

Energy Harvesting in E-Health Applications

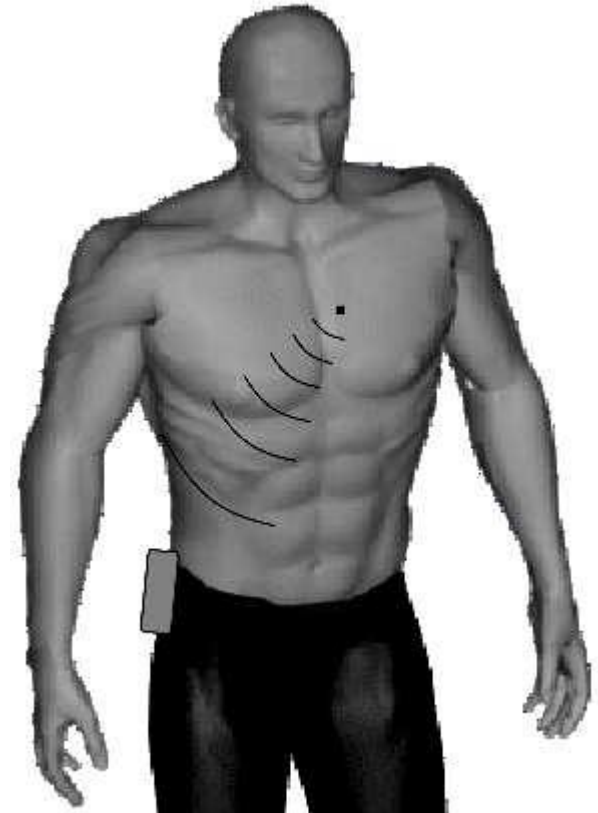
Paul D. Mitcheson

Why are we still using batteries?

- Batteries are actually hard to beat
 - Reliable
 - Trusted (FDA approved)
- Always on (until discharged)
- Energy densities of around 2000 J/cm^3
($\sim 500 \text{ mAh/cm}^3$ at 1 V)
- Existing medical devices may consume $10 \mu\text{W}$ average – which a 1cc battery can supply for 6 years
- Can we do better?

Energy Harvesting for wearable devices

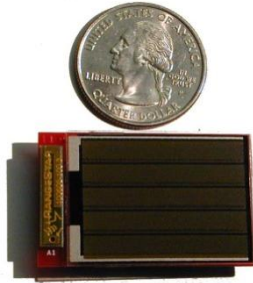
- Ideally we want inexhaustible power supplies for wearable applications
- Rather not use batteries
- There are several options
 - Solar – but availability of light is a problem
 - Kinetic – several types
 - Fuel-cell
 - Thermoelectric
 - Ambient RF
- Wireless power transfer has been used in medical implants but this is not harvesting
- **For safety and encapsulation purposes, kinetic and thermoelectric devices look best**



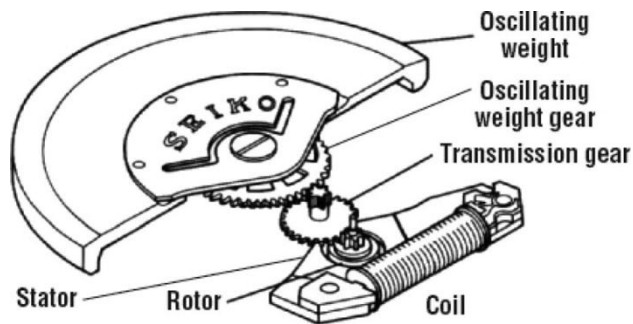
Which of these techniques is the most promising and when?

Energy Harvesting – commercial products

- Can't we use commercial Energy harvesting products in wearable devices? Most are designed for machinery...



