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ARTICLE

Body-Integrated Self-Powered System for Wearable and Implantable Applications

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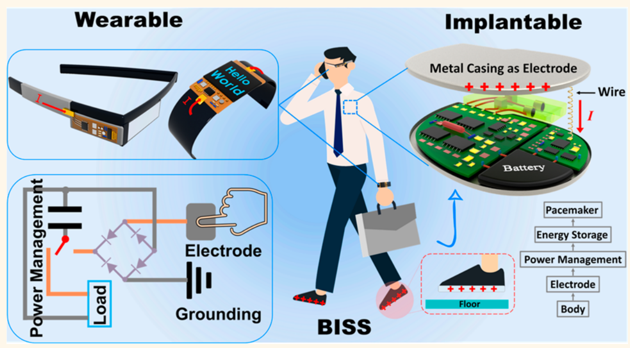
Supporting Information

ABSTRACT: **The human body has an abundance of available energy from the mechanical movements of walking, jumping, and running. Many devices such as electromagnetic, piezoelectric, and triboelectric energy harvesting devices have been demonstrated to convert body mechanical energy into electricity, which can be used to power various wearable and implantable electronics. However, the complicated structure, high cost of production/maintenance, and limitation of wearing and implantation sites restrict the development and commercialization of the body energy harvesters. Here, we present a body-integrated self-powered system (BISS) that is a succinct, highly efficient, and cost-effective method to scavenge energy from human motions. The biomechanical energy of the moving human body can be harvested through a piece of electrode attached to skin. The basic principle of the BISS is inspired by the comprehensive effect of triboelectrification between soles and floor and electrification of the human body. We have proven the feasibility of powering electronics using the BISS *in vitro* and *in vivo*. Our investigation of the BISS exhibits an extraordinarily simple, economical, and applicable strategy to harvest energy from human body movements, which has great potential for practical applications of self-powered wearable and implantable electronics in the future.**



KEYWORDS: *energy harvesting, body integrated, self-powered, wearable, implantable*

Wearable and implantable electronics are evolving into flexible, stretchable, integrated, miniaturized, and self-powered devices.[1−5] The technologies of harvesting energy from ambient environment to power-wearable and implanted electronics have been studied for a long time and are expanding rapidly.[6−9] The human body contains abundant energy from the mechanical movements of walking, jumping, and running and organ motions like heartbeat and respiration.[10−12] Some devices based on electromagnetic induction[13−15] or piezoelectric[16−19] and triboelectric[20−22] effects have been presented for scavenging these mechanical energy. Electromagnetic devices usually consist of coils and moving mass that make those devices bulk and rigid. Meanwhile, some additional structures are required for immobilization, protection, or other purposes, which also add to the size, weight, and complexity of those energy harvesters. Piezoelectric materials such as zinc oxide (ZnO), lead zirconate titanate (PZT), and poly(vinylidene fluoride) (PVDF) have been demonstrated to harvest kinetic

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energy *in vitro* and *in vivo*.[23−25] The characteristics of these devices are applicable for powering micro/nano devices and working over a wide range of frequencies. However, the fabrication processes of piezoelectric devices are usually complex due to some special processing techniques adopted, such as photolithography, inductively coupled plasma (ICP), physical vapor deposition (PVD), and electric field poling, which might enhance the cost of them.

Triboelectric nanogenerators (TENGs) have caught the attention of researchers in recent years, which can harvest mechanical energy from vibration, contacting, sliding, and rotating motions.[26−29] The mechanism of TENGs is based on the combination effect of contact electrification and electrostatic induction. Researchers have developed various types of TENGs for wearable applications, such as using TENGs integrated in soles or cloth to harvest walking energy and human skin based TENGs *via* patting triboelectric materials to generate electricity.[30−34] Implantable TENGs have also been demonstrated to harvest *in vivo* biomechanical energy.[35−38] The advantages of TENGs include the wide choice of materials, light weight, small size, and flexibility.[39−43] Meanwhile, the outputs of TENGs are strongly influenced by structures, working models, and positions of wear or implantation.

