A Battery-Like Self-Charge Universal Module for Motional Energy Harvest

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Wearable and portable electronics have brought great convenience. These battery-powered commercial devices have a limited lifetime and require recharging, which makes more extensive applications challenging. Here, a battery-like self-charge universal module (SUM) is developed, which is able to efficiently convert mechanical energy into electrical energy and store it in one device. An integrated SUM consists of a power management unit and an energy harvesting unit. Compared to other mechanical energy harvesting devices, SUM is more ingenious, efficient and can be universally used as a battery. Under low frequency (5 Hz), a SUM can deliver an excellent normalized output power of 2 mW g^{-1}. After carrying several SUMs and jogging for 10 min, a commercial global positioning system module is powered and works continuously for 0.5 h. SUMs can be easily assembled into different packages for powering various commercial electronics, demonstrating the great application prospects of SUM as a sustainable battery-like device for wearable and portable electronics.

Recent years, wearable and portable electronics have experienced tremendous development.[1–3] Nowadays, they are influencing every aspects of our lives and have brought great convenience to us.[4] Most of these electronics are powered by batteries.[5–7] While, the battery has limited lifetime and will eventually run out of electricity. Even if using the rechargeable battery, a power grid is needed, which brings time and space constraints on the use of these widely distributed wearable and portable electronic devices.[8] Therefore, developing a sustainable power source to match up with the wearable and portable devices is of great importance. It will extend the use time of wearable/portable electronics especially in some extreme situations, such as during the blackouts time or in the wild.

Mechanical energy is widely existing in the environment around us, which has been utilized by humans for a long time.[9] For example, the electricity from wave energy,[10,11] wind energy.[12–14] Besides, the movement of human beings and various vehicles motion also contain a large amount of mechanical energy.[15–17] It would be a potential auxiliary for today's battery technology if these energies can be gathered and converted into electricity. And it will bring new opportunities for developing wearable/portable electronics to overcome some of lifetime related limitations.[18,19]

In order to utilize widely distributed, random mechanical energy in environment, many sophisticated design[20] and advanced materials of energy conversion devices have been invented.[21,22] Representatives among them are electromagnetic generator (EMG),[23] piezoelectric nanogenerator (PENG),[24–26] and triboelectric nanogenerator (TENG),[27,28] each of them has its unique characteristics. Generally speaking, with a same mechanical load, TENG exhibits the highest voltage output, while EMG demonstrates a better performance in current output,[29,30] which can form a good complementary in power generation process. On the other hand, TENG and EMG can easily respond to displacement produced by mechanical motion, while PENG is more suitable for responding to strain.[31,32] In consideration of those interesting properties, a hybrid generator can be designed to integrate these three modes of generators. It will improve the power efficiency and the ability to collect various kinds of mechanical energies for an energy conversion device.[33]

There have been several researches on hybrid generator for improving output performance (Table S1, Supporting

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DOI: 10.1002/aenm.201901875

Information).[13,33–35] In most of these researches, the TENG has been coupled with EMG, and PENG respectively to fabricate different kinds of “2-in-1” hybrid generators.[13,34,35] While, in order to cover as many as advantages of the existing mechanical energy harvesters and to collect mechanical energy more efficiently, advanced design capable of accommodating more powerful generator modes is needed. It is worth pointing out that the universality of the hybrid generators is crucial for expanding their application scenario.[7,36] If the structure and size of the hybrid generators are well designed under the same standard of batteries, they can be easily assembled in any form to adapt to the existing battery-powered electronics with different power consumption.[37]

In this paper, we design and manufacture a self-charge universal module (SUM), and it can efficiently harvest mechanical energy to build a self-powered system for multiple applications. The SUM consists two functional parts: an energy harvesting unit (EHU) which is a “3-in-1” hybrid generator (EMG, PENG, and TENG) and a power management unit (PMU) that converges and stores electricity from three generators. The SUM demonstrates an outstanding electrical performance, by collecting mechanical energy in frequency of 5 Hz, it can charge its built-in battery to 2.7 V in 400 s. The SUM is designed in the shape of a standard AA battery so that it can be used as a possible compensatory method for AA battery, especially in case of emergency. Moreover, just like the battery pack, we can simply assemble different number of SUMs for various electrical appliances, such as global positioning system (GPS) module, calculator, mobile phone and small electric fan, which shows the universality of SUM and its great potential to be a backup power for wearable/portable electronics.

Figure 1a illustrates the detailed structure of SUM. A standard device could divide into two components, the upper component is the PMU and the bottom component is the hybrid generator based EHU. A 3D printed cylindrical polylactic acid (PLA) tube (diameter of 14 mm, height of 50 mm) is used to store those two components. The PMU consists of three rectifier bridges and a miniature lithium battery, which are stacked vertically and connected by two metal pins. Three rectifier bridges are used for transforming the alternating current (AC) generated by EHU to direct current (DC), and transmitted to the miniature lithium battery.

Three different types of generators (TENG, EMG, and PENG) are integrated together to form the EHU component (Figure 1a). To build an EMG part, a groove (depth of 1 mm) is reserved on the surface of PLA tube, and about 2000 turns of copper coils are twined around it. An NdFeB permanent magnet (diameter of 10 mm and height of 15 mm) is placed in the PLA tube and positioned in the middle of the chamber by magnetic levitation, which is achieved by another two reverse small magnets (diameter of 10 mm and thickness of 1 mm) settled at each end of the tube. The PENG part consists of two $Pb(Zr_{1-x}Ti_x)O_3$ (PZT) ceramic sheets (diameter of 10 mm, thickness of 0.5 mm), which are placed at each end of tube beyond the

