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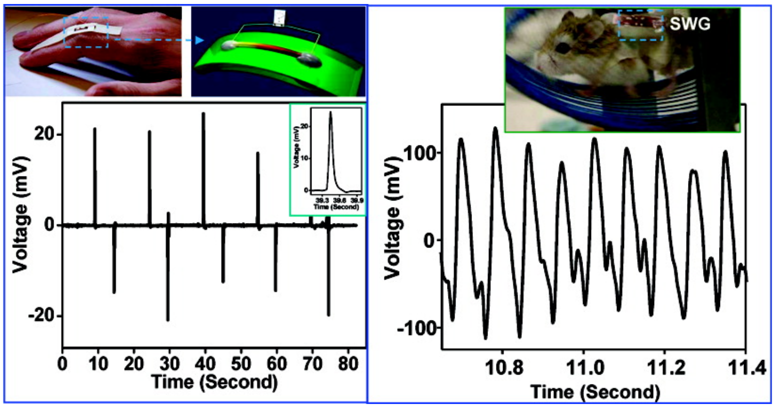

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Converting Biomechanical Energy into Electricity by a Muscle-Movement-Driven Nanogenerator

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ABSTRACT

A living species has numerous sources of mechanical energy, such as muscle stretching, arm/leg swings, walking/running, heart beats, and blood flow. We demonstrate a piezoelectric nanowire based nanogenerator that converts biomechanical energy, such as the movement of a human finger and the body motion of a live hamster (Campbell's dwarf), into electricity. A single wire generator (SWG) consists of a flexible substrate with a ZnO nanowire affixed laterally at its two ends on the substrate surface. Muscle stretching results in the back and forth stretching of the substrate and the nanowire. The piezoelectric potential created inside the wire leads to the flow of electrons in the external circuit. The output voltage has been increased by integrating multiple SWGs. A series connection of four SWGs produced an output voltage of up to ∼0.1−0.15 V. The success of energy harvesting from a tapping finger and a running hamster reveals the potential of using the nanogenerators for scavenging low-frequency energy from regular and irregular biomotion.

Owing to the small power consumption of nanodevices, typically in the nano- to microwatt range, harvesting energy from the environment for building self-powered nanosystems is attracting a lot of interest.[1−4] In addition to the most extensively studied solar[5] and thermal energy,[6] vibration energy and mechanical energy are probably the most popular sources of energy in our living environment that is available almost any where and any time. Piezoelectric beams/cantilevers have been demonstrated as an effective approach for harvesting mechanical and vibration energy.[7] A general approach for harvesting vibration energy is through a spring and mass system.[8] These available technologies rely on mechanical resonance at a specific frequency or frequency range as defined by the system, and they are applicable under well-defined and stable environment and conditions.[9]

A human body has numerous sources of mechanical energy, including muscle stretching, arm swings, walking, heart beats, and blood flow. But the frequencies and amplitudes of these movements are fairly irregular and random in nature.[10] A recent approach has been demonstrated to harvest a human walking energy by designing a mechanical gear and clutch system that drives the rotor for a conventional electromagnetic generator.[11] But this generator has to be driven by a significantly strong physical movement such as walking legs. To harvest the energy generated by a smaller scale muscle movement, such as a tapping finger, muscle vibration near the throat, or stretching on a face, a new approach has to be developed.

Recently, an alternating-current (ac) generator is demonstrated based on cyclic stretching−releasing of a piezoelectric fine-wire (PFW) (microwire, nanowire),[12] which is firmly contacted at its two ends with metal electrodes, laterally bonded, and packaged on a flexible substrate. When the PFW is stretched as driven by substrate bending, a piezoelectric potential drop is created along the PFW. A Schottky barrier formed at least at one end-contact of the PFW serves as a "gate" that prevents the flow of electrons in the external circuit through the PFW so that the piezoelectric potential is preserved. The PFW acts as a "capacitor" and "charge pump", which drives the back and forth flow of the electrons in the external circuit to achieve a charging and discharging process when the PFW is stretched and released, respectively. This single wire generator (SWG) demonstrates a robust and packageable nanotechnology in polymer films for harvesting low-frequency energy from vibration, air flow/wind, and mechanical deformation. The SWG is expected to work at frequencies to which the substrate can respond. It is anticipated to be feasible and practical to be implanted in muscles, embedded in clothes, built in surface layers, and placed in shoe pads for harvesting low-frequency energy.