The inherent characteristics of electromagnetic devices, piezoelectric devices, and TENGs, including complicated structure, high cost of maintenance, and limitations of the wear and implantation sites, may confine their development. Especially for *in vivo* applications, implantable sites such as space between the diaphragm and liver, or heart and pericardium, are limited, which means that the dimension of implanted energy harvesters should be controlled and more additional difficulties on the fabrication and implantation could appear. It is valuable to find some alternative approaches to fabricating energy harvesters with characteristics of low cost, efficient output, and simple and reliable structure, which can be used conventiently in wearable and implantable electronics.

Electrification of the human body by walking is a common phenomenon. A mechanism can be illuminated as that charge is generated when soles contact with the floor and the change of human body capacitance during movement. Many researchers are focused on methods to reduce harm to the human body by static electricity,[44,45] but few try to utilize it as a power source. Here, we present the body-integrated self-powered system (BISS), which is inspired by the combined effect of triboelectrification between soles and floor and electrification of the human body. Only a piece of electrode attached to the skin is needed to harvest biomechanical energy during body movement. Our investigation exhibits an extraordinarily simple and efficient method to harvest biomechanical energy during human body movement, which has great potential for applications to self-powered wearable and implantable electronics in the future.

RESULTS AND DISCUSSION

Device Structure. The basic structure of the BISS includes three parts: human body, electrode, and electrical appliance (Figure 1a). The electrode is attached on human skin and connected with a current meter through a metal wire. When walking, electron flow can be detected by the current meter, which is driven by the body electric potential (BEP). The BEP is caused by electrification of the human body during movement, such as stepping, walking, jumping, and running.

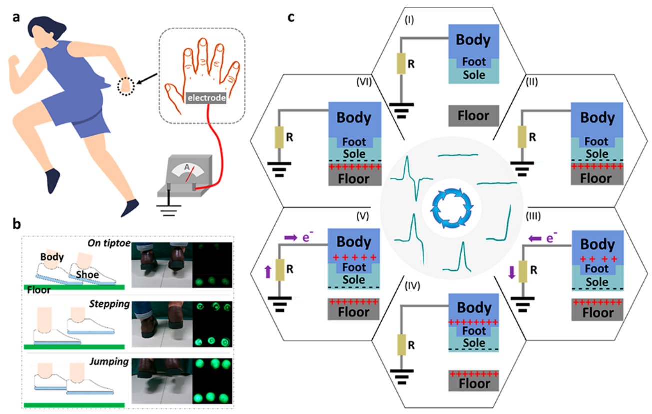

Figure 1. Basic mechanism of BISS. (a) Schematic diagram of BISS when human body runs. (b) Six LED bulbs lighted up by BISS under three moving models. (c) Process of electric energy conversion of BISS in one moving cycle.

Six LED bulbs are connected with a metal electrode that is attached to an experimenter's hand. The LEDs are lit when movement occurs under three models (on tiptoe, stepping, and jumping). The lightness of the LEDs is the weakest when on tiptoe and the brightest when jumping (Figure 1b and video S1). The electron-transfer process of the BISS is demonstrated in Figure 1c. When the soles contact with the floor, opposite charges are generated on both surfaces by triboelectric effects. When one of the soles lifts away from the floor, the BEP is established between the human body and the floor. If a load is connected with the human body and the ground, free electrons would be driven from the human body to the ground to balance the potential difference. Then the sole moving close to the floor leads to an opposite BEP change, which causes a reversed electron flow from the ground to the human body.

Electrical Output Characteristics and Mechanism. To study the output properties of the BISS in more detail, the experimenter puts his hand on a metal electrode (3 cm × 4 cm × 180 μm) that is connected to an oscilloscope to measure the open-circuit voltages (V_{oc}) and short-circuit currents (I_{sc}) of the BISS under three motion models with a frequency of 1 Hz. The typical outputs of the BISS are shown in Figure 2a: (1) on tiptoe, V_{oc} ~ 82 V, I_{sc} ~ 0.5 μA; (2) stepping, V_{oc} ~ 134 V, I_{sc} ~ 1.1 μA; (3) jumping, V_{oc} ~ 560 V, I_{sc} ~ 4.5 μA. The results are consistent with the previous lighting phenomena of LEDs showed in Figure 1b. The amounts of transferred charge of the BISS are 19, 90, and 161 nC that correspond to on tiptoe, stepping, and jumping, respectively (Figure 2b). The output characteristics when the BISS connected with different external loads are shown in Figure 2c. The maximum output power is ~84.7 μW, and the typical internal resistance of the BISS is ~120 MΩ.