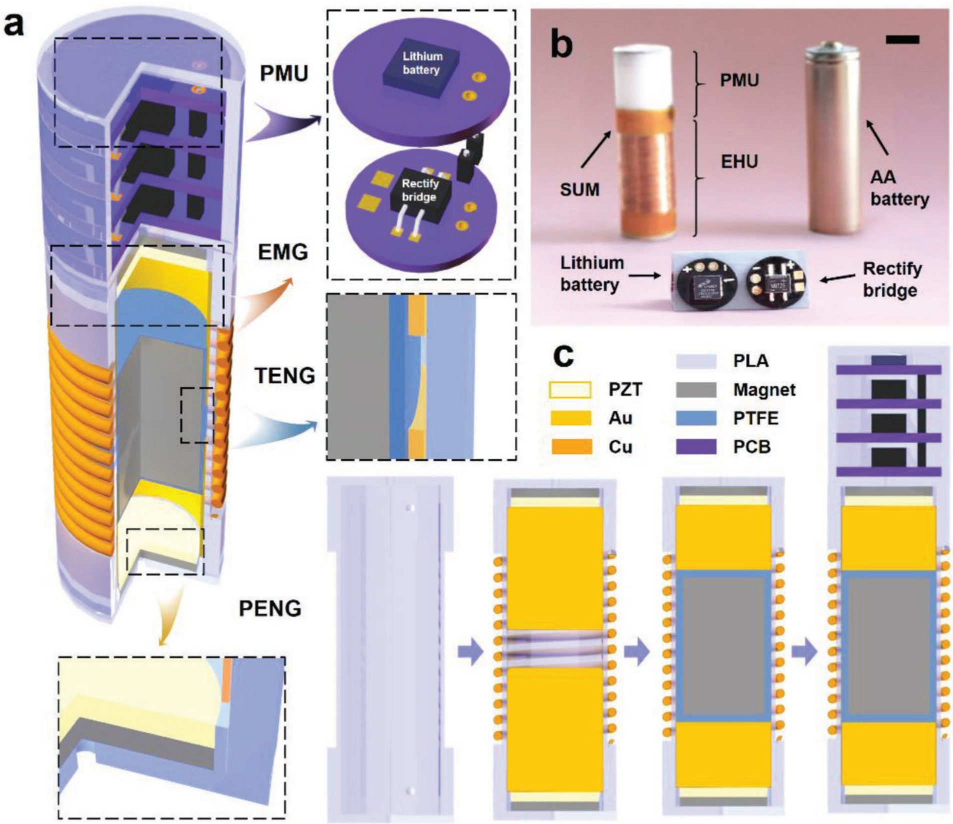

Figure 1. Structure and fabrication process of the SUM: a) Structure of the SUM, the details of the PMU, PENG, and TENG are shown from the dotted box. b) Optical photo of the SUM compared to a standard AA battery (scale bar: 1 cm). c) Fabrication process of the SUM.

reverse magnets. The PENG gathers mechanical energy from the main magnet's strike when external force is large enough to overcome the magnetic levitation bondage, Free-standing mode of TENG is chosen for fabricating the TENG part. The polytetrafluoroethylene (PTFE) thin film covering the surface of main magnet (thickness of 0.2 mm) is used as the sliding friction layer. For the purpose of increasing the effective contact area, the surface of the PTFE film was treated by the inductively coupled plasma (ICP) method to form a nanostructure surface in advance. Scanning electron micrograph (SEM) image of the microstructure of PTFE film is presented in Figure S1 (Supporting Information). Two separated Kapton thin films (thickness of 0.2 mm, length of 30 mm) are sputtered previous, and pasted at the inner wall of the tube as another friction layer. Two Al thin sheets are used as two electrodes like an AA battery, they are located on the both ends of SUM.

Aiming to be a potential auxiliary of AA battery, SUM follows the specification of AA battery strictly. The total length of SUM is 50 mm, and the diameter is 14 mm. The detailed fabrication process can be divided into five steps (Figure 1c). The first three steps are preparations of three kinds of generator under the shape and size requirements of the above-mentioned AA battery standards. The fourth step is assembling each part of the device in sequence including the PMU component. The last step is connecting PMU and four generators by wires according to circuit diagram (**Figure 2**g).

The electricity is generated by EHU component which consist of 4 parts: one TENG, one EMG, and two PENGs (Figure 2a–c). The TENG part involved in this work is operated in freestanding mode, which is based on the coupling of contact electrification effect and electrostatic induction principle.[38,39] After the iterative sliding friction between the main magnet and the Au electrode, the PTFE film produces triboelectric charges with negative polarity and the Au electrode produces positive charge according to the triboelectric sequence.[39,40] The negative charge bound in PTFE film are stable, while the positive