In this paper, we demonstrate the application of the SWG for harvesting energy from small-scale dynamic muscle movement, including human finger tapping and body movement of a hamster (running and scratching). A series

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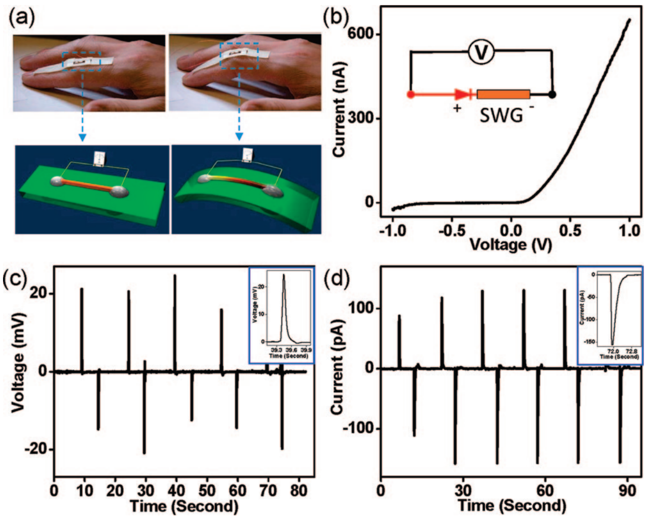

Figure 1. Energy harvesting from an oscillating human index finger using an SWG. (a) An SWG attached to a human index finger, which drove the SWG to bend and produce power output. (b) $I-V$ characteristic of the SWG. The inset illustrates the connection configuration of the SWG in reference to the measurement system. Open-circuit voltage (c) and short-circuit current power output (d) from the SWG when the finger was periodically bent back and forth.

connection of four SWGs has been shown for outputting an alternating voltage of ~0.1−0.15 V in amplitude. This work shows the feasibility of harvesting biomechanical energy created by small-scale muscle stretching, with the potential to work in vivo.

The fabrication of the SWG was described in detail in our previous publication.[12] In brief, a flexible polyimide film was used as a substrate, and the two ends of a ZnO piezoelectric nanowire were fixed on the top surface of the substrate. The entire SWG was packaged with a flexible polymer for improving its robustness and adaptability. The measurement system was well-grounded and screened so that the noise level is minimized.

Careful and detailed measures were taken to rule out possible artifacts in the measurements. Many factors, such as the measurement system, change in capacitance of the nanowire and the electric circuit, and the coupling of the SWG with the measurement system, can affect the experimental result and produce artifacts. In order to distinguish the true electric power signal from artifacts, caution must be exercised and the following tests have to be performed.[12,13] First of all, SWG must have a Schottky contact at one of its ends for outputting electricity. Second, the output voltage and current of a SWG must satisfy the switching polarity test. Finally, the output current and voltage of multiple SWGs must satisfy the linear superposition rule if they are connected in parallel and series, respectively.

The first example we demonstrated is to harvest energy from a human finger movement. The SWG was attached to the joint position of the index finger, as shown in Figure 1a. The diameter of the nanowires was 100−800 nm with lengths of ~100−500 μm. Bending a finger can drive a nanogenerator. When a nanogenerator is affixed to the top side of an index finger, repeatedly bending of the finger can produce a cycled strain in the NW. The deformation of the ZnO NW produces a piezoelectric potential within the wire, which drives the flow of external electrons and produces electric power output (video 1 in Supporting Information). For a SWG that can effectively produce electric power output, the $I-V$ characteristic always shows Schottky behavior,[14] as shown in Figure 1b. The reason has been discussed in detail elsewhere.[12] We define the side with Shottky contact as the positive side for easy notation and reference. When the positive probe and negative probe of the measuring instrument are connected to the positive and negative sides of the SWG, respectively, the configuration is defined as a forward connection. Otherwise the configuration is defined as a reverse connection. Both connection methods have to be tested for the SWG. The magnitude of the signal from different connecting methods might differ due to the contribution from the bias current of the measurement system, which is usually a few picoamperes. However, the switching polarity has to be satisfied to ensure the true signal generated by the SWG.

