\alpha = 92^\circ$) to a mechanical vibration to attain the efficiency of energy conversion. To evaluate the energy harvesting performance, we monitored the output of the sensor attached to a shaker, which is driven at 14 Hz signal of different wave form (triangular, sine, and pulse), Fig. 3**a**. In these experiments, the sensor is subjected to a homogeneous magnetic field of 2 kOe and exposed to a 4% applied strain. The sensor can operate at any of these excitations, but the highest energy conversion efficiency is observed for the case, when the sensor is driven with a triangular wave. This finding can be explained by considering that the output of the sensor depends on the rate of the magnetic flux change yet by taking into account the relaxation time of the elastomer. Indeed, in the case of a pulse excitation, the flux change appears to be not large, as the elastomer cannot be stretched substantially during a very short in time excitation. In this respect, it is of advantage to increase the duration of the pulse to allow the elastomer to follow the actuator in full. In this respect, for the mechanical properties of our elastomer, we found out that the triangular wave excitation provides a larger output in the inflection points, which leads to the maximum total output voltage. Therefore, this wave form is used for further experiments.

The effect of stretching and the vibration frequency on the energy conversion efficiency of the self-powered sensor is shown in Fig. 3**b**. When the device is exposed to a uniform magnetic field with the strength of 2 kOe and vibrates at low frequency of 2 Hz, its output rises from 15 μA to 60 μA when the strain increases from 4% to 40%. Fig. 3**c** and Fig. S5 shows the current output of our sensors when actuated at