*Pico Radio solar cell
[UC Berkeley]*



Seiko kinetic watch generator

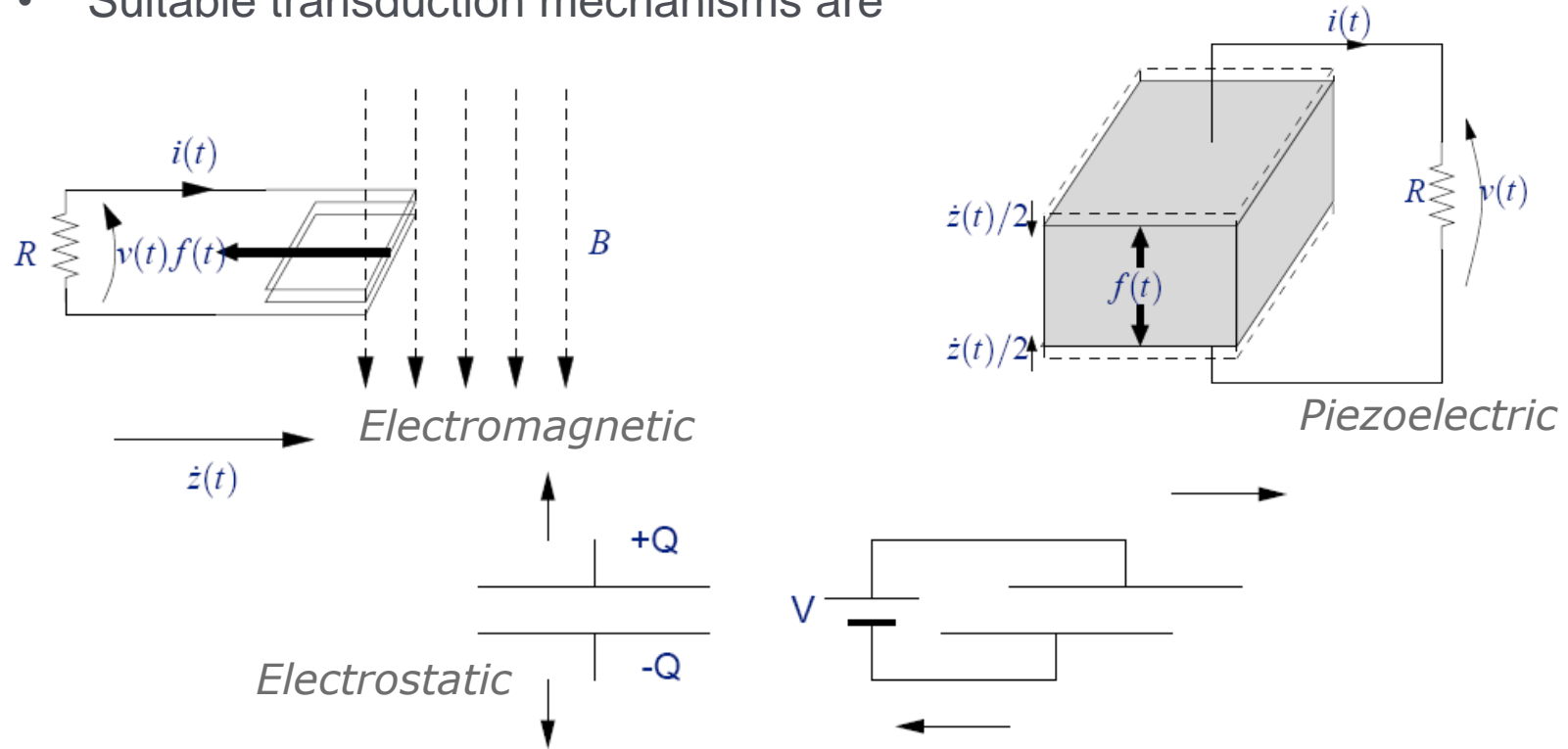


- PMG17 from Perpetuum Ltd
- Resonant generator tuned to 100 or 120 Hz
- 55 mm diameter x 55 mm length
- 4.5 mW output power (rectified DC) at 0.1g acceleration

The Seiko kinetic is a good device, for body motion power, but still relatively large

Kinetic Energy Harvesting

- Want to use motion to excite a transducer and generate electrical energy
- Suitable transduction mechanisms are