The BISS can be used as a power source for wearable low-power electronics, but the size of the electrode should be taken into consideration. Five metal electrodes with different areas are used to estimate the influence of the electrode's size on the output of the BISS. The results demonstrate that the outputs are not significantly affected by electrode size under a certain range (≤25 cm^2), which can meet most requirements of portable and wearable electric devices (Figure 2d). Different people generate different electricity energies. Eight people put their finger on an electrode connected with a 10 μF capacitor through a rectifier. The voltages of the capacitor charged by the BISS were tested while different people stepped 100 times.

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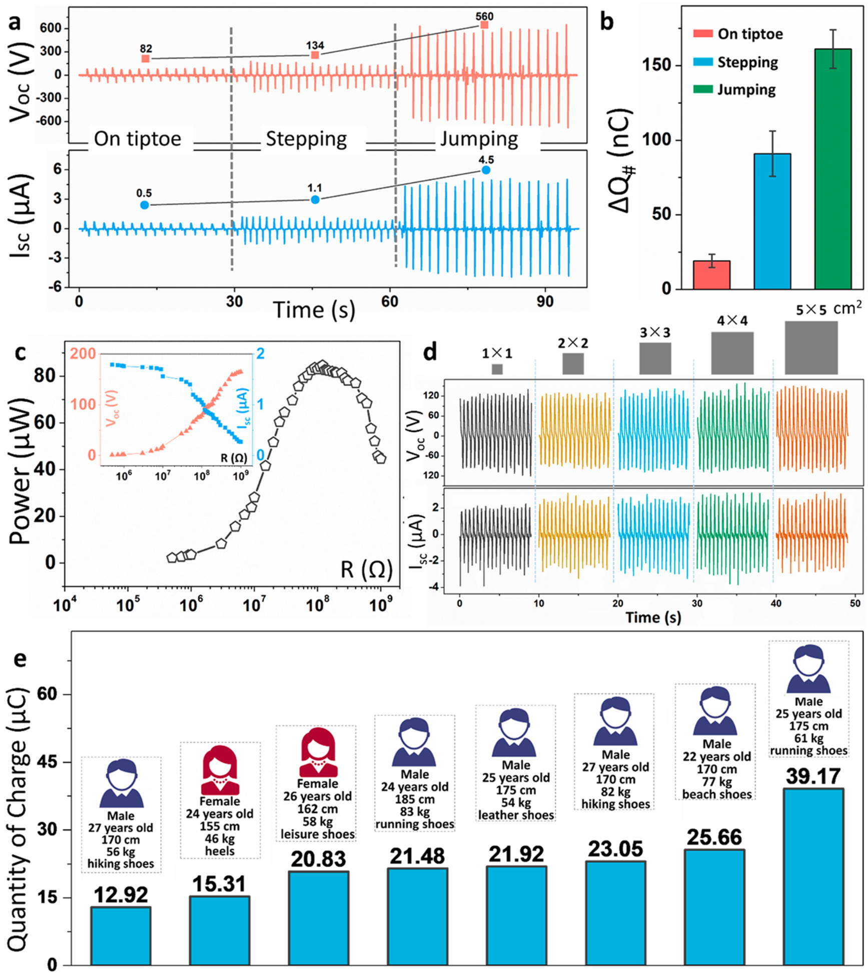

Figure 2. Typical output characteristics of the BISS. (a) Open-circuit voltage and short-circuit current when on tiptoe, stepping and jumping with the distances between heel and floor 10, 15, and 20 cm, respectively, during feet lifting. (b) Comparison of charge generated by one step with three moving models. (c) Output characteristics of the BISS when connected with different loads from 100 kΩ to 1 GΩ. (d) Outputs with different sizes of the BISS. (e) Amounts of stored charge of a 10 μF capacitor that is charged by the BISS of eight people stepping 100 times, respectively.

The equivalent electricity quantity (Q_{equ}) is calculated by $Q_{equ} = 10\ \mu\text{F} \times \text{V}$ (Figure 2e). The energy outputs are diverse among different people due to properties of the friction between their feet and the floor and because equivalent capacitances are not similar.