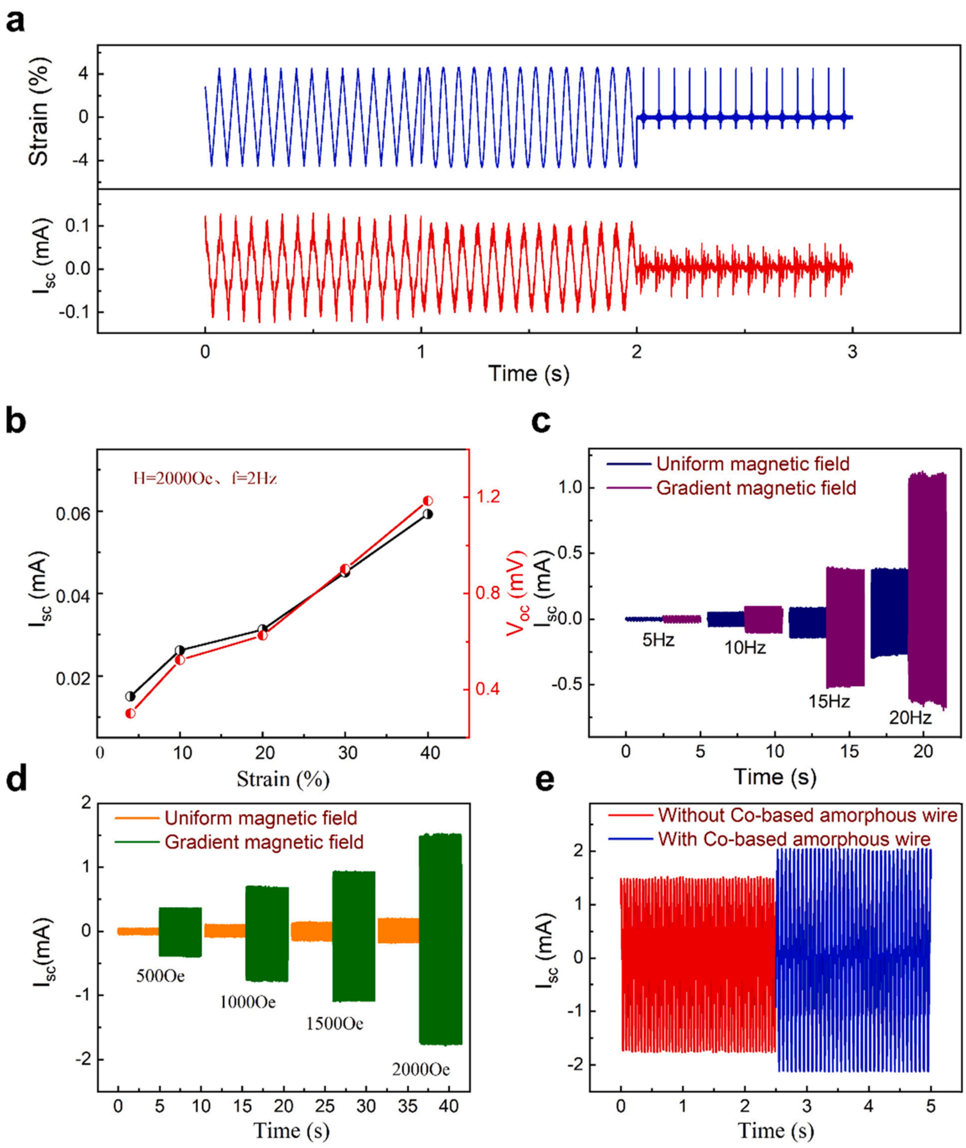

Fig. 3. Energy harvesting performance of the stretchable LM spiral coil. a) The short-circuit current signal (I_{SC}) of the stretchable spiral coil obtained upon application of periodic triangular, sine, and pulse vibrations (frequency = 14 Hz) under a uniform external magnetic field of 2 kOe and applied strain of 4%. b) I_{SC} and V_{OC} (open circuit voltage) of the stretchable spiral coils measured at different degree of stretching when the device is exposed to a magnetic field of 2 kOe and vibrated at 2 Hz. c) Isc of the device, exposed to the uniform and gradient magnetic field, dependent on the vibration frequency when the sensor is subjected to 4% tensile strain and exposed to a magnetic field of 2 kOe. d) Effect of the uniform and gradient magnetic field on the output of the device when it is subjected to 4% applied strain and vibrates at 20 Hz. e) Output of the stretchable LM spiral coil with and without insertion of the CoAW, evaluated under 2 kOe magnetic field, 4% applied strain, and 20 Hz vibration frequency.

different frequencies. The sensor's output increases strongly with the vibration frequency and reaches 1 mA at 20 Hz under a moderate strain of 4% (Fig. 3**c**).

The magnetic field strength and its spatial profile plays an important role in the efficiency of the energy conversion. We studied the energy harvesting performance of the device by applying uniform and gradient magnetic fields. The magnetic field gradient is characterized in Fig. S6. The strain sensor was subjected to the magnetic field of various magnitudes, under a vibration frequency of 20 Hz (Fig. 3**d**). The output of the sensor increases with the increase of magnetic field strengths. The use of gradient instead of homogeneous magnetic fields boosts the energy conversion efficiency up to 650%. The maximum I_{SC} of the sensor reaches about 1.5 mA under the gradient magnetic field of 2 kOe. In the uniform magnetic fields, the sensor output is only related to the change in the coil cross-section upon stretching. In addition to this effect, for gradient magnetic fields, the spatial change of the magnetic field experienced by the coil during the stretching process does additionally increase the sensor output. As a result, a substantially enhanced energy harvesting performance, when operated in a gradient magnetic field, is of strong advantage as this highlights the potential to use it being driven with a permanent magnet. In this way, portability and autonomous operation can be readily achieved.

To assess the performance of the sensor in an arbitrarily oriented magnetic field, we investigated the effect of the magnetic field direction on the energy conversion by exposing the sensor to the magnetic field of 1 kOe oriented perpendicular and parallel to the main symmetry axis of the spiral coil. The strain sensor was stretched to 4% and vibrated at a frequency of 15 Hz. The corresponding output of the sensor is shown in Fig. S7. Due to the torsional spring geometry of the LM coil, the sensor can operate even in the unfavorable case, when the magnetic field is applied perpendicular to the cross-section area of the coil. To further enhance the energy conversion efficiency of the device, we inserted CoAW inside the hollow TPE tube. Benefiting from the high permeability of the amorphous wire, the distribution of the magnetic field changes, increasing the number of magnetic induction lines passing through the coil cross-section. As shown in Fig. 3**e**, the output of the sensor with the CoAW core reaches up to 2 mA, which is about 33% higher than the output of the sensor without the CoAW. This is 2 orders of magnitude higher than values reported for other biomechanical energy harvesters (Table S1). In this respect, the peak power of our device can be as high as 20 μW. The simulation results (Fig. S14, S15) also show that the amorphous magnetic wire can significantly change the magnetic flux nearby, resulting in a large increment of the output of the sensor. Furthermore, we note that simulations show that the increase of the bending angle can also significantly enhance the output, which is again consistent with our experimental results. With this performance, our device successfully addresses one of the major issues of biomechanical energy harvesters related to a low output current. In this respect, our work opens exciting perspectives of using conventional electromagnetic induction based harvesters for wearable sensors, which are conditioned using low-power electronics.