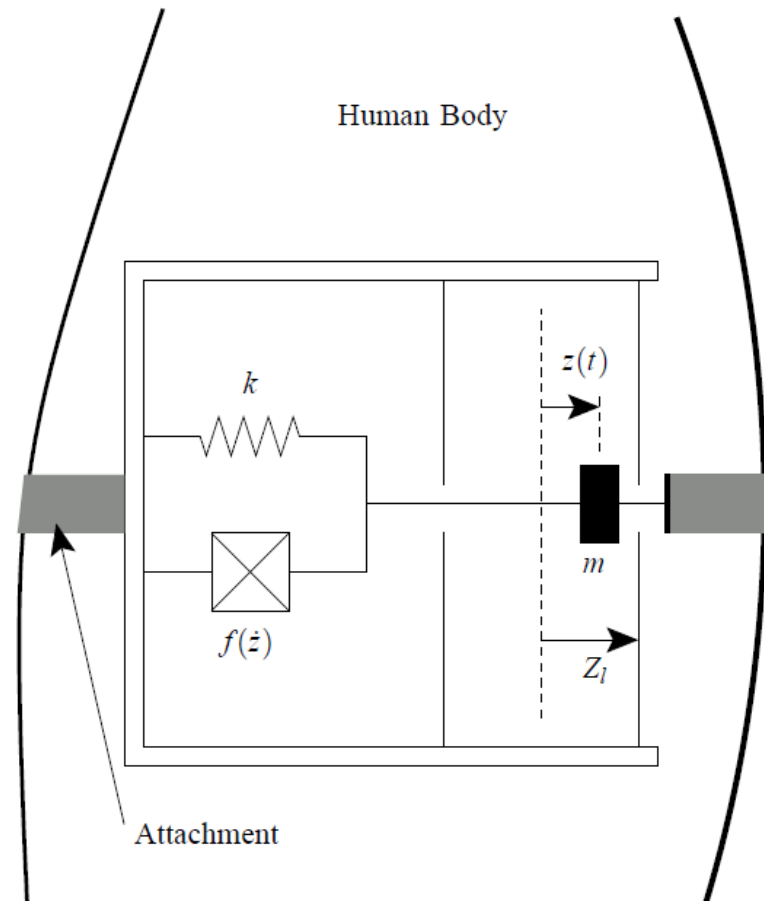
Transducer choice is important but there are more fundamental limits

Direct Force Microgenerator

- The limit on energy generation is simply given by:

$$E = \int_0^{z_l} f \cdot dz$$

- Assuming the transducer can generate sufficient force, limit on power generation is displacement
- Ultimate limit is how much force can the body generate over what distance
- But – is this generator really practical?



Prototype Direct-Force Devices

- These two devices are examples of direct force driven generators
- In shoe harvester (~1W when walking)
 - But can be noticeable to wearer
- Knee brace (~5W when walking)
 - Can actually make walking easier (generates as leg swings down)



J Paradiso (Media lab)

