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Review Article

Wearable self-powered biosensors

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Abstract

Wearable self-powered biosensors are devices that operate without an external electronic power source or onboard battery and that use a biorecognition detection element to relay sensing information. Such devices are becoming more widespread following the larger trend of more ubiquitous wearable devices in general. Self-powering can be a particularly important characteristic in situations where replacing/recharging a battery is either impossible or impractical. Most wearable self-powered biosensors rely primarily on enzymatic reactions to supply the energy required for operation, but there are also other innovative approaches that combine multiple signal transduction techniques to simultaneously provide power and produce a detection signal. Areas of needed research include developing higher power energy harvesting techniques and more wearable self-powered biosensor devices that have integrated low-power wireless electronics.

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Keywords

Wearables, Self-powered, Biosensors.

Introduction

Twenty years ago, wristwatches were nearly the only wearable devices on the market. Today, an array of commercial wearable devices exists that are capable of performing electrocardiography while at the same time measuring acceleration and global positioning [1]. There are currently roughly 73 million wearable devices in the United States alone and the outlook is quite healthy with 18.3% growth projected from 2018 to 2021 [2]. Wearables are here to stay and their impact will influence the medical field by advancing the trend toward more personalized, patient-controlled health care.

Now that wearable devices are commonplace, users desire them to have advanced capabilities. In this regard, there are two important current thrusts that provide the backdrop for this mini-review. One current research push is to remove the need for external electronic power or rechargeable batteries. Another very active research area is to augment wearable devices so they are capable of extracting information from body fluids, which would provide real-time biological information potentially useful for medical diagnostics. Wearable devices with these two capabilities would continuously collect biological data for diagnostic and predictive purposes and be able to perform maintenance-free month after month. This would have major impacts on health care, for both high-risk individuals and the general population. For example, self-powered maintenance-free remote patient-monitoring devices could reduce the length of hospital stays and significantly decrease health care costs across the board.

While the broader wearables landscape includes many health trackers and other devices that monitor various biological systems, this review focuses solely on those that fulfill multiple specific criteria: they are wearable, self-powered, and are biosensors (see Figure 1). This subset of wearable electronic devices is an important class of wearables, but they currently only exist as academic prototypes with limited functionality and there are few examples in the academic research literature.

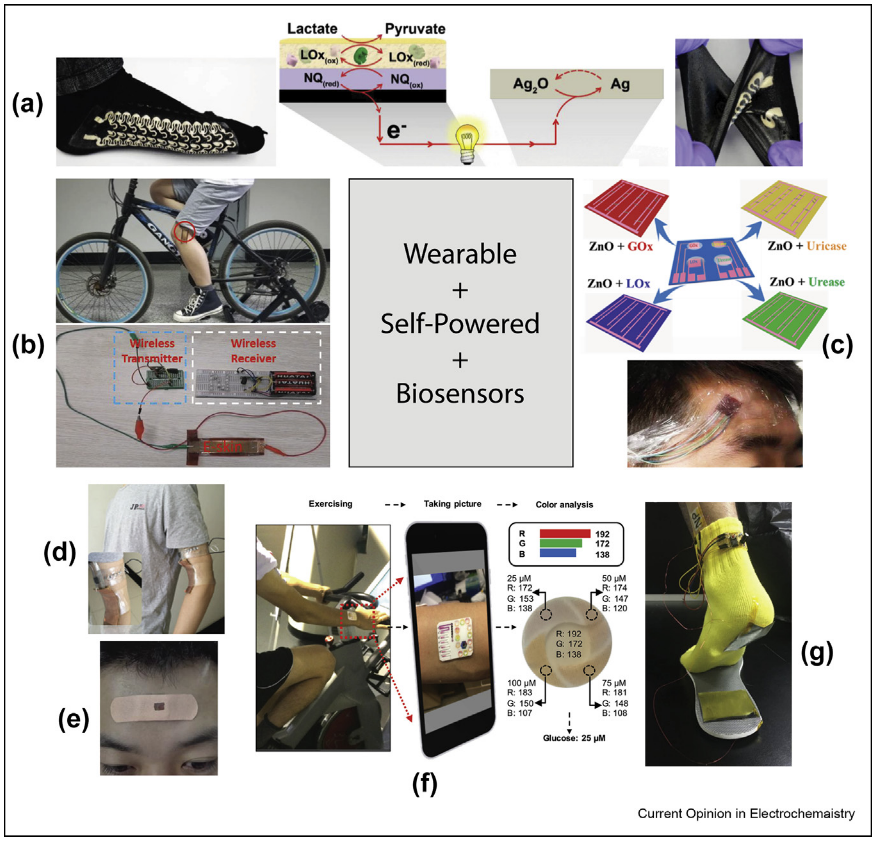
Definitions

For the sake of clarity, it is important to define the three terms that together describe the devices in this brief review because scientific and engineering literature is often inconsistent in how these terms are used when labeling devices. The three key terms that must be defined are wearable, self-powered, and biosensor.