2.4. Applications of self-powered stretchable strain sensor

To investigate the potential of the self-powered stretchable strain sensor for electronic skin applications, we mounted our sensor on the forefinger. To assure quantitative characterization, the finger was located in the spatially uniform magnetic field of 2 kOe. The sensor readily detects the finger movement and its output increases with the increase of the bending angle (Fig. 4**a**). Similarly, the sensor can be used to detect motion of other body parts, as exemplarily shown with the monitoring of the wrist motion (Fig. 4**b**). The sensor's output changes correspondingly (positive or negative) with the upward or downward wrist joint bending, which is attributed to the increase or decrease of the magnetic flux, which occurred due to the bi-directional bending. We note that in these experiments the energy to power the sensor is harvested from the body motion only, which confirms the significant application prospect of this technology in the field of wearable devices.

The self-powered sensor on the forefinger can be applied to detect different degrees of hand trembling. When the hand trembles periodically, like in the case of the Parkinson's disease, the periodic change of the sensor's output occurs, which is shown in Fig. 4**c**. The sensor's output changes when the hand trembling occurs at low (about 1 Hz), medium (about 2 Hz), and fast (about 5 Hz) speeds. Our self-powered strain sensor successfully detects the amplitude and speed of the hand trembling and converts the vibrational energy of the hand into electrical energy. This signal can be used for a wearable healthcare system to detect the abnormal hand tremor, deviant finger and wrist movements.

For everyday operation, the sensors should be portable. In this case, bulky electromagnets cannot be used for excitations. Instead, the sensor should be able to work when exposed to a magnetic field of a tiny permanent magnetic ring. This assures portability of the entire sensor platform and makes it entirely autonomous as neither the sensor nor the permanent magnet needs any additional energy source. In the following demonstrations (Fig. 5), we use a small permanent magnetic ring to provide a magnetic field of about 80 Oe only at the sensor location that is already sufficient for the sensor to monitor body movements. Fig. 5**a and Video S2** show the stretchable self-powered device applied to the finger. As the finger bends downward and upward and returns to the initial position, the output voltage of the sensor changes from being negative to positive. To demonstrate applicability in the smart textile technologies for fitness and lifestyle applications, we fixed the sensor on the cloth, as shown in Fig. 5**b** and **c**. As a component of smart textiles, the sensor can accurately sense the bending of the arm and correctly captures the direction of bending (Fig. 5**b** and **Video S3**) as well as detects the bending of the leg when riding a bicycle (Fig. 5**c** and **Video S4**).

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To show the advantages of the high current provided by our self-powered device, we connect the sensor to an inductive coil (Fig. 6**a**).

