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Human Powered Piezoelectric Batteries to Supply Power to Wearable Electronic Devices.

José Luis GONZÂLEZ, Antonio RUBIO and Francesc MOLL

※Electronic Engineering Department, Universitat Politècnica de Catalunya, C/Jordi Girona, 1-3, Modul C4-Campus Nord, 08034 Barcelona, Spain
E-mail : jlgonzalez@eel.upc.es

Consumer electronic equipments are becoming small, portable devices that provide users with a wide range of functionality, from communication to music playing. The battery technology and the power consumption of the device limit the size, weight and autonomous lifetime. One promising alternative to batteries (and fuel cells, that must be refueled as well) is to use the parasitic energy dissipated in the movement of the wearer of the device to power it. We analyze in this work the current state-of-the-art and the future prospect of energy conversion from mechanical movement in the human environment to electrical energy based upon the piezoelectric effect. This is an interdisciplinary field where material technology and electrical circuits have to advance together to improve the conversion efficiency in order to reach the energy demands of the typical portable consumer electronic devices that will become in this way autonomous wearable devices.

Key Words : Power generators, Piezoelectric materials, Wearable devices.

1 INTRODUCTION

The most important trend in the electronic equipment technology from its beginning has been the reduction in size and the increase of the functionality. Nowadays small, hand held, and very powerful devices are commercially available that allow the wearer of the device to play music, to wirelessly communicate or to compute practically everywhere or, in other words, *ubiquitously*. In the next years there will be more units available providing extended functions to the wearer. The size of such devices is becoming so small that instead of portable devices they are becoming *wearable* devices that can be integrated in everyday use objects like watches, glasses, clothes, etc [1, 2]. All those units are based in today's microelectronic technology and need an external power supply. The size of the electronic circuit and the energy needed to perform a single (binary) operation [3] has been drastically reduced during the last decades, following Moore's Law. However, as the system performance is increased (the clock frequency is scaled up) and the system functionality improves (the number of switching devices per system increases) the total power requirements are higher.

The energy necessary to power such systems is stored in batteries. Batteries are a significant source of size, weight and inconvenience to present-day portable, hand held and wearable systems. Battery technology has evolved very slowly compared with electronic technology as shown in figure 1, where the evolution of two fundamental battery parameters: the energy density (energy per unit of volume) and the specific energy (energy per unit weight) of Lithium-ion cells are plotted against time [4]. However, new approaches are on the way for very small size portable batteries that will enable the size and weight reduction of wearable systems. They are based on new technologies as the thin-film Lithium-ion or Lithium-polymer cells now at the development phase [5, 6].

Alternatives to conventional batteries for portable electronics have been considered recently [7]. One of the most promising is the fuel cells, power generators that use chemical fuels (i.e. Hydrogen or Methanol). The specific energy of fuel cells is reported to be three to five times larger than the Lithium-ion cells and more than ten times better than NiCd or NiMH batteries whereas the energy density is six to seven times larger than Lithium-ion [8, 9]. However these cells need to be refueled or

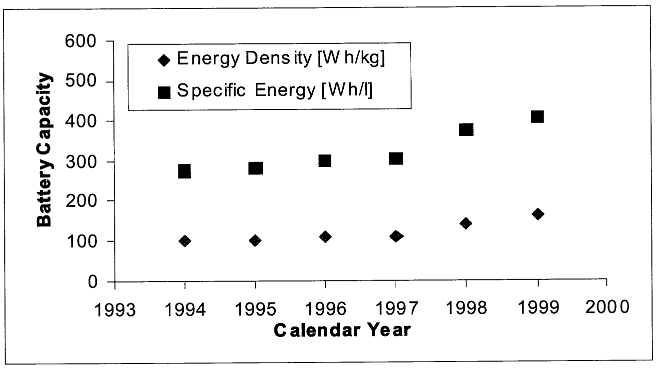

Figure 1 Evolutionn of Lithium-ion battery performance over time.

alternatively they have to be manufactured carrying enough fuel to sustain the battery operation during all its expected lifetime.

