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A Technology for Soft and Wearable Generators

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1. Introduction

Never again needing to recharge the batteries of portable electronic devices is an exciting prospect. The uptake of portable electronics is increasing and recharging or replacing batteries is not only an inconvenience, but also contributes to an environmental hazard. Furthermore, with technologies such as GPS, pressure sensors, and cameras becoming smaller and cheaper, smart clothing such as the Adidas miCoach range are now a reality [1]. For seamless integration of smart devices into clothing, the inconvenience of battery replacement or recharging needs to be eliminated.

Conveniently there is an alternative source of energy in the exact location where portable and wearable devices operate: biomechanical energy from human movements. Interestingly, the device often credited as being the first ever power generator was a biomechanical energy harvester. 17th century engineer Otto von Guericke produced a sulfur globe which was charged through the triboelectric effect[1] when it was rubbed with a dry hand [2]. However, four centuries later the ability to harvest appreciable amounts of energy from biomechanical motions remains a research challenge. In this chapter we will discuss recent progress towards harvesting biomechanical energy using a soft and wearable electro-active polymer technology.

To provide sufficient power for portable devices a biomechanical energy harvester needs to supply in the order of a few Watts. For instance, an insulin pump consumes approximately 5 Watts [3] and the Nexus One smartphone (HTC Corporation, Taiwan) consumes 25 milli-Watts in standby, 330 milli-Watts in idle, and 750 milli-Watts during a phone call [4]. So to eliminate the need to recharge batteries, a similar or greater quantity of power needs to be sourced.

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[1] The triboelectric effect refers to the transfer of electrons between two materials when they come into contact. Some materials are more susceptible to donating electrons when the contact is separated and some are more likely to hold on to electrons so the materials remain charged when separated.

Starner and Paradiso provide a good review of the energy available for scavenging from human movement and identify walking as a rich source of energy [5]. They highlight that 13 Watts of power is available from the heel-strike of a 68Kg person if the sole of their shoe is compressed by 1cm when walking at 2 steps per second. Furthermore, a typical running shoe midsole dissipates a relatively large amount of energy as heat. Shorten's analysis of the energetics of a shoe midsole worn by a 76Kg runner suggests that a running shoe will dissipate between 2 and 10 Joules per step [6]. A well designed energy harvesting shoe could instead turn this energy into electricity, without altering the comfort or energy expenditure of the person wearing the shoe.

The most prevalent energy harvesting technology, electromagnetic generators, have been used to harvest energy from human gait, but additional mechanisms are required to condition the mechanical energy [5, 7]. Donelan et al. developed a knee-brace generator for harvesting energy from human gait. Their generator contained auxiliary components including a gear train, bearings, and a separate input shaft to convert the mechanical energy to suit their electromagnetic generator. Their system cost on average 59W of metabolic power to carry without harvesting energy, whereas an additional 5W of metabolic power was required to produce 4.8W of electrical power [7]. Although their harvesting mechanism was extremely efficient, they could have achieved larger efficiency gains if their system's mass was reduced and the device did not alter gait patterns. This begs the question: why are auxiliary mechanical components required for an electromagnetic biomechanical energy harvester?

The system by Donelan et al. was relatively heavy because it required additional componentry for it to work efficiently: electromagnetic generators produce more energy during a single rotation or stroke as velocity increases and are poorly suited for the low induced velocities associated with walking unless augmented mechanically. Thus the viability of harvesting energy from human motions could be improved by utilizing a different energy harvesting technology.

We propose the key characteristics of an ideal technology for harvesting biomechanical energy below:

1. Efficient operation at low biomechanical "walking" speeds.
2. Ability to couple directly to large walking motions.
3. A high energy density.
4. Good mechanical impedance matching to muscle.
5. Cheap to produce and maintain.

The first two criteria eliminate the need for additional mechanisms to condition the mechanical energy when it is transferred to the generator. The first three criteria therefore provide low mass/bulk. By having good impedance matching to muscle, the generator will be comfortable to wear, reducing its effects on the person wearing it. For the mass market, it is essential that the generator is low cost because consumers are unlikely to pay a premium for generators that produce power of approximately 1 Watt.

The research efforts of the authors of this chapter have focused on an energy harvesting technology called dielectric elastomer generators (DEG) which have been identified as a

highly promising technology for biomechanical energy harvesting [8-11]. Furthermore, DEG fit the five listed criteria particularly well, so this chapter will focus on our recent developments towards portable and wearable DEG. For the interested reader, Anderson et al. provide a good, broad review of dielectric elastomer transducers [12].

2. The dielectric elastomer generator

DEG are a class of variable capacitance generators that are fabricated from a rubbery dielectric material sandwiched between stretchable electrodes. They have excellent impedance matching to natural muscle [13], can be fabricated from a wide range of low cost materials (commonly acrylic or silicone membranes sandwiched between carbon-based electrodes), have demonstrated extremely high energy densities, can undergo strains in excess of 100% [14], and have the ability to work over a wide frequency range without sacrificing efficiency [15].