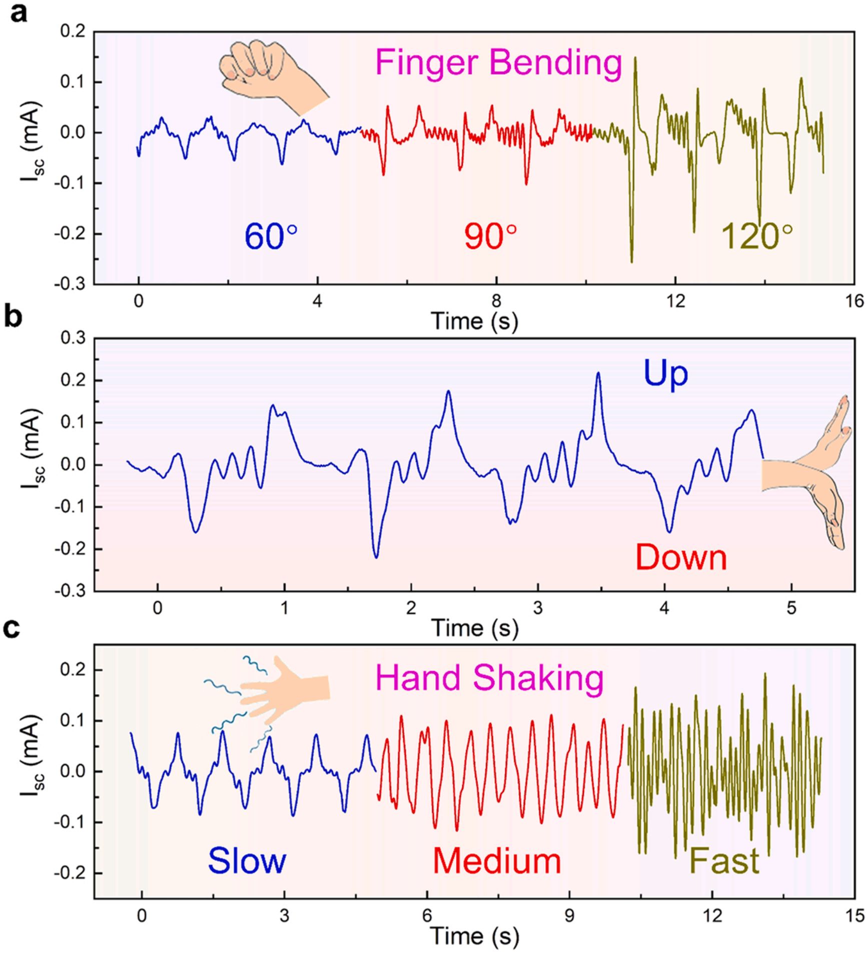

Fig. 4. Use of the self-powered stretchable strain sensor for monitoring the hand motion. Sensor's output signal acquired during a) finger bending, b) wrist bending, and c) hand trembling at slow, medium, and fast speed. In these demonstrators, the energy harvesting is done in a homogeneous field of 2 kOe.