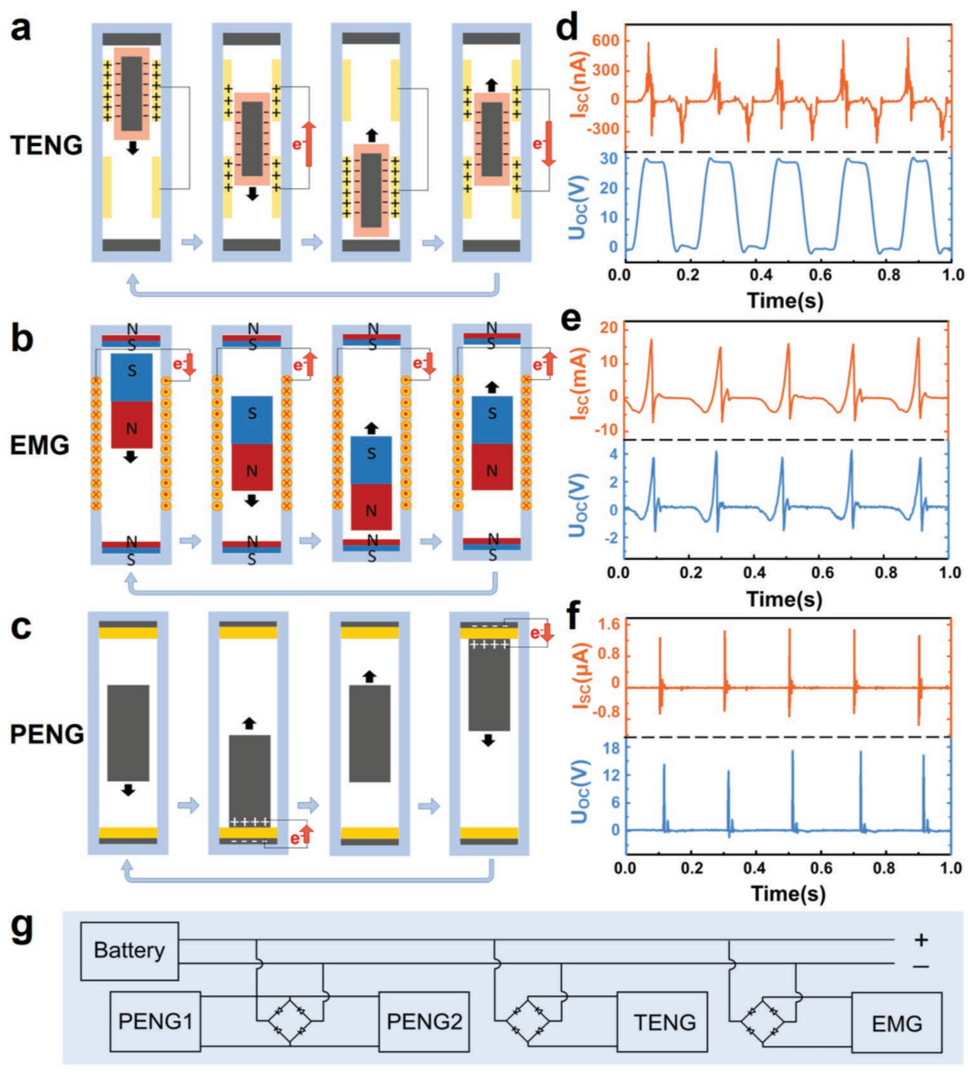

Figure 2. Working principle of the SUM and electrical output of its each part, each SUM contains two PENGs, what depicted here is the bottom one: a–c) Working principle of TENG, EMG, and PENG, respectively. d–f) Short-circuit current and open-circuit voltage of TENG, EMG, and PENG, respectively. g) Circuit diagram of the SUM.

charges in Au electrodes can be redistributed freely. Along with the redistribution of the charges, a current is generated from the external circuit. As the main magnet goes back and forth, the direction of the current changes. After one motion cycle of the main magnet, TENG generates an AC (Figure S2a,b, Supporting Information).

The EMG part used here generates electricity according to Lenz's law, the current induced in a conductor by a changing magnetic field (Figure 2b).[34] When the main magnet moves from top to middle, in other words, when main magnet is inserting into the coil, the current in the coil flows clockwise. When main magnet moves from middle to bottom, the current in the coil flows counterclockwise. In the next half recycle, the current changes twice, too. Also, along with a movement cycle of the main magnet, the current directions change four times, an AC with four peaks is generated by EMG (Figure S2c,d, Supporting Information).

Two reverse magnets are set to each end of the PLA tube, and the main magnet is posited in the middle of the chamber by magnetic levitation. When external force is large enough to break the constraint of reverse magnets, and the main magnets may strike one of PENG parts. This will produce internal strain of PZT sheet, yields opposite piezoelectric potential on both sides,[24] and then the AC is generated from the external circuit. Each SUM contains two PENGs, both of them can generate electricity by piezoelectric effect (Figure S2e,f, Supporting Information).

In this work, a linear motor (LinMot PS01-37*120-C) is used to provide the mechanical excitation. The open-circuit voltage and short-circuit current are measured by an electrometer (Keithley6517) and recorded by an oscilloscope (Teledyne LeCroy HD 4096). The TENG produces an open circuit voltage (V_{OC}) of 30 V and a short circuit current (I_{SC}) of 600 nA at a stimuli frequency of 5 Hz. Meanwhile, the EMG produces a higher I_{SC} (15 mA) and a relatively lower V_{OC} (4 V) compared with TENG. The V_{OC} (15 V) and I_{SC} (1.2 μA) of PENG are between the other two's (Figure 2d–f). As we can see, in each working cycle, TENG produces two opposite peaks, while EMG produces four peaks, and PENG produces one peak, demonstrating their different working state in a motion cycle (**Figure 3**). It is worth mentioning that the output of bottom PENG is better than the top PENG's due to the superposition of gravity of the main magnet. The information of comparison between the top PENG and the bottom PENG could be found in Figure S3 (Supporting Information).

The power output of various parts of hybrid generator is also estimated at different external resistances with a unified condition of 5 Hz. Figure 3 illustrates the resistance dependence