Mechanical energy can be converted to electrical energy by cyclically deforming a DEG and placing charges on its flexible electrodes in the deformed state. DEG are typically produced from incompressible polymers so that an area stretch results in a decreased thickness. Relaxation of the charged, deformed DEG forces the opposite charges apart and packs like charges closer together and this transfers the mechanical energy to the electrical charges. The energy flows during an ideal DEG cycle are highlighted by the red arrows in Figure 1. The system receives 1 unit each of mechanical and electrical energy and converts the unit of mechanical energy into electrical, so that it outputs two units of electrical energy.
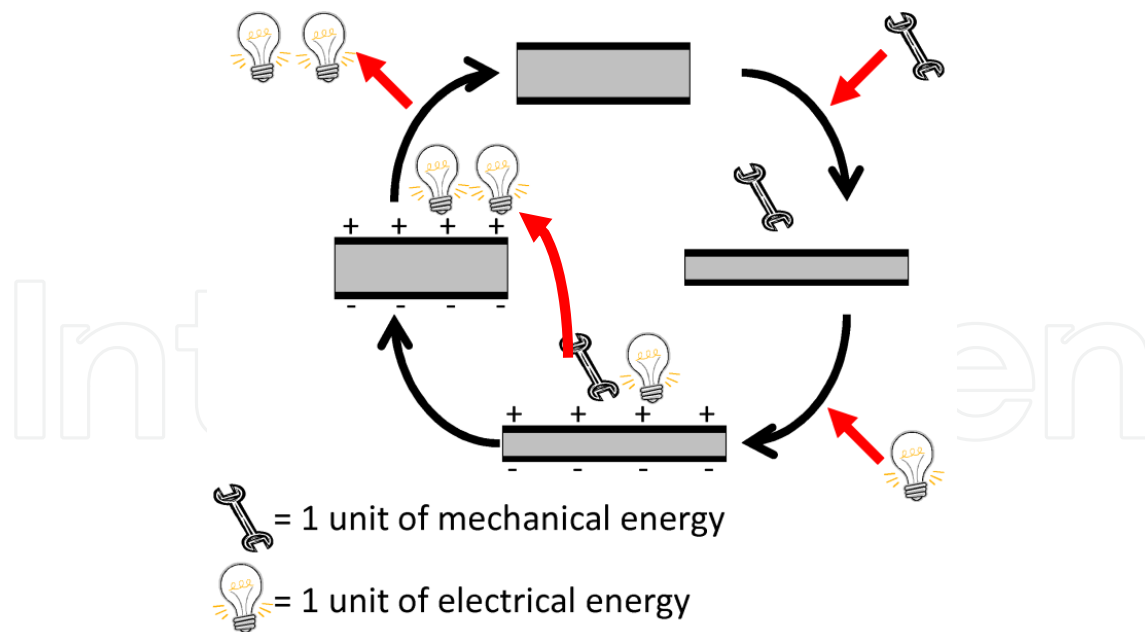

Figure 1. Schematic of the DEG states during a generation cycle. The grey area represents the dielectric and the black area represents the electrodes. From top moving clockwise, mechanical energy is input to the system deforming the DEG; an electrical energy input then charges the stretched DEG; the mechanical energy is then transferred to the charges by separating opposite and compressing like charges together. The electrical energy is then extracted and the cycle repeats (From [16]).

The major advantage that DEG hold for biomechanical energy harvesting is their ability to directly harvest low frequency motions without any gear mechanisms. To illustrate why this is true we will briefly describe their fundamental energy harvesting mechanism. As illustrated in Figure 1, DEG convert mechanical energy to electrical when the deformation of a stretched charged DEG is relaxed. During this relaxation period the thickness of the dielectric increases and the electrode area decreases, both resulting in a reduction of the capacitance. If charge is trapped on the generator during this relaxation phase, the voltage on the DEG will increase and there will be an increase in energy given by equation 1 where C_d and V_d are the capacitance and voltage of the DEG in its deformed state, and C_r and V_r are the relaxed DEG's capacitance and voltage, respectively.

$$E = 0.5 C_r V_r^2 - 0.5 C_d V_d^2 \qquad (1)$$

Since we are considering the case where the charge on the DEG is fixed during the relaxation period, and that the charge on a capacitor can be calculated from its voltage and capacitance ($Q=CV$), we can relate the voltage of the deformed DEG to the voltage of the generator in its relaxed state using equation 2. We substitute equation 2 into equation 1 to get equation 3.

$$V_R = \frac{C_d}{C_r} V_d \qquad (2)$$

$$E = 0.5 \left(\frac{C_d^2}{C_r} - C_d \right) V_d^2 \qquad (3)$$

These equations emphasise that along with driving voltage, C_r and C_d are the key parameters that influence the energy output of a DEG. The capacitance is dependent on the geometry of the DEG and the driving voltage is controlled by the generator's associated electronics. Neither of these parameters are dependent on the velocity at which the generator is deformed, so the fundamental mechanism of DEG is not dependent on driving velocity.

