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ARTICLE

Self-Powered Safety Helmet Based on Hybridized Nanogenerator for Emergency

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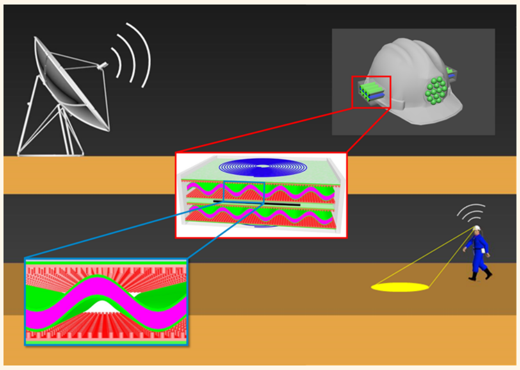
S *Supporting Information*



ABSTRACT: **The rapid development of Internet of Things and the related sensor technology requires sustainable power sources for their continuous operation. Scavenging and utilizing the ambient environmental energy could be a superior solution. Here, we report a self-powered helmet for emergency, which was powered by the energy converted from ambient mechanical vibration via a hybridized nanogenerator that consists of a triboelectric nanogenerator (TENG) and an electromagnetic generator (EMG). Integrating with transformers and rectifiers, the hybridized nanogenerator can deliver a power density up to 167.22 W/m^3, which was demonstrated to light up 1000 commercial light-emitting diodes (LEDs) instantaneously. By wearing the developed safety helmet, equipped with rationally designed hybridized nanogenerator, the harvested vibration energy from natural human motion is also capable of powering a wireless pedometer for real-time transmitting data reporting to a personal cell phone. Without adding much extra weight to a commercial one, the developed wearing helmet can be a superior sustainable power source for explorers, engineers, mine-workers under well, as well as and disaster-relief workers, especially in remote areas. This work not only presents a significant step toward energy harvesting from human biomechanical movement, but also greatly expands the applicability of TENGs as power sources for self-sustained electronics.**

KEYWORDS: *hybridized nanogenerator, vibration, wireless transmission, self-powered*

The rapid development of Internet of Things and the related sensor technology plays a critical role of advancing the modern industry and information technology. Powering the sensor nodes with different functionalities in the network entirely by batteries has become more and more unpractical and unfavorable,[1−5] mainly for the limited battery lifetime, large scope of distribution of these nodes, and potential health and environmental hazards.[6−11] In this regard, developing technologies of self-powered sensors[12−15] that can utilize the ambient environmental energy to drive themselves is highly desirable and mandatory.[16−21]

Vibration energy, as one of the most common renewable energy sources, widely exists in our living environment.[22−26] In recent years, it has become an attractive target for energy harvesting as a potentially alternative power source for battery-operated electronics.[27−33] By utilizing the conjunction of contact electrification and electrostatic induction, triboelectric nanogenerators (TENGs) have been proved as a simple, reliable, cost-effective, and efficient means to harvest ambient mechanical energy,[34−36] especially it is superior of its kind for ambient vibration energy harvesting.[37−40] However, compared to the traditional electromagnetic generator (EMG) for mechanical energy conversion, the TENG suffers from a low current output with a relatively high voltage output. While the EMG encountered a complementary problem with a low voltage output compared to its relatively high current output.[41,42] As a consequence, a hybridization of the two could be a superior solution to make a compensation and use to their advantages. Moreover, the structure design has a high power density rather than just adding or stacking parallel components.

Here, in this work, we reported a hybridized nanogenerator by a rational integration of the TENG and EMG in a double-deck sandwiched structure for high-performance ambient

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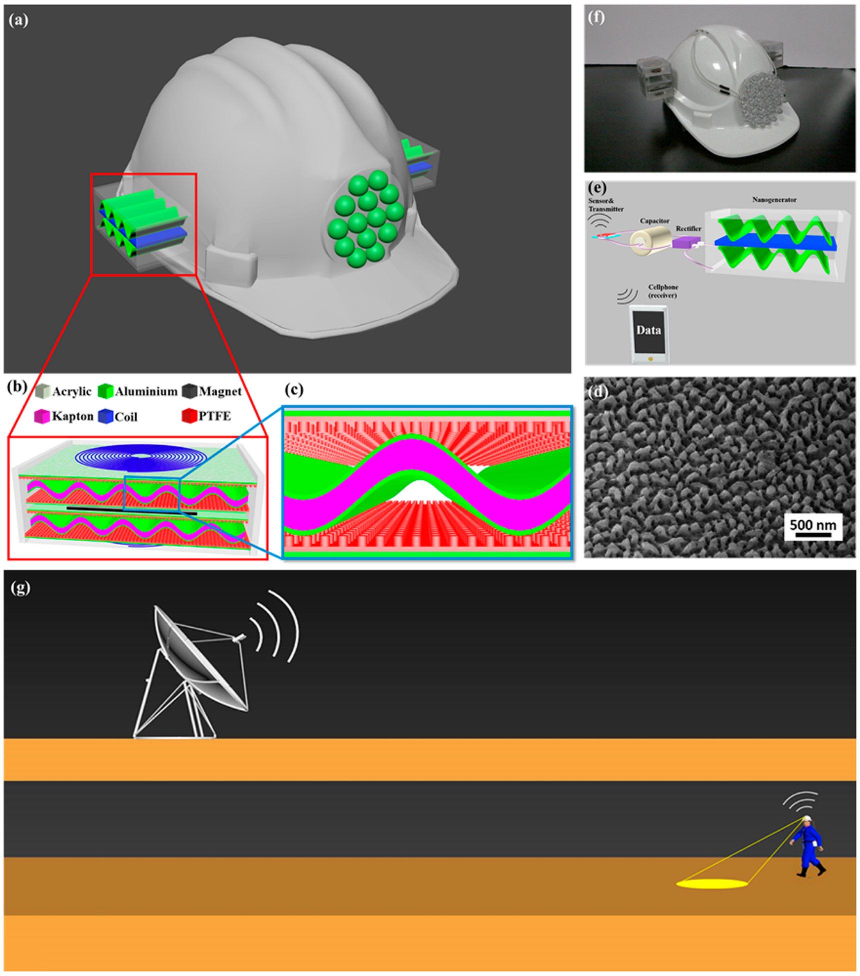

Figure 1. Structural design of the self-powered helmet. (a) Schematic illustration of the helmet with equipped hybridized nanogenerator. A general illustration (b) and a partially enlarged view (c) showing the device structure of the hybridized nanogenerator. (d) SEM image showing the polymer nanowire structure on the PTFE surface. (e) Illustration showing the hybridized nanogenerators in the safety helmet to power the transmitter and lights. (f) Photograph of as-fabricated self-powered positioning safety helmet with lights for illumination. (g) Schematic illustration of the developed helmet as an integrated self-powered positioning system by using the energy converted from the human walking.

vibration energy harvesting. By creatively employing an Al-Kapton-Al wavy structure,[43,44] the device is self-restorable to external mechanical excitation, which can convert the mechanical vibration into the contact-separation of the triboelectric layers, as well as the varying magnetic flux in the coil. In this processing, both the TENG and EMG are capable of generating power from the external mechanical excitation. The double-deck structure allows four TENGs and two EMGs to work simultaneously. By way of an electric connection by transformers and rectifier, the hybridized nanogenerator of TENG and EMG can deliver a power density of 167.22 W/m^3 ($P_d = P/V$; see detailed calculation in the Supporting Information). Based on the hybridized nanogenerator, a self-powered helmet with similar weight as commercial ones was developed to convert vibration energy into electricity when a human wore the helmet to do daily movement naturally. And a wireless pedometer was demonstrated to be powered for real-time running data reporting to the cell phone. This work paved a way to boost the output power harvesting from human biomechanical motions to a practical level via a rationally designed helmet, which could provide both protection and an ideally sustainable power source for people working in the remote area, for instance, explorers, engineers, mine-workers under well, and disaster-relief workers.

RESULTS AND DISCUSSION

The self-powered helmet is a rational integration of the hybridized nanogenerator with a commercial helmet without adding much extra weight due to the employing of the polymer materials as the framework, as schematically illustrated in Figure 1a. While the rationally designed hybridized nanogenerator holds a multilayered structure, as an enlarged view shown in Figure 1b. And the wavy-like Al-Kapton-Al films are sandwiched by Al back-coated polytetrafluoroethylene (PTFE) thin films (a material's tendency to gain or lose electrons at contact can be seen in Table S1). These two parts completed the TENG, as an enlarged view shown in Figure 1c. Meanwhile, two coils are respectively inlaid into the top substrate and bottom substrate, with a magnet anchored into the middle movable acrylic plate as the EMGs. And the output performance of EMG varies with variable vertical distances between the middle magnet and the upper coil, as shown in Figure S1. Finally, acrylic was employed as the framework and platform to structurally hybridize the TENGs and EMGs. A full

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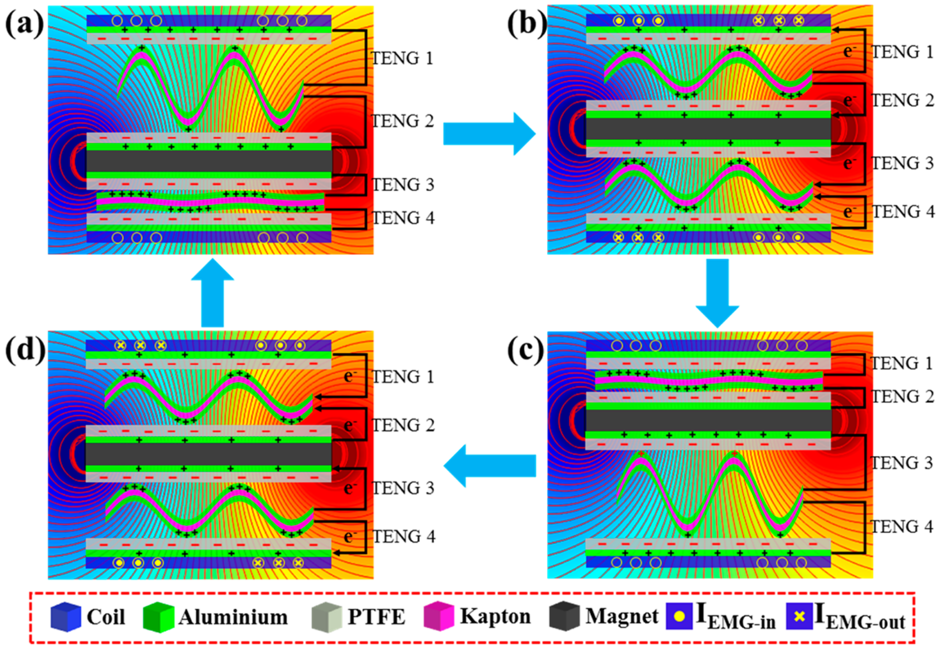

Figure 2. Electricity generation process of the hybridized nanogenerator. Both two-dimensional schematic illustration and COMSOL simulation were employed for elucidation. (a) The external vibration lowers the position of middle substrate, resulting in a compression to the bottom wavy electrode and relaxation of the upper electrode. (b) The moving upward of the middle substrate causes the releasing of bottom wavy electrode and a compression to the upper electrode. (c) When the middle substrate is above the middle balance position, the upper wavy electrode will be compressed while the bottom one will be released. (d) When the elastic resistance pushed the middle substrate downward, the upper wavy electrodes would be gradually released until reached the middle balance position.

schematic illustration of the fabrication diagram was presented in Figure S2. To enhance the output performance of TENG, PTFE nanowires arrays are created by an inductively coupled plasma (ICP) process to increase the surface roughness, and also the effective contact area between triboelectric layers. A scanning electron microscopy (SEM) image of PTFE film polymer nanowires is presented in Figure 1d. To give a clear picture of the operation principle, an illustration was presented in Figure 1e to show the hybridized nanogenerators equipped in the safety helmet as the power source to drive the transmitter and lights. Basically, the generated alternating current (AC) by nanogenerators is transformed to direct current (DC) through rectifier, and then stored in the capacitor for lighting and transmitting. And a photograph of the as-fabricated self-powered positioning safety helmet with lights for illumination was demonstrated in Figure 1f. In a system level, Figure 1g is a schematic illustration of the developed helmet as an integrated self-powered positioning system by using the energy converted from the human walking. Here, transmitted signals underground are capable of being received by the people above ground, which could be especially useful for mine-workers under well for positioning and communication. A detailed fabrication processing of the hybridized nanogenerator and self-powered helmet is presented in Experimental Section.

To elucidate the working principle of the self-powered helmet, a key step was taken to describe the electricity generation process of the hybridized nanogenerator (Movie S1). Here, both two-dimensional schematic illustration and COMSOL simulation were employed for elucidation. On one hand, for the TENG, at the initial state, the external vibration lowers the position of middle substrate, which results in a compression to the bottom lower wavy electrode and thus a relaxation to the upper electrode. In this process, an intimate contact between the PTFE and aluminum will result in a charge transfer due to an electron affinity difference between the two. And the PTFE will be positively charged while the aluminum negatively charged. Then, the moving upward of the middle substrate causes the releasing of the bottom wavy electrode and a compression to the upper electrode. And a reduced effective contact area between the aluminum and PTFE will result in a flow of electrons from PTFE back-coated aluminum to wavy Al electrode. At the same time, the upper wavy Al electrodes are changed from released state to compressed state, brought into full contact with PTFE. Therefore, electric potential difference is produced, injecting electrons from Al into PTFE back-coated aluminum, as shown in Figure 2b. When the lower wavy Al electrode fully reverts back to its original position, charges are redistributed owing to the electrostatic induction, resulting in an accumulation of negative charges on the wavy Al and positive charges on the PTFE. Conversely, the upper wavy Al electrode has a minimum deformation and an intimate contact with PTFE, leaving a maximum amount of induced charges on the wavy Al electrode in Figure 2c. Subsequently, the impact from vibration drives middle substrate to move downward. As a result, the lower wavy Al electrode repeats the upper one's movement in Figure 2d, driving electrons from wavy Al electrode to PTFE back-coated aluminum, similarly, the upper wavy Al electrode repeats the lower one's movement in Figure 2b, driving electrons from PTFE to wavy Al electrode as shown in Figure 2d. Finally, the middle substrate moves to the bottom-most position again, recurring the initial state and completing a whole cycle of electricity generation in the TENGs.

On the other hand, EMG will also generate electricity in the above-mentioned process due to the varying magnetic flux in the coil. Since a magnet was anchored on the middle plate, the distances between the magnet and the bottom and upper coil were changing with the vibration of the middle plate under the

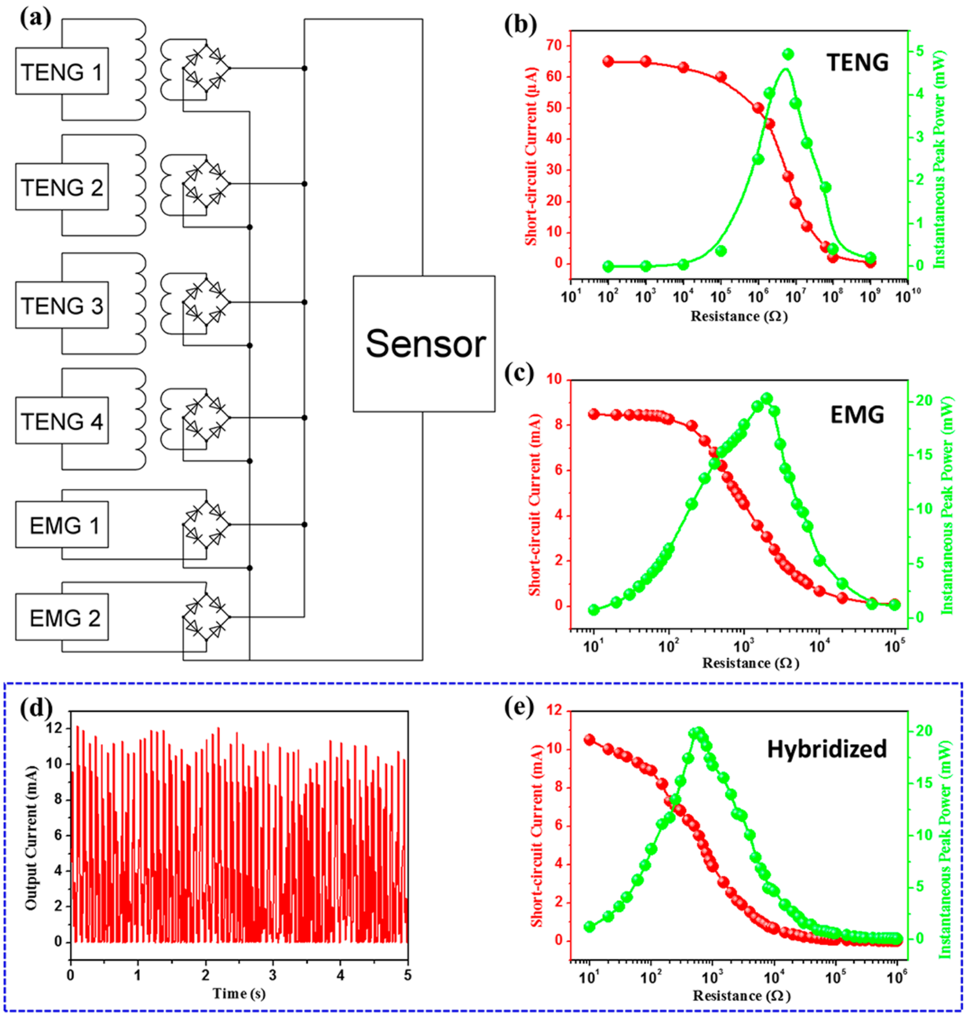

Figure 3. Electrical output characterization of the hybridized nanogenerator. (a) Circuit diagram of the energy harvesting system including four TENGs with transformers, two EMGs, and rectifiers. (b) Dependence of output current and output power of TENG 1 on the external loading resistance. (c) Dependence of output current and output power of EMG 1 on the external loading resistance. (d) Short-circuit current (I_{SC}) of hybridized nanogenerator at harmonic-resonator vibration frequency of 22 Hz. (e) Dependence of output current and output power of hybridized nanogenerator on the external loading resistance, indicating maximum power output 19.8 mW when R = 600 Ω.

external excitation, in which process a varying magnet flux was generated in the two coils. The distribution of the magnetic field was also calculated through COMSOL, as shown in Figure S3. And the varying magnet flux will also induce a alternating current in the bottom and upper coil due to the electromagnetic induction. As a consequence, the hybridized nanogenerator is capable of converting the external mechanical vibration into electricity via both the EMG and TENG, as a sustainable power source.

To begin with, for a quantitative characterization of the output performance of the hybridized nanogenerator, a standard vibration shaker system was employed as a vibration source with adjustable frequencies and amplitudes. To measure, one end of the hybridized nanogenerator was anchored onto the shaker with the other end being free-standing. And the electric output of both TENG and EMG under various external vibration frequencies is, respectively, demonstrated in Figures S4 and S5, which all indicate a natural vibration frequency of 22 Hz for the hybridized nanogenerator.

And under the device resonance frequency (22 Hz), the open-circuit voltage and short-circuit current of the TENG can reach up to 147 V and 70 μA, respectively. And a peak voltage of 7 V and current of 8.5 mA were also obtained for the EMG. The TENG delivers a large voltage output compared to its relatively low current output due to its large internal impedance, while the EMG follows a reverse trend with a low internal impedance. For an effective combination of the electric output from the two generators, transformers and rectifiers[41,45] were employed to electrically connect the two types of generators, as the circuit diagram shown in Figure 3a. Resistors were utilized as external loads to further investigate the output power the hybridized nanogenerator and its individuals. As depicted in Figure 3b, the output current decreases with the election of the external loading resistances. Consequently, the instantaneous peak power density of 41.36 W/m^3 of the TENG is maximized at a load resistance of 10 MΩ. For the EMG, as shown in Figure 3c, the output current decreases markedly as the external loading resistance increasing from 100 to 10 000 Ω. And a maximum output power of 20.28 mW was obtained at 2000 Ω, corresponding to a power density of 169.81 W/m^3. A systematical integration of four TENGs with transformers and two EMGs, the hybridized nanogenerator can produce a direct current (DC) up to 11 mA after rectifiers, as shown in Figure 3d, as well as an output

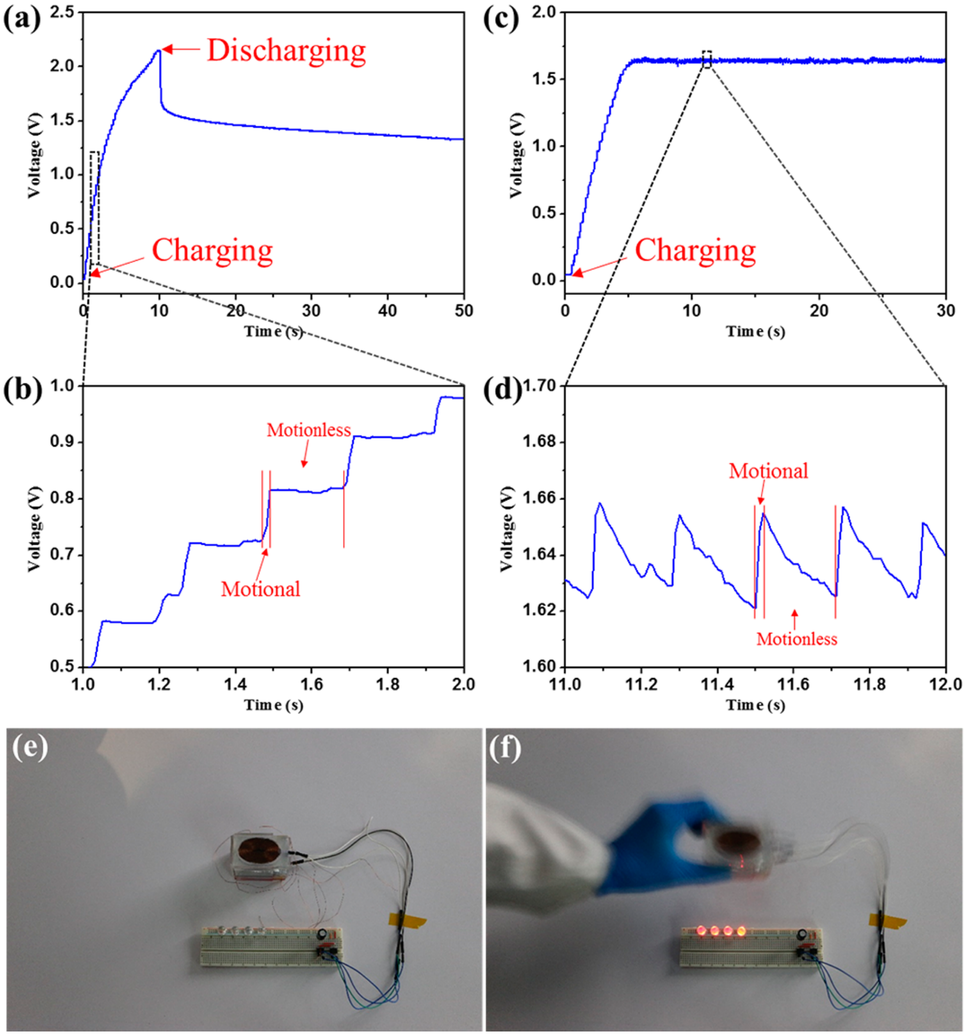

Figure 4. Demonstration of the hybridized nanogenerator to charge a supercapacitor as a sustainable power source. (a) Voltage curve showing the cycle of a supercapacitor charged by the nanogenerator. (b) Enlarged view of the charging curve at the initial stage. (c) Voltage curve showing the cycle of a supercapacitor connecting to four LEDs, charged by hybridized nanogenerator. (d) Enlarged view of the charging curve of when the LEDs lighted up sustainably. Photograph of the LEDs before (e) and being charged (f) by the hybridized nanogenerator.

power of 19.8 mW, shown in Figure 3e, corresponding to a power density of 167.22 W/m^3.

To demonstrate the hybridized nanogenerator as a sustainable power source, a first step was taken to charge a supercapacitor. As shown in Figure 4a, via a hand-shaking of the helmet at 5 Hz, almost the frequency of human motion,[46] the voltage of the supercapacitor increased from 0.04 to 2.15 V in about 10 s. Figure 4b presents an enlarged view of the charging curve at the initial stage of charging. Figure 4c depicts the voltage curve of supercapacitor when it is connected to four LEDs. The hand-shaking of the helmet will charge the supercapacitor from 0.04 to 1.66 V, and the constant 1.64 V voltage will sustainably power the LEDs without stroboflash. Figure 4d is an enlarged view of the charging curve when the LEDs lighted up sustainably. The serration-like fluctuation of the voltage curve is a combining effect of the mechanical energy conversion and the LEDs power consumption. Figure 4e is the photograph of the LEDs before being charged by the nanogenerator. And Figure 4f is a photograph of the LEDs lighted up sustainably by the hybridized nanogenerator (Movie S2).

To prove the hybridized nanogenerator based helmet as a sustainable mobile power source, three other demonstrations was presented. By way of a vibrostand of 22 Hz, a total of 1000 LEDs were simultaneously lighted up directly by TENGs (Figure 5a and Movie 3). Figure 5b is a photograph showing a pedometer continuously powered by EMGs via shaking by hand at about 8 Hz (Movies S4 and S5). Here, a capacitor of 1000 μF was employed as the energy storage unit between the sensor/transmitter and rectifier. The pedometer was demonstrated to sustainably work well during walking and running. After running for 21 s, 0.01 miles and 1 calorie consumption were recorded by the pedometer, and then wirelessly transmitted to the personal cell phone (Figure S6). As shown in Figure S7a and b, the generated power by the wearable helmet can easily light up LEDs for illumination when jumping (Movie 6). In the meanwhile, via hand-shaking, the generated power can transmit personal signals wirelessly to a cell phone (Figure 5c and Movie S7). Figure 5d is an enlarged view of the personal location data received by a cell phone. As a consequence, the developed self-powered helmet can act as a sustainable power source for both lighting and positioning,

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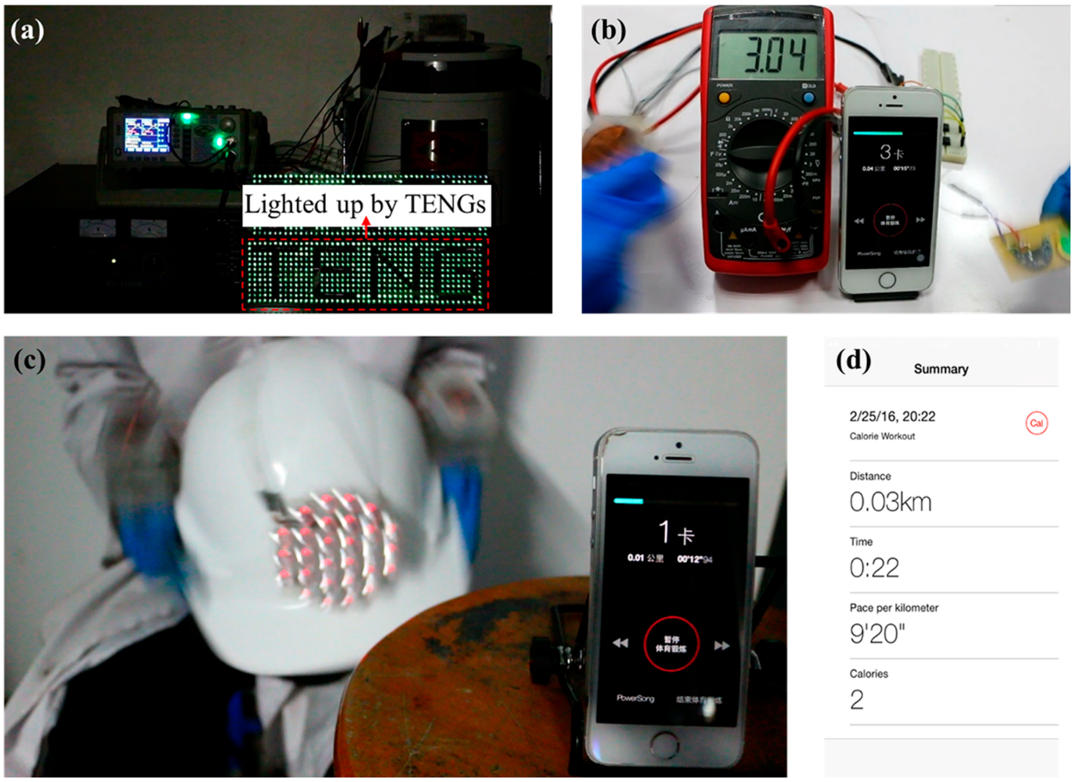

Summary
2/25/16, 20:22
Calorie Workout
Distance
0.03km
Time
0:22
Pace per kilometer
9'20"
Calories
2

Figure 5. Demonstrate of the nanogenerator based helmet as a sustainable mobile power source. (a) Photograph showing 1000 LEDs connected in series lighting up simultaneously when the TENGs were anchored onto a vibration frequency of 22 Hz via a vibrostand. (b) Photograph showing a pedometer continuously powered by the EMGs via shaking by hand. (c) Photograph showing helmet powering a wireless pedometer and LEDs simultaneously by hand-shaking. (d) Acquired data by the personal cell phone from the wireless pedometer.

which provides great convenience especially to the mine-workers under well.

CONCLUSION

In summary, we have demonstrated self-powered helmet for emergency, which was powered by the electric power by the energy converted from the ambient mechanical vibration via a hybridized nanogenerator. As a sustainable and mobile power source, the self-powered helmet is capable of powering electronics when people are walking, jumping, running, or shaking hands. With similar weight to a commercial one, the developed helmet was demonstrated to be a superior mobile sustainable power source for both human illumination and personal communication, which will provide great conveniences to explorers, engineers, mine-workers under well, as well as disaster-relief workers, especially in remote areas. This work presents a significant step toward energy harvesting from human biomechanical movement and will be widely adopted by the communities in their way of living.

EXPERIMENTAL SECTION

Fabrication of the Hybridized Nanogenerator. The framework of the device was constructed by acrylic sheets. First, two acrylic sheets of 11 mm were fabricated by using a laser cutter as the substrates of the device. Then the Kapton film of 100 μm was periodically bent into a wavy shape. Then Al foil of 70 μm was sputtered on both sides of the wavy Kapton film as electrodes. Second, two slides of PTFE films of 30 μm were prepared by applying ICP etching on one side of the films to create the polymer nanowires. Then, Al was subsequently sputtered on the other side of the PTFE film, acting as electrodes. Cu coil of 7 mm with turns of about 5000 was fixed onto the bottom and upper layers of the framework. As a result, the nanogenerator device has a small dimension of 7.7 cm × 4.7 cm × 3.3 cm (Figure S8).

Electrical Measurement. The output voltage signals of the nanogenerator were measured by using a low-noise voltage preamplifier (Keithley 6514 system electrometer). The output current signals of the nanogenerator were measured by uisng a low-noise current preamplifier (Stanford Research SR570).

ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsnano.6b03760.

Calculation of power of generator with external resistance; ranking of materials according to gain/loss of electrons; open- and short-circuit current curves; schematic diagram of hybridized nanogenerator; 2D axisymmetric COSMOL model; output performances of TENG and EMG; data from pedometer; photographs of LED on the helmet before/after charging and of the as-fabricated device (PDF)
Electricity generation process of the hybridized nanogenerator (AVI)
LEDs lighted up by the hybridized nanogenerator (AVI)
Total of 1000 LEDs lighted up directly by TENGs (AVI)
Pedometer continuously powered by EMGs (AVI)
Pedometer information during running transmits signals to a mobile device (AVI)
LEDs lighted up via power generated by a wearable helmet (AVI)
Power generated via hand shaking of the helmet transmits signals to a mobile device (AVI)

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Author Contributions

⊥L.J. and J.C. contributed equally to this work.

Notes

The authors declare no competing financial interest.

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