Primary batteries (non-rechargeable) limit the autonomy of the units because they need to be replaced from time to time, and they have also environmental effects. Secondary batteries are a better choice for ubiquitous and/or wearable systems because they can be recharged in several ways, in many cases without extracting the battery from the system. One of the choices to recharge such batteries is to use energy from power harvesting of the human body [10, 11]. This work is focused in the evaluation of the feasibility of using the energy produced by the human body to power wearable electronic devices. This energy is initially a mechanical energy and it needs to be transformed into electrical energy to power the wearable devices. Piezoelectric materials are used for such purpose. The electrical energy obtained in that way can be used to recharge a secondary battery or, in some cases, to power directly the electronics.

This paper is organized as follows. Section 2 contains a survey of the main functionalities needed for wearable devices (computing, displaying, wireless communications, etc). Then the power consumption for current implementations of such functions is presented. In section 3 a power consumption model is used to forecast the change in the power requirements with technology evolution. In section 4 the energy sources found in normal human body activity are presented. Next the implication of using piezoelectric materials as mechanical to electrical energy converters is addressed in section 5. The results are summarized in section 6 where a time perspective of the feasibility of using human body powered piezoelectric power supplies for wearable devices is analyzed.

2 BASIC WEARABLE DEVICES FUNCTIONS

In this section a set of typical wearable device functions are considered, showing the power requirements for each one. All the indicated power consumption values are for 0.35/0.25 μm technology devices and correspond to commercial systems in the year 2001.

2.1 Description of the functions and its power consumption

2.1.1 Programmable microprocessor : ARM 720T, in the form of on internal IP macrocell exhibits a consumption of 1.8 mW/MHz. Typically the processor runs at 50 MHz in load mode and 50 kHz in standby mode, corresponding to consumption of 90 mW and 90 μW respectively.

2.1.2 Bluetooth System : including the RF and digital baseband sections, the power consumption is very dependent on the working mode. When establishing a connection the consumption is 300 mW. The power consumption for an emitting communications is 100 mW and 25 mW for a receiving communication, giving an average consumption for a typical bi-directional communication of 50 mW. The power consumption for standby and shutdown modes is 30 mW and 4 μW respectively.

2.1.3 MP3 player : including all the decoder function as well as the flash memory reading it exhibits a consumption for the processing section of 10 mW. This gives for a case of 100 mW of acoustical power to headphones a total power consumption of 110 mW.

2.1.4 Personal assistant/organizer : corresponding to a device equivalent to the Palm Pilot III. When shutdown the power is 50 μW. When switched on but standby the consumption is 1 mW while 50 mW is the power consumption for a typical application and 200 mW for the HotSync function.

Table 1 User profiles and functions usage.

Function ↓ Profile→	Low	Typical	Intensive
Shutdown	33.33% (8h)	33.33% (8h)	0% (0h)
MP3	4.16% (1h)	16.66% (4h)	25% (6h)
Organizer	2.08% (0.5h)	4.16% (1h)	8.33% (2h)
Communications	2.08% (0.5h)	4.16% (1h)	25% (6h)
Standby	58.33% (14h)	41.66% (10h)	41.66% (10h)
Average power*	17.7 mW	37 mW	110 mW
Energy in a day	1529 J	3197 J	9504 J
Average power† Bluetooth comm.	12.5 mW	26.5 mW	48.5 mW

*Power consumption used in the table: shutdown 100 μW, MP3 110 mW, organizer 50 mW, communication 300 mW, standby 10 mW. †In the case the communication is performed by a Bluetooth system the power consumption should be 50 mW.

2.1.5 CMOS image decoder MPEG-2 : a digital processor working at 14 MHz, consumes 5 mW of power when running this algorithm.

2.1.6 Advanced GSM terminal with extended functions : like the Siemens SL45, WAP terminal with digital voice recorder, MP3 player and personal organizer. As a phone terminal the power consumption in standby mode is 10 mW, with an average consumption in talking mode of 300 mW and 100 μW when shutdown.

2.2 Evaluation of the wearable average power consumption for different user profiles

In this section we will evaluate the dairy average power consumption for a wearable with three of the previous functions : music player, personal organizer and GSM communication, for three user profiles : Intensive (24h/24h and intensive use of the three functions), Typical (16h/24h and moderate use of the device) and Low (16h/24h and low use). In Table 1 the percentage for each activity is shown (as well as the corresponding usage hours indicated between brackets). The bottom rows indicate the average power consumption and the global consumed energy for 24h. The last row corresponds to the average power consumption considering that Bluetooth instead of GSM mobile phone is used for communications.