Wearable

Wearable refers to a device that is worn on the body as opposed to one that is implanted. Garments, skin patches, contact lenses, and mouthguards are wearable because they are noninvasive or minimally invasive and can be applied and removed without the need of medical assistance or specialized equipment/tools. Even skin patches with microneedle arrays can be considered

Figure 1



Examples of wearable self-powered biosensors. **(a)** A textile glucose/lactate biosensor powered by a hybrid Lox/Ag_2O BFC, adapted from Ref. [20] with permission from the Royal Society of Chemistry. **(b)** Ca^{2+} biosensor powered by a TENG/enzymatic reaction coupling, adapted with permission from Ref. [30], copyright 2019 American Chemical Society. **(c)** Lactate, glucose, uric acid, urea biosensor patch powered by ZnO piezoelectricity, adapted with permission from Ref. [27], copyright 2017 American Chemical Society. **(d)** A Na^+, K^+, urea, uric acid, lactate, glucose biosensor patch, adapted from Ref. [28] with permission from The Royal Society of Chemistry. **(e)** Lactate biosensor powered by an enzymatic anode and photovoltaic cathode, adapted from Ref. [22], with permission from the Royal Society of Chemistry. **(f)** Sweat loss/rate, pH, temperature, chloride, glucose, lactate biosensor that used colorimetric detection, adapted with permission from Ref. [29], copyright 2019 American Chemical Society. **(g)** On-ankle lactate biosensor powered by a TENG (on the heel), adapted from Ref. [18], copyright 2017, with permission from Elsevier.

wearable devices because the microneedles are small enough to be pain-free [3] and the user can quickly and easily apply and remove the patch without a doctor or special tools. There are excellent reviews that highlight recent progress in wearable devices, some of which are cited here [2,4,5].

Self-powered

Self-powered is a term that is used differently throughout the literature. The original self-powered biosensor published by Katz et al. [6] was self-powered in the sense that the detection signal was an electrical power output that was directly related to analyte (in their case, glucose or lactate) concentration. Self-powered has also been used to refer to a microneedle array that uses capillary action instead of active pumping to transport biological fluids to the sensor [7]. Still, other devices are labeled self-powered if the energy required for operation is harvested from ambient heat, vibration, light, radio frequency emissions, chemicals, etc. The reader is pointed to recent reviews for an excellent overview of self-powering methods for sensors [8–10].

Regardless of how the term “self-powered” is used, researchers generally consider their device self-powered as long as at least one principal device function (i.e. bio-signal transduction, power/signal conditioning, or data transmission) occurs without relying on a battery or wireless power transmission. A truly self-powered device, under ideal conditions, is capable of full functionality for an unlimited amount of time without any energy source beyond what is already available in/on the device or naturally occurs in its surroundings.

Biosensors

Biosensors are analytical devices that use a biological detection element [10,11], which could be an enzyme, nucleic acid, tissue, bacteria, organelle, or similar biomimetic component. The biorecognition element interacts with the analyte and transduces the interaction into a detectable signal (e.g. electrical, optical, etc.). The bio-prefix, therefore, refers to the recognition element and not necessarily to the substance that is being detected or to the living subject being monitored.

Wearable self-powered biosensors

There are many excellent examples of wearable sensors and wearable biosensors, such as those described in recent comprehensive reviews [4,5,11]. However, there are fewer examples of wearable sensors that are self-powered and even fewer of those are biosensors. Most of the existing wearable biosensors are powered by wireless induction, radio frequency transmission, and lithium batteries.

Available and required energy

There is theoretically more than enough energy in body heat, motion, bodily fluid chemical bonds, sunlight, etc., to power wearable biosensors. For example, a theoretical analysis by Riemer and Shapiro [12] found that up to 2 W of electrical power could be harvested using a thermoelectric transducer covering a person as they walk. The authors' analysis also concluded that approximately 34 W and 20 W of harvestable power is available from knee and ankle movement, respectively (without preventing normal motion). The theoretical power that can be harvested from lactate in tears using a lactate/oxygen biofuel cell during exercise (assuming 10 mM lactate) is nearly 0.1 mW [13] and, using a similar calculation with 60 mM lactate [14], 0.6 mW can be extracted from sweat. Direct normal solar irradiance is approximately 0.02 W cm^{-2} [15], so a 100-cm^2 solar cell with 10% efficiency could produce 200 mW. Of course, these rough estimates are for illustration only and do not include many factors that would affect power output in reality.

The amount of power needed to operate a wearable biosensor varies depending on various factors, such as the type of biosensor (e.g. electrochemical, colorimetric, etc.), measurement frequency, and data transmission. Intermittent sensing and wireless data transmission commonly require hundreds of μW during peak consumption [16,17]. To supply this power, a wearable self-powered biosensor may harvest chemical or kinetic energy and use it to charge a capacitor. Once the capacitor charges to a certain voltage, it discharges the energy that is used to take the sensor measurement and/or wirelessly transmit data [18,19]. Biosensor operation requires a steady power source but most ambient energy sources vary in time. For example, light intensity changes depending on the time of day, cloud cover, and if the person is inside or outside. Diet and physical activity affect the concentration of lactate and glucose in body fluids and also affects the amount of harvestable biomechanical and biothermal energy. Therefore, an energy storage component such as a rechargeable battery [20], capacitor [18,19], or supercapacitor [21] is essential for practical wearable self-powered biosensors.

