Hybridized Electromagnetic–Triboelectric Nanogenerator for Scavenging Biomechanical Energy for Sustainably Powering Wearable Electronics

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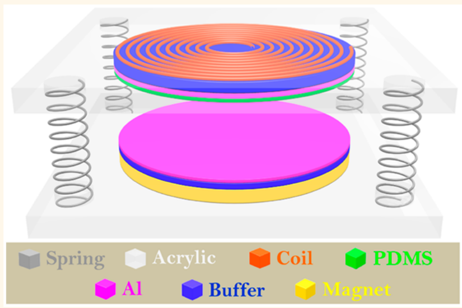
ABSTRACT We report a hybridized electromagnetic–triboelectric nanogenerator for highly efficient scavenging of biomechanical energy to sustainably power wearable electronics by human walking. Based on the effective conjunction of triboelectrification and electromagnetic induction, the hybridized nanogenerator, with dimensions of 5 cm × 5 cm × 2.5 cm and a light weight of 60 g, integrates a triboelectric nanogenerator (TENG) that can deliver a peak output power of 4.9 mW under a loading resistance of 6 MΩ and an electromagnetic generator (EMG) that can deliver a peak output power of 3.5 mW under a loading resistance of 2 kΩ. The hybridized nanogenerator exhibits a good stability for the output performance and a much better charging performance than that of an individual energy-harvesting unit (TENG or EMG). Furthermore, the hybridized nanogenerator integrated in a commercial shoe has been utilized to harvest biomechanical energy induced by human walking to directly light up tens of light-emitting diodes in the shoe and sustainably power a smart pedometer for reading the data of a walking step, distance, and energy consumption. A wireless pedometer driven by the hybrid nanogenerator can work well to send the walking data to an iPhone under the distance of 25 m. This work pushes forward a significant step toward energy harvesting from human walking and its potential applications in sustainably powering wearable electronics.



KEYWORDS: hybridized nanogenerator · biomechanical energy · walking · wearable device · self-powered shoes

Wearable electronics has attracted increasing attention in the past decade due to expanding our capabilities and enabling us to communicate and interact better with our environment and objects.[1] Usually, the wearable electronic devices use Li-ion batteries as the external power sources. Due to the limited lifetime and the environmental pollution problem of Li-ion batteries, it is desirable to replace them by using the energy-harvesting units as a long-lasting power source to maintain sustainable operation of wearable electronics. Since wearable electronic devices are usually attached on the human body, an ideal solution is to convert the waste biomechanical energy from human movement (such as body movement, muscle stretching, blood pressure) to power these devices.[2] Several methods to scavenge biomechanical energy from human activity have been reported,[3−7] where most of them are based on electromagnetic or piezoelectric effect. However, the main limitation of them is that the electromagnetic generator (EMG) is too cumbersome (>1 kg) to be conveniently integrated on the human body and the output performance of the piezoelectric nanogenerator is not powerful enough to power wearable devices.

Recently, a new type of energy-harvesting device named triboelectric nanogenerator (TENG) has been demonstrated and widely utilized in converting low-frequency mechanical energy into electricity.[8−12] This technology depends on the conjunction of triboelectrification and electrostatic induction through the relative sliding or

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contact/separation between two materials that possess opposite tribopolarity. Although some attempts to use TENG for harvesting biomechanical energy from human activity to light up some light-emitting diodes (LEDs) have been achieved by integrating the device in a shoe pad,[13−15] the obtained electric power is still not high enough to sustainably drive the wearable devices. A hybridized mechanical-energy-harvesting technology may enhance the overall power output.[16−19] By integrating two kinds of mechanical-energy-harvesting units, more electricity can be extracted from one mechanical motion, which may meet the power needs of some wearable electronic devices.

For current commercial wearable devices, one of the important functions is to accurately record the walking data including the walking step, distance, and energy consumption, which requires the integration of the wearable devices and the energy-harvesting unit near the human foot such as in a commercial shoe. To achieve this, several challenges need to be addressed: a lightweight (<100 g) device with small size (<5 cm × 5 cm × 3 cm), a convenient method to integrate the device, and the capability to convert intermittent energy at low frequency (<10 Hz).