To further investigate the influence of the materials on the floor to the output of the BISS, a kapton film (27 cm × 12 cm × 100 μm) was pasted under the bare feet of the experimenter, and four materials including PET (90 μm thick), acrylic (2 mm thick), copper film (180 μm thick), and aluminum film (100 μm thick) with the same area of 35 cm × 20 cm are placed on the floor (Figure 3a). Considering that the thickness magnitudes of those materials are far less than the area, the influence of thickness can be ignored here. The finger touches the metal electrode that is connected with an oscilloscope. The outputs of the BISS with 15 cm foot lifting height are shown in Figure 3b. It is obvious that materials between the feet and floor significantly impacted the outputs, which is regularity compatible with triboelectric series. Meanwhile, the correlations of V_{oc}, capacitance change of body (C), and magnitude of charge (Q) in one moving cycle are studied (Figure 3c). Four testing materials (shoes, PET, Kapton, and PTFE films) are pasted under the feet. Then the left foot is moved up and down periodically, and the right foot is kept still on the floor. When the foot up, a positive voltage pulse is generated when using shoes and PET; a negative voltage pulse is generated when using Kapton and PTFE. When the foot is lowered, the direction of the pulse is reversed. It can be seen that the polarity and magnitude of charge matched with the characteristics of the voltage pulse. For example, a positive voltage corresponds to a positive charge; a higher voltage corresponds to a larger change of charge quantity.

The theoretical model of the BISS is also studied, which can be mainly explained by the methods of capacity change of the human body and charges generated by friction between the shoe sole and floor (Figure 3d). The equivalent circuit of the human body can be simplified to a capacitance and a resistance connected in series.[46−48] The relationship of quantity of electric charge (Q), equivalent capacitance of the human body (C_{body}), and the value of BEP (U) is deduced as follows

$$C_s = \varepsilon_{rs}\varepsilon_0 \frac{A}{t} \quad (1)$$

$$C_{body\text{-}s} = \frac{C_s C_f}{C_s + C_f} + C_w \approx C_s + C_w \quad (2)$$

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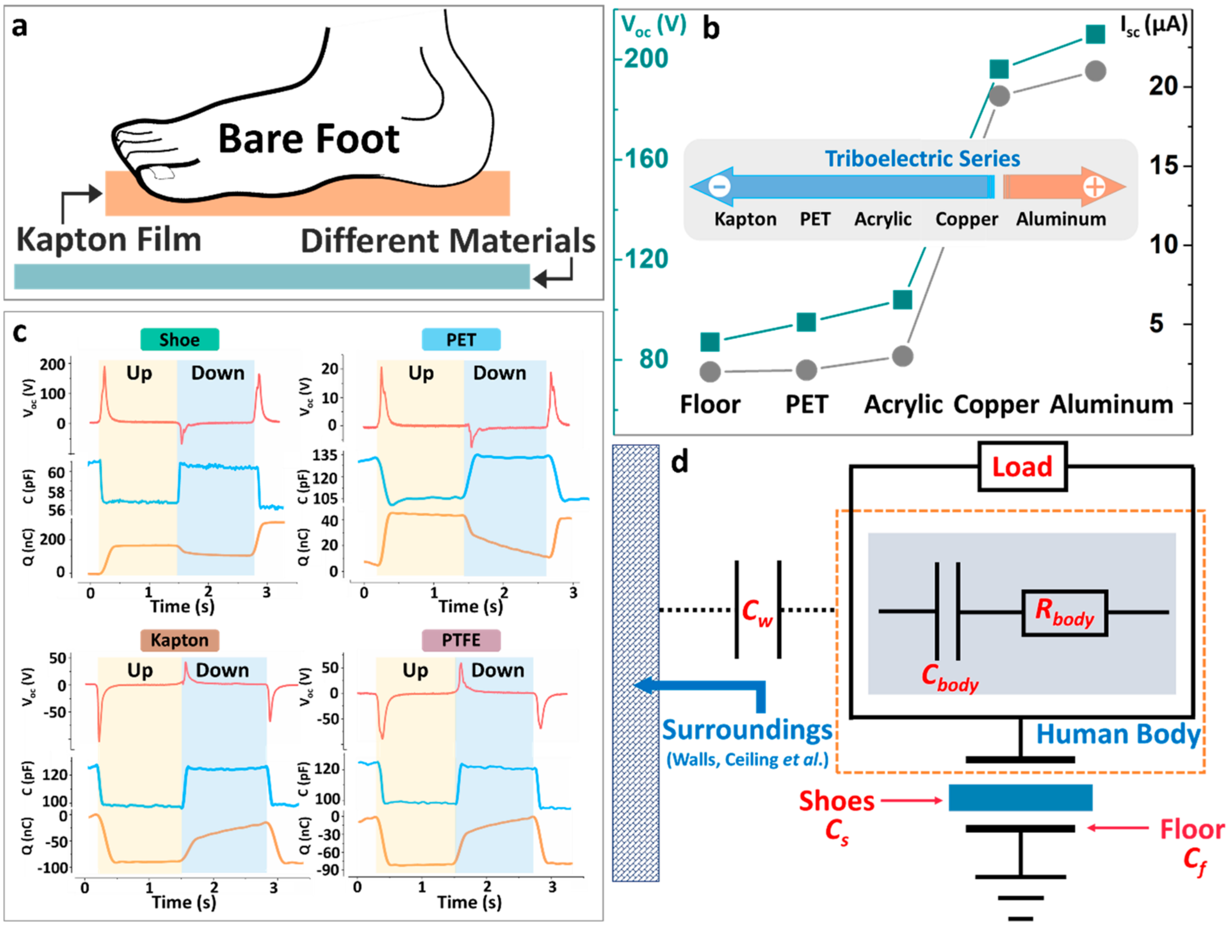