Although we have highlighted that DEG have a highly suitable mechanism and characteristics for harvesting biomechanical energy, Figure 1 highlights that DEG need an electrical circuit that will control the flow of charge onto and off of the generator at appropriate stages of the energy harvesting cycle. Such circuitry can add weight and is typically composed of stiff and bulky parts. Furthermore the requirement for the electronics to replace charge delivered to the load has traditionally reduced the portability of DEG because they have been either tethered to the grid or used batteries that need periodic replacement [10]. This chapter will focus now on recent developments that eliminate the need for a secondary power source and reduce external DEG circuitry mass and stiffness.

3. Portable dielectric elastomer generator electronics

A passive DEG circuit for controlling the charge state of the DEG appropriately as it is mechanically cycled called the Self-Priming Circuit (SPC) [17, 18] has been developed to

eliminate the need for a secondary power source and thus improve DEG portability. The circuit works as a charge pump that provides energy in a higher charge form than the energy supplied to it. The self-priming circuit is configured so that it harvests energy from a DEG and then supplies that energy in a higher charge form to a load or to the DEG when it requires priming. This effectively boosts the charge of the generated energy before it is used, thus a secondary power source is not necessary because the generated energy is used to replace circuit charge losses and charge delivered to the load. A schematic of the simplest form of an SPC is given in Figure 2, showing that an SPC is simply a capacitor bank that has diodes to convert the topology of the circuit between a low capacitance when it is charged (Figure 2c, capacitors in series) and a high capacitance when it discharges (Figure 2d, capacitors in parallel). This toggling of state provides the SPC with a higher output capacitance which converts the energy to a higher charge form. This can be explained using equation 4, which provides two expressions for the energy (E) stored on a capacitor. If the energy is conserved when the capacitance (C) of the SPC increases, then the charge (Q) must increase too, and since the SPC is an adiabatic process the increased charge is accompanied by a decreased voltage (V). Thus the SPC outputs energy in a higher charge, lower voltage form than the input.

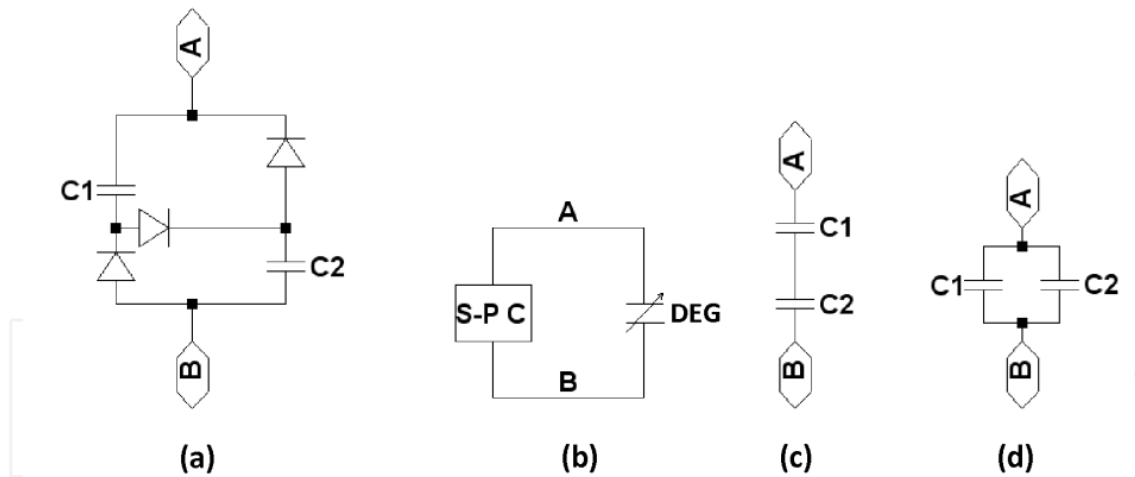$$E = \frac{Q^2}{2C} = \frac{CV^2}{2} \tag{4}$$

Figure 2. Schematic of a self priming circuit (a) which connects to a DEG in parallel (b), the diodes control current flow so that the SPC capacitor bank takes on the form given in (c) when energy is transferred to it from the DEG, when energy is transferred off the SPC the diodes configure it to take on the higher charge form given in (d).