In this paper, we have demonstrated a hybridized electromagnetic−triboelectric nanogenerator for scavenging biomechanical energy to sustainably power wearable electronics. During walking, the hybridized nanogenerator is pushed by the heel and the energy is continuously harvested based on the combination of triboelectrification and electromagnetic induction. The fabricated device has the total dimensions of 5 cm × 5 cm × 2.5 cm and the light weight of 60 g, which can be directly integrated in a commercial shoe. The output power densities of the TENG and EMG parts in the hybridized nanogenerator reached 5.1 and 3.6 W/m^2, respectively. The hybridized nanogenerator exhibits a good stability and a much better charging performance than that of the individual energy unit, where the stored electric capacity reached about 0.66 mAh for charging a Li-ion battery. When utilized as the power source of wearable electronics, the scavenged biomechanical energy from human movement can sustainably power the on-shoe LEDs and a wireless pedometer to send the walking data under the distance of 25 m. The designed hybridized nanogenerator has potential for powering wearable devices, including on-shoe lights, health and performance monitors, charging cell phones, or even for portable electronics.

RESULTS AND DISCUSSION

Figure 1a illustrates the schematic diagram of the hybridized electromagnetic−triboelectric nanogenerator that includes a magnet, a set of coils, triboelectric materials, electrodes, and springs. Double-layered acrylic substrates as the framework of the whole device are separated by four springs at the corners. The bottom

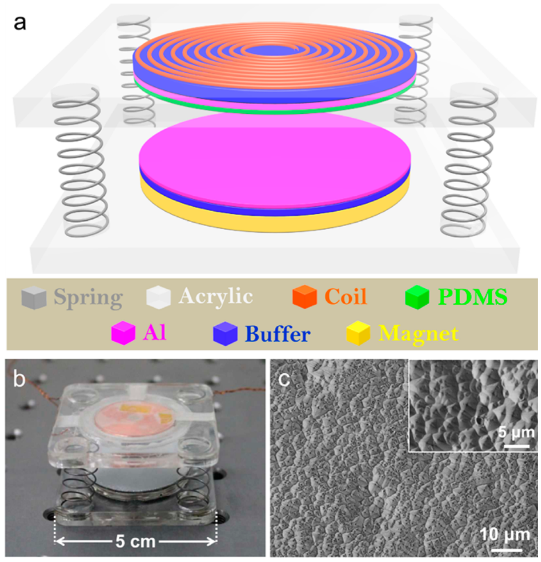

Figure 1. (a) Schematic diagram of the hybridized nanogenerator. (b) Photograph of a fabricated hybridized nanogenerator. (c) SEM image of the prepared PDMS film. Inset shows the enlarged view of the PDMS surface.

NdFeB permanent magnet with a radius of 35 mm and a height of 4.5 mm is nickel-plated to avoid being corroded. An Al film is attached onto the bottom magnet as both the triboelectric material and the corresponding electrode of the TENG. To provide sufficient magnetic flux, the top coil possesses high turns of approximately 5000 with the total weight of about 6 g. The polydimethylsiloxane (PDMS) directly attached on an Al film is fixed onto the top coil as the other side triboelectric material and the corresponding electrode of the TENG. Also, a thin buffer layer is attached between the coil and Al electrode to decrease the force of springs and protect the PDMS film when pressing. The fabricated device is in a cube with 5 cm on each side and 2.5 cm in the height, as shown in Figure 1b. To induce a larger triboelectric charge density, the PDMS film is prepared using a Si pyramid template to make a micro/nanostructure on its surface. Figure 1c shows SEM images of the prepared PDMS film. The surface is uniformly covered with pyramid-patterned structures with a space of 2−4 μm between the nanodots.

The working principle of the hybridized nanogenerator can be divided into two parts: the triboelectric part and the electromagnetic part, as schematically depicted in Figure 2. When the top substrate of the device is pressed by an external force (Figure 2a), the top PDMS film and the bottom Al film are brought into full contact with each other, generating triboelectric charges due to the different triboelectricity between them. As determined by the triboelectric series,[9] Al is much more triboelectrically positive than PDMS, thus electrons are injected from Al into PDMS, resulting in the accumulation of positive charges on the Al side and negative charges on the PDMS side. That is, charges are redistributed due to electrostatic induction. Then,