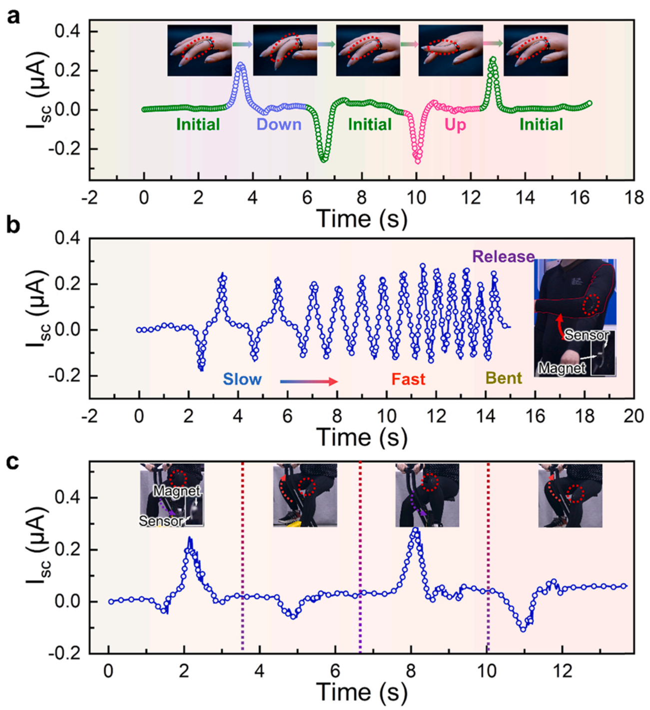

Fig. 5. Self-powered stretchable strain sensor based on stretchable LM spiral coil for smart wearables. In these demonstrators, the sensor is exposed to the magnetic field of a permanent magnetic ring, integrated next to the sensor. The strength of the magnetic field is 80 Oe at the sensor location. The entire sensor system is fully portable and autonomous. a) Smart skin applications: The sensor is applied to the finger. The motion of the finger is monitored upon its bending up and down. b,c) Smart textile applications. b) Photograph of the sensor integrated in a textile for monitoring of the arm bending and the output of the sensor, while the arm is bent and released at different speed mimicking a fitness workout. The magnification figure is the location of the sensor and the magnet. c) Photograph of the sensor integrated in a textile to monitor the motion of the knee joint upon riding bicycle and the corresponding sensor output signal. The magnification figure is the location of the sensor and the magnet.

When the finger is bent, the current provided by the harvester changes resulting in the change of the magnetic field generated by the inductive coil. We use a magnetic field sensor to detect the change of the magnetic field and input it to a computer to control the movement of a robotic hand wirelessly. The distance of the magnetic sensor from the inductive coil is 0.5 cm. When the finger is bent or returns back to the initial states, the magnetic field detected by the magnetic field sensor also changes (Fig. 6**b**). We use this magnetic field signal to realize a wireless signal transmission and control a robotic hand to perform the corresponding movements (**Video S5**). The use of a more sensitive signal detection unit for longer-distance signal transmission enables integration of the inductive coil directly into our sensor. This could further facilitate integration of our sensors and harvesters and make the entire system more efficient.

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3. Experimental section/methods

3.1. Preparation of the LM spiral coil

High purity metals Gallium, Indium, and Tin (99.99%, Beijing Founde Star Sci. & Technol. Co., Ltd) were mixed in the ratio of 68.2:21.8:10 by mass. Then the mixture was heated and stirred at 60 °C for 30 min to obtain LM Galinstan alloy ($Ga_{68.2}In_{21.8}Sn_{10}$). Afterward, the prepared Galinstan and the micron-sized copper powder was mixed in a mass ratio of 9:1 and the resultant mixture was heated and vacuumed several times to remove air bubbles. The copper powder added in the liquid metal can form semi-liquid metal (Cu-EGaIn), which increase wettability and adhesion. This high adhesive mixture was further used to prepare LM spiral coil on the TPE tube.

3.2. Preparation of the strain sensing element

Thermoplastic elastomeric tube (TPE, Ningbo ELasTech Co., Ltd, China) of 50 mm length, 0.5 mm inner diameter, and 1 mm outer diameter was twisted along its longitudinal axis by using a winding machine. The angle with the axis of tube (α) depends on the number of windings of the TPE tubing. LM was coated on the top side of the twisted TPE tube. CoAWs made of CoFeSiCr alloy of 30 μm diameter were