Figure 3. Output characteristics of the BISS when different materials are between the foot and floor. (a) Testing method of exploration of the influence of the materials between the bare foot and floor. (b) Open-circuit voltage and short-circuit current during stepping, where trends are accorded with triboelectric serials. (c) Results of open-circuit voltage: shoe ~185 V/−72 V, PET ~20 V/−8 V, Kapton −106 V/42 V, PTFE ~−89 V/60 V. Capacitance change of body: shoe ~56.8 pF/60.5 pF/, PET ~102.7 pF/133.2 pF, Kapton ~99.5 pF/127.9 pF, PTFE ~98.1 pF/126.9 pF. Magnitude of charge in one moving cycle (Up/Down). (d) Equivalent model of BISS.

where C_s is the capacitance of the shoes, A is the area of the soles, t is the thickness of the soles, ε_{rs} is relative permittivity of the soles, ε_0 is permittivity of vacuum, C_f is the capacitance of the floor, and C_w is the capacitance of the body related to the surroundings such as walls and ceiling. Because C_s is usually far less than C_f, the whole body capacitance when standing ($C_{body\text{-}s}$) can be simplified as shown in eq 2. During walking, the feet were alternatively lifted making an air gap between the soles and ground, which was an additional series capacitor (C_m) to $C_{body\text{-}s}$

$$C_m = \varepsilon_{ra}\varepsilon_0\frac{A}{h} \tag{3}$$

where ε_{ra} is relative permittivity of the air and h is the average distance between the sole and the floor, considering that naturally the heel and the forefoot will not be at the same level during walking. The capacitance of the body during walking (C_{body}) is deduced as follows:

$$\frac{1}{C_{body}} = \frac{1}{C_{body\text{-}s}} + \frac{1}{C_m} \tag{4}$$

Therefore, the value of BEP can be derived as

$$U = \frac{Q}{C_{body}} = \frac{h\varepsilon_{rs}\varepsilon_0 A + thC_w + t\varepsilon_{ra}\varepsilon_0 A}{\varepsilon_{ra}\varepsilon_{rs}\varepsilon_0^2 A^2 + t\varepsilon_{ra}\varepsilon_0 A C_w} Q \tag{5}$$

The U is closely related to factors including the characteristics of shoes (ε_{rs}, A, t), the surrounding environments (ε_{ra}, C_w), the height of the feet lifted when walking (h), and the instantaneous charge caused by triboelectricity (Q) with the friction between soles and floor.