Panels c and d of Figure 1 present the open-circuit voltage output and short-circuit current output, respectively, from the SWG when the index finger oscillates at a relatively slow rate. On average, the straining rate of the SWG attached to the finger is about $(4-8) \times 10^{-3}$ s^{-1} with a maximum strain of the nanowire ~0.2%. Periodic motion was recorded here for easy interpretation. Irregular finger movement can also produce power output. The variation of bending speed and extent of the finger oscillation results in the fluctuation in the output voltage and the current. Figure 1c indicates that the voltage output is up to 25 mV, and the current output is more than 150 pA from a single SWG device.

The second example is SWGs driven by a live hamster belonging to the Campbell's dwarf type, which can produce various regular and irregular motions such as running or scratching. The body length of the hamster was ~2 in. To use the muscle stretching of the hamster for generating electricity, we have made a special "yellow jacket", on which SWGs were built on its surface. Necessary measures have been taken to avoid effects from electrostatic charges. The hamster wore the jacket, and the SWGs were attached over its back. When the hamster moved, the back of the hamster bent back and forth, which forced the jacket to be wrinkled and so did the substrates of the SWGs. This deformation process drove the SWGs. When the hamster was running or scratching itself in a specially designed round cage (video 2 in Supporting Information), we measured the electrical output from the SWGs without disturbing the movement of the hamster, as shown in Figure 2, panels a and d, where snapshots of the hamster at two different moving configurations are shown. When the hamster was running at a fairly constant frequency, the SWG on its back bent periodically and produced oscillating current and voltage output. Enlarged view of the electric outputs from the running hamster presented in panels b and e of Figure 2 clearly shows the period output signals, which are consistent with the periodic movement of the running hamster at a frequency of ~10−11