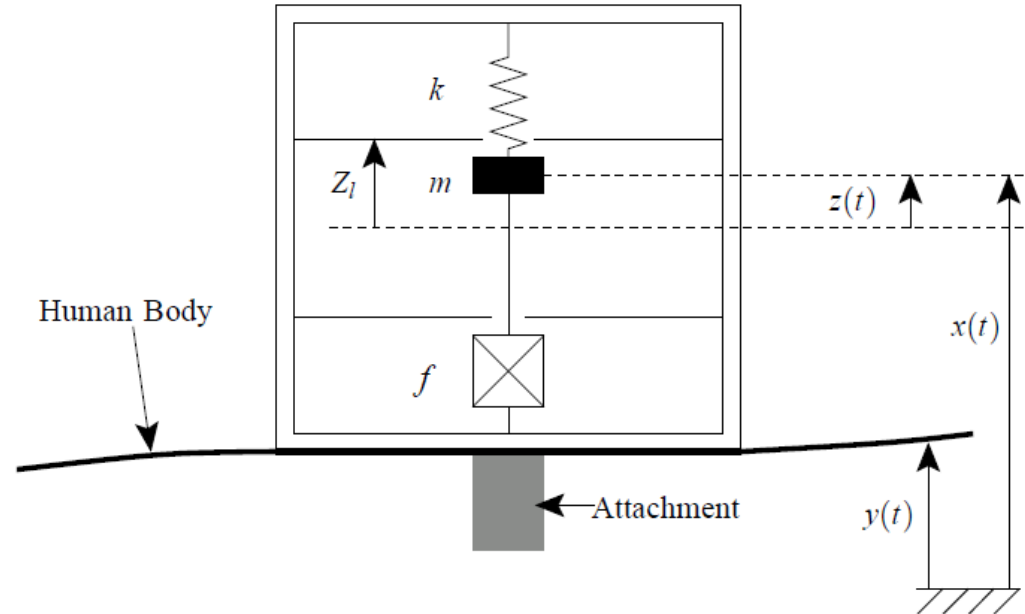


M. Donelan (Simon Fraser)

Many applications require something less constrained in placement - and much smaller

Inertial Microgenerator - Principle

- A more practical device due to single point of attachment
- Can be encapsulated
- Could be implanted
- Limit on power is still force distance product, but now increasing damping force reduces distance
- Optimal damping force exists



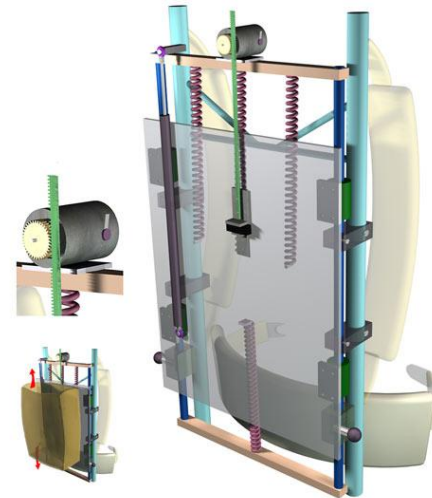
$$P_{\max} = \frac{1}{16} Y_0 \rho L^4 \omega^3$$

For a running subject, generator on lower leg moves through about 0.15m, 0.8Hz whilst walking

Von Bueren, Mitcheson et al, 2006, IEEE Sensors Journal

Assuming a cube shaped generator

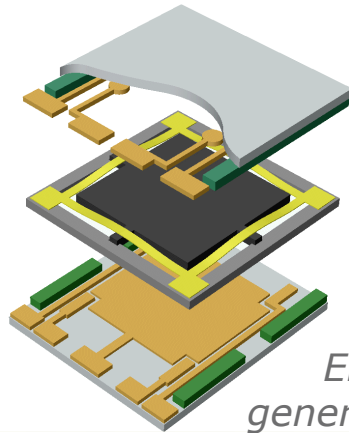
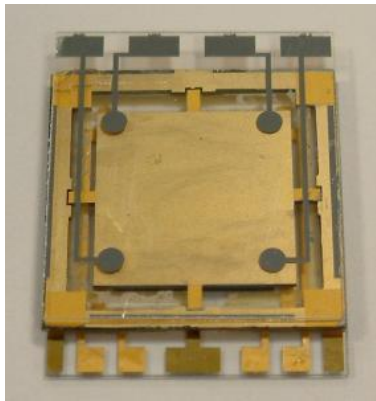
Example of an inertial harvester



- Back pack by Larry Rome of University of Pennsylvania
- Generates around 7 W whilst subject walks
- Applications probably in military rather than health care

What about a "truly wearable" device within this context?