Examples of wearable self-powered biosensors

Table 1 contains a summary of recent examples of wearable self-powered biosensors. Biofuel cells (BFCs) are commonly used for self-powered wearable biosensors [20,22–24] because they combine detection and power supply, simplifying the design. Lactate oxidase and glucose oxidase (both generally mediated) are common biorecognition elements. Self-powered BFC sensors have been screen-printed on socks [20] and integrated onto a Band-Aid [23] and even on a diaper [25]. AC–DC signal rectification is not needed for a BFC power supply because it does not produce an AC signal; however, power conditioning is still necessary because the voltage from a single BFC is generally not sufficiently high [26] and the signal is not constant due to variations in analyte concentration. Other recent wearable self-powered biosensors use enzymatic reactions coupled with either the piezoelectric effect [27], the triboelectric effect [28] or streaming potential [19]. In these instances, enzymatic reactions contributed to charge carrier density, which modified the piezoelectric or triboelectric voltage or the streaming potential. The voltage change was correlated to the analyte concentration.

Wearable biosensors powered by triboelectric nanogenerators (TENGs) are becoming increasingly popular because of their inexpensive, flexible materials, and simple construction. Chen, Lee, et al. powered their lactate biosensor using a contact-separation TENG consisting of polydimethylsiloxane and gelatin [18]. The TENG charged a capacitor at 1 Hz for 30 s to 0.1 V and then a single lactate measurement could be taken. In addition, the TENG provided the energy needed to supply power to electrochemically deposit metal nanoparticles on carbon fibers during sensor fabrication.

Another very promising approach for wearable biosensors is to altogether remove the need for a power source by using colorimetric detection zones that respond to the analyte concentration. Existing smartphone imaging tools can be calibrated to determine analyte concentration based on sensor color. Eliminating power source dependence has obvious advantages and could make colorimetric wearable biosensor devices very widespread, similar to home pregnancy tests. An excellent example of a colorimetric wearable biosensor is an adhesive sweat patch created by Choi, Bandodkar, et al. [29], which had various colorimetric microfluidic reservoirs that could separately detect sweat loss/rate, pH, temperature, as well as chloride, glucose, and lactate concentrations. An ongoing challenge for this device is making it reusable because the glucose and lactate sensors were irreversible.

Table 1

Recent examples of wearable self-powered biosensors.

What was detected	Biorecognition element(s)	Where worn	Power source	Comments	Ref.
Glucose or lactate in sweat	GOx or LOx	In a sock on foot	Glucose or lactate BFC	The first textile BFC biosensor. Wireless data transmission was battery powered.	[20]
Lactate in sweat	LOx	Forehead	LOx anode/photovoltaic cathode	The photoelectric BFC could operate on lactate or light exposure.	[22]
Lactate in artificial sweat	LOx	Sensor on ankle and TENG on heel	TENG	The TENG charged a capacitor sufficiently for a lactate measurement every 30 s.	[18]
Lactate, glucose, uric acid, urea in sweat	LOx, GOx, uricase, urease	Forehead	ZnO piezoelectric effect	The enzymatic reaction contributed charge carriers to the ZnO, which shielded the piezo effect when strained.	[27]
Glucose in sweat	GOx	Arm	Glucose/O_2 BFC	Paper-based sensor defined with a wax printer, integrated onto a Band-Aid	[23]
Na^+, K^+, urea, uric acid, lactate, glucose in sweat	Urease, LOx, GOx, uricase, b-galactosidase, pyruvate kinase	Elbow	Polyaniline-PDMS TENG coupled to enzymatic reactions	Elbow bending action provided the pumping force to cycle sweat through the device.	[28]
Sweat loss/rate, pH, temperature; chloride, glucose, lactate in sweat	GOx, LOx	Forearm, forehead, torso, armpit	None (colorimetric)	Temperature, chloride and pH sensors were reversible but the glucose and lactate sensors were not.	[29]
Lactate in sweat	LOx	Forehead	Anodic enzymatic reaction	Power came from the combination of the enzymatic reaction and the streaming potential due to evaporation. Measurements could be transmitted once an hour.	[19]
Glucose in artificial urine	GOx	On a diaper	Glucose/O_2 BFC	The device hasn't been field tested and didn't have wireless capability.	[25]
Ca^{2+} in sweat	Nicotinamide adenine dinucleotide phosphate oxidase 5 (NOX5) and NADPH	Knee	Polyaniline-PDMS TENG coupled to enzymatic reactions	The device was connected to a breadboard wireless transmitter for demonstrating future wireless capability.	[30]

PDMS, polydimethylsiloxane.