***In Vitro* Applications.** A metal electrode is pasted on a table, which is used to harvest energy from the experimenter whose fingers touch the electrode. Once stepping, the generated electricity is stored into a 10 μF capacitor through a rectifier. After 50 steps, the voltage of the capacitor is charged from 0 to 1.62 V. To verify the reliability that energy generated by the BISS is able to drive an electronic device, an electronic calculator is connected to the power management unit (PMU) consisting of capacitor, rectifier, and switch, which can regulate the outputs of the BISS. After 20 steps, the 10 μF capacitor of the PMU is charged from ~1 to 1.58 V, being capable of powering the electronic calculator to finish a calculation (Figure 4a and video S2). The rectified outputs are shown in Figure 4b. For the purpose of determining whether wet or sweating conditions can influence the outputs of the BISS, a dry carbon cloth electrode is attached to the back of the hand and the outputs during stepping are measured. Then the

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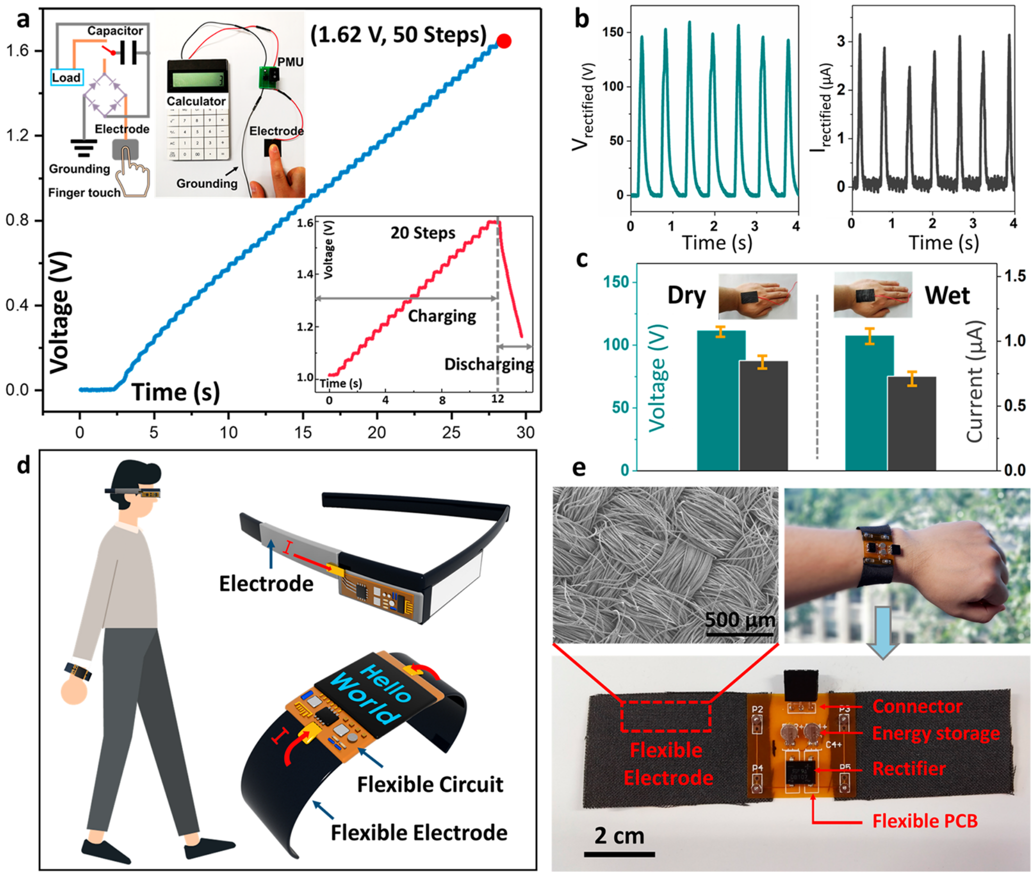

Figure 4. *In vitro* **applications of the BISS. (a) Diagram, practicality picture, and results of a 10 μF capacitor charged by the BISS. (b) Rectified voltage and current of the BISS. (c) Output comparison between different electrode conditions of dry and wet. (d) Diagram of wearable applications of the BISS. (e) Diagram of flexible wearable self-powered electronic based on the BISS.**

carbon cloth electrode is wetted by normal saline, and the outputs exhibit a small decrease but not failure (Figure. 4c). This indicates that the BISS can work normally with perspiration.