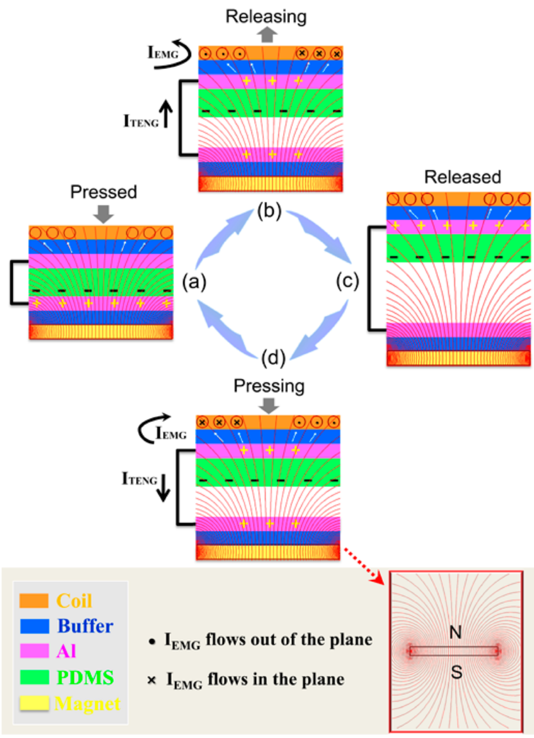

Figure 2. Schematic diagrams of the generation process of electricity, indicating the relationship between the direction of current flow, the change of magnetic flux, and the distance of separation. A 2D axisymmetric model was established, and the distribution of magnetic lines was calculated by COMSOL. The magnetic scalar at infinity was set to 0, and the relative permeability of the magnet was set to 1.

when the external force is withdrawn, the Al and PDMS films move apart due to the elastic force of springs. Under the driving force of the inner electric field, the electrons will flow from the top electrode to the bottom electrode and neutralize the positive triboelectric charges on the bottom Al film. Thus, the current is generated in the triboelectric part of the hybridized nanogenerator.

On the other hand, current flow in the electromagnetic part is caused by the electromagnetic induction: the change of the magnetic flux that crosses the coil causes an inductive electromotive force to arise in the coils. When the separation between the Al film and the PDMS film increases, the magnetic flux crossing the top coil decreases, thus inducing current to flow in the coil, as shown in Figure 2b. By continuously increasing the separation, the positive triboelectric charges on the bottom Al film are gradually neutralized, leaving an equal amount of inductive charges on the top electrode. Until the top substrate of the device is fully released, the positive charges on the bottom Al film are entirely neutralized, and no current flow can be observed (Figure 2c). Subsequently, the external force once again decreases the separation, producing a reversed inner electric field and change of magnetic flux. Hence, a reversed direction of current can be observed for both the triboelectric part and the electromagnetic part of the hybridized nanogenerator (Figure 2d). Until the top substrate of the device is pressed, a full cycle of the electricity generation process finishes and another cycle starts. Therefore, the hybridized nanogenerator acts as an electron pump to drive electrons to flow back and forth, generating an alternating current flow in the external circuit.

The output performance of the hybridized electromagnetic–triboelectric nanogenerator was measured under a fixed external force produced by a linear motor. The bottom substrate of the device was anchored, leaving the top substrate free-standing to bear the external force. Figure 3a shows the measured short-circuit current of the TENG part, where the current reached 61 μA during fast contact/separation between the Al and PDMS films. The negative current of 32 μA is due to the negative triboelectric charges on the PDMS film. The corresponding open-circuit voltage of the TENG part reached as high as 268 V, as shown in Figure 3b. To obtain the optimum output power, the output current was measured under different external loading resistances. As depicted in Figure 3c, the output current decreases with the increasing value of an external loading resistance, especially after a loading resistance of 1 MΩ. Consequently, the TENG possesses a high internal resistance of 6 MΩ at which the maximum output power reached 4.9 mW, corresponding to an output power density of 5.1 W/m^2. Besides the output of TENG, the relative movement of the coil and the magnet will generate current flow in the spiral-shaped coil. As shown in Figure 3d,e, a short-circuit current of 3.6 mA was produced with a peak voltage of 4.9 V for the EMG part. Although the voltage generated in the EMG part is relatively low, large current can be obtained. This is mainly because the internal resistance of the EMG is comparatively lower than that of the TENG. As shown in Figure 3f, the output current decreases dramatically as the external loading resistance varies from 100 to 1000 Ω. Maximum output power of 3.5 mW with the corresponding power density of 3.6 W/m^2 (considering the area of magnet) was obtained at 2 kΩ. Moreover, the short-circuit current of the TENG part and EMG part was measured for more than 1000 contacts/separations. As shown in Figures 3g,h, no decline is observed for both the TENG part and the EMG part.

From the above analysis, it is obvious that the characteristics of TENG and EMG are quite different: TENG is equal to a current source with a large internal resistance, while the EMG can be considered as a voltage source with a small internal resistance.[20] The output impedance of the TENG is larger than that of EMG by 3 orders of magnitude, which would cause non-negligible power consumption when these two parts are connected in parallel. To get an impedance match between these two parts, the TENG was connected with a transformer in parallel. As shown in Figure 4a,b, a short-circuit current of 1.3 mA and an