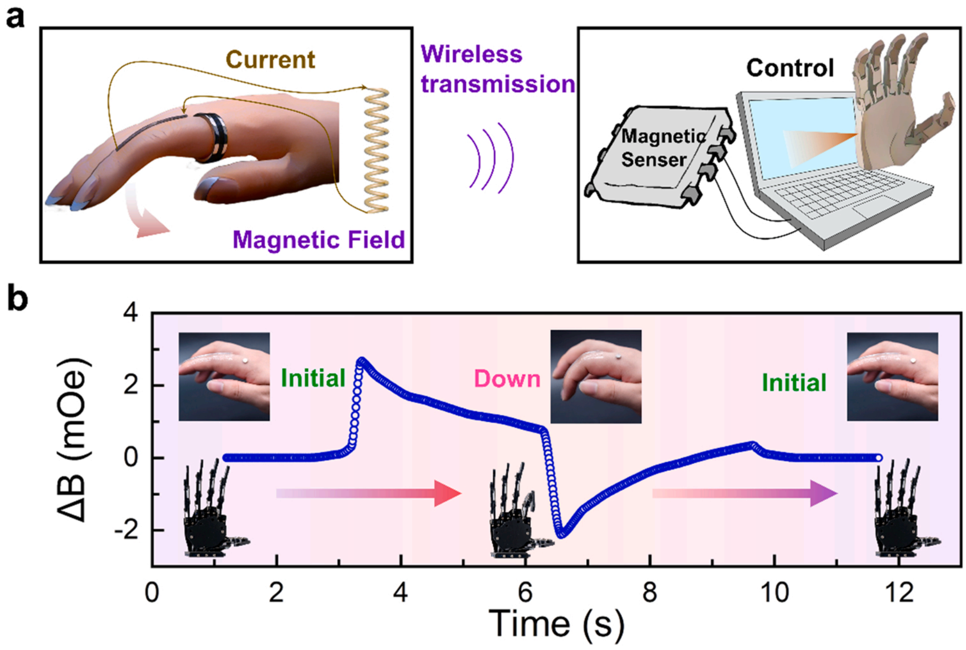

Fig. 6. Self-powered stretchable strain sensor based on stretchable LM spiral coil for Wireless Control. a) Schematics of the wireless control of a robotic hand. The sensor is connected to an inductive coil. The short-circuit current of the sensor changes when the finger is bent, resulting in the change of the magnetic field generated by the inductive coil. The change of the magnetic field is measured by the magnetic sensor to realize a wireless control of the movement of a robotic hand. b) Demonstrator of a wireless control of a robotic hand using the self-powered stretchable strain sensor.

inserted inside the hollow TPE tube to increase the efficiency of the energy conversion. The final sensor assembly was encapsulated in PDMS (Sylgard 184, Dow Corning, USA), which was prepared in a 10:1 w/w ratio (base to curing agent), applied, and then dried at 80 °C for 30 min in an oven.

3.3. *Mechanical characterization*

Mechanical tests of the TPE tube were carried out by using computer-controlled material testing machine (Instron 5943, USA) at the rate of 5 mm/min (Fig. S2). Stretching experiments were done using a laboratory tensile test machine.

3.4. *Microscopy characterization*

The scanning electron microscope (SEM) image and energy dispersive spectrometer (EDS) of the LM (Fig. S8 and Fig. S9) and Co-based amorphous wires (Fig. S10 and Fig. S11) were taken using a microscope (Sirion200, FEI, USA).

3.5. *Magnetic characterization*

The hysteresis loop (Fig. S12) of the Co-based amorphous wire was measured by applying magnetic field along the wire in a vibrating sample magnetometer (Lakeshore7410, Lakeshore, USA). When an amorphous wire is inserted into the induction coil, the internal magnetic permeability of the coil increases significantly. The relationship between them can be expressed by the following formula: $\mu = 2.1\frac{S_0}{S_x}\frac{l_x}{l_0-1}$, where S_0 and S_x represent the cross-sectional area of the coil (3.591 mm^2) and amorphous wire, l_0 and l_x represent the inductance before and after inserting the amorphous wire. The frequency dependence of the magnetic permeability of the Co-based amorphous wire (Fig. S13) can be calculated based on the measurement of the initial inductance of the inductive coil and the inductance after insertion into the amorphous wire. The inductance was measured using the impedance analyzer (4294 A, Agilent, USA).

3.6. *Device characterization*

Electro-mechanical tests were performed at room temperature by using a two-probe configuration. The electrical current was provided by the current source device (Keithley 237, Keithley Instruments, USA), while the voltage was measured by a voltmeter (Keithley 34420A, Keithley Instruments, USA). Periodic triangular, sine, and pulse signals were generated by a signal generator (AFG 3101C, Tektronix, USA), then applied on a shaker (LDS V201, Br üe & Kjær Sound & Vibration Measurement, UK), which brings the sensor into mechanical vibration. The magnetic field was applied along the tube/wire axis. The magnetic field of the gradient magnetic field was measured by the Gauss meter (PF-035, Litian, China). The output voltage of the sensor is measured using the oscilloscope (DLM2024, Yokogawa Electric Corporation, Japan). The short-circuit current was obtained by dividing the measured open-circuit voltage by the corresponding internal resistance.

