



Power from the people: A review of technologies behind wearable energy harvesters

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Abstract: The dramatic reduction in electric power requirements of modern personal electronic devices has opened up the potential for human body power to sustain continuous, low-power electronic operation without adding significant user effort. This paper investigates the feasibility of harvesting energy from daily human biomechanical and metabolic activity. Four key energy conversion mechanisms are considered: Electromagnetic, Piezoelectric, Triboelectric, and Thermoelectric generation. Special attention is paid to capturing "negative work", i.e., forces absorbed during movement, such as foot-ground impacts, and waste body heat, both of which minimize the metabolic burden on the user. Since each energy transduction method has inherent limitations, current research focuses on multi-effect hybrid energy harvesters which combine mechanisms to optimize power density and continuous energy capture. However, implementation challenges continue to persist. These include mechanical fatigue, high impedance losses, and gait disruption. Even so, advances in miniaturization and flexible materials could soon enable users to power personal electronic devices through their own bodies.

Index Terms: *Energy Harvesting, Human Movement, Piezoelectric, Triboelectric, Electromagnetic, Low-energy Electronics*

1. INTRODUCTION

Throughout human history, the conversion of metabolic energy into kinetic movement has served as a primary foundation for physical work, technological development, and power generation. The human muscular system operates at a biomechanical efficiency of approximately 20% to 25% when converting metabolic food energy into mechanical work (Cicchella, 2023).

Before the widespread adoption of fossil fuels and automated steam power, human movement was the primary mechanism for building infrastructure, processing agricultural yields, and driving primitive industrial machinery. In fact, pre-Industrial societies built great structures with ingenuity and the power of human muscle. From the ancient cities of Indus Valley, to 19th century railway networks, if you wanted something built you would turn to humans who moved levers, turned cranks, and heaved on pulleys to get it done.

Industrialization, precision manufacturing, and advanced control electronics have rapidly reduced the need for human muscle to be the primary source of power in the modern world. Nevertheless, humans do produce heat and mechanical power during our day-to-day activities. This energy is usually lost as body heat, sweat, or friction that wears out footwear and clothing, since the amounts of energy that could be harvested are very small.

The 21st century has seen an exponential increase in the efficiency of electronic devices, with a corresponding decrease in size. The S9 System-on-a-chip in the 2023 Series 9 Apple Watch contains 5.6 billion transistors with an estimated maximum power consumption of 1 watt. In contrast, a first generation Intel Core i7 processor released in

2007 had 731 million transistors and was designed to use 130 watts at maximum load (Lal Shimpi, 2007; Wiggers, 2023). That is roughly an 8-fold increase in processor count, with a 130x decrease in thermal design power in 16 years. Not to mention the Apple Watch has its own screen and battery, all of which fit on one's wrist.

Modern wearable electronics are an ideal beneficiary of human-generated power, since they are highly efficient and are worn on the body for much of the day. Drawing energy from the wearer's body will also reduce the energy storage needed for all-day usage of these devices. This has other benefits such as adding more processing power or reducing the size of batteries installed on these devices. Devices such as GPS trackers can be made to work indefinitely to find missing persons even after they have lost access to a power source. This paper explores some principles of how energy can be harvested from everyday human activities.

2. MUSCLE POWER TO ELECTRIC POWER

Michael Faraday's discovery of electromagnetic induction in the 1830s showed that physical movement could be converted into electrical energy, and vice versa. As more electrical devices came into widespread use in the late 19th and early 20th centuries, engineers developed the earliest human-powered generators that could run low-power devices for short periods of time. Pedal-powered generators and hand-crank magnetos emerged as critical solutions for remote and emergency communications.

In 1929, Australian inventor Alfred Traeger developed the pedal radio, combining a bicycle pedal mechanism with a small electrical generator to power radio transmitters across the Australian Outback. During World War II, military operations relied heavily on hand-cranked generators, such as the SCR-578 "Gibson Girl" survival radio, which allowed downed aircrews to manually turn a crank handle to transmit distress signals without battery reliance (Cicchella, 2023). These mid-century systems proved that human kinetic effort could guarantee reliable, on-demand low-wattage electricity in off-grid environments.