The BISS is suitable for use on wearable electronics such as smart glasses and wristbands. Conducting materials like titanium alloy, aluminum, stainless steel, and conducting polymer can be fabricated on these regions (spectacle frames or straps) of contact with skin (ear, face, and wrist) to harvest body-moving energy for powering wearable electronics (Figure 4d). Here, we fabricate a prototype to briefly describe the components of the BISS-based wearable electronics, including electrode, rectifier, energy storage device, and electrical appliance. The electrodes are made by carbon cloth, and the circuit is fabricated by a flexible printed circuit (FPC) method (Figure 4e).

***In Vivo* Performances.** For *in vivo* applications, the BISS is also an appropriate approach. A titanium alloy film with a size of 1.5 cm × 2 cm, which is cut from a metal casing of commercial pacemaker, is implanted between the skin and muscle layer in the back region of a rabbit. The titanium alloy film is connected to a pattern of NG formed by 20 LED bulbs through a conducting wire. When the rabbit moves, the LED bulbs flash rhythmically (Figure 5a and video S3). The outputs of the BISS based on the rabbit are shown in Figure 5b. The V_{oc} is ~25 V, and I_{sc} is ~80 nA (video S4). To measure the outputs of the implanted BISS quantifiably, a rat was chosen to be implanted an electrode in the same site as the rabbit's to

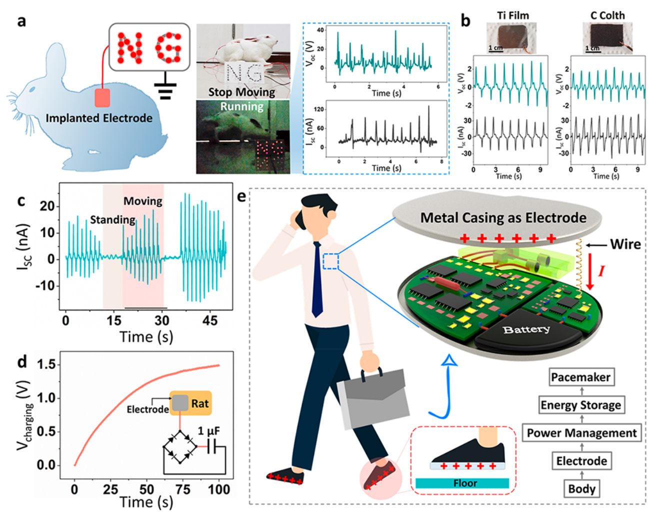

Figure 5. Implantable BISS. (a) LED bulbs lit by BISS implanted in rabbit and open-circuit voltage and short-circuit current of the BISS during running. (b) Open-circuit voltage and short-circuit current of two conductive materials (Ti film and carbon cloth) implanted in rat. (c) Short-circuit current of the BISS implanted in rat when moved up and down. (d) Charging property of the BISS implanted in rat. (e) Diagram of self-powered pacemaker based on the BISS.

form a smaller BISS, of which motions can be controlled easily. Meanwhile, to study whether the materials of the electrode

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would influence the output of the implanted BISS, titanium alloy film and carbon cloth are fabricated as implanted electrodes in the rat, respectively. Then the rat is lifted up and down gently and regularly while the outputs of the BISS based on the rat are tested (Figure 5c,d). The moving frequency is about 1 Hz. The typical V_{oc} is ~2 V, and I_{sc} is ~30 nA. There is not much difference between the output values of the two types of BISS with different electrodes. The result of a 1 μF capacitor charged by the BISS is shown in Figure 5e. To prove the feasibility of the BISS in human body, a metal electrode connected with LED bulbs is held in the experimenter's mouth, which mimics the *in vivo* environment of the human body. The LED bulbs are lit during stepping (video S5).

To illuminate the energy supply for implantable electronics by the BISS, we present a design of the self-charging cardiac pacemaker based on the BISS (Figure 5f). The metal casing is not just used for encapsulation but also acts as the electrode of the BISS. When a human walks, the generated electricity is stored in a battery or supercapacitor through the power management unit to drive the pacemaker. This is a refreshing type of self-powered cardiac pacemaker, which might have a longer working life than present designs.