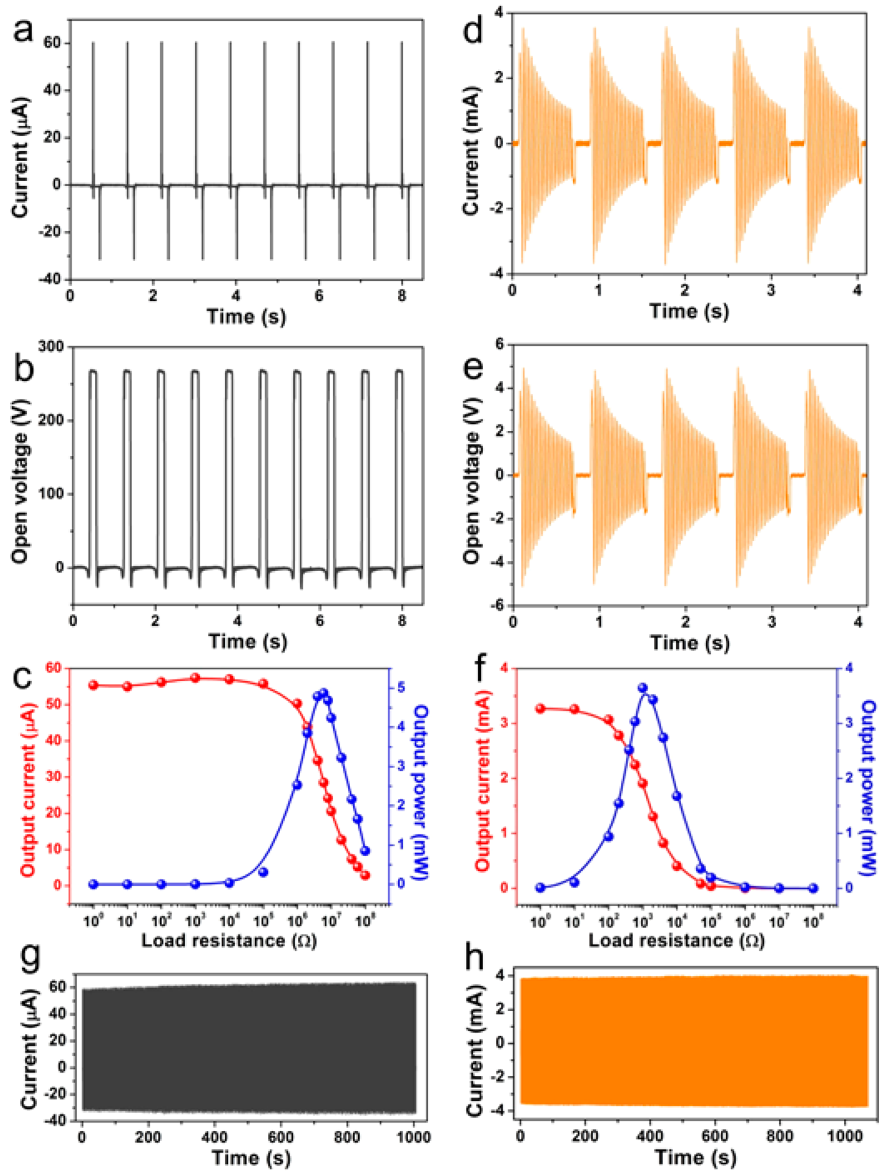

Figure 3. (a) Short-circuit current of the TENG. (b) Open-circuit voltage of the TENG. (c) Dependence of output current and output power of the TENG on the external loading resistance. (d) Short-circuit current of the EMG. (e) Open-circuit voltage of the EMG. (f) Dependence of output current and output power of the EMG on the external loading resistance. (g) Short-circuit current of the TENG measured for more than 1000 contacts/separation. (h) Short-circuit current of the EMG measured for more than 1000 contacts/separations. Note: the time is limited by the storage of our measuring instrument.

open-circuit voltage of 4.3 V were produced for the TENG with a transformer. Figure 4c shows the dependence of output current and output power of the TENG with a transformer on the external loading resistance. The output impedance was adjusted to 2 kΩ with maximum output power of 1.4 mW. Apparently, part of the generated power was consumed by the supplementary load of the transformer. Figure 4d shows current pulses produced when contact is made for the TENG and the generated electricity at loading resistances of 6 MΩ and 2 kΩ. Herein, the generated electrical energy ($E_{electricity}$) can be calculated as

$$E_{electricity} = \int_{t_1}^{t_2} I^2 \cdot R \cdot dt \qquad (1)$$

where I is a single current pulse recorded by an electrometer and R is the loading resistance. The time interval between t_1 and t_2 represents a single contact of the TENG. From Figure 4d, it can be seen that the one-pulse energy decreased from 7.8 to 1.1 μJ after being connected with a transformer. Although only 14% electricity energy was converted, the transformer-induced lower voltage and larger current are beneficial to charge a capacitor or Li-ion battery. The output voltage and current of the TENG was adjusted to a similar level compared to the EMG, which is also beneficial for the efficient integration of these two parts. The remarkable effect was further confirmed by comparison of the short-circuit current in one device for the TENG with a transformer, EMG, and a