However, these types of devices required deliberate effort from the users to generate electrical power. This makes them impractical because power sources are far more plentiful today, between improved batteries and the growth in electricity transmission networks. Commercial-grade lithium batteries have a specific energy density at least four times greater than early 20th century lead-acid batteries, and newer battery chemistries are expected to further triple or quadruple those figures (Albright et al., 2012; Machín et al., 2024). Meanwhile, nearly 92% of households across the world had access to electricity in 2023, either from utility power or distributed renewable sources (World Bank, 2023). As a result, using human effort to generate electricity is both inefficient and unnecessary in most of the world.

That being said, humans are constantly releasing energy into our surroundings through our daily activities. Any movement such as walking also requires energy. Muscular movements fall under two categories of work. The first is positive work, where muscular movement applies force to a limb and causes it to move. The second is negative work, where muscles slow down the limb or absorb external forces, such as the reaction force from the ground while taking a step. Negative work does not contribute to the effort needed to carry out the movement itself. Therefore harvesting negative work will not meaningfully increase the effort required to move (Riemer & Shapiro, 2011). Microharvesting electromechanical devices can generate electrical power from these activities and run low-power electronics. Based on theoretical maximum energy spent at each joint, Riemer and Shapiro estimate that approximately 60W is lost through negative work at the ankles, knees, hip, elbows and shoulders. However harvesting energy from multiple joints poses several challenges and is not feasible at the moment. Riemer and Shapiro estimate that 2W can be generated just from the heel striking the ground with every step.

Current research into electricity generation from human activities focuses on three electromechanical phenomena that generate electricity through movement:

- 1) Electromagnetic generation
- 2) Triboelectric generation
- 3) Piezoelectric generation

In addition to these, maintaining a core body temperature of 37°C requires the constant generation of heat which must be dissipated into the environment. Thermoelectric generation uses the temperature gradient between human skin

and the environment to generate electricity through the Seebeck effect. This is the only truly passive mechanism for electricity generation from human activity.

The following sections will discuss how each of these principles are being applied to human electricity generation.

3. ELECTROMAGNETIC GENERATORS (EMG)

As mentioned earlier, electromagnetic power generation is the oldest and most commonly used method of electricity generation at present. Apart from solar photovoltaics, every utility grade power source uses an electromagnetic generator to produce energy. Thermal power plants, whether powered by fossil fuels or nuclear fission, use steam to drive a generator. Similarly, wind and hydro power convert the kinetic energy of flowing air and water to electricity through a generator. Electromagnetic generation is a proven technology.

Current research has focused on miniaturization of the magnets and coils to fit comfortably on a human body. Researchers have taken several approaches to solve this problem. One approach uses very small coils within which even smaller magnets are suspended. When external perturbations cause the magnet to move within the coil, electricity is generated. These coils can be embedded within boots, forearm sections of jacket sleeves or other areas of clothing that can move without bending. (Li et al., 2021) estimate that a mechanism consisting of three magnet-coil pairs mounted within a single 120mm x 24mm cylinder could produce 10.5 mW during a brisk walk.

Another approach has been to embed magnetic and conducting materials into fabric to create multiple microscale magnet-coil pairs within clothing. (Zhou et al., 2026) created magnetic yarn by infusing neodymium-iron-boron powder in hollow polyurethane ribbons. These were then woven into a fabric containing conducting polyethylene fibers. Stretching and relaxing the fabric causes the magnets to move relative to the conducting fibers, producing current. Zhou et al. estimate that if such a fabric were used in jacket sleeves, it would have a power density of over 460mW / m² with arms swinging at a normal walking pace.

4. PIEZOELECTRIC GENERATORS (PEG)

The direct piezoelectric effect is a linear electromechanical interaction between mechanical and electrical states in non-centrosymmetric crystalline materials. When mechanical force applies stress to a piezoelectric material, the internal cations and anions undergo relative displacement. This spatial shift disturbs the crystal's electrical neutrality, inducing an internal electric dipole moment and generating a surface electrical polarization (H. S. Kim et al., 2011).

Walking is characterized by high force, low frequency, and variable trajectory movements. Integrating piezoelectric generators requires coupling high-strain anatomical regions with mechanical harvesters optimized for low-frequency excitation.