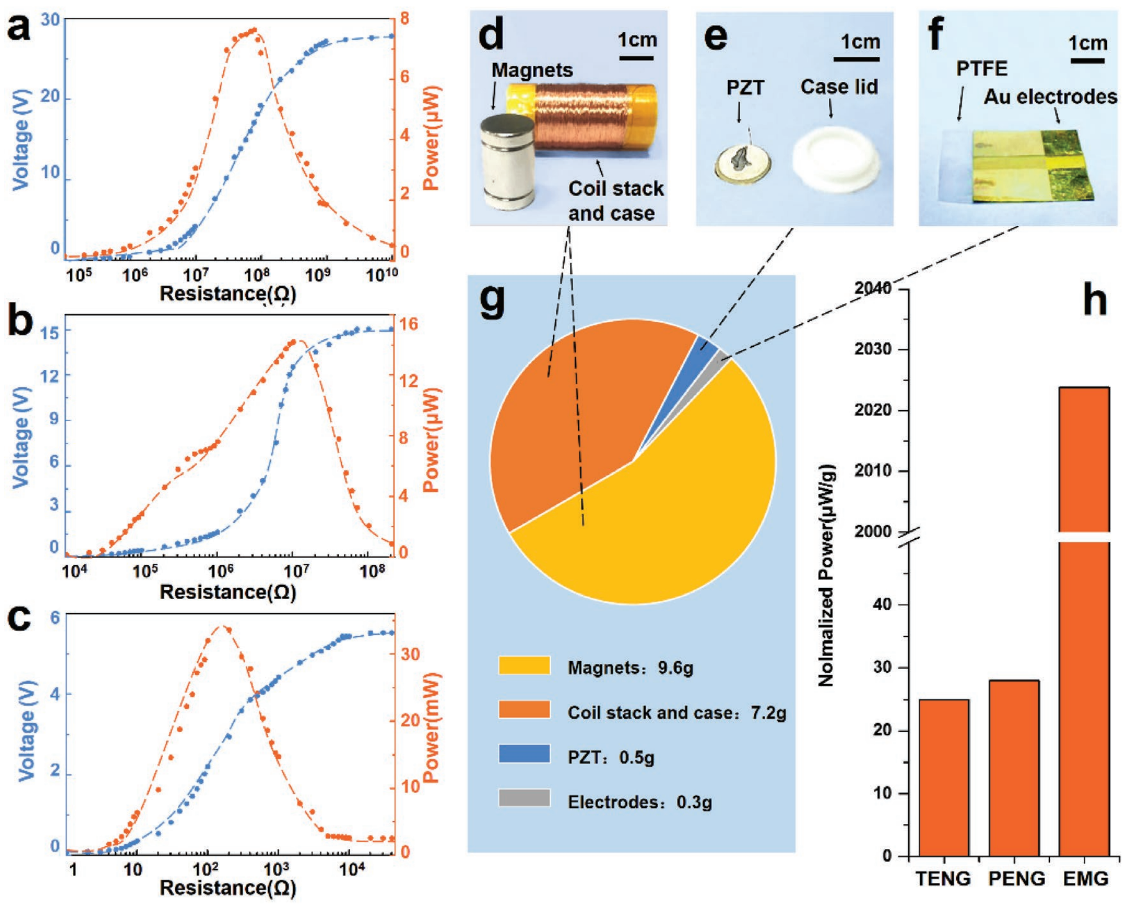

Figure 3. Normalized power output performance of each part: a–c) Resistance dependence of the open-circuit voltage and output power of TENG, PENG, and EMG, respectively. d–f) Optical photos of EMG, PENG, and TENG, respectively. g) Weight of different parts. h) Normalized power density of each part.

of the open-circuit voltage and output power of TENG, PENG and EMG, respectively (Figure 3a–c). The TENG reaches a maximum power of 7.5 μW at the load resistance of 80 MΩ. Similarly, the power output of PENG reaches a maximum of 14 μW when the load resistance increases to 10 MΩ. Compared to TENG and PENG, EMG has a lower load resistance and higher output performance. The output power of EMG reaches maximum at the resistance of 200 Ω, and the maximum is 35 mW. Although, EMG demonstrates much higher output power compared to TENG and PENG, it occupies a larger weight in the whole generator. In considering the effect of weight, the difference of power contribution between the TENG and EMG has been reduced by nearly 57 times. Specifically, the power density of TENG can reach to 25 μW g^{-1}, while the power density of EMG is 2023 μW g^{-1}.

A whole charging process in practice usually consists of two parts, turbulent charging and trickle charging. Relating previous data of output performance, EMG outputs a low voltage and high power density, which is suitable for turbulent charging process. TENG and PENG perform a high voltage and relative low power density, which correspond to trickle charging. This will also be verified in the analysis of the charging curve.

The initial electric energy generated from four generators is an AC signal. Therefore, PMU that contains three full-bridge rectifiers and a lithium battery is used to convert AC to DC and store it.

The charging capacity of hybrid generator and each part of this "3-in-1" generator is systematically studied. The charging ability of hybrid generator is obviously better than that of each part (**Figure 4**a). Detailed investigation shows that in the early period of whole time, EMG contributes most charging capacity of the three parts, but quickly stagnate because of its low output voltage. About 400 s later, the charging capacity of PENG catches up with that of EMG, becoming the largest contribution of the three parts to charge. With time increasing, the charging capacity of TENG will surpass the other two parts and become the highest contribution of the three kinds of generator (data not shown). Put it another way, EMG contributes the most in the process of turbulent charging, while the energy of trickle charging is mainly provided by PENG and TENG.

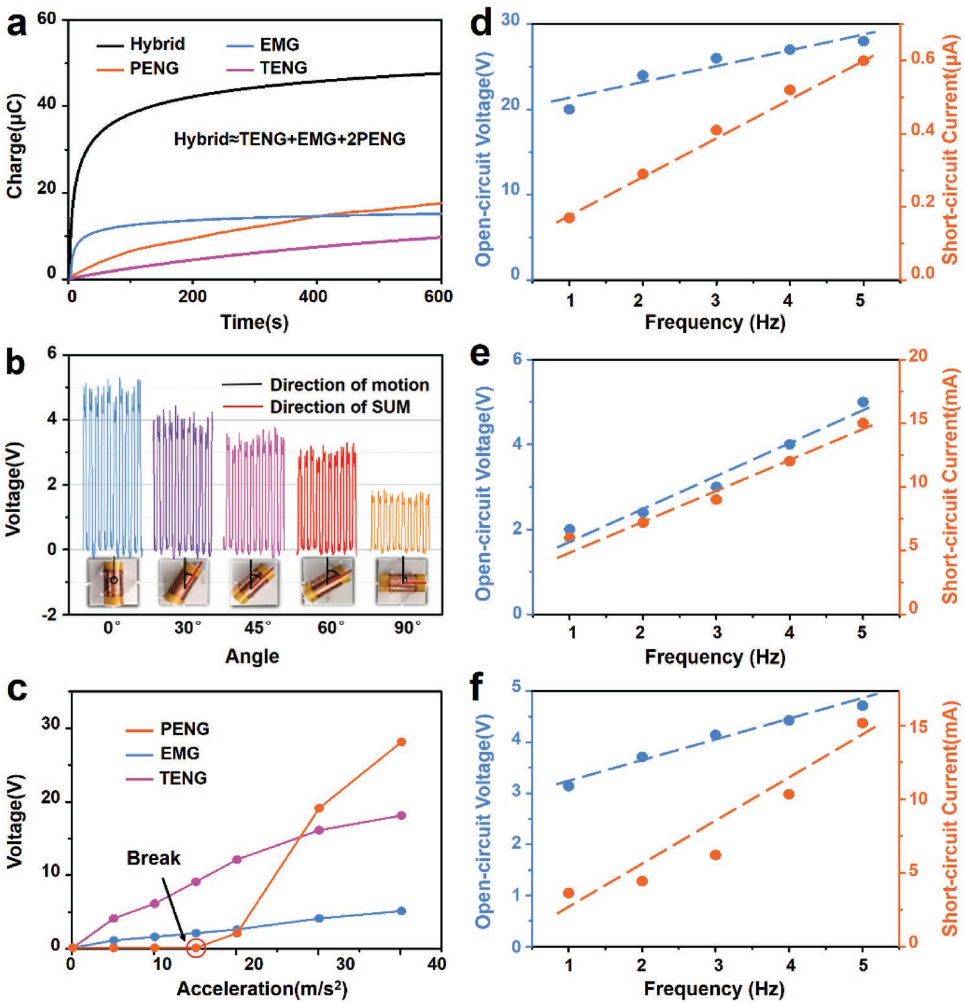

Figure 4. Electrical output under specific conditions, and the comparison of each part: a) Charge curve of each part and hybrid generator. b) Voltage output of the hybrid generators at different angles. c) Peak voltage output of each part at different acceleration. d–f) Peak open-circuit voltage output and peak short-circuit current output of TENG, EMG, hybrid generator at different frequency.