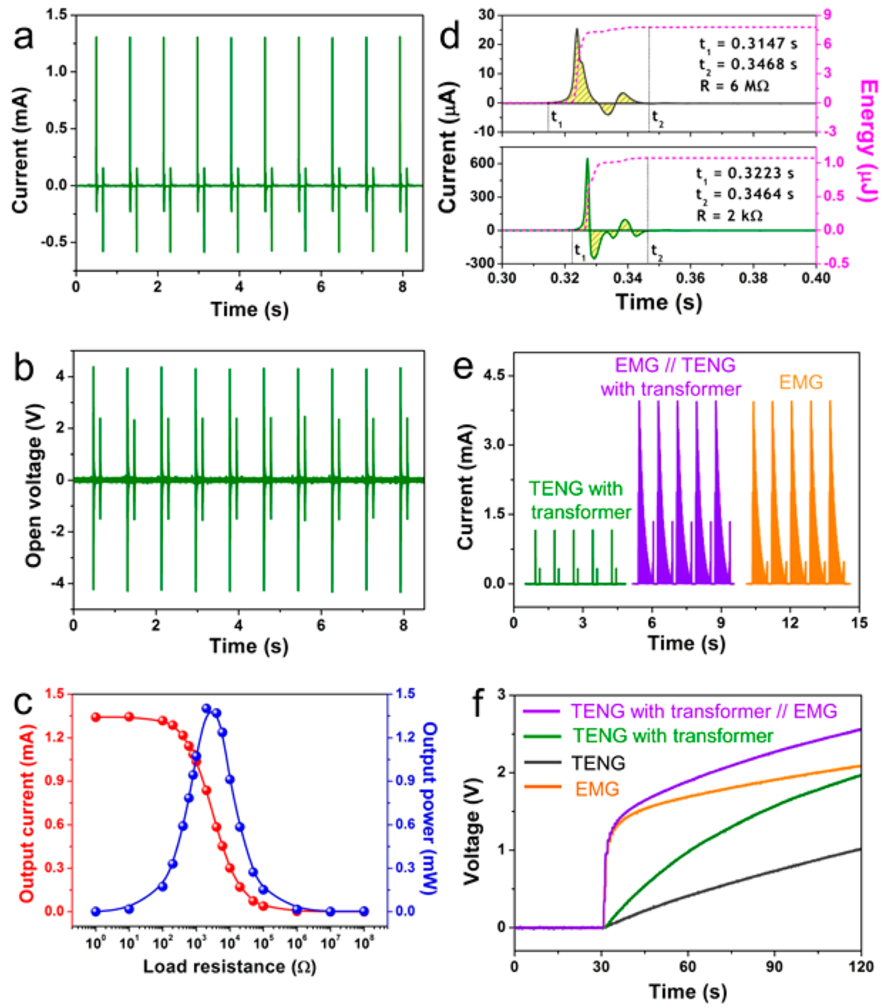

Figure 4. (a) Short-circuit current of the TENG with a transformer. (b) Open-circuit voltage of the TENG with a transformer. (c) Dependence of output current and output power of the TENG with a transformer on the external loading resistance. (d) Single current pulse produced when contact is made and the corresponding electricity is generated for the TENG without a transformer (at a loading resistance of 6 MΩ) and with a transformer (at a loading resistance of 2 kΩ). (e) Comparison of short-circuit current using one device for the TENG with a transformer, EMG, and TENG with a transformer connected in parallel with EMG. (f) Measured voltage of a 47 μF capacitor charged by the TENG, EMG, TENG with a transformer, and the hybridized nanogenerator (EMG and TENG with a transformer in parallel).

TENG with a transformer connected in parallel with EMG, as revealed in Figure 4e. In our case, two independent rectifier bridge circuits were used for the EMG and TENG with a transformer, respectively, and then the rectified signals were connected in parallel. The peak current generated by only the EMG and only the TENG with a transformer is about 4.0 and 1.2 mA, respectively. When these two parts were connected in parallel, no obvious enhancement for the current signals can be observed here, which is due to the nonsynchronous effect for the output of the EMG and TENG. For an energy device, the generated energy needs to be stored in energy storage elements such as capacitors and Li-ion batteries.[21−23] Figure 4f indicates the charging curves of the TENG, TENG with a transformer, EMG, and the hybridized nanogenerator (TENG with transformer//EMG) for charging a capacitor of 47 μF. Under a fixed charging time, the highest charging voltage was obtained by the hybridized nanogenerator, indicating that the charging performance of the hybridized nanogenerator is much better than that of an individual energy-harvesting unit.