3 POWER AND ENERGY TRENDS OF WEARABLE DEVICES

3.1 The effect of the scaling down trend

Following the Moore's law integrated circuits evolve through a device size shrinking trend. Together with this trend and because of reliability reasons the supply voltage (V_{DD}) is also reduced. When the scaling factors of the two magnitudes (minimum feature size and supply voltage) are equal it is said that the evolution follows a Constant Field (CF) trend. Because of the parasitic components size reduction, the scaling down evolution diminishes the power consumption of a digital circuit (assuming a given fixed function). For a scale reduction with a factor α (α>1) the minimum feature size of the layout is reduced by $1/\alpha$ and the V_{DD} voltage is reduced by the same factor. With the CF trend the power consumption is reduced by the factor $(1/\alpha)^2$. Because the intrinsic delay of a digital block is also reduced by $(1/\alpha)$, the energy consumed by a given shrunk circuit performing a given task is reduced by $(1/\alpha)^3$.

The power reduction is applied to all the sections of the digital

Table 2 Evolution of the power consumption.

Device/Year/Scenario ↓ Profile→	Low	Typical	Intensive
GSM 1998	17.7 mW	37 mW	110 mW
Bluetooth 1998	12.5 mW	26.5 mW	48.5 mW
GSM 2005 max. performance	9 mW	25 mW	70 mW
Bluetooth 2005 max. perf.	6.1 mW	19 mW	34 mW
GSM 2005 constant # services	8 mW	23.8 mW	65 mW
Bluetooth 2005 constant # serv.	5.1 mW	18 mW	32 mW

processors, but certain factors as the acoustic power in the case of the MP3 player or the radiated power in the case of the transmitters are not affected by the scaling down.

Additionally the power consumption of a wearable can be scaled following two different scenarios :

1) *Maximum performance use* : the improvement in technology is used to reduce the service time and to give a higher number of services. In this case the total power consumption for the processing functions is scaled by $(1/\alpha)^2$.

2) *Constant number of services* : the improvement in technology reduces the service time and the power consumption but the user does not increase the number of required services. The power consumption for the processing functions is scaled by $(1/\alpha)^3$.

3.2 Evolution of the power consumption

In this sub section the effect of the scaling down on the power supply consumption for the circuits indicated in Table 1 is evaluated. Table 2 shows the power consumption for the year 1998, for the three profiles and the two communication techniques: Bluetooth and GSM. The same data has been calculated for the year 2005 following CF trend and considering the two previous scenarios of service trend. In the calculation a scaling factor $\alpha =$ 2.5 has been used (considering a technology of 0.25μm for 2001 and 0.10μm for 2005).

4 SOURCES OF MECHANICAL ENERGY IN THE HUMAN BODY

A complete work about the sources of energy that can be found in the human body to power wearable computing devices can be found in [10]. Here we will focus on mechanical energy sources where piezoelectric effect can be used to transform this mechanical energy into electrical power and most of the data is taken from that reference. Other sources of human-body energy (heat, friction) need other conversion mechanisms like thermoelectricity or triboelectricity that are out of the scope of this paper, although they are also very interesting issues for both materials and electronic engineering researchers.

4.1 Mechanical power generated by human body

Our everyday dynamics can be classified into continuous activities (as breathing and heart beating) and discontinuous (as walking, upper limbs movements, etc).

4.1.1 Breath and blood pressure : Energy can be harvested from breathing in two ways. The exhalation generates a flow of air. Using the intake will affect the effort required for breathing so only exhalation is considered. The mechanical power that is used is around 1W, but it is necessary to wear a breath mask with a turbine to transform this mechanical power into electrical power and the efficiency is only about 40%. This source of energy is only feasible for professionals that usually use a breath mask.

Breathing can be also used to generate power by taking advantage of the chest circumference increase when inhaling air. In this case a piezoelectric material can be use to transform the average 2.5 cm (5 cm when breathing deeply) of chest circumference change into electrical power. At the average breathing rate of 10 breaths per minute a mechanical power of 0.83W is used.