The complementarity between them greatly improves charging capacity of the hybrid generator.

In our daily life, mechanical motions are random and anisotropic. Therefore, the output performance of hybrid generator at different angles is also tested here. The angle between direction of SUM and direction of motion is taken as the object of study. Here, the situation when these two directions are coincident is set as the initial state (0°), and the peak voltage output of SUM at different angles are acquired (Figure 4b). When the angle is 0°, the output of SUM is the highest, which can generate a voltage of 5 V. As the angle increases, the output gradually decreases. Until the direction of SUM is just perpendicular to the direction of motion (90°), the output reaches its minimum, which can still reach 1.8 V. These results indicate that our device can harvest the mechanical energy of various directions, even though the efficiencies are different because of the inherent structure of SUM.

Based on the magnetic levitation effect, the main magnet is stabilized in the chamber by setting two reversed small magnets at each end of the tube, which allows the main magnet moving smoothly and responding to tiny mechanical more easily (Figure S4, Supporting Information). Since its special structure, accelerated velocity takes a critical effect on output of hybrid generator. When the accelerated velocity is lower than 15 m s^{-2}, only TENG and EMG are working. The output performance of PENG has a dramatic break when the acceleration increases to about 15 m s^{-2}, because the main magnet surmounts the magnetic binding beyond this acceleration, and directly hits the PENG, resulting in a sudden increased strain force. As with the increment of the accelerated velocity, the output of PENG is obvious incremental, which significantly improves the efficiency of SUM in the case of high acceleration change.

Human motion in nature has different frequencies, while most of them are below 5 Hz.[41] Here, the frequency condition is set to 1–5 Hz to investigate the output performance of three kinds of generator. As shown in Figure 4d,e, the current and voltage output of TENG and EMG both increase as frequency increases, while the growth rates are different from each other because of their different working principle. The voltage output of TENG increases very slow as the frequency increases just as the reported results that the voltage of TENG and working frequency are weakly correlated.[41] As comparison, both voltage and current output of EMG show a near liner positive correlation with the frequency. Take hybrid generator as research object, the overall trend of the voltage and current output are also investigated. It can be found that the increasing trend of voltage of hybrid generator is same like that of TENG, while the current shares the similar trend with that of EMG. Especially, when the frequency is nearly 2 Hz, the voltage output of hybrid generator is significantly improved by the contribution of TENG, which goes from 2 to 3 V. Because the lithium battery charging voltage threshold is exactly between 2 and 3 V, this increase is crucial for gathering mechanical energy successfully at low frequencies. This phenomenon reveals the different contributions of TENG and EMG to the whole device under different frequency condition.

In order to demonstrate that SUM can be used as an auxiliary for the battery, it is utilized to provide electricity for a GPS device. Four SUMs are combined by series connection, and the mechanical energy generated by running and walking is harvested to charge the commercial GPS device and start a signal transmitting process. In this way, we successfully monitor the real-time position of moving people and display it by satellite positioning system on electronic map. This will provide potential help in searching for the missing the old and children. **Figure 5**d explains the charging and discharging of a GPS's battery, and the charging process is completed by SUM. The battery in the GPS is firstly charged from 2.5 to 3.2 V in 10 min, and there will be a significant drop in voltage within 60 s after startup, demonstrating the instantaneous high energy consumption of GPS's cold start. After 60 s, the voltage maintains at a relatively stable state because the energy consumption of the device is relatively slow when it is continuously working (Video S1, Supporting Information).

In addition to being able to integrate in some self-powered appliance, we can also use SUM to power the appliance directly. Figure 5e–g delineate the actual working condition of different electrical appliances powered by SUM pack. In practical applications, the rated voltage required by various electrical appliances is different. Here we use SUM pack of different number of SUM (1, 4, and 9) to power a few representative electrical appliances, such as calculator (rated voltage of 1.5 V), mobile phone (rated voltage of 5 V), small fan (rated voltage of 12 V) respectively, which fully reveals the universality of SUM (Figure S5 and Video S2, Supporting Information). It should be pointed that the SUM pack can only work for a short period of time because of the low capacitance of the built-in miniature battery. By converting mechanical energy into electricity and store it, the SUM can power numerous wearable/portable devices, which could be used as a universal power source for various electric appliances (Figure 5h).

For the purpose of fabricating a battery-like universal electricity power source, our device is designed and manufactured in strict accordance with AA battery specifications in all aspects. In line with the battery pack, the assembly of SUM pack is also connected in series, which is depicted in Figure S6 (Supporting Information). Here, we use linear motor to provide mechanical loading for SUM pack. Setting the motion frequency as 5 Hz, the amplitude of motion as 30 mm, we measured the output voltage by an electrometer and recorded it by an oscilloscope. And the electrical test results are also favorable indication that SUM can work like an AA battery. Like a battery pack, the voltage of SUM pack will also go up with the increase of the number of SUM. **Figure 6** reveals that the voltage value of SUM pack is approximately equal to 2 times of the number of SUM units. Under a continuous mechanical stimulation, a single SUM can charge the built-in miniature battery to 2.7 V within 400 s. When the number of SUMs is 27, it takes about 3000 s to charge to 48 V. All these data demonstrate that the SUM could become a potential supplement for standard AA battery.