Key areas for device development

While the number of biosensor examples that are both wearable and self-powered is still small, there are many exciting recent examples of research that advance the supporting technology needed for future wearable self-powered biosensors.

Compliant materials

Wearable devices must be—to one degree or another, depending on their function—flexible enough to conform to the body to obtain accurate biological information. This is especially true for wearable biosensors because their usefulness requires a continuous supply of uncontaminated, unmodified biological fluid samples, which makes the device–body interface a critical aspect. For skin-worn patch biosensors, a continuous supply of fresh sweat samples has been accomplished using microfluidic channels that transport fluid through in a thin substrate by capillary action [29] or using iontophoretic delivery of a chemical sweat stimulator [31]. However, for oral [32] or ocular [33] wearable biosensors, which are somewhat continuously bathed in body fluid, the interface may not be as crucial as it is for sweat sensors.

Wearable biosensors must also have high mechanical stability and maintain electrical conductivity after many deformation cycles. A recent wirelessly powered contact lens glucose biosensor was reported that contained all its sensor and wireless components within the lens [33]. Transparent thin-film islands and silver nanofibers provided support and electrical wiring. A recent self-powered glucose sensor printed electronic circuits on nanocellulose membranes that proved to be very flexible and easily adhered to other substrates [34]. Another example is a textile BFC-supercapacitor that could harvest energy from sweat using a lactate/Ag_2O hybrid BFC to charge a MnO_2-CNT supercapacitor [35]. 37 min of exercise was sufficient to charge the supercapacitor to 0.4 V. The device maintained 86% of its power output after 100 cycles of 20% strain. These examples illustrate the two most commonly used substrates for wearable biosensors: thin polymer films and textiles. Each of these has its advantages [36]; e.g., polymers can adhere and conform more closely with the skin, eye, mouth, etc., and allow easier electrode patterning, but textiles are more breathable, can cover larger areas, and have more mature production techniques.

Energy harvesting and storage

Portable power sources have for many years struggled to keep up with device requirements. New and improved energy transduction mechanisms are being pursued so that the power supply does not dominate device volume. This is especially important for wearables. One interesting example of a novel energy harvesting method was a self-powered polyvinylidene fluoride–based wearable respiration monitoring sensor that harnessed the required energy from exhaled air [37]. In this system, the polyvinylidene fluoride–based piezoelectric transducer converted nasal airflow pressure into an electrical signal, which was utilized to power up read-out electronics. The generated charge/current integrated over a capacitance created the AC voltage signal with a frequency ranging from 0.1 Hz to 1 Hz, depending on the respiration rate. A custom full-wave rectifier was able to achieve 52.2% power conversion efficiency and a voltage conversion efficiency of 98.7%, which was comparable with the prior published works with a much lower input power [38].

The form factor and volumetric power density of power sources can be improved through multifunctional designs that integrate power sources and structure such as textile-based solar cells [39], thermoelectric generators [40], TENGs [41], piezoelectric generators [42], and biofuel cells [20] or that combine multiple energy harvesting techniques. For example, a recent composite textile consisting of photovoltaic and TENG fibers was capable of simultaneously harvesting solar and mechanical energy [43]. Another example of multifunctionality are biosupercapacitors, which combine energy-harvesting BFCs and pseudocapacitor energy storage into one material [21,44,45].

Energy-harvesting circuit design and low-power design schemes

The energy-harvesting circuitry of ambient sources typically includes AC to DC rectification, a voltage regulation circuit, and a charge storing elements, such as a battery or supercapacitor, to store the generated power while dissipating the minimum possible current. The objectives of the power management circuit are to maximize harvested power and minimize energy dissipation. Moreover, the power management circuitry needs to adapt to a varying input excitation when no stored energy is available, thus requiring some initial startup mechanisms [46]. Tabesh et al. in Ref. [47] presented some of the requirements of these circuit designs in terms of efficiency, stand-alone operation, circuit complexity, and adaptivity. Performance metrics such as the minimum input power level or the ability of the circuit to achieve the maximum output power need to be considered. Another challenge is developing an efficient rectifier and DC–DC converter topologies that can start up with input voltages of hundreds of millivolts [48]. In addition, the challenges associated with harvesting energy from complex, nonsinusoidal vibrations or kinetic movements with varying magnitude and frequency need to be addressed to utilize kinetic/vibration energy as an alternative power source.

Low-power design schemes are very important for future wearable biosensors that use ambient energy sources or natural movement. Wireless radio communication poses the most significant energy consumption problem necessitating a design trade-off/optimization between the communication and computation capability of the sensor. Because the transmitter usually consumes most of the power in a sensor system, any reduction in the power consumption of the transmitter block is expected to decrease the overall power consumption by tenfold [49]. One of the approaches for reducing the average power consumption is to duty-cycle the radio so that the transmitter is active only for a short period dissipating only the leakage power. An example is impulse-radio ultrawideband architecture that converts the baseband data into an impulse signal to be transmitted wirelessly to a remote receiver [49–53]. In these radios, it is necessary to make sure the leakage power or the "off-state" power is significantly lower than the active power to reduce the overall power consumption.