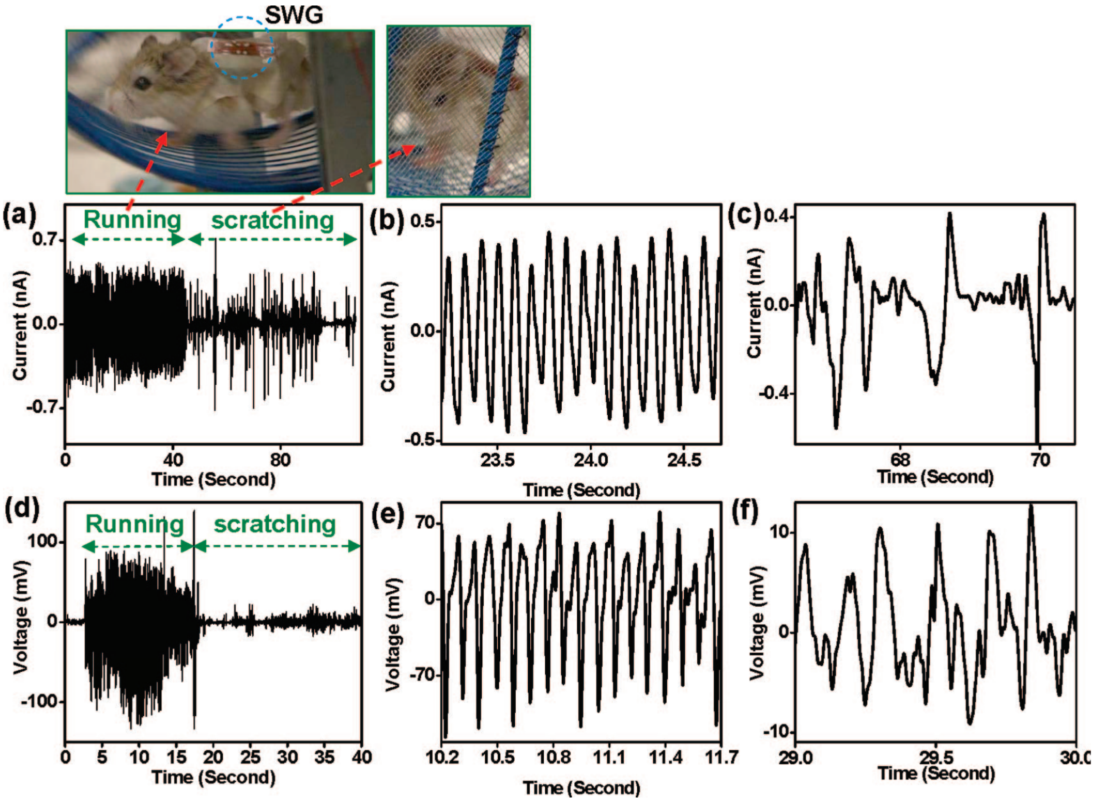

Figure 2. Energy harvesting from a live hamster using an SWG. (a) Short-circuit current output when the hamster was running or scratching. Photos at the top illustrate snapshots of the hamster when it was running and scratching. (b and c) Enlarged view of current output in (a) received from the SWG when the hamster was running and scratching, respectively. (d) Open-circuit voltage output of the SWG when the hamster was running and scratching. (e and f) Enlarged view of the voltage output in (d) when the hamster was running and scratching, respectively.

Hz. In comparison, when the hamster was scratching, Figure 2, panels c and f, the signal did not have a clear pattern and its magnitude dropped dramatically. Due to a much higher stress and straining rate than a human finger, the output signal from the hamster is much larger. The short-circuit current from a running hamster reached ∼0.5 nA, and the open-circuit voltage reached ∼50−100 mV.

In order to ensure the measured signal was truly from the piezoelectric ZnO nanowire, we performed the same experiment using a carbon fiber to replace the ZnO nanowire in the SWG. No output electric signal was captured since carbon is nonpiezoelectric (Figure S1 in Supporting Information). Alternatively, using a Kevlar fiber coated with polycrystalline ZnO film produced only very small noises less than 1 mV (Figure S2 in Supporting Information). In addition, the noise is completely irregular and has no clear relationship with the periodic movement of a running hamster. This is because the ZnO film coated on the Kevlar fiber was made of nanocrystals that had random orientations; thus the piezoelectric effect was minimized or fully canceled out. After these studies, we are confident that the signal presented in Figure 2 truly revealed the energy harvesting of the SWG.

Integration of multiple SWGs is a major step toward practical applications. Our first test was to have two SWGs on the jacket of the hamster. Panels a and b of Figure 3 show the individual voltage outputs of the two SWGs, SWG-1 and SWG-2, when they were driven by the body movement of the hamster. Each SWG produced a voltage output of ∼40 mV. The enlarged views of voltage outputs in Figure 3b reveal that both SWGs have the same period