The foot-ground impact during walking generates compressive forces that often exceed an individual's body weight. Footwear-integrated harvesters place piezoelectric discs, cantilever beams, or flexible plates under the heel or ball of the foot. During the stance phase of walking, the heel strikes the ground, delivering high compressive stress that forces maximum charge separation across the dielectric medium. H.S. Kim et al. report that the theoretical energy density of piezoelectric generators is 3 to 5 times higher than electromagnetic devices. The challenge has been to create durable piezoelectric materials that can withstand the normal wear and tear that clothing experiences.

Effective harvesters must balance electromechanical coupling with structural flexibility. Two classes of piezoelectric materials are emerging as possible solutions for wearable generators.

- **Piezoelectric Ceramics:** Materials such as Lead Zirconate Titanate ($\text{Pb}(\text{Zr}_{1-x}\text{Ti}_x)\text{O}_3$ or PZT) and Barium Titanate (BaTiO_3) possess exceptionally high piezoelectric coupling coefficients ($d_{33} \approx 300 - 600 \text{ pC/V}$). However, their inherent brittleness makes them prone to mechanical fatigue under cyclic human loading unless embedded in protective polymer matrices (Roundy et al., 2003).

- **Piezoelectric Polymers:** Polyvinylidene Fluoride (PVDF) and its copolymer PVDF-TrFE offer lower piezoelectric coefficients ($d_{33} \approx -30 \text{ pC/V}$) but exhibit superior mechanical flexibility, high breakdown strength, and

excellent biocompatibility. These properties allow PVDF to conform seamlessly to skin, clothing, and flexible footwear insoles (Yang et al., 2018).

5. TRIBOELECTRIC GENERATION

While electromagnetic and piezoelectric power generation are based on 19th and 20th century principles, triboelectric power generation is essentially ancient technology in a 21st century wrapper. At its core, a triboelectric generator relies on two primary phenomena: the triboelectric effect and electrostatic induction. When two dissimilar materials with distinct electron affinities come into physical contact, surface charge transfer occurs, leaving one material positively charged and the other negatively charged. Upon mechanical separation, a potential difference is established, driving the flow of electrons between back-side electrodes on each surface to re-establish electrical equilibrium.

Z.L. Wang invented the first triboelectric nanogenerator (TENG) in 2012. TENG devices operate primarily through four fundamental mechanical configurations (W.-G. Kim et al., 2021; Wang, 2013) :

- **Vertical Contact-Separation Mode:** The two friction surfaces move perpendicularly toward and away from each other, suitable for foot-strikes or pressing actions.
- **Lateral Sliding Mode:** The materials maintain contact while sliding relative to one another, generating electricity via lateral displacement (common in fabric and joint motion).
- **Single-Electrode Mode:** Features a single grounded electrode connected to a mobile triboelectric layer, making it ideal for harvesting energy directly from human skin touch without trailing wires.
- **Freestanding Triboelectric-Layer Mode:** A moving dielectric layer slides or bounces between two symmetrical, stationary electrodes without direct wiring to the moving object.

TENGs are uniquely suited for harvesting biomechanical movement because their energy conversion efficiency remains high even at low operating frequencies. In addition, TENGs can be produced from a wide variety of highly biocompatible materials, making them even more suitable as wearable energy harvesting devices (Karimmirza & Manavizadeh, 2025). TENGs can be used in footwear insoles, woven into clothing, or even as patches on prominent joints such as elbows and knees. Karimmirza and Manavizadeh were able to generate 10mW of power at a normal walking pace from TENGs made of silicone with embedded silver nanoparticles. This is comparable to the electromagnetic coil arrangement proposed by (Li et al., 2021)

6. THERMOELECTRIC GENERATORS (TEGS)

Unlike the three types of generators discussed earlier, thermoelectric generators (TEGs) are truly passive and do not require physical movement to function. TEGs are solid-state devices with no moving parts that convert thermal energy directly into electrical energy. The underlying physical principle is the Seebeck effect, discovered by Thomas Johann Seebeck in 1821. When a temperature gradient exists across a conductive or semiconducting material, electrical charge carriers (electrons or holes) diffuse from the hot junction to the cold junction, establishing an internal electric field. The potential difference between the junctions is proportional to the temperature gradient ΔT .