As the power generated by an energy-harvesting system (e.g. electromagnetic, thermoelectric, piezoelectric or electrostatic) is very low, to generate a useable DC voltage from the harvested energy, the design of a voltage-boosting rectifier is important. One of the downsides of the existing diode-based rectifier circuits is that they require at least 500–700 mV of input voltage. Zero-turn on voltage transistors could be used instead but they require expensive fabrication processes [54]. Recent work in this area includes multistage voltage-boosting rectifiers, voltage doublers, voltage multipliers, and DC–DC converters that used standard CMOS processes [55–60]. To rectify the current generated by the transducer, typically full-bridge rectifiers are used because of their simplistic design. However, the low conversion efficiency of full-bridge rectifiers limits the output power, especially when the input signal is low in amplitude [61,62].

Conclusions

Although there are relatively few examples of wearable self-powered biosensors, the pace of progress indicates that we will soon see many more examples that are sophisticated and fully functional, including those that are capable of wireless data transfer. However, market acceptance of these devices completely hinges on demonstrating that they provide reliable sensing over extended periods (consecutive days or possibly even many months). There are a number of challenges impeding accurate long-term self-powered operation, such as low power conversion efficiency, electrode biofouling, biorecognition element stability, and body fluid transport through the device [11]. Once these challenges are addressed, motivation for creating self-powered biosensors will increase dramatically. Until then, it will be difficult for wearable self-powered biosensors to compete against wearable biosensors that use well-established power sources, such as rechargeable batteries and wireless power transfer.

Conflict of interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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References

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. Dunn J, Runge R, Snyder M: **Wearables and the medical revolution**. *Pers Med* 2018, **15**:429–448, https://doi.org/10.2217/pme-2018-0044.

2. • Mück JE, Ünal B, Butt H, Yetisen AK: **Market and patent analyses of wearables in medicine**. *Trends Biotechnol* 2019, **37**: 563–566, https://doi.org/10.1016/j.tibtech.2019.02.001.
This is a broad market overview of wearable electronics and, more specifically, wearable medical devices.

3. Prausnitz MR: **Microneedles for transdermal drug delivery**. *Adv Drug Deliv Rev* 2004, **56**:581–587, https://doi.org/10.1016/j.addr.2003.10.023. 2004/03/27.

4. •• Heikenfeld J, *et al.*: **Wearable sensors: modalities, challenges, and prospects**. *Lab Chip* 2018, **18**:217–248, https://doi.org/10.1039/C7LC00914C. 10.1039/C7LC00914C.
This is a very good comprehensive review of wearable sensors written by some of the most prominent wearable sensor research groups.

5. • Ray TR, *et al.*: **Bio-integrated wearable systems: a comprehensive review**. *Chem Rev* 2019, **119**:5461–5533, https://doi.org/10.1021/acs.chemrev.8b00573. 2019/04/24.
This is a very detailed review. Although portions of the content can be found separately in other reviews, this review synthesizes the information in one place and also includes additional original perspectives.

6. •• Katz E, Bückmann AF, Willner I: **Self-powered enzyme-based biosensors**. *J Am Chem Soc* 2001, **123**:10752–10753, https://doi.org/10.1021/ja0167102. 2001/10/31.
This is the first self-powered enzymatic biosensor and is also the origin of the term "self-powered biosensor."

7. Strambini LM, *et al.*: **Self-powered microneedle-based biosensors for pain-free high-accuracy measurement of glycaemia in interstitial fluid**. *Biosens Bioelectron* 2015, **66**: 162–168, https://doi.org/10.1016/j.bios.2014.11.010. 2015/04/15.

8. Lou Z, Li L, Wang L, Shen G: **Recent progress of self-powered sensing systems for wearable electronics**. *Small* 2017, **13**, 1701791, https://doi.org/10.1002/smll.201701791.

9. Conzuelo F, Ruff A, Schuhmann W: **Self-powered bioelectrochemical devices**. *Curr Opin Electrochem* 2018, **12**: 156–163, https://doi.org/10.1016/j.coelec.2018.05.010. 2018/12/01.

10. Grattieri M, Minteer SD: **Self-powered biosensors**. *ACS Sens* 2018, **3**:44–53, https://doi.org/10.1021/acssensors.7b00818. 2018/01/26.

11. • Kim J, Campbell AS, de Ávila BE-F, Wang J: **Wearable biosensors for healthcare monitoring**. *Nat Biotechnol* 2019, **37**: 389–406, https://doi.org/10.1038/s41587-019-0045-y. 2019/04/01.
This review contains excellent graphics and tables summarizing the progress and current state of wearable biosensors. In addition, future

prospects are discussed with a focus on how to make wearable biosensors that actually make it to the marketplace.