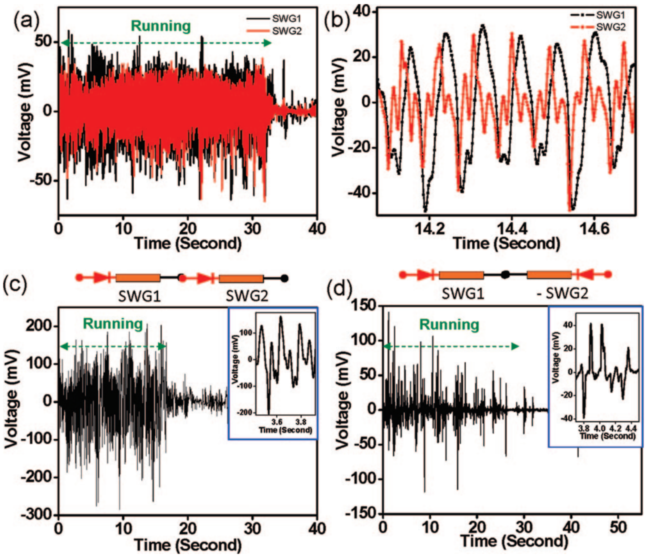

Figure 3. Energy harvesting from a live hamster with two SWGs connected in series. (a) Open-circuit voltage output of individual SWGs. (b) Enlarged view of voltage output in (a). (c) Open-circuit voltage output of the two SWGs connected in series and in phase. (d) Open-circuit voltage output of the two SWGs in series and out of phase. The insets in (c) and (d) are enlarged views of output voltages for the corresponding figures.

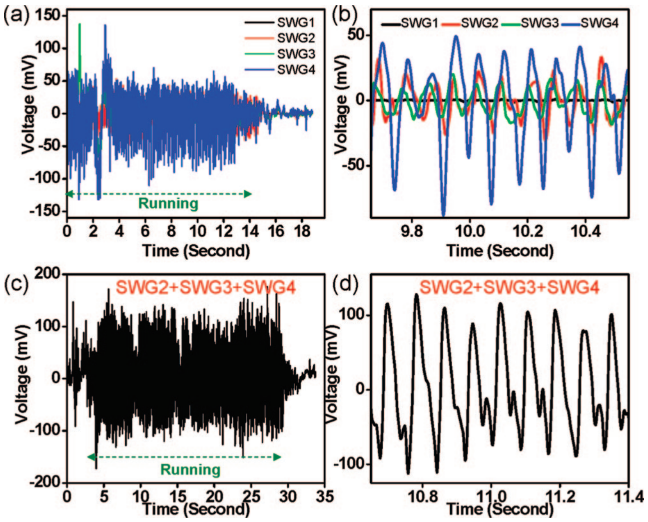

Figure 4. Energy harvesting from a live hamster using three working SWGs and one nonfunctioning SWG. (a) Open-circuit voltage outputs of the four individual SWGs built on a common substrate. (b) Enlarged view of the voltage output in (a), SWG1 does not produce power output due to its Ohmic $I-V$ transport behavior. (c) Open-circuit voltage output of SWG2 + SWG3 + SWG4 connected in series and in phase. (d) Enlarged view of the voltage output in (c).

of cycles as the movement of the hamster. In addition, the synchronization of those two SWGs was reasonably good and the curves are only off phase slightly. In Figure 3c, we connected the two SWGs in series following the same polarity. The output voltage was apparently increased, and the average magnitude was close to ∼100 mV. Alternatively, when the two SWGs were connected in series but with opposite polarity, the average output magnitude of the voltage was dramatically decreased, as shown in Figure 3d. Some large signals were also observed in Figure 3d, which might be due to the nonperiodic body movement of the hamster and the nonperfect synchronization of the two SWGs. However, the apparent enhancement with in-phase connection and decrease with opposite-phase connection clearly indicate linear superposition of the output voltages of the two SWGs.

By careful synchronization of the operations of four SWGs on a common substrate, the integrated output is much enhanced. First, by measuring the $I-V$ characteristics of an individual SWG, we can identify if the SWG would be suitable for energy generation. The $I-V$ transport of SWG1 showed an Ohmic behavior, and the remaining three SWGs showed Shottky behavior (Figure S3 in Supporting Information), indicating that SWG1 failed to meet the first criterion required for an effective nanogenerator. This is the reason that the output voltage from SWG1 is almost zero (see Figure 4a and b). In contrast, the other three SWGs had good output voltages. By connecting the three SWGs in series, the resultant output voltage is very close to the sum of the individual output voltage from each of them (Figures 4, panels c and d). The voltage output can be greater than 0.1 V.