The SPC has additional benefits for portable DEG. First, the SPC is passive and requires no active switching or control, so it does not require any power to drive it. Second, the SPC accumulates charge from cycle to cycle, this means that the system voltage climbs (see Figure 3). The ability to boost its own voltage is highly desirable because as demonstrated in equation 3, generated energy climbs with priming voltage. This high voltage has

traditionally been supplied by a high voltage power supply or converter, so the SPC eliminates the need for these typically high cost components.
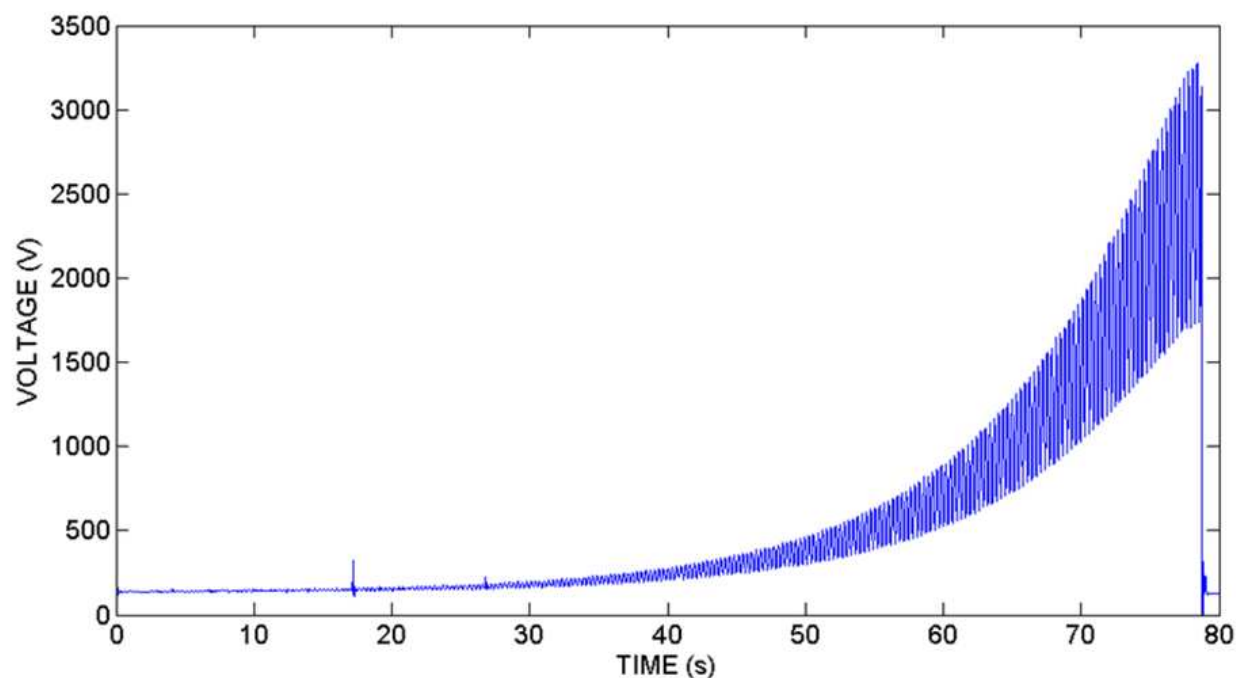

Figure 3. The output voltage waveform of a self-priming generator mechanically deformed at 3 Hz. The voltage climbs from cycle to cycle because the generated energy accumulates in the form of extra charge stored on the generator and priming circuit (From [19]).

Although the SPC is low cost, low complexity, and autonomous it still adds considerable mass and stiffness to the DEG system. The SPC consists of diodes and capacitors. The function of the capacitors is to store priming charges and the diodes control the transfer of charge to and from the DEG, so that an appropriate generation cycle is achieved. We will now discuss how these functions have been integrated onto the DEG membrane to produce a generator that can be fabricated entirely from soft elastomers.

4. Dielectric elastomer generators with integrated soft electronics

The DEG membrane is essentially a soft capacitor and one can take advantage of this, using the DEG to provide the energy storage function of the SPC. This means the generator can be fabricated with its external circuitry consisting solely of a few diodes [16, 20]. One configuration that has been used to integrate the SPC storage function into the DEG membrane is given in Figure 4 where DEG1 is electrically configured as an SPC [16]. Because the generator's elastomer membranes are integrated into the self-priming circuit, this system has been referred to as the integrated self-priming circuit [21]. The generator was configured into two DEG membranes which were deformed so that as one membrane was stretched the other was relaxed. When the voltage of DEG1A and DEG1B connected electrically in parallel exceeded the voltage of DEG2, energy was transferred from the SPC to DEG 2 through the path shown in Figure 4c; when the voltage of DEG2 exceeded that of