12. Riemer R, Shapiro A: **Biomechanical energy harvesting from human motion: theory, state of the art, design guidelines, and future directions**. *J NeuroEng Rehabil* 2011, **8**:22, https://doi.org/10.1186/1743-0003-8-22. 2011/04/26.

13. Reid RC, Minteer SD, Gale BK: **Contact lens biofuel cell tested in a synthetic tear solution**. *Biosens Bioelectron* 2015, **68**: 142–148, https://doi.org/10.1016/j.bios.2014.12.034. 2015/06/15.

14. Sakharov DA, Shkurnikov MU, Vagin MY, Yashina EI, Karyakin AA, Tonevitsky AG: **Relationship between lactate concentrations in active muscle sweat and whole blood**. *Bull Exp Biol Med* December 01 2010, **150**:83–85, https://doi.org/10.1007/s10517-010-1075-0. Journal article.

15. https://globalsolaratlas.info/. (accessed August 10, 2019.

16. Lee H, *et al.*: **Toward all-day wearable health monitoring: an ultralow-power, reflective organic pulse oximetry sensing patch**. *Sci Adv* 2018, **4**:eaas9530, https://doi.org/10.1126/sciadv.aas9530.

17. Oletic D, Bilas V: **System-level power consumption analysis of the wearable asthmatic wheeze quantification**. *J Sensors* 2018, **18**, https://doi.org/10.1155/2018/6564158. 2018, Art no. 6564158.

18. Chen C-H, Lee P-W, Tsao Y-H, Lin Z-H: **Utilization of self-powered electrochemical systems: metallic nanoparticle synthesis and lactate detection**. *Nano Energy* 2017, **42**: 241–248, https://doi.org/10.1016/j.nanoen.2017.10.064. 2017/12/01.

19. Guan H, *et al.*: **A self-powered wearable sweat-evaporation-biosensing analyzer for building sports big data**. *Nano Energy* 2019, **59**:754–761, https://doi.org/10.1016/j.nanoen.2019.03.026. 2019/05/01.

20. Jeerapan I, Sempionatto JR, Pavinatto A, You J-M, Wang J: **Stretchable biofuel cells as wearable textile-based self-powered sensors**. *J Mater Chem* 2016, **4**:18342–18353, https://doi.org/10.1039/C6TA08358G. 10.1039/C6TA08358G.

21. • Bobrowski T, González Arribas E, Ludwig R, Toscano MD, Shleev S, Schuhmann W: **Rechargeable, flexible and mediator-free biosupercapacitor based on transparent ITO nanoparticle modified electrodes acting in μM glucose containing buffers**. *Biosens Bioelectron* 2018, **101**:84–89, https://doi.org/10.1016/j.bios.2017.10.016. 2018/03/15.

This is the first example of a flexible, transparent biosupercapacitor. The authors used enzymatic reactions to charge ITO nanoparticles and the device powered a low-voltage display. Potential applications: transparent wearable electronics such as electronic contact lenses.

22. Yu Y, Zhai J, Xia Y, Dong S: **Single wearable sensing energy device based on photoelectric biofuel cells for simultaneous analysis of perspiration and illuminance**. *Nanoscale* 2017, **9**: 11846–11850, https://doi.org/10.1039/C7NR04335J. 10.1039/C7NR04335J.

23. Cho E, Mohammadifar M, Choi S: **A self-powered sensor patch for glucose monitoring in sweat**. In *IEEE 30th international conference on micro electro mechanical systems (MEMS)*, vols. 22–26; 2017:366–369, https://doi.org/10.1109/MEMSYS.2017.7863417. Jan. 2017 2017.

24. Garcia SO, Ulyanova YV, Figueroa-Teran R, Bhatt KH, Singhal S, Atanassov P: **Wearable sensor system powered by a biofuel cell for detection of lactate levels in sweat**. *ECS J Solid State Sci Technol* 2016, **5**:M3075–M3081, https://doi.org/10.1149/2.0131608jss.

25. Shitanda I, Fujimura Y, Nohara S, Hoshi Y, Itagaki M, Tsujimura S: **Paper-based disk-type self-powered glucose biosensor based on screen-printed biofuel cell array**. *J Electrochem Soc* 2019, **166**:B1063–B1068, https://doi.org/10.1149/2.1501912jes.

26. Gamella M, Koushanpour A, Katz E: **Biofuel cells – activation of micro- and macro-electronic devices**. *Bioelectrochemistry* 2018, **119**:33–42, https://doi.org/10.1016/j.bioelechem.2017.09.002. 2018/02/01.

27. • Han W, *et al.*: **A self-powered wearable noninvasive electronic-skin for perspiration analysis based on piezo-biosensing unit matrix of enzyme/ZnO nanoarrays**. *ACS Appl Mater Interfaces* 2017, **9**:29526–29537, https://doi.org/10.1021/acsami.7b07990. 2017/09/06.