The resting human body continuously dissipates metabolic heat at a rate of approximately 100W. This results in a thermal flux of 20-60W/cm² across the skin tissue. However, physical movement greatly increases this thermal output. Skeletal muscles convert food energy into mechanical movement with an efficiency of only 20% to 25% due to complex multi-step metabolic processes and negative work discussed earlier.. The remaining 75% to 80% is dissipated as waste metabolic heat. During strenuous exercise metabolic energy expenditure can go as high as 1000W, which means metabolic heat generation can approach 800 W (Cicchella, 2023).

Human movement enhances TEG performance through two primary mechanisms:

- **Elevated Skin Temperature and Heat Flux:** Physical exertion triggers vasodilation, increasing cutaneous blood flow to dump excess internal heat to the skin surface. This elevates skin surface temperature (T_h), widening the temperature differential relative to ambient air (T_a).
- **Forced Convective Cooling:** Movement through space creates relative airflow across the outer surface of the wearable TEG. This forced convection drastically increases the heat transfer coefficient on the cold side (T_c), preventing heat buildup and maintaining a sharp ΔT across the TEG junctions (Mytafides et al., 2021)

To efficiently harvest energy from the contoured and dynamic human body, modern engineering has shifted from rigid, brittle inorganic semiconductors (like bismuth telluride, Bi_2Te_3) toward flexible thermoelectric generators (FTEGs). FTEGs incorporate conductive polymers (such as PEDOT:PSS) or organic-inorganic nanocomposites printed onto stretchable elastomer substrates or woven into smart textiles (M.-K. Kim et al., 2014).

Worn as wristbands, chest straps, or clothing linings, FTEGs capture body heat continuously. The surface temperature of human skin typically ranges from 32°C to 35°C. An ambient temperature of 20°C, provides a ΔT of 12-15°C. Under these conditions, wearable TEGs have power densities ranging from 5 to 30 $\mu\text{W}/\text{cm}^2$. During vigorous movement, increased airflow and skin heating can boost output to several hundred microwatts; sufficient to power low-power pulse oximeters, heart-rate monitors, and wireless Bluetooth Low Energy (BLE) transmitters without battery assistance (Soleimani et al., 2020).

7. HYBRID HARVESTING IMPROVES EFFICIENCY AND UTILITY

As mentioned earlier, human movement is broad, irregular, and low-frequency, yielding complex kinetic profiles alongside continuous thermal dissipation. Therefore, relying on a single transduction mechanism has inherent limitations. To overcome the performance bottlenecks of isolated harvesters, modern research has turned toward multi-effects hybrid energy harvesters (HEHs). By integrating electromagnetic generators (EMGs), piezoelectric generators (PEGs), triboelectric nanogenerators (TENGs), and thermoelectric generators (TEGs) into unified structural architectures, hybrid devices harvest multiple physical phenomena simultaneously. This multi-transduction paradigm significantly increases overall power density, broadens frequency response bandwidth, and achieves continuous, reliable micro-energy output from everyday human locomotion and metabolic activity (Li et al., 2024)

Combining multiple transduction effects does not merely add power outputs sequentially, but fundamentally alters the overall thermodynamic and electromechanical efficiency of the energy harvesting system in three key ways:

7.1. Spectral and Kinetic Complementarity

Individual harvesters operate efficiently only within narrow operational regimes: EMGs require high relative velocities, PEGs require large mechanical stresses, TENGs excel at low-frequency displacements, and TEGs depend on thermal gradients regardless of motion velocity. A hybrid system decouples energy capture from a single mechanical state variable. When an individual walks slowly, TENGs and TEGs maintain steady micro-power output; when that individual breaks into a sprint, PEGs and EMGs scale up exponentially to capture high-impact kinetic forces.

7.2. Impedance Matching and Power Management Optimization

A primary challenge in energy harvesting is managing output impedance mismatches:

In single-effect harvesters, transforming high-voltage/low-current outputs (TENGs) or low-voltage/high-current outputs (EMGs) to match energy storage units (e.g. lithium batteries) results in substantial power losses within power management circuits. Hybrid architectures utilize custom multi-channel power conditioning networks. High-voltage TENG pulses can be used to actively bias or switch active rectifiers for low-voltage EMG circuits, effectively raising overall system conversion efficiency (Iqbal et al., 2021).