Blood pressure can be also used to harvest mechanical power but it is very difficult to find practical applications where this can be done. Independently of that, 60 beats per minute blood flowing through the aorta will need 0.93W of mechanical power. Only a minor part of this power can be actually used for other purposes without affecting the heart load.

4.1.2 Walking and upper limbs motion : The energy generated with typing can be useful in some applications. Depending on the type of keyboard mechanical power from 7 mW to 19 mW is involved in the movement.

The movement of the upper limbs in a normal activity needs 3 W of mechanical power although biceps curls at a rate of 1.3 lifts per second generates a maximum mechanical power of 60 W.

Walking is the most powerful movement we do. An average 68 Kg person generates 67 W of power when walking at 2 steps per second.

4.2 Available energy from human body motion

Disregarding exhalation and blood pressure the other continuous or discontinuous body movements can be used to power electronic devices using electromechanical generators or piezoelectric materials to convert mechanical energy into electrical energy. However, not all the mechanical energy is available for conversion. The way the mechanical energy is harvested from the body movement reduces the amount of mechanical power available for conversion into electrical power. The conversion mechanisms from mechanical to electrical power (either piezoelectric generators or other approaches) also reduce the efficiency.

4.2.1 mechanical to mechanical conversion : In some cases the total mechanical power generated in the human body motion can't be completely transmitted to the mechanical to electrical converter. For example, in [12] a comparison was presented between the human power collected by a rotary generator and two piezoelectric generators mounted in a shoe. The 5 cm of displacement of the heel used to compute the walking power in the previous section are reduced in the rotary generator to 3 cm of displacement of its moving lever. All the energy used in this displacement goes directly into the mechanism that converts mechanical energy into electrical energy. However in the case of the piezoelectric generators the displacement is only 7 mm because it is mounted inside the sole. In this case most of the energy is stored as potential energy in the elastic parts of the shoe sole and then dissipated as heat.

4.2.2 mechanical to electrical conversion : The fraction of the mechanical energy that arrives to the generator is then converted into electrical energy. In this process again only a fraction of the energy is actually available at the output of the mechanical to electrical converter or generator. Following with the previous example, the rotary generator has 50% efficiency if loaded with a resistor that matches its internal impedance. A fraction of the input mechanical energy is lost basically because of the friction between the moving parts of the generator. The efficiency of the piezoelectric materials depends on the type of material and the way it is used, as it will be explained later. In previous example for a PVDF generator the mechanical to electrical efficiency is

Table 3 Summary of power and energy available from everyday human body activity [10]

Activity	Mechanical power generated	Electrical power available	Electrical energy available per movement
Blood flow	0.93 W	0.37† W	0.37 J
Exhalation	1.00 W	0.40# W	2.4 J
Breath	0.83 W	0.091‡ - 0.42† W	0.5 - 2.5 J
Upper limbs	3.00 W	0.33‡ - 1.5† W	1.5 - 6.7 J
Fingers (type)	6.9-19.00 mW	0.76‡ - 2.1‡ mW	143 - 266 μJ
Walk	67.00 W	5‡ W - 8.4* W	8.3 - 14.0 J

† mechanical generator 50% efficiency; # turbine + generator 40% efficiency; ‡ piezoelectric generator 11% efficiency; * mechanical generator 12.5% efficiency including mechanical to mechanical conversion loses.

Table 4 Electrical power output for shoe mounted generators

Generator type	Mechanical power input	Electrical power output	Ref
Rotary generator	500 mW	250 mW	[12]
Piezoelectric PZT unimorph under heel mode 3-1	120 mW	1.8 mW	[11]
Piezoelectric PVDF insole stave mode 3-1	220 mW	1.1 mW	[11]
Piezoelectric PZT bimorph under heel mode 3-1	71.8 mW	8.4 mW	[13]
Piezoelectric PZT driven by a μ-hydraulic hammer from under the heel	-	1 W	[14]
Electrostrictors under heel	-	1 W	[14]

reported to be 25%. This efficiency is also obtained when loading the generator with an appropriate resistive load that maximizes its power output. Table 3 shows the expected electrical power output corresponding to the several sources of energy due to human body motion of section 4.1 taking into account the mechanical to electrical conversion efficiency. This table allows us to have an idea of the upper bound of the electrical power that can be harvested from human body.