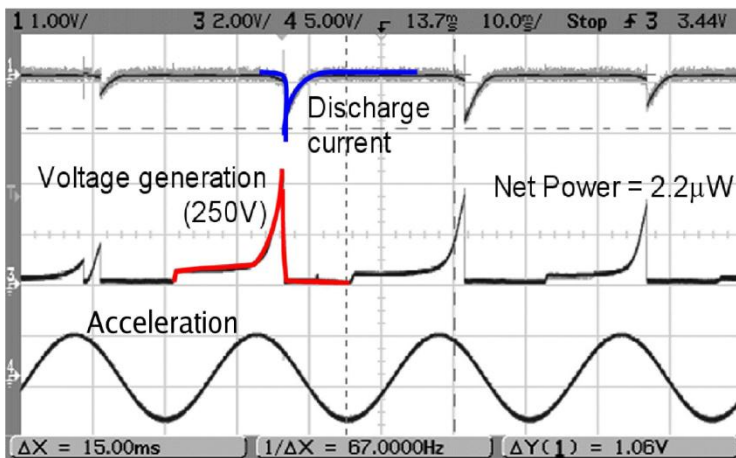
Small Low Frequency Inertial Harvester



Electrostatic
generator - Imperial
College, 2004

- Capacitor charged at high capacitance
- Inertia and motion causes plates to move apart
- Voltage on plates rises
- Electrical energy generated
- Pre-charge the capacitor to get just the right force to maximise force times distance

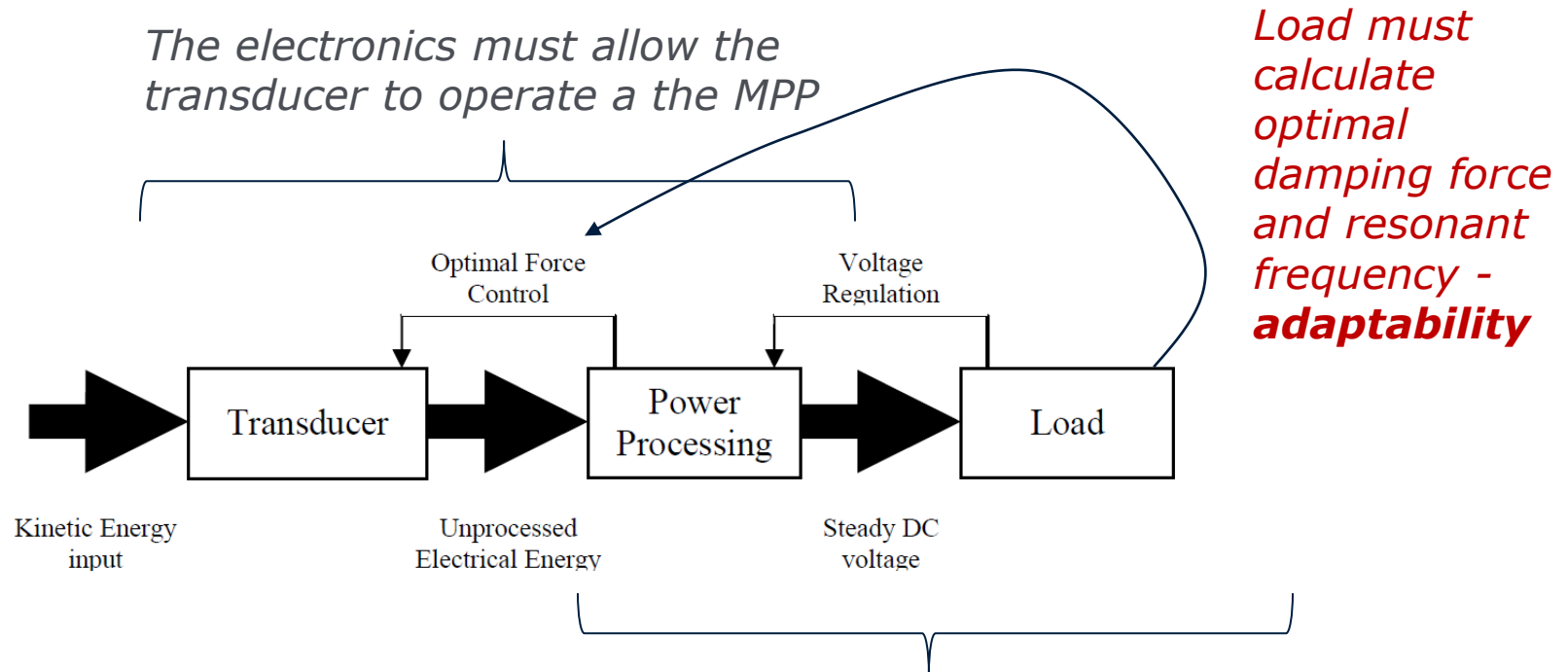
Design of power processing electronics is very difficult due to V:Q ratio