DEG1A and DEG1B connected in series, energy was transferred onto the SPC from DEG2 through the path shown in Figure 4d.
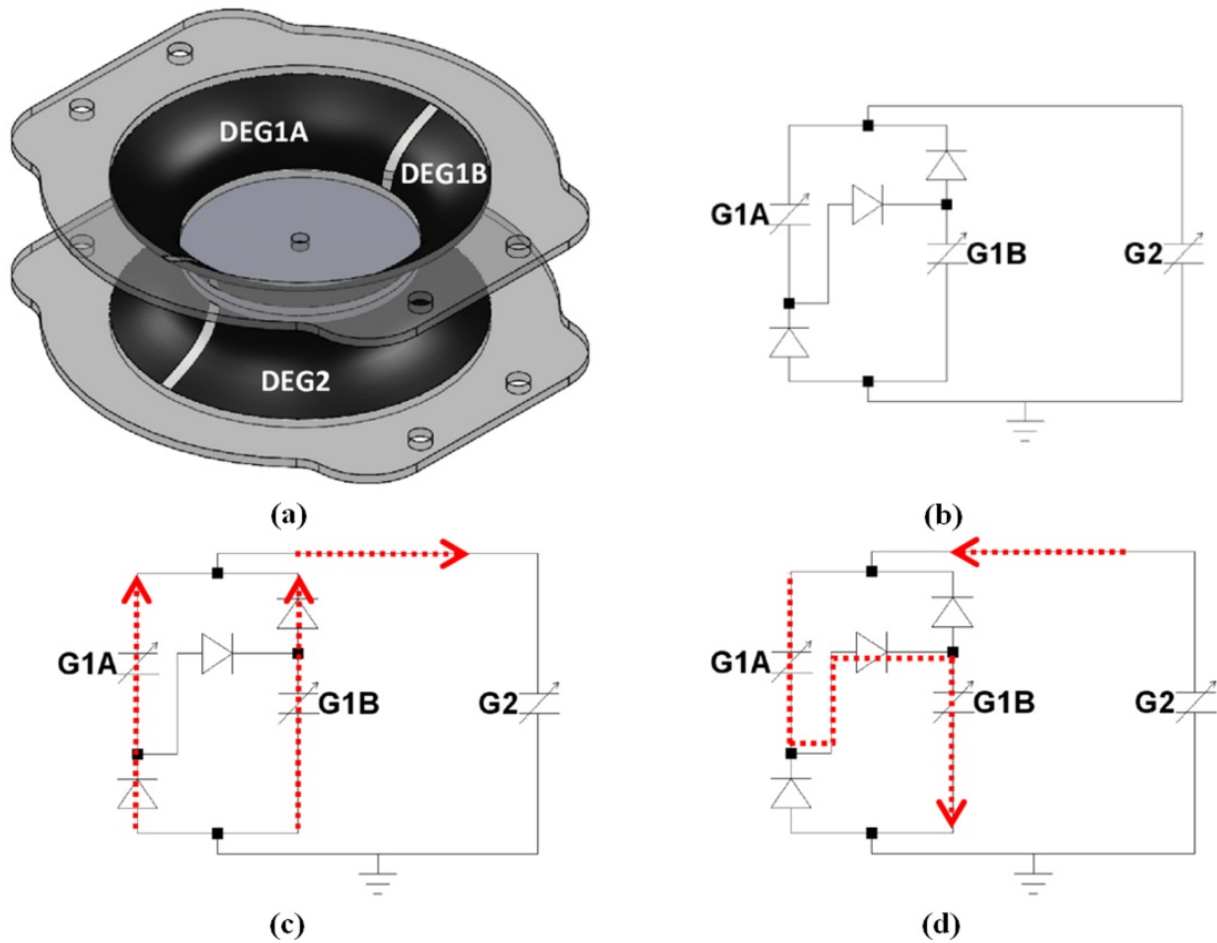

Figure 4. A segmented generator which consists of two membranes that are antagonistically deformed when the inner hub displaces up and down (a). The top membrane DEG1 can be electrically interconnected with diodes to form a self-priming circuit (b). The paths along which current flows off (c) and onto (d) the SPC are also illustrated.

For a small scale portable and potentially wearable generator the diodes of the SPC can represent a significant mass. For instance, the prototype of the generator shown in Figure 4 consisted of DEG membranes with a combined mass of 0.35 grams, whereas the diodes weighed 0.63 grams. If we could remove the diodes, 64% of the total mass (ignoring the mass of the frame) could be eliminated.

The function of the diodes is to control the charge transfer between the DEG and SPC. The diodes simply allow current to flow along one path when one diaphragm is stretched, and along an alternative path when that diaphragm is relaxed. This means that the diodes can be replaced by switches that are toggled at the appropriate time. Since this timing is dependent on the material stretch state, the diodes can be replaced by stretch-sensitive switches coupled to the DEG.