The electrical power is available at the output of the generator at the same rate associated with the human body action. Electronic devices consume power at a different rate in most cases so a storage element is needed to store the electrical power and usually a voltage conversion is also needed. Another fraction of the energy is lost during this storage and voltage conversion process yielding as a result only a small fraction of the initial mechanical power as electrical power. As a reference, Table 4 shows power output for shoe mounted generators found in the literature. As seen in the table, power ranges from a few miliwatts up to 1 W. It is important to note how by accurate design of the generator and the electrical power converter an important increase has been obtained from the work in [11] to the work in [13] for the same generator type. This shows that there is still room for improvements in the efficiency of such converters.

5 GENERATION OF ELECTRICAL POWER USING PIEZOELECTRIC MATERIALS

Certain crystals show piezoelectric effect as well as other composites after being subjected to a certain process to make them piezoelectric materials. When they are subjected to a mechanical strain they become electrically polarized and the degree of polarization is proportional to the applied strain. The opposite effect is also possible: when they are subjected to an external electrical field they are deformed. This behavior is modeled with the following equations :

$$\begin{aligned} D &= dX + \varepsilon^X E \\ x &= s^E X + dE \end{aligned} \qquad (1)$$

The upper expression above relates the electrical displacement D with the mechanical stress X applied and the electrical field E generated. The proportionality constants are the d coefficient and the dielectric constant measured at constant stress ε^X. The lower expression relates the mechanical strain developed when an electrical field E is applied with the field and the mechanical stress X developed. The proportionality constants are the same d coefficient and the elastic compliance measured at constant electrical field s^E. Indeed as the materials are three dimensional structures and the mechanical and electrical magnitudes can be applied or measured in any of the three axis the proportionality constants are tensors that relate one magnitude across the axes to the other magnitudes across all the axes. The axes are defined in Figure 2 where the most usual modes of operation of the piezoelectric generators are also displayed.

5.1 Parallel compression generator

In this mode of operation the electrical field is generated across the same axis where the external stress is applied. The short circuit charge displacement generated can be expressed as the charge Q in the surface of the piezogenerator of area $L \times W$, where L is the length along the 1 axis and W the width along the 2 axis. The electric field can be expressed as open circuit voltage V across the 3 axe of the generator divided by its thickness T. The applied stress can be rewritten as the quotient between the applied force F and the top surface area $L \times W$. Introducing another piezoelectric coefficient named g that verifies that $d_{ij} = \varepsilon^X_{i0j} \varepsilon_0 g_{ij}$, where j is the axis where the input magnitude is applied and i the axis where the output magnitude is obtained, the upper equation of (1) can be rewritten for parallel compression generator operating in short circuit and open circuit as follows.

$$\text{Short circuit charge generated : } Q_3 = d_{33} F_3$$
$$\text{Open circuit electric field generated : } \frac{V_3}{T} = \frac{F_3}{L} \frac{g_{33}}{W} \qquad (2)$$

By manipulating expression (2) it can be demonstrated that the generator can be modeled as a capacitor of value $C_3 = \varepsilon_{33}^X \varepsilon_0 WL/T$. The electrical energy generated can be calculated as the energy stored in the capacitor :

$$W_3^e = \frac{1}{2} C_3 V_3^2 = \frac{1}{2} g_{33} d_{33} \frac{T}{WL} F_3^2 \qquad (3)$$

From expression (3) it is clear that for maximizing the electrical energy generated the generator must have a small surface and a large thickness. This is very inconvenient because the mechanical force must be applied on a small surface and the shape of the generator makes it difficult to integrate in everyday objects. However, the mechanical to electrical efficiency of this mode of operation is the largest. This efficiency is expressed through another piezoelectric constant called the coupling coefficient. For the parallel generator this coefficient is named K_{33} indicating that the mechanical and the electrical magnitudes share the same axis.