Currently, providing sustainable energy to the widely distributed, randomly moving wearable/portable electronic devices is still a challenge. Aiming to solve this problem, in this work, we successfully integrate three different kinds of generators (TENG, EMG, and PENG) and manufacture a SUM which can efficiently convert mechanical energy into electricity and store it for further applications. Compared to other reported

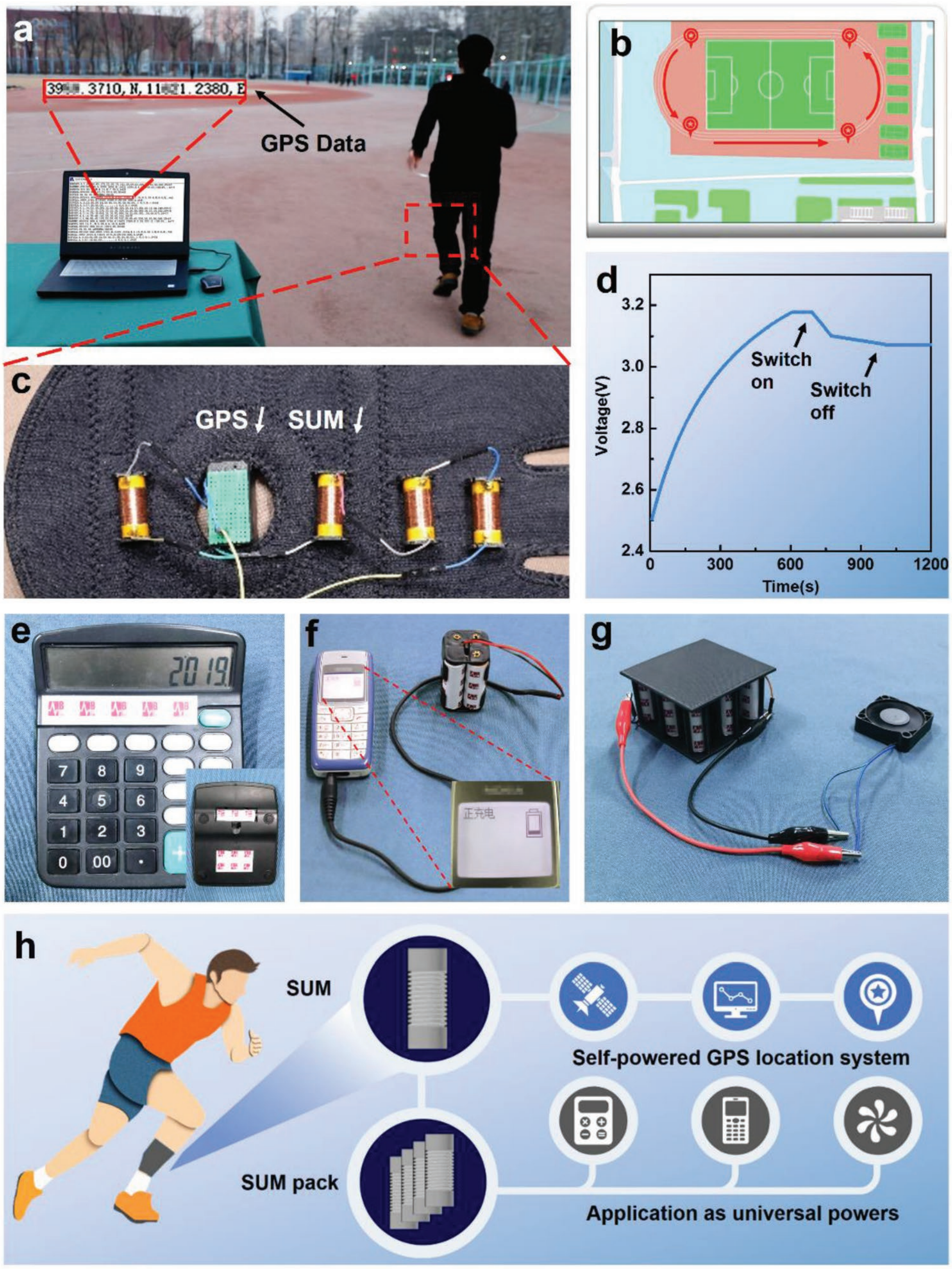

Figure 5. Application of the SUM, SUM could be used in self-powered GPS location system, also, its application range can be greatly broadened after assembly: a) Application of SUM as power source of GPS. b) Image of Navi system. c) Picture of a self-powered GPS location system. d) Charge curve of GPS's battery by SUM. e–g) Application as universal powers of calculator, mobile phone charger and small fans, respectively. h) Design concept of the SUM. SUM could be utilized in self-powered GPS location system, and SUM pack could be used as universal powers for various electronic.

hybrid nanogenerators, the "3-in-1" hybrid generator consisted in SUM demonstrates outstanding output performance and applicability. By collecting mechanical energy in frequency of 5 Hz, SUM can charge its built-in battery to 2.7 V in 400 s. The SUM is designed in the shape of a standard AA battery so that it can be used as a possible compensatory method for AA battery, especially in case of emergency. SUM can also harvest the mechanical energy of various directions, for the mechanical motions of our daily life are random and anisotropic. The output voltage can reach up to 5 V. Meanwhile, when the motion frequency is nearly 2 Hz, the voltage output of SUM is significantly improved by the contribution of TENG, which is crucial for its charging capability.

We portray how the SUM powers different electronics. The mechanical energy produced by 10 min of jogging can allow the battery in the GPS to charge from 2.5 to 3.2 V and drives GPS to work for more than half an hour, showing great potential of SUM as emergency power supply. Moreover, through a special structural design and an auxiliary circuit, SUM can be easily assembled and provides tunable charging voltage, which