This paper is one in a series from a group researching the unique approach of using enzymatic reactions to modify the piezoelectric or triboelectric effect. The change in voltage can be measured without any external power source.

28. He H, *et al.*: **A self-powered electronic-skin for real-time perspiration analysis and application in motion state monitoring**. *J Mater Chem C* 2018, **6**:9624–9630, https://doi.org/10.1039/C8TC03296C. 10.1039/C8TC03296C.

29. •• Choi J, *et al.*: **Soft, skin-integrated multifunctional microfluidic systems for accurate colorimetric analysis of sweat biomarkers and temperature**. *ACS Sens* 2019, **4**:379–388, https://doi.org/10.1021/acssensors.8b01218. 2019/02/22.

Excellent example of a zero-power colorimetric biosensor with a sophisticated microfluidic sweat collection system. Extensive characterization and field testing were performed.

30. Zhao T, *et al.*: **A self-powered biosensing electronic-skin for real-time sweat Ca^{2+} detection and wireless data transmission**. *Smart Mater Struct* 2019, **28**, 085015, https://doi.org/10.1088/1361-665x/ab2624. 2019/07/01.

31. Sonner Z, Wilder E, Gaillard T, Kasting G, Heikenfeld J: **Integrated sudomotor axon reflex sweat stimulation for continuous sweat analyte analysis with individuals at rest**. *Lab Chip* 2017, **17**:2550–2560, https://doi.org/10.1039/C7LC00364A. 10.1039/C7LC00364A.

32. Kim J, *et al.*: **Wearable salivary uric acid mouthguard biosensor with integrated wireless electronics**. *Biosens Bioelectron* 2015, **74**:1061–1068, https://doi.org/10.1016/j.bios.2015.07.039. 2015/12/15.

33. Park J, *et al.*: **Soft, smart contact lenses with integrations of wireless circuits, glucose sensors, and displays**. *Sci Adv* 2018, **4**, eaap9841, https://doi.org/10.1126/sciadv.aap9841.

34. • Yuen JD, *et al.*: **A fully-flexible solution-processed autonomous glucose indicator**. *Sci Rep* 2019, **9**:6931, https://doi.org/10.1038/s41598-019-43425-x. 2019/05/06.

This paper describes a self-powered flexible glucose biosensor coupled with a flexible, self-adhering nanocellulose prited circuit board, which contained a charge pump, capacitor, and LED. The LED could continuously flash when the biosensor was in contact with glucose and the entire device could collapse down to an area of 0.25 cm^2.

35. • Lv J, *et al.*: **Sweat-based wearable energy harvesting-storage hybrid textile devices**. *Energy Environ Sci* 2018, **11**:3431–3442, https://doi.org/10.1039/C8EE02792G. 10.1039/C8EE02792G.

Although not technically a biosensor, the device in this paper is notable because it is the first example of a textile BFC-supercapacitor that harvests energy from sweat. The fabrication is well-explained and the resulting device appears quite mature.

36. Bandodkar AJ, Jeang WJ, Ghaffari R, Rogers JA: **Wearable sensors for biochemical sweat analysis**. *Annu Rev Anal Chem* 2019, **12**:1–22, https://doi.org/10.1146/annurev-anchem-061318-114910.

37. Mahbub I, Oh T, Shamsir S, Islam SK, Pullano S, Fiorillo A: **Design of a pyroelectric charge amplifier and a piezoelectric energy harvester for a novel non-invasive wearable and self-powered respiratory monitoring system**. In *IEEE region 10 humanitarian technology conference (R10-HTC), 2017*. IEEE; 2017:105–108.

38. Zhang Q, Gu L, Yang K, Halim MA, Rantz R, Roundy S: **Kinetic energy harvesting using improved eccentric rotor architecture for wearable sensors**. In *IEEE sensors, 2016*. IEEE; 2016: 1–3.

39. Jinno H, *et al.*: **Stretchable and waterproof elastomer-coated organic photovoltaics for washable electronic textile applications**. *Nat Energy* 2017, **2**:780–785, https://doi.org/10.1038/s41560-017-0001-3. 2017/10/01.

40. Allison LK, Andrew TL: **A wearable all-fabric thermoelectric generator**. *Adv Mater Technol* 2019, **4**, 1800615, https://doi.org/10.1002/admt.201800615.

41. Dong K, *et al.*: **3D orthogonal woven triboelectric nanogenerator for effective biomechanical energy harvesting and as self-powered active motion sensors**. *Adv Mater* 2017, **29**, 1702648, https://doi.org/10.1002/adma.201702648.

42. Lund A, Rundqvist K, Nilsson E, Yu L, Hagström B, Müller C: **Energy harvesting textiles for a rainy day: woven piezoelectrics based on melt-spun PVDF microfibres with a conducting core**. *npj Flex Electron* 2018, **2**:9, https://doi.org/10.1038/s41528-018-0022-4. 2018/03/22.

43. Chen J, *et al.*: **Micro-cable structured textile for simultaneously harvesting solar and mechanical energy**. *Nat Energy* 2016, **1**:16138, https://doi.org/10.1038/nenergy.2016.138. 09/12/online.