Stretch sensitive electronics called Dielectric Elastomer Switches (DES) have been used to integrate the functionality of the diodes into the DEG membrane. DES consist of piezoresistive electrodes fabricated directly onto a highly stretchable dielectric elastomer membrane. They exhibit very large changes in resistance with stretch. O'Brien et al. first presented the concept [22] and characterized M-shaped DES as illustrated in Figure 5 [23]. These DES had a resistance of several MΩ in their rest state, which increased to several GΩ when they were stretched to approximately 1.4 times their original length (see Figure 5b) [23].
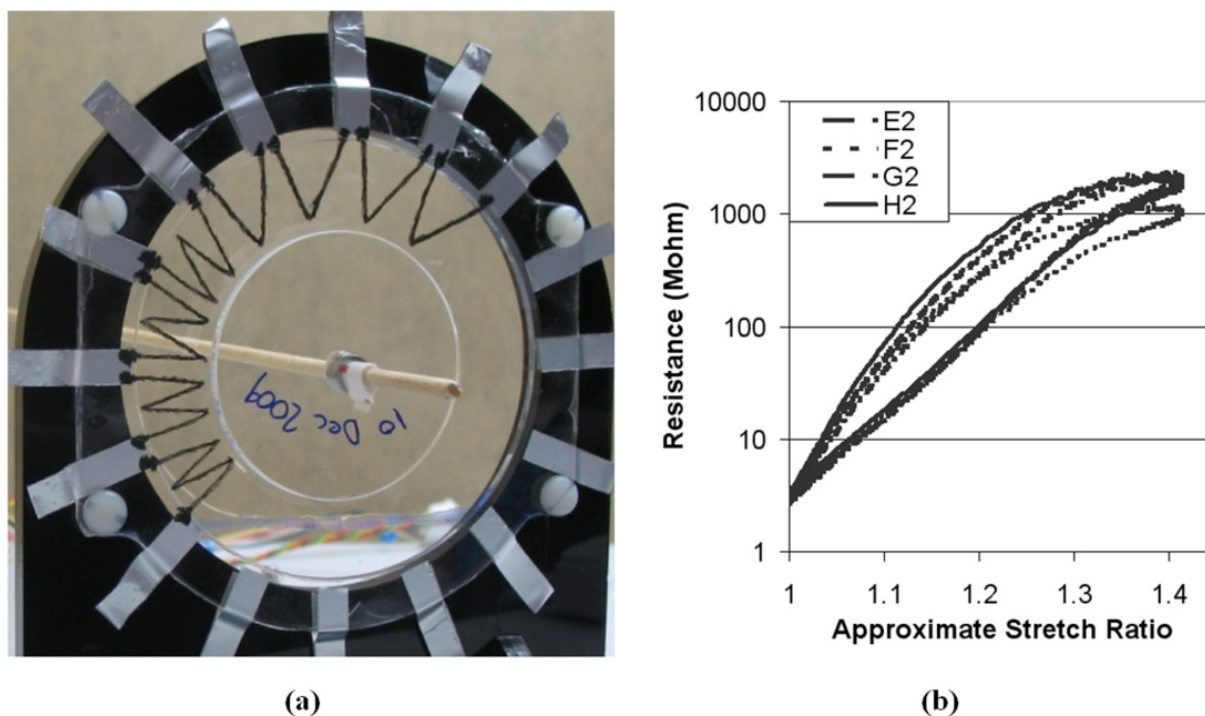

(a)   (b)

Figure 5. Carbon powder-based DES applied to a dielectric elastomer diaphragm (black "M" and "V" shaped tracks) for characterisation by O'Brien et al. (a), and a plot of measured DES resistance versus approximate radial stretch ratio showing that the resistance climbed several orders of magnitude when the DES were stretched (b). Images taken from O'Brien [23].

The generator illustrated in Figure 4 was redesigned by placing DES onto the membrane to replace the hard diodes as illustrated in Figures 6 and 7. The SPC capacitors were fabricated onto diaphragm 1. When diaphragm 1 was relaxed the switches Q1 and Q2 were also relaxed and therefore conducted, configuring the SPC capacitors into a parallel topology (high charge form). When diaphragm 1 was stretched so too were Q1 and Q2, so they no longer conducted, but diaphragm 2 was simultaneously relaxed, causing Q3 to conduct, connecting the SPC capacitors in series. This generator can be fabricated entirely from soft elastomers, so we refer to it as the soft generator.

The output voltage of a prototype soft generator is given in Figure 8. When compared to the output of the self-priming circuit given in Figure 3, the soft generator's voltage climbs very rapidly. But the most profound advantages are the ability to produce DEG that maintain the

advantages of high flexibility, softness, low volume, low cost, low component count, and low mass at the system level.
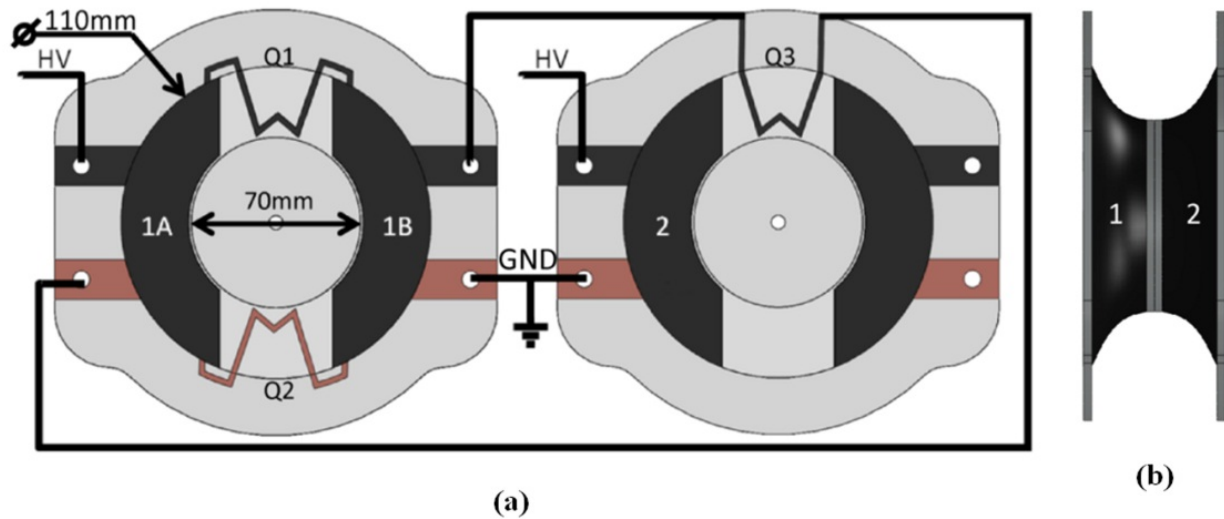