To demonstrate the generated energy as an effective power source, it was used to power commercial LEDs. As shown in Figure 5a, two rows of LEDs were connected with the EMG and the TENG with a transformer. When a human hand touched the device, the electricity generated from both the EMG and the TENG with a transformer simultaneously lighted up 20 red LEDs and 20 green LEDs, respectively (see movie 1 in Supporting Information). Furthermore, the hybridized nanogenerator was utilized as a power source for on-shoe LEDs. A total of 32 commercial LEDs connected in parallel on two twines were assembled at the translucent sole of the shoe (Figure 5c). When a human hand touched the device, the hybridized nanogenerator simultaneously lighted up 32 green LEDs in a commercial shoe, as illustrated in Figure 5d (see movie 2 in

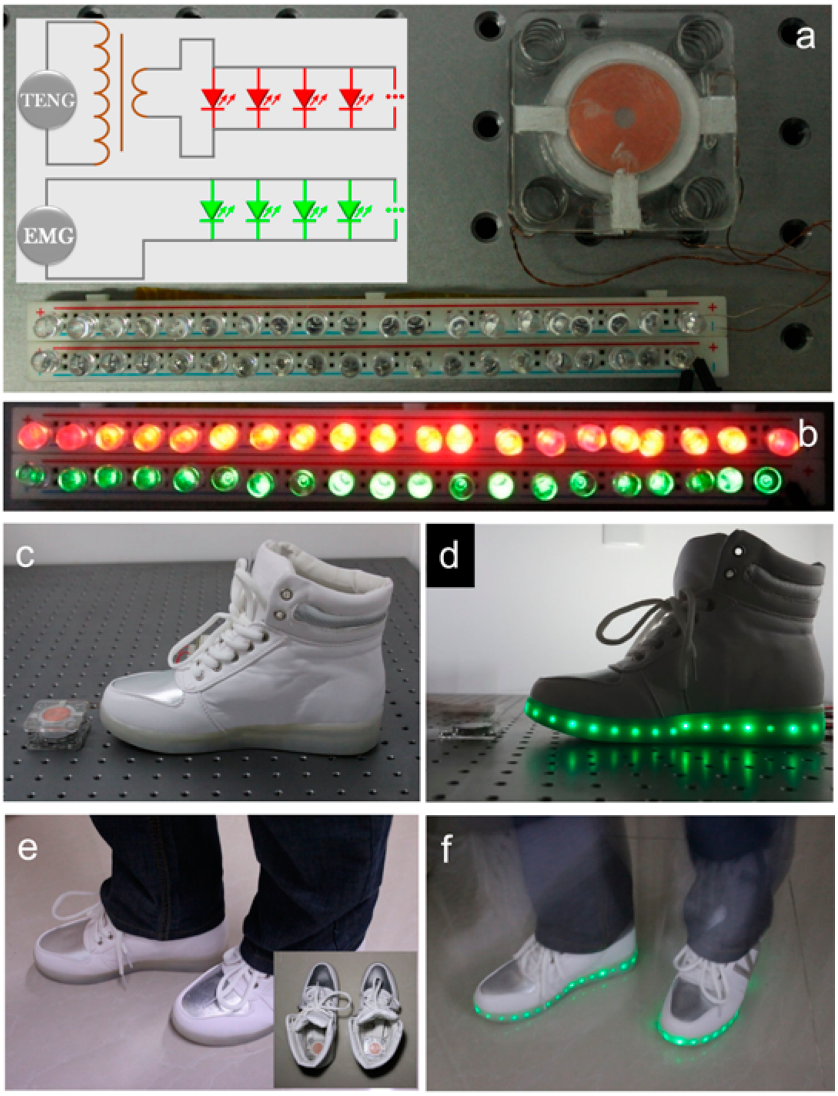

Figure 5. (a) Photograph of LEDs connected with the hybridized nanogenerator and (b) when a hand touches the hybridized nanogenerator, simultaneously lighting up the red and green LEDs (20 red LEDs for EMG and 20 green LEDs for TENG with a transformer). The LEDs are connected in parallel. (c) Photograph of the hybridized nanogenerator acting as a power source for on-shoe LEDs and (d) when a hand touches the hybridized nanogenerator, simultaneously lighting up 32 LEDs. (e) Photograph of a fully packaged self-driven shoe that incorporates the hybridized nanogenerator and LEDs and (f) when footstep falls, simultaneously lighting up the on-shoe LEDs.