The coefficients K_{ij} are equal to the square root of the mechanical energy across the j axis (W_j^e) divided by the electrical energy across the i axis (W_i^e) or which is the same, the electromechanical efficiency :

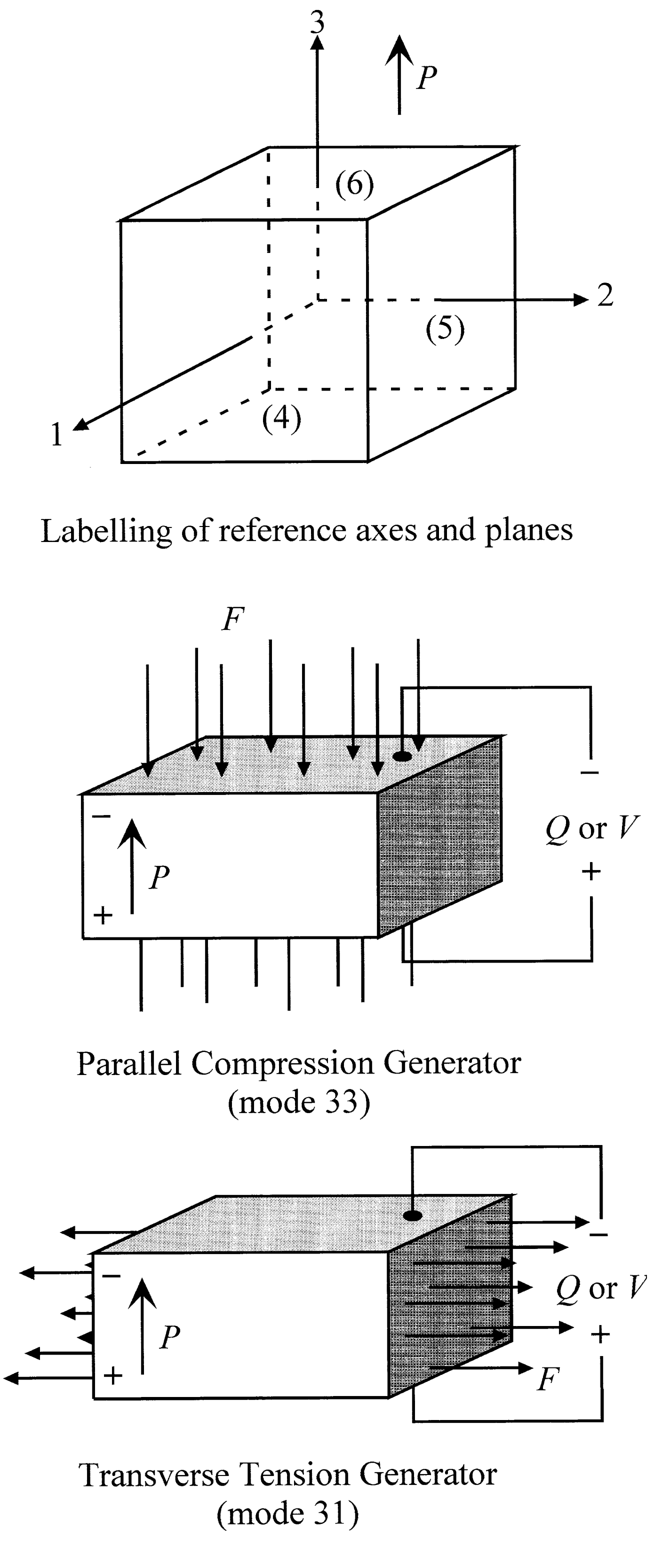

Figure 2 Reference axes and most usual modes of operation for piezoelectric generators.

$$K_{ij}^2 = \frac{W_i^e}{W_j^m} \qquad (4)$$

5.2 Transversal tension generator

In this case the force is applied in a different axis than the electrodes. Therefore the surface where the charge is collected and the surface where the force is applied are independent, yielding a more convenient generator shape suitable for integration into clothes or shoes. For this type of generator the upper equation of (1) is transformed in the following expression for short circuit and open circuit operation, respectively :

$$\text{Short circuit charge generated : } \frac{Q_3}{LW} = d_{31}\frac{F_1}{TW}$$
$$\text{Open circuit electric field generated : } \frac{V_3}{T} = \frac{F_1}{T}\frac{g_{31}}{W} \qquad (5)$$

Here the piezoelectric coefficients indicate that the mechanical force is applied across the 1 axis and the electrical magnitudes obtained across the 3 axis. From (5) An expression for the generated electrical energy can be derived from (5) by considering the generator as a capacitor of value $C_3 = \varepsilon_{31}^X \varepsilon_0 WL/T$.