7.3. Spatial and Parasitic Energy Extraction

In single-mechanism devices, substantial input mechanical energy is dissipated unused as parasitic thermal heat or uncaptured friction. Hybrid harvesters reclaim these secondary energy losses. For instance, mechanical friction generated during the sliding contact of a TENG produces localized frictional heating, which can be captured by an underlying TEG layer. Similarly, the shock absorption of a foot strike, which is typically lost to mechanical dampening, is simultaneously harvested as high-impact stress by a PEG and wide-area surface displacement by a TENG (Iqbal et al., 2021).

Current research has identified promising hybridization strategies, which are summarized in Table 1.

Hybrid Coupling Pair	Mechanical Mechanism	Practical Wearable Implementation
PEG + TENG	Combined compression and surface friction	Shoe insoles where heel-strike pressure flexes a piezoelectric PVDF film while the sliding contact between insole layers simultaneously drives a TENG layer.
EMG + TENG	Magnetic displacement triggering mechanical contact	A swinging backpack or wrist-worn pendulum contains a moving magnet that induces coil current (EMG) while its outer casing periodically impacts a triboelectric membrane (TENG).
TEG + Kinetic (PEG/TENG)	Thermal flux integrated with surface movement	A smart wristband whose flexible inner layer captures metabolic heat via TEGs, while its outer fabric layer experiences joint friction and skin contact to drive TENG/PEG output.

Table 1: Hybrid energy harvesting strategies currently under development (Iqbal et al., 2021; Wang, 2013; Yang et al., 2018)

8. CHALLENGES AND LIMITATIONS TO PASSIVE BIOMECHANICAL ENERGY HARVESTING

Significant scientific, engineering, and ergonomic barriers limit the widespread usage of wearable passive generators. Some of these barriers are described in this section.

- Frequency and Motion Mismatch:** Electromagnetic and piezoelectric generators perform optimally under high-frequency (>100 Hz), resonant conditions. Translating low-velocity, non-linear human movements (such as gait or joint flexion) into high-frequency excitation requires complex mechanical gearboxes or motion-up-conversion mechanisms, which add weight, bulk, and mechanical friction losses (Cicchella, 2023; Riemer & Shapiro, 2011).
- Electrical Impedance Mismatch:** Transduction methods like triboelectric nanogenerators (TENGs) produce high open-circuit voltages (> 100V) but extremely low short-circuit currents, yielding high internal impedance. Conversely, conventional microelectronics operate at low impedance and low DC voltages (1.8-3.3V). Converting and regulating these irregular AC pulses into usable DC power results in substantial energy dissipation across rectification circuits and voltage step-down converters (Iqbal et al., 2021).
- Metabolic Cost:** If an energy harvesting device increases the user's effort or disrupts natural biomechanical gait cycles, it incurs a metabolic penalty. Studies show that poorly designed joint or foot harvesters force the user to expend significantly more food calories than the micro-watt or milli-watt electrical equivalent retrieved, limiting their viability for daily use (Donelan et al., 2008).
- Material Fatigue and Environmental Degradation:** Flexible polymers (like PVDF) and triboelectric surfaces experience material fatigue, degradation, and surface wear over millions of cyclic movements. Furthermore,

environmental factors like atmospheric humidity and perspiration degrade the electrostatic surface charges of TENGs, drastically reducing electrical power output during exercise (Karimmirza & Manavizadeh, 2025; H. S. Kim et al., 2011).

9. CONCLUSION

The human body is a marvel of biochemical and biophysical capabilities. However, it also loses energy to the environment through the inherent complexity of its metabolic processes and the hard realities of physics. 100 W in thermal losses at rest and 60 W in the negative work of walking, and other similar losses are significant amounts of energy per person. These losses serve physiological purposes. For instance, the negative work of walking provides the brain with kinematic information about the ground surface and fatigue at each muscle. However, a sizable amount of lost energy could be harvested by devices that are light and do not significantly impede movement.

Future research that focuses on the miniaturization of harvesting devices, coupled with lighter batteries and more efficient power electronics, could give every person the ability to run personal electronic devices just off their own power. Such harvesting devices could even provide people with an additional incentive to exercise. Jogging both for your health and to charge your smartphone could get more people off their couches and out onto the street.

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