Supporting Information). Here, a fully packaged self-driven shoe was developed, demonstrating the ability of the hybridized nanogenerator in harvesting biomechanical energy during human walking. The device was mounted in the heel of the shoe, as displayed in Figure 5e. Due to the small size of the device, the packaged self-driven shoe does not look obviously different than other sneakers. During walking or jumping, the periodically generated electricity lighted up all of the on-shoe LEDs (Figure 5f and movie 3 in Supporting Information), which makes the shoe look fascinating.

Figure 6a depicts a typical charging and discharging cycle of a Li-ion battery when the hybridized nanogenerator was periodically pressed by a motor. The voltage of the battery increased from 0.5 to 1.7 V in about 43 min. Under a constant current of 1 mA, the discharging process of the battery lasted for about 40 min before it was discharged back to its original voltage of 0.5 V. That is, the hybridized nanogenerator can be utilized to charge up a Li-ion battery by directly converting mechanical energy to chemical energy. Herein, the stored electric capacity was about 0.66 mAh. To confirm that the battery can be charged by the hybridized nanogenerator under human activity, the battery was charged when the hybridized nanogenerator was pressed by hand touches and footstep falls, as shown in Figure 6b. At the same charging time of 5 min, the battery was charged from 0.5 to 1.2, 1.1, and 0.8 V for the hybridized nanogenerator pressed by a motor, hand touches, and footstep falls, respectively. This difference is mainly attributed to the different frequency of the motion. Figure 6c,d shows that the Li-ion battery charged when the hybridized

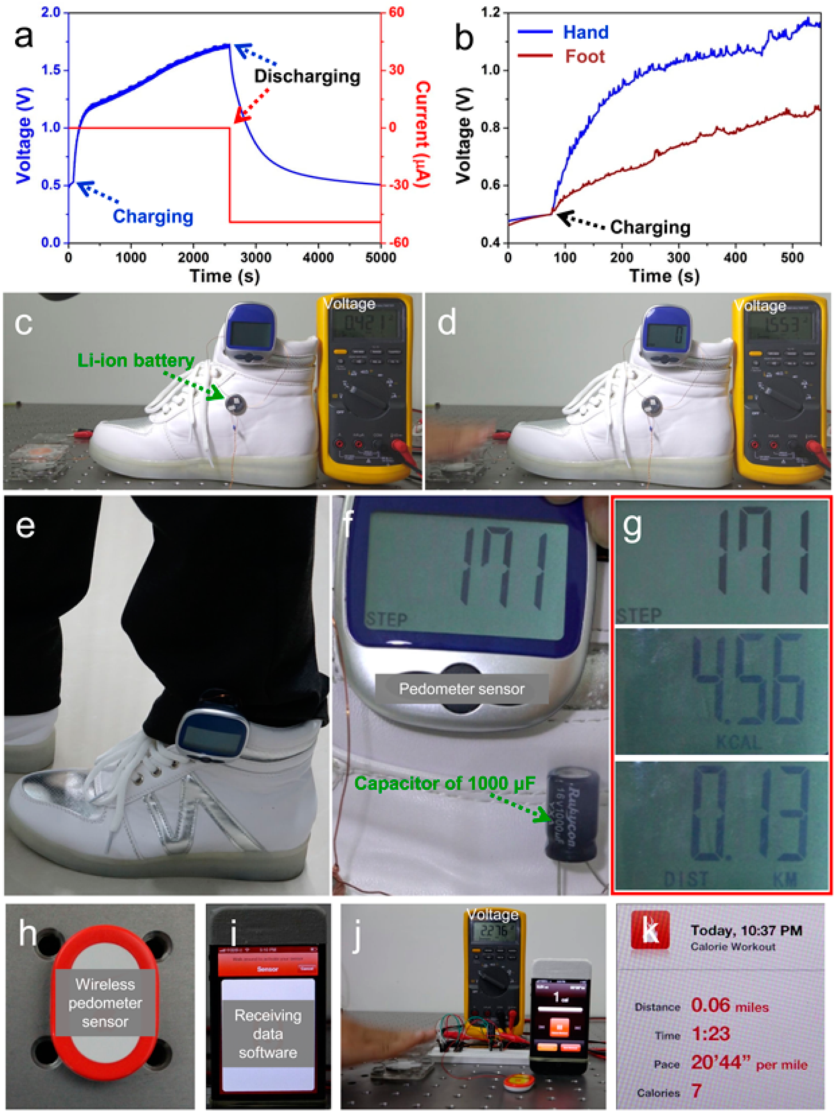

Figure 6. (a) Voltage curve showing the entire cycle of a Li-ion battery charged by the hybridized nanogenerator, with the subsequent constant current discharge at 1 mA. (b) Voltage curve showing the charge cycle of a Li-ion battery charged by the hybridized nanogenerator pressed by hand touches and footstep falls. Photograph of the Li-ion battery before (c) and after (d) charged by hand touches. (e) Photograph of the packaged self-powered shoe for powering a pedometer, (f) working pedometer during human walking, and (g) step, energy, and distance results recorded by the pedometer. (h) Photograph of a wireless pedometer. (i) Photograph of an iPhone for receiving the data from the wireless pedometer. (j) Photograph of the hybridized nanogenerator to drive the wireless pedometer to send the walking data to the iPhone. (k) Received data from a wireless pedometer under the distance of 25 m.