$$W_3^e = \frac{1}{2}C_3V_3^2 = \frac{1}{2}g_{31}d_{31}\frac{L}{WT}F_1^2 \qquad (6)$$

Now minimizing the cross section and maximizing the length of the generator will maximize the electrical energy. This yields to generators having thick film shapes, with a large top surface to collect enough charge but a small lateral surface (small thickness) to maximize the stress transversal for a fixed force. However the mechanical to electrical efficiency of the transversal mode, expressed through the coupling coefficient K_{31}, is more than two times smaller than the efficiency of the parallel mode. Despite this limitation, the thick film generators operating in transversal mode are the most used in the works published until now due to the ease of integration of this type of generators in everyday objects and the ease to couple the mechanical energy from human movements to them.

The materials used to implement these generators are mainly of two different types : piezoceramics like Barium Titanate ($BaTiO_3$) or Lead Zirconate Titanate (PZT) and piezopolimers like Polyvinylidene Fluoride (FVDF). The latter are more flexible but show smaller coupling coefficients as shown in Table 5.

The maximum mechanical to electrical efficiency of 49.7% (K_{33}^2) is obtained in parallel mode for PZT-5A ceramic. The efficiency for the transversal mode is lowered to 11.8% in the PZT-5A. For PVDZ generators parallel and transversal efficiencies are 2.2% and 1.4%, respectively. This explains the difference in almost one order of magnitude in the final electrical power output between the PZT and the PVDZ shoe mounted generators shown in Table 2. This is true besides the products $g_{31}d_{31}$ and $g_{33}d_{33}$ are quite similar for the two materials, which means that for equal geometry and applied force the electrical energy generated is almost the same for PZT and PVDZ materials in the two modes (parallel or transversal). The differences in the efficiency arise from the fact that the same force applied for the same geometry produces a smaller mechanical work in the PZT material than in the PVDZ because the former is stiffer than the latter.

In conclusion, the maximum available piezoelectric generators electromechanical efficiency is approximately 50% (the same that

Table 5 Comparison of piezoelectric materials

Property	Units	PVDZ Film	PZT-5A	$BaTiO_3$
Density	103kg/m3	1.78	7.5	5.7
Relative Permittivity	$\varepsilon/\varepsilon_o$	12	1200	1700
d_{31}	10^{-12}C/N	23	-171	78
g_{31}	10^{-3}Vm/N	216	-11.4	5
K_{31}	10^{-2}	12	34.4	21
d_{33}	10^{-12}C/N	-33	374	149
g_{33}	10^{-3}Vm/N	-330	24.8	14.1
K_{33}	10^{-2}	15	70.5	48

Table 6 Human electrical power available using piezoelectric generators

Activity	Mechanical power losses	Electro-mechanical efficiency	Electrical power losses	Daily activity	Electrical power available
Typing	10%	50%	10%	16.6%	283.5 μW
U. limbs	50%	11.2%	10%	16.6%	24.6 mW
Breath	10%	11.2%	10%	100%	74.8 mW
Walk	75%	50%	10%	16.6%	1.265 W

for rotary mechanical generators) and corresponds to parallel mode and PZT material. However, the more flexible PVDZ material is more suitable for embedded generators in everyday objects but its electromechanical efficiency is almost one order of magnitude smaller. In most of the reported experimental shoe mounted generators transversal (3-1) mode is used having an electromechanical efficiency of 11.2% that is the value used to compute available electrical power in Table 3 for piezoelectric generators.

6 FEASIBILITY OF HUMAN POWERED WERABLE DEVICES

In the previous sections both the power consumption of typical wearable units and its evolution and the power generated by the human body have been presented. In order to analyze the possibility to use autonomous power systems harvesting energy from human body motion to power wearable devices we need to scale the power obtained in section 4 to the daily percentage of activity for each human energy source. We will discard blood flow and exhalation because they are not suitable for piezoelectric generators. Breathing is a continuos activity so it has a 100% of daily generation. However typing, upper limbs movement and walking are discontinuous activities. We will assume here an activity model that considers an average of 4 hours of daily activity in that case, it is, a 16.6% of daily generation of power. Table 6 shows the available electrical power for different activities and the various efficiencies considered (due to mechanical losses in the coupling from the body movement to the generator, its electromechanical efficiency and the power losses due to the electrical power converter). The results of Table 6 are an upper bound for the available energy for the human body activities considered. The PZT generators parallel or transversal efficiency has been used depending on the type of movement.