Figure 6. A schematic of the soft generator. The switches Q1-Q3 control the charge flow within the self-priming circuit in a similar manner to the diodes in the integrated self-priming circuit. The two diaphragms in (a) are connected together to form the antagonistic pair shown in (b). (From [24]).
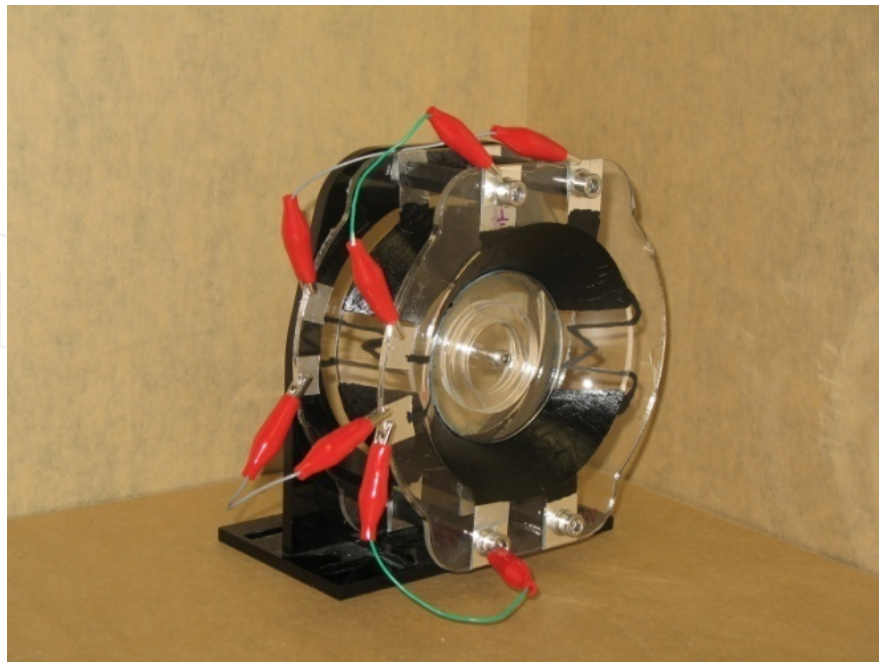

Figure 7. A photograph of a soft generator prototype. The large black regions are the generator electrodes and the thin "M-shaped" electrodes are the piezo-resistive switches.
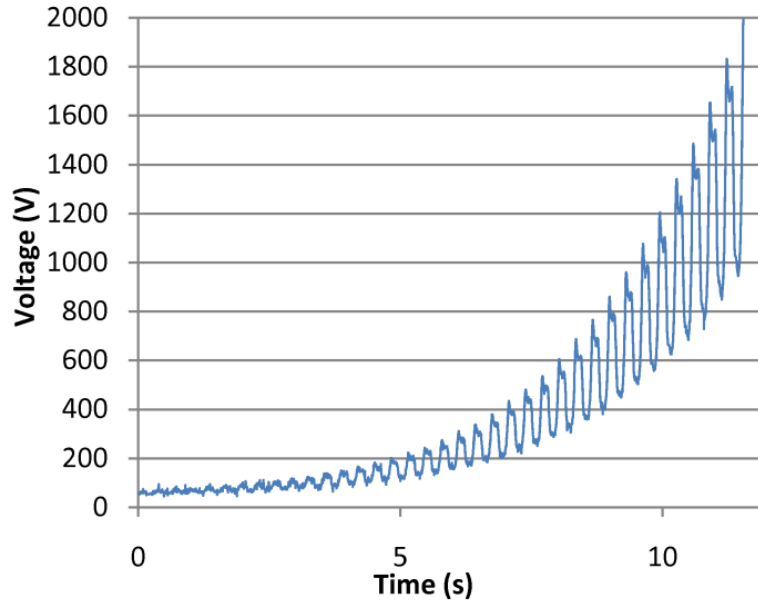
Figure 8. The output voltage waveform of a soft generator initially primed to 10 Volts then mechanically deformed at 3 Hz showing that the generator rapidly boosts its operating voltage through accumulation of generated energy (From [24]).