CONCLUSION

In summary, we have reported a succinct and efficient device to harvest energy during body movement in a cost-effective approach, which is formed by a piece of electrode attached directly to the skin or implanted in the body. The mechanism of electricity generation is inspired by interaction of tribo-electrification and electrification of the human body during movement. The characteristics of outputs are influenced by many factors, mainly including the process of friction between shoes and the floor and capacitance changes of the body caused by feet lifting and dropping during movement. As we know, outstanding biocompatability, stability, and mechanical compliance are crucial for wearable and implantable devices. The BISS exhibits wide choices of construction materials to fabricate the most appropriate device for *in vitro* and *in vivo* applications. Furthermore, the electrode of the BISS can be made into various structures, sizes, and styles to satisfy some special requirements, such as ultrathin, super conformable, and soft, allowing the device be attached directly to the human skin with a complex surface. We have proven the feasibility for *in vivo* application by implanting the electrode subcutaneously in rabbit and rat. To present BISS usage in the human body, an electrode is placed in the experimenter's mouth, which mimics the inner environment of human body, to convert the energy during stepping. The BISS is a convenient and universal method for powering wearable and implantable electronics, which may greatly enhance development and commercialization of self-powered systems. In addition, BISS is not just an energy-harvesting device; the outputs can also be interpreted as sensing signals which have potentials for gait analysis, human activity recognition, and motion sensing.

EXPERIMENTAL SECTION

Fabrications and Electric Measurements of the BISS. An electrode of the BISS was made from various conducting materials, such as titanium, aluminum, copper, and carbon cloth. The electrode was connected to the probe of an oscilloscope (Lecroy HDO 6104) with an input impedance of 100 MΩ through a wire to measure the output voltage of the BISS. The experimenter touched his fingers to the electrode and moved under different models (on tiptoe, stepping, jumping). When current and quantum of charge of the BISS were measured, the oscilloscope was replaced by an electrometer (Keithley 6517B) with other testing conditions remaining unchanged. The types of conducting materials of the electrode had little influence to the output of the BISS in this work. The capacitance of the BISS was measured by an LCR meter (Agilent E4980A) under conditions where one probe connected to the electrode and another probe connected to the ground.

Fabrications and Measurements of Electronic Wristband Based on the BISS. The flexible circuit was fabricated by commercialized technology of flexible printed circuits (FPC). The carbon cloth electrodes were purchased from industrial suppliers. The microbattery (Seiko, MS412FE) was connected to the electrodes through a rectifier (DB107). Scanning electron microscopy (SU 8020) was used to characterize the morphology of the carbon cloth electrodes.

***In Vivo* Experiments of the BISS.** Adult rabbit (male, 2.6 kg) and Sprague−Dawley (SD) rats (male, 400−500 g) were used for this research, which were purchased from the Department of Laboratory Animal Science, Peking University Health Science Center, Beijing. The surgery procedures strictly followed the "Beijing Administration Rule of Laboratory Animals" and the national standards "Laboratory Animal Requirements of Environment and Housing Facilities (GB 14925-2001)". The anesthesia procedure of the rat started with the intake of isoflurane gas (4% in pure medical grade oxygen), followed by the injection of 1% sodium pentobarbital (intraperitoneal, 40 mg/kg) for anesthesia induction and maintenance, respectively. The devices were sterilized by ultraviolet and 75% alcohol for 4 h. A 3 cm surgical incision was made to implant the device, and the BISS was implanted between the skin and muscle layer in back region. The electrode contained in experimenter's mouth was made by a titanium alloy film which was disinfected by alcohol and ultraviolet light.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsnano.9b02233.

- Six LED bulbs are lit by BISS based on human body with three different moving modes (AVI)
- Electronic calculator is powered by BISS based on human body after stepping (AVI)
- Twenty LED bulbs are lit by implanted BISS based on rabbit (AVI)
- Outputs of implanted BISS based on rabbit (AVI)
- Twenty LED bulbs are lit by BISS based on human body with an electrode placed in the mouth to stimulate the internal environment of human body (AVI)

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Notes

The authors declare no competing financial interest.

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