The numbers shown in Table 6 represent a theoretical upper bound for the electrical power generated by piezoelectric generators using human body motion. In Table 4 experimental results are shown for actual implementation of piezoelectric and other types of shoe mounted generators. In Figure 3 the available electrical power, either from theoretical calculations (plain text) and from experimental data (italic text) is plotted as horizontal dashed lines. In the same figure the power consumption of wearable units for the user profiles and communication options presented in section 2 have been plotted against time for the maximum performance scaling scenario discussed in section 3.

Concerning the power consumption scaling it is clear from the graphs that the constant power required for communications or acoustic transducers dominates leading to an almost constant power requirement beyond year 2005. Due to this fact the results for the other considered scaling trend (constant number of services) are very similar and not shown here.

From the comparison of generated and consumed power it is clear how just the walking or breath power would be enough to power any of the wearable units and profiles. However most of today's implemented walking based generators (PZT bimorph, PVDZ insole stave) are still far away from the theoretical results. Only the Hammer + PZT generator is capable of powering all the wearable units considered. The walking based rotary generator will be able to power all but the intensive use GSM wearable in the next years. Piezoelectric generators based on upper limb motion would be capable of powering typical and low use wearable with either GSM or Bluetooth communication capabilities by the year 2006. The results for the constant number of services scaling trend show slightly smaller power consumption. This allows advancing three years the time when the output power of some generators will be capable of powering some wearable units. For example the upper limbs movement based generator will be able to power all the typical and low use wearable with either

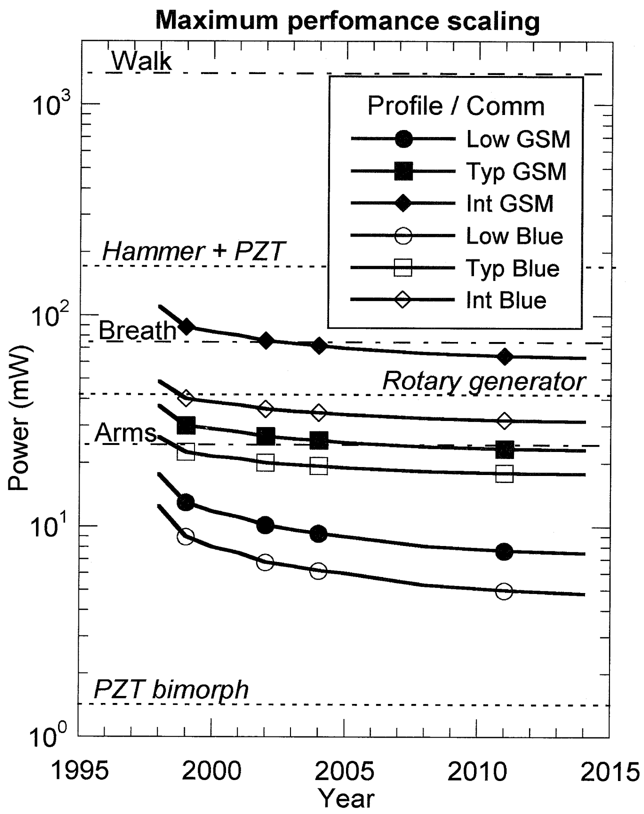

Figure 3 Power consumption of wearable units and power generation from human body motion.

GSM or Bluetooth communication capabilities by the year 2003 instead of 2005 if a constant number of services scaling approach is considered.

7 CONCLUSIONS

This work has shown how it is feasible to use the energy harvested from human body to power wearable units incorporating computing, communication and audio functions. Existing shoe mounted rotary electromechanical generators can provide enough power from walking to supply these devices. The generators based on piezoelectric effect are or will be also capable of powering wearable units. However more investigation and development is necessary to raise the electrical output power for the existing prototypes to the power level that can be obtained theoretically. An important result is that the wearable power consumption evolution is dominated by the communication and acoustic power that don't scale with time, and only a small benefit is obtained from the scaling down of the technology.

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