Mitcheson, P.D. et al, MEMS Electrostatic micropower generator for low frequency operation, *Sensors and Actuators A*, 2004, Vol 115, Pages 523-529

Holistic approach (EPSRC Project)

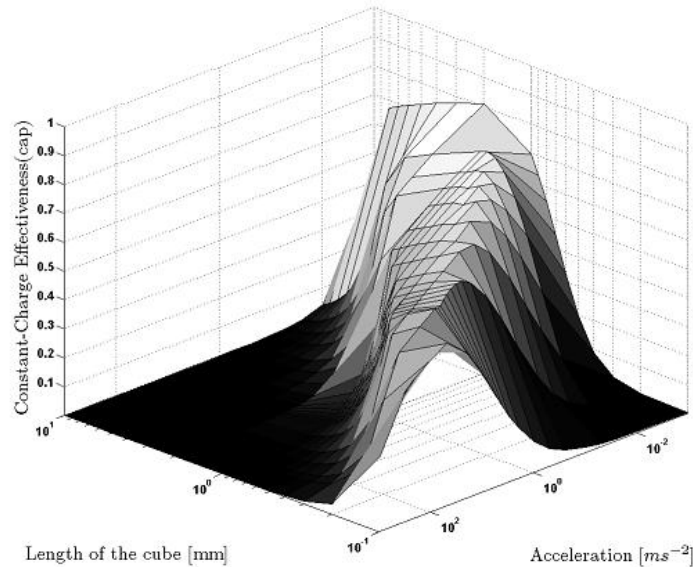
There are two direct interactions to take account of:



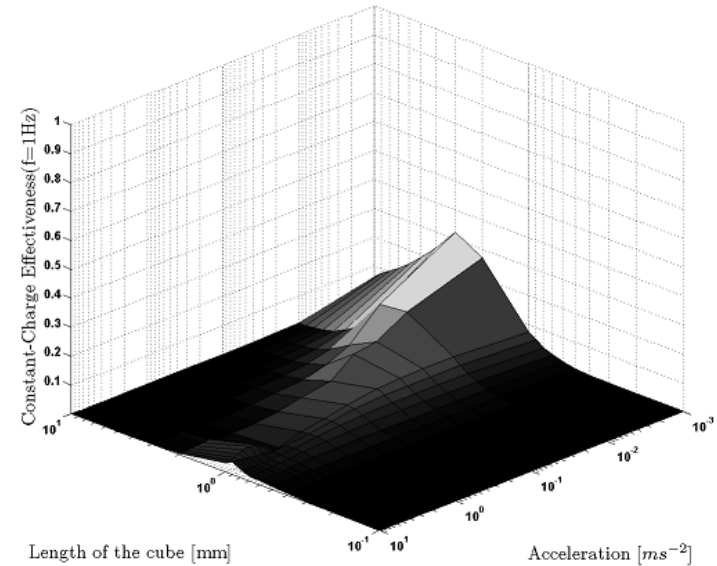
The load should operate efficiently off a poorly regulated supply

And one other interaction...

Results of global optimisation



Effectiveness at 1 kHz



Effectiveness at 1 Hz

- Electrostatic transducers are very poor at low frequency and at large sizes
- Very hard to make one work well at a few Hz or greater than 10mm in length
- **So, electrostatic microgenerators are difficult to make work well.... Can we address any of the issues?**

Now let's look at thermoelectric devices...