The total mass of biomechanical energy harvesters has a great influence on the metabolic cost of their use and can be easily compared in a quantitative manner. In Figure 9 we compare the energy density of each DEG system described in this chapter with the mass of their associated electronics included in the calculations (see equation 5).

$$EnergyDensity = \frac{EnergyGenerated}{Mass_{dielectric} + Mass_{ExternalCircuit}} \tag{5}$$

The energy and energy densities produced by similarly sized DEG membranes (~0.3 grams) mechanically cycled at a rate of 3 Hz and operating at 2 kV are compared in Figure 9. The soft generator energy density was superior to both the integrated and external SPC generators because their respective external circuit masses are approximately 0 grams, 0.6 grams, and 13.4 grams. The soft generator's energy density of 9.5 mJ/g is highly competitive with the predicted practical maxima of electromagnetics (4 mJ/g) and piezoelectrics (17.7 mJ/g) at the ~1cm3 scale [25], demonstrating the utility of DEG for small-scale energy harvesters.

The recent developments discussed in this chapter have provided progress towards wearable, soft power generators becoming a reality, but there are still issues that need to be addressed:

1.   The switching technology used in the soft generator, DES, are in their infancy. Material and process developments are required to create more reliable DES with resistances that can be tuned to their application.
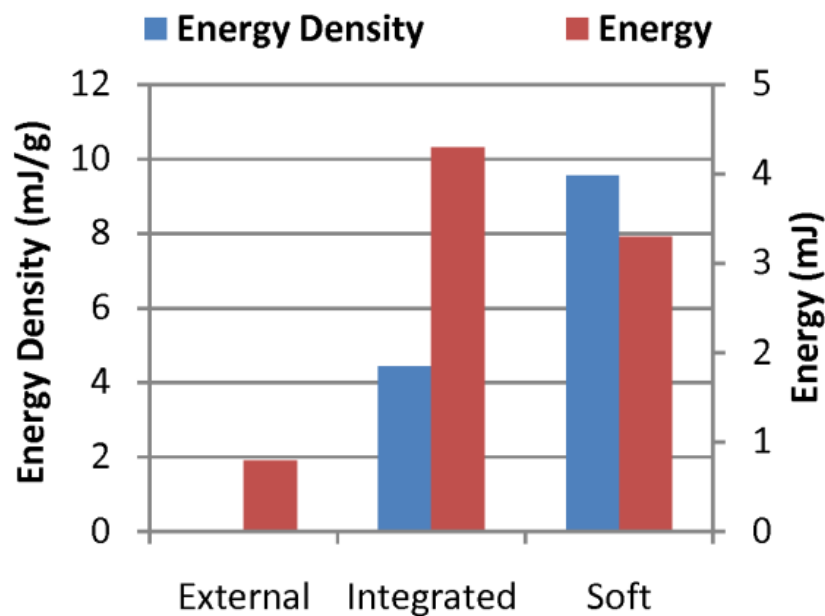
Figure 9. The energy and energy density produced by the external SPC, integrated SPC, and soft generators.

2. The prototypes discussed in this chapter are 1 to 2 orders of magnitude smaller than those required to produce sufficient power to drive the more power hungry portable electronics such as smart phones, which begs the question: How do we expect them to scale? Figure 9 illustrates that the integrated SPC generator produced more energy than the soft generator, so as the generator is scaled up and the diode mass becomes insignificant the integrated generator may outperform the soft generator in terms of energy density. When scaled up to produce an order of a Watt, are the soft generator's advantages sufficient to provide a worthwhile alternative to more complex DEG control strategies that will provide superior energy production [26-29].

3. The soft and integrated generators have an antagonistic pair of membranes. What is the best configuration for harvesting energy from a given biomechanical source?

4. DEG provide the best energy production when operated at high voltages (typically kV range). Compact energy-efficient circuitry is required to reduce this voltage down to consumer electronics levels (~5 Volts) or perhaps the high voltage energy can be used to drive another high voltage device such as a dielectric elastomer actuator.

With these challenges comes an exciting future: the emergence of smart, wearable soft devices. The DEG membranes are multifunctional; they can be operated as actuators or generators and simultaneously sense strain [12]. Furthermore DES have been used to fabricate rubber-based NAND-gates and memory elements, the two primitives required to build a computer [30-32]. Perhaps the future will not only include soft generators to power portable electronic devices, but it may also include a new breed of smart, multifunctional self-powered portable soft devices. These possibilities open the door for smart devices to be integrated directly into clothing. So soft wearable generators will not only revolutionize the use of today's portable devices, but they will be an integral part of a distributed body-area

network of sensors and smart devices that will improve future prosthetic devices, sports monitors, and video gaming interfaces.

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