44. Pankratov D, González-Arribas E, Blum Z, Shleev S: **Tear based bioelectronics**. *Electroanalysis* 2016, **28**:1250–1266, https://doi.org/10.1002/elan.201501116.

45. Shleev S, González-Arribas E, Falk M: **Biosupercapacitors**. *Curr Opin Electrochem* 2017, **5**:226–233, https://doi.org/10.1016/j.coelec.2017.09.023. 2017/10/01.

46. Sze N-M, Ki W-H, Tsui C-Y: **Threshold voltage start-up boost converter for sub-mA applications**. In *4th IEEE international symposium on electronic design, test and applications*. IEEE; 2008:338–341.

47. Tabesh A, Fréchette LG: **A low-power stand-alone adaptive circuit for harvesting energy from a piezoelectric micropower generator**. *IEEE Trans Ind Electron* 2009, **57**:840–849.

48. •• Ramadass YK, Chandrakasan AP: **A battery-less thermoelectric energy harvesting interface circuit with 35 mV startup voltage**. *IEEE J Solid State Circuits* 2010, **46**:333–341.
This is an excellent example of a battery-less thermoelectric energy harvesting circuit that extracts electrical energy from human body heat. An efficient control circuit is proposed to maximize the power transfer to the storage capacitor.

49. Mahbub I, Shamsir S, Islam SK: **A low-Power low-data rate impulse radio ultra-wideband (IR-UWB) transmitter**. *Int J High Speed Electron Syst* 2017, **26**, 1740013.

50. Lee G, Park J, Jang J, Jung T, Kim TW: **An IR-UWB CMOS transceiver for high-data-rate, low-power, and short-range communication**. *IEEE J Solid State Circuits* 2019, **54**(8).

51. Mahbub I, Islam SK, Fathy A: **Impulse radio ultra-wideband (IR-UWB) transmitter for low power low data rate biomedical sensor applications**. In *IEEE topical conference on biomedical wireless technologies, networks, and sensing systems (BioWireleSS), 2016*. IEEE; 2016:88–90.

52. Mahbub I, Shamsir S, Islam S, Pullano SA: **Low-power low-data-rate IR-UWB transmitter for pediatric apnea monitoring system**. *IET Circuits, Devices Syst* 2019:494–498, https://doi.org/10.1049/iet-cds.2018.5334.

53. Na K, Jang H, Ma H, Choi Y, Bien F: **A 200-Mb/s data rate 3.1–4.8-GHz IR-UWB all-digital pulse generator with DB-BPSK modulation**. *IEEE Trans Circuits Syst II: Express Briefs* 2015, **62**:1184–1188.

54. Yao Y, Wu J, Shi Y, Dai FF: **A fully integrated 900-MHz passive RFID transponder front end with novel zero-threshold RF–DC rectifier**. *IEEE Trans Ind Electron* 2008, **56**:2317–2325.

55. Tasneem NT, Suri SR, Mahbub I: **A low-power CMOS voltage boosting rectifier for wireless power transfer applications**. In *Texas symposium on wireless and microwave circuits and systems (WMCS), 2018*. IEEE; 2018:1–4.

56. Suri RS, Tasneem NT, Mahbub I: **Low-power highly efficient voltage-boosting rectifier for wide-band inductively-coupled power telemetry**. In *United States national committee of URSI national radio science meeting (USNC-URSI NRSM), 2019*. IEEE; 2019:1–2.

57. Li X, Tsui C-Y, Ki W-H: **A 13.56 MHz wireless power transfer system with reconfigurable resonant regulating rectifier and wireless power control for implantable medical devices**. *IEEE J Solid State Circuits* 2015, **50**:978–989.

58. Lee EK: **A voltage doubling passive rectifier/regulator circuit for biomedical implants**. In *IEEE custom integrated circuits conference (CICC), 2015*. IEEE; 2015:1–4.

59. Wu C-Y, Qian X-H, Cheng M-S, Liang Y-A, Chen W-M: **A 13.56 MHz 40 mW CMOS high-efficiency inductive link power supply utilizing on-chip delay-compensated voltage doubler rectifier and multiple LDOs for implantable medical devices**. *IEEE J Solid State Circuits* 2014, **49**:2397–2407.

60. Silveira GC, Tofoli FL, Bezerra LDS, Torrico-Bascopé RP: **A nonisolated DC–DC boost converter with high voltage gain and balanced output voltage**. *IEEE Trans Ind Electron* 2014, **61**:6739–6746.

61. Khaligh A, Zeng P, Zheng C: **Kinetic energy harvesting using piezoelectric and electromagnetic technologies—state of the art**. *IEEE Trans Ind Electron* 2009, **57**:850–860.

62. Szarka GD, Stark BH, Burrow SG: **Review of power conditioning for kinetic energy harvesting systems**. *IEEE Trans Power Electron* 2011, **27**:803–815.