3.7. *Demonstrators*

The sensor was fixed on skin and clothes with a polyurethane (PU) tape (Jiangsu Guangyi Medical Dressing co., Ltd, China). For the case of portable demonstrators, we used a permanent magnetic ring (Aoduoke Co., Ltd, China; NbFeB alloy). The magnetic field intensity on the surface of the magnet was 1 kOe, which results in the field of about 80 Oe at the sensor location. The time evolution of the sensor signal was shown on the screen of the oscilloscope (DLM2024, Yokogawa Electric Corporation, Japan). A 750-turn inductive coil (resistance of 26 Ω) was connected to the self-powered sensor to generate wireless signals. The change of the magnetic field generated by the inductive coil upon deformation of the self-powered sensor was measured by a magnetic field sensor (Aichi, MI-CB-1DH, Japan). The output of the magnetic field sensor was measured by a voltmeter (Keithley 34420A, Keithley Instruments, USA). The movement of a robotic hand (ZL-robot, China) was controlled by a program written in a software (NI LabVIEW).

4. Conclusion

In this work, we demonstrate self-powered stretchable strain sensors based on coil-shaped liquid metal stripes that can be used to monitor the motion of body parts. The device harvests electrical energy for strain sensing electromagnetically, according to the Faraday's law of electromagnetic induction. We provide a set of design rules related to the geometry of the coil allowing to realize sensors exhibiting ultrahigh stretchability (strain = 200%). The latter is facilitated by the high elasticity of the TPE tube and the capability of LM to retain its outstanding electrical properties even at the extreme stretch condition. By performing a detailed study of the impact of the magnetic field strength and its spatial distribution, we demonstrate that the harvesting performance of the stretchable LM spiral coil can be significantly enhanced when the device is exposed to a gradient magnetic field. The reliable operation can be achieved in the field of 80 Oe, which is readily achievable using small-sized permanent magnetic rings. As those magnets do not require any additional energy for their operation, the sensor platform equipped with a tiny permanent magnet is fully portable and self-powered. The energy conversion efficiency increases with the increase of the tensile strain and the vibration frequency. Furthermore, the use of amorphous Co-based wires inserted in the interior of the hollow TPE tubing helps to gain further 33% in the efficiency of the energy harvesting. The key advantage of this magnetoelectric energy harvester is that it can supply high values of peak current in the range of 2 mA which is much higher than the previous work and resulting in a peak power provided by our device of about 20 μW. This is sufficient to drive even low impedance sensors relying on the conventional low-power electronics. We evaluated the performance of our self-powered portable sensor for wearable electronics applications. The sensor can be readily applied to skin or integrated in a textile and offers high output current in response to human motion, such as the bending of finger, arm, and leg. For instance, for the case of lifestyle and fitness applications, we demonstrate that the sensor can accurately measure the arm swing and legs motion upon cycling without any external power supply. Furthermore, we confirmed that the sensor is extremely sensitive to a trembling motion of a hand. This is relevant for the realization of self-powered portable medical appliances for monitoring of the Parkinson disease. The mechanical stability, portability and full autonomous operation of our sensor system in everyday settings highlights its applicability as a vital component of smart skins and smart textiles for personalized health monitoring. Its large short-circuit current can drive an inductive coil to realize a wireless signal transmission enabling the control of the movement of a robotic hand. This is the very first work where it is demonstrated that electromagnetic induction is sufficient to power fully portable wearable electronics. In this respect, our work opens up exciting perspectives for the community of wearable electronics to realize different functional devices, which do not need to rely on wired connections and rigid batteries.

CRediT authorship contribution statement

Shengbin Li: Conceptualization, Methodology , Investigation , Writing – original draft , Writing – review & editing , Visualization. **Pengjuan Cao** : Investigation, Validation, Visualization. **Fali Li**: Conceptualization, Investigation, Formal analysis. **Waqas Asghar**: Writing – original draft. **Yuanzhao Wu**: Methodology, Supervision. **Huiyun Xiao**: Formal analysis. **Yiwei Liu**: Conceptualization, Supervision, Funding acquisition. **Youlin Zhou**: Resources. **Huali Yang**: Formal

analysis. **Ye Zhang**: Validation. **Jie Shang**: Visualization. **Denys Makarov**: Supervision, Visualization, Writing – original draft, Writing – review & editing. **Run-Wei Li**: Conceptualization, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.nanoen.2021.106754.

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