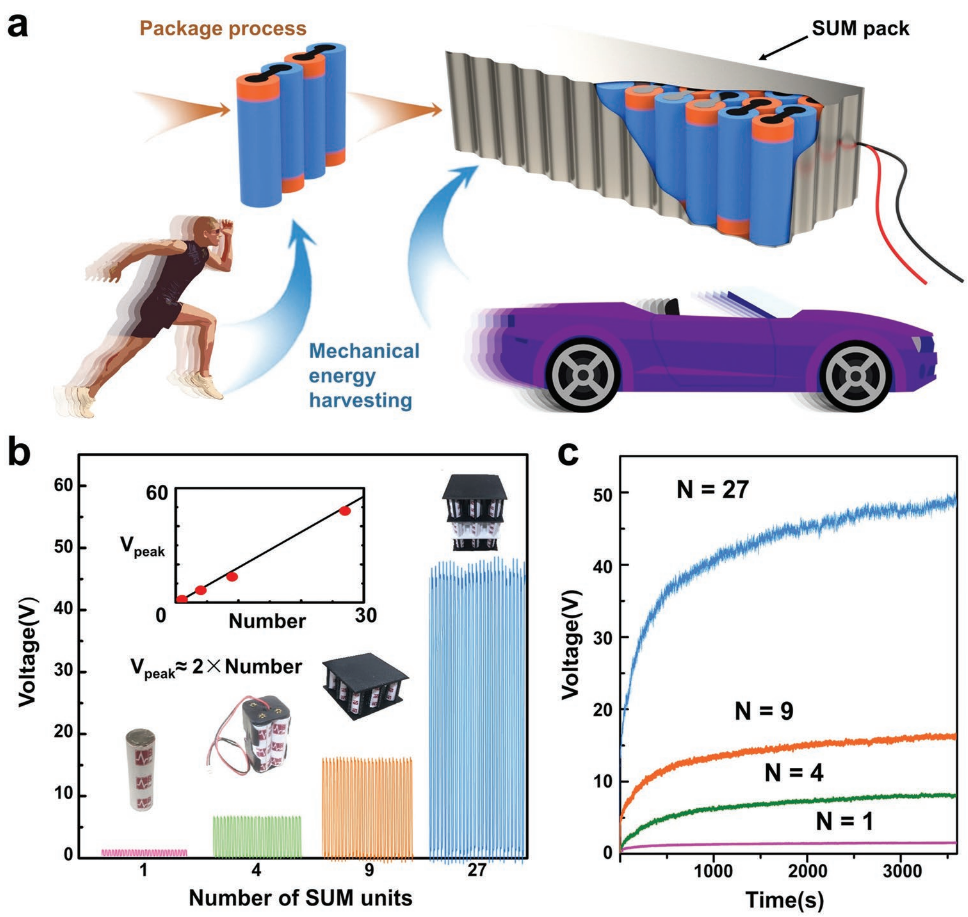

Figure 6. Application of SUM as a battery pack: a) Mechanical energy harvesting and package process of SUM pack, SUM has a very broad frequency scope of application. b) Output voltage and optical photos of the SUM packs with different number of units. c) Charge curve of each SUM pack with different number of units (*N* is the number of SUM units).

can greatly expand the scope of application. In this way, we successfully power commercial calculator, mobile phone, small fan by SUM packs, respectively.

There are many devices used as wearable/portable electronics' power supply. Most of them face the challenges of miniaturization and integration. Here, SUM is designed following the same shape and size standards of AA battery. So that it can be conveniently placed in electrical appliances, rather than as an external power supply. However, to a certain degree, the same shape and size standards of AA battery limit the application of SUM. With the development of wearable/portable electronics, AA Battery is gradually replaced by smaller built-in batteries. Studies about innovative materials, simpler preparation methods and more efficient structures are needed for the purpose of miniaturization, lighter weight, and industrial production in the future. So that it can meet ever-changing requirements of powering wearable/portable devices.

Experimental Section

Fabrication: First of all, a tube, which is fabricated by a 3D printer (Raize 3D), is used as a frame structure for supporting several different parts. For fabrication of PMU component, three rectifier bridges and one miniature lithium battery are soldered on four printed circuit boards (PCB) which are designed and made in advance, four PCBs are stacked vertically and connected by two pins.

EHU component could divide into three parts, TENG, EMG, and PENG. In the part of EMG, the necessary two units are stationary coil and floating magnet. The stationary coil is twined on the surface of the tube, which has reserved enough space for the coil, the floating magnet is placed into the tube, and two reversed small magnets are stuck to each end of tube. So that the big magnet can float in the device and gather weeny mechanical energy. In the part of the TENG, the essential units are two different materials which exist at two opposite terminals of triboelectric series. Here, PTFE and Au are chosen for fabricating TENG. The surface of the PTFE film was treated by the ICP, and two Au thin film are fabricated by DC reactive magnetron sputtering. The PTFE film is stuck on the surface of the magnet, two Au thin films are stuck on the inwall of the tube as two electrodes. Two PZTs are stuck on the top of the reverse magnets as PENG.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements

The authors thank the support of National Key R&D Project from Minister of Science and Technology, China (2016YFA0202703), National

Natural Science Foundation of China (No. 61875015, 31571006, 81601629, and 21801019), the Beijing Natural Science Foundation (2182091), China Postdoctoral Science Foundation (2018M641148), Beijing Council of Science and Technology (Z181100004418004) and the National Youth Talent Support Program.

Conflict of Interest

The authors declare no conflict of interest.

Keywords

battery-like, hybrid generators, motional energy, nanogenerators, self-charge

Received: June 12, 2019
Revised: July 8, 2019
Published online:

[1] H. Ouyang, J. J. Tian, G. L. Sun, Y. Zou, Z. Liu, H. Li, L. M. Zhao, B. J. Shi, Y. B. Fan, Y. F. Fan, Z. L. Wang, Z. Li, *Adv. Mater.* **2017**, *29*, 1703456.
[2] H. Wang, G. Pastorin, C. Lee, *Adv. Sci.* **2016**, *3*, 1500441.
[3] H. Y. Guo, M. H. Yeh, Y. C. Lai, Y. L. Zi, C. S. Wu, Z. Wen, C. G. Hu, Z. L. Wang, *ACS Nano* **2016**, *10*, 10580.
[4] W. Seung, M. K. Gupta, K. Y. Lee, K. S. Shin, J. H. Lee, T. Y. Kim, S. Kim, J. Lin, J. H. Kim, S. W. Kim, *ACS Nano* **2015**, *9*, 3501.
[5] X. Q. Zhao, J. Cai, Y. Guo, C. B. Li, J. L. Wang, H. W. Zheng, *Smart Mater. Struct.* **2018**, *27*, 085008.
[6] Q. Zhang, Q. J. Liang, Q. L. Liao, F. Yi, X. Zheng, M. Y. Ma, F. F. Gao, Y. Zhang, *Adv. Mater.* **2017**, *29*, 1606703.
[7] B. J. Shi, Q. Zheng, W. Jiang, L. Yan, X. X. Wang, H. Liu, Y. Yao, Z. Li, Z. L. Wang, *Adv. Mater.* **2016**, *28*, 846.
[8] Q. Zhang, Z. Zhang, Q. J. Liang, F. F. Gao, F. Yi, M. Y. Ma, Q. L. Liao, Z. Kang, Y. Zhang, *Nano Energy* **2019**, *55*, 151.
[9] Z. L. Wang, *Energy Harvesting for Self-Powered Nanosystems,* **2008**.
[10] Z. L. Wang, *Nature* **2017**, *542*, 159.
[11] U. Khan, S. W. Kim, *ACS Nano* **2016**, *10*, 6429.
[12] S. H. Wang, X. J. Mu, Y. Yang, C. L. Sun, A. Y. Gu, Z. L. Wang, *Adv. Mater.* **2015**, *27*, 240.
[13] R. Cao, T. Zhou, B. Wang, Y. Y. Yin, Z. Q. Yuan, C. J. Li, Z. L. Wang, *ACS Nano* **2017**, *11*, 8370.
[14] S. Lee, S. H. Bae, L. Lin, Y. Yang, C. Park, S. W. Kim, S. N. Cha, H. Kim, Y. J. Park, Z. L. Wang, *Adv. Funct. Mater.* **2013**, *23*, 2445.
[15] B. J. Shi, Z. Li, Y. B. Fan, *Adv. Mater.* **2018**, *30*, 1801895.
[16] Z. Li, G. A. Zhu, R. S. Yang, A. C. Wang, Z. L. Wang, *Adv. Mater.* **2010**, *22*, 2534.
[17] Q. Zheng, B. J. Shi, F. R. Fan, X. X. Wang, L. Yan, W. W. Yuan, S. H. Wang, H. Liu, Z. Li, Z. L. Wang, *Adv. Mater.* **2014**, *26*, 5851.
[18] X. Pu, M. M. Liu, L. X. Li, C. Zhang, Y. K. Pang, C. Y. Jiang, L. H. Shao, W. G. Hu, Z. L. Wang, *Adv. Sci.* **2016**, *3*, 1500255.
[19] H. Ouyang, Z. Liu, N. Li, B. J. Shi, Y. Zou, F. Xie, Y. Ma, Z. Li, H. Li, Q. Zheng, X. C. Qu, Y. B. Fan, Z. L. Wang, H. Zhang, Z. Li, *Nat. Commun.* **2019**, *10*, 1821.
[20] C. K. Jeong, J. H. Han, H. Palneedi, H. Park, G. T. Hwang, B. Joung, S. G. Kim, H. J. Shin, I. S. Kang, J. Ryu, K. J. Lee, *APL Mater.* **2017**, *5*, 074102.
[21] Q. Zheng, B. J. Shi, Z. Li, Z. L. Wang, *Adv. Sci.* **2017**, *4*, 1700029.
[22] M. B. Khan, D. H. Kim, J. H. Han, H. Saif, H. Lee, Y. Lee, M. Kim, E. Jang, S. K. Hong, D. J. Joe, T. I. Lee, T. S. Kim, K. J. Lee, Y. Lee, *Nano Energy* **2019**, *58*, 211.
[23] C. R. Saha, T. O'Donnell, N. Wang, R. McCloskey, *Sens. Actuators, A* **2008**, *147*, 248.
[24] Z. L. Wang, J. H. Song, *Science* **2006**, *312*, 242.
[25] X. D. Wang, *Nano Energy* **2012**, *1*, 13.
[26] Y. L. Zi, L. Lin, J. Wang, S. H. Wang, J. Chen, X. Fan, P. K. Yang, F. Yi, Z. L. Wang, *Adv. Mater.* **2015**, *27*, 2340.
[27] F. R. Fan, Z. Q. Tian, Z. L. Wang, *Nano Energy* **2012**, *1*, 328.
[28] H. S. Wang, C. K. Jeong, M. H. Seo, D. J. Joe, J. H. Han, J. B. Yoon, K. J. Lee, *Nano Energy* **2017**, *35*, 415.
[29] C. Zhang, W. Tang, C. B. Han, F. R. Fan, Z. L. Wang, *Adv. Mater.* **2014**, *26*, 3580.
[30] J. He, T. Wen, S. Qian, Z. X. Zhang, Z. M. Tian, J. Zhu, J. L. Mu, X. J. Hou, W. P. Geng, J. D. Cho, J. Q. Han, X. J. Chou, C. Y. Xue, *Nano Energy* **2018**, *43*, 326.
[31] S. Y. Chung, S. Kim, J. H. Lee, K. Kim, S. W. Kim, C. Y. Kang, S. J. Yoon, Y. S. Kim, *Adv. Mater.* **2012**, *24*, 6022.
[32] G. T. Hwang, H. Park, J. H. Lee, S. Oh, K. I. Park, M. Byun, H. Park, G. Ahn, C. K. Jeong, K. No, H. Kwon, S. G. Lee, B. Joung, K. J. Lee, *Adv. Mater.* **2014**, *26*, 4880.
[33] T. Quan, Y. C. Wu, Y. Yang, *Nano Res.* **2015**, *8*, 3272.
[34] M. L. Seol, J. W. Han, S. J. Park, S. B. Ron, Y. K. Choi, *Nano Energy* **2016**, *23*, 50.
[35] Z. Saadatnia, E. Esmailzadeh, H. E. Naguib, *Nano Energy* **2018**, *50*, 281.
[36] J. Gong, H. J. Lin, J. W. C. Dunlop, J. Y. Yuan, *Adv. Mater.* **2017**, *29*, 1605103.
[37] C. Wu, J. H. Park, B. Koo, X. Y. Chen, Z. L. Wang, T. W. Kim, *ACS Nano* **2018**, *12*, 9947.
[38] S. H. Wang, Y. N. Xie, S. M. Niu, L. Lin, Z. L. Wang, *Adv. Mater.* **2014**, *26*, 2818.
[39] Z. L. Wang, *Mater. Today* **2017**, *20*, 74.
[40] H. Y. Zou, Y. Zhang, L. T. Guo, P. H. Wang, X. He, G. Z. Dai, H. W. Zheng, C. Y. Chen, A. C. Wang, C. Xu, Z. L. Wang, *Nat. Commun.* **2019**, *10*, 1427.
[41] Y. L. Zi, H. Y. Guo, Z. Wen, M. H. Yeh, C. G. Hu, Z. L. Wang, *ACS Nano* **2016**, *10*, 4797.