Synchronization is critical for a successful integration of SWGs for reaching the maximum output voltage and current.

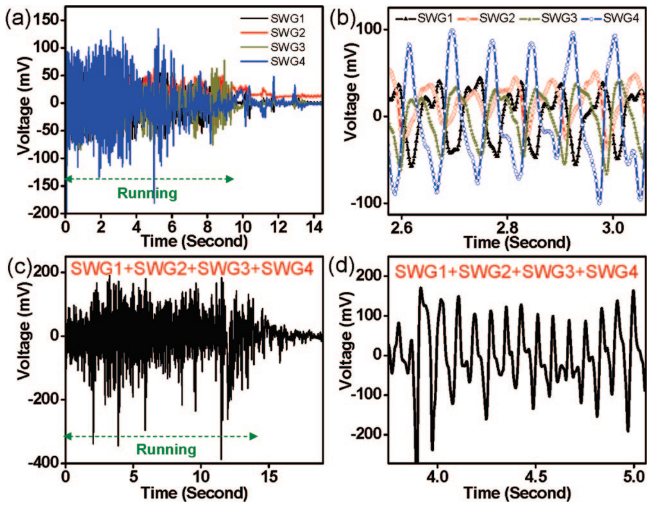

Figure 5. Energy harvesting from a live hamster using four working SWGs, for illustrating the importance of synchronization. (a) Open-circuit voltage output of individual SWG built on a common substrate. (b) Enlarged view of voltage output in (a). (c) Open-circuit voltage output of the four SWGs connected in series and in phase. (d) Enlarged view of voltage output in (c)

The piezoelectric potential drop of each SWG is determined by the *c*-axis of the ZnO nanowire and the deformation condition, either stretching or compressing. When we integrate multiple SWGs together, voltage outputs from all of the SWGs should be in phase such that the resultant output can be constructively added up. Figure 5 presents an integration of four SWGs. The $I-V$ measurements for all four SWGs confirmed Schottky behavior and every SWG produced voltage output when the hamster was running (Figure 5a). The fluctuation of the output voltage was mainly due to the variation in the running status of the hamster. But the outputs of the SWGs were not very well synchronized, possibly due to the complexity in muscle/body movement. Enlarged views of the output voltage curves in Figure 5b indicate that SWG1 and SWG2 are roughly out of phase from SWG3 and SWG4. When these SWGs are connected in series following the correct polarity, the resultant output in Figure 5c and 5d was not much larger than the output of SWG4, which was the most powerful one among the four.

Since the output of each SWG is like an ac source, it is important to have all of them in phase so that the output can reach the maximum. Owing to the complexity and uncontrollability in hamster body movement, achieving a good synchronization among all of the SWGs is challenging.

In summary, the SWG has been demonstrated to effectively harvest biomechanical energy from muscle stretching, such as a human finger tapping and the body movement of a live hamster. Integration of up to four SWGs has been demonstrated for raising the output voltage up to ∼0.1−0.15 V. Our research shows that SWGs can be used to harvest energy from body motion and other irregular disturbances in the environment. This research demonstrates the potential of using nanogenerators to harvest mechanical energy from live biological systems.

We demonstrate a nanowire nanogenerator that converts biomechanical energy, such as the movement of a human finger and the body motion of a live hamster, into electricity. A series connection of four nanogenerators produced an output voltage of up to ∼0.1−0.15 V. The success of energy harvesting from a tapping finger and a running hamster reveals the potential of using the nanogenerators for scavenging low-frequency energy from regular and irregular biomotion.

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Supporting Information Available: Figures S1 and S2 show measurements of the SWGs made using carbon fiber and polycrystalline ZnO film coated Kevlar fiber, respectively, Figure S3 shows *I*−*V* characteristic of four SWGs presented in Figure 4, and video 1 and video 2 show real-time live views of experiments on energy harvesting using a SWG for harvesting energy from an oscillating human finger and the body movement of a live hamster, respectively. The material is available free of charge via the Internet at http://pubs.acs.org.

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