nanogenerator pressed by hand touches can be used to power a smart pedometer (see movie 4 in Supporting Information). Figure 6e,f shows the packaged self-powered shoe for sustainably driving a pedometer. A capacitor of 1000 μF was attached on the shoe as the energy storage element. The pedometer worked very well during hand touches or walking, as seen from movie 5 and movie 6 (see the Supporting Information). After walking for several minutes, total steps of 171, energy of 4.56 kcal, and distance of 0.13 km were recorded by the pedometer, as shown in Figure 6g. Although the walking information can be recorded by the pedometer, the wireless transmission of the obtained data is more attractive due to more convenient operation. Figure 6h illustrates a photograph of a wireless pedometer, where an iPhone was used to receive the walking data from the wireless pedometer, as displayed in Figure 6i. Figure 6j shows that the hybridized nanogenerator can be used to sustainably power the wireless pedometer to send the walking data to the iPhone. Figure 6k displays the received data from the wireless pedometer with the distance of 25 m, where the corresponding data including the distance, time, pace, and calories were recorded (see movie 7 in Supporting Information). These results indicate that the hybridized nanogenerator has potential applications for powering wearable electronics.

CONCLUSIONS

In summary, we have demonstrated a hybridized electromagnetic–triboelectric nanogenerator for scavenging biomechanical energy to sustainably power wearable electronics during human walking. By using the conjunction of triboelectrification and electromagnetic induction, the hybridized nanogenerator consists of a TENG and an EMG with the peak output powers of 4.9 and 3.5 mW, corresponding to output power densities of 5.1 and 3.6 W/m^2, respectively. The hybridized nanogenerator has a small dimension of 5 cm × 5 cm × 2.5 cm, a light weight of 60 g, and a good stability for the output performance. As compared with the TENG without using a transformer, the charging rate was largely increased by using a transformer to decrease the impedance of TENG. Moreover, the hybridized nanogenerator has a charging performance much better than that of an individual energy-harvesting unit and can be utilized to not only charge a Li-ion battery but also sustainably power wearable electronics such as on-shoe LEDs and smart wireless pedometers. This work pushes forward a significant step toward energy harvesting from human walking and its potential applications in powering wearable devices.

EXPERIMENTAL SECTION

Preparation of the Pyramid-Patterned PDMS Film. The pyramid-patterned PDMS film was prepared using an etched Si micropyramid template. Micropyramid structures, with a nanodot in the center, were fabricated. First, the fluid PDMS elastomer and corresponding cross-linker (Sylgard 184, Dow Corning) were thoroughly mixed in 10:1 ratio (w/w). Then, the mixture was transferred onto the Si template and spin-coated at 500 rpm for 60 s. After being degassed for 10 min, the Si template was cured at 80 °C for 1 h in an oven.

Fabrication of the Hybridized Nanogenerator. The framework of the device was constructed by acrylic sheets. First, two acrylic sheets with a size of 50 mm × 50 mm were fabricated by a laser cutting machine as the double-layered acrylic substrates of the device. Both of the two acrylic substrates have a round groove of 35 mm × 35 mm at the center and four round grooves of 5 mm × 5 mm at the corners. The two acrylic substrates were separated by four springs at the corners. After the framework of the device was constructed, a NdFeB permanent magnet with a radius of 35 mm and a height of 4.5 mm was fixed in the groove of the bottom acrylic substrate. Then, a thin buffer and an Al film were attached onto the bottom magnet in sequence. On the other side, a Cu coil with turns of about 5000 was fixed in the groove of the top acrylic substrate. Then, a thin buffer, an Al film, and a PDMS film with a radius of 35 mm were attached onto the top coil in sequence. The Al films acted as the electrodes of the TENG part, while two Cu wires were connected to the inside and outside of the coil as the electrodes of the EMG part. The fabricated device has the total dimensions of 5 cm × 5 cm × 2.5 cm and the weight of 60 g.

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

Conflict of Interest: The authors declare no competing financial interest.

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Supporting Information Available: Additional movie files include the hybridized electromagnetic–triboelectric nanogenerator for lighting up LEDs and sustainably powering a pedometer. This material is available free of charge *via* the Internet at http://pubs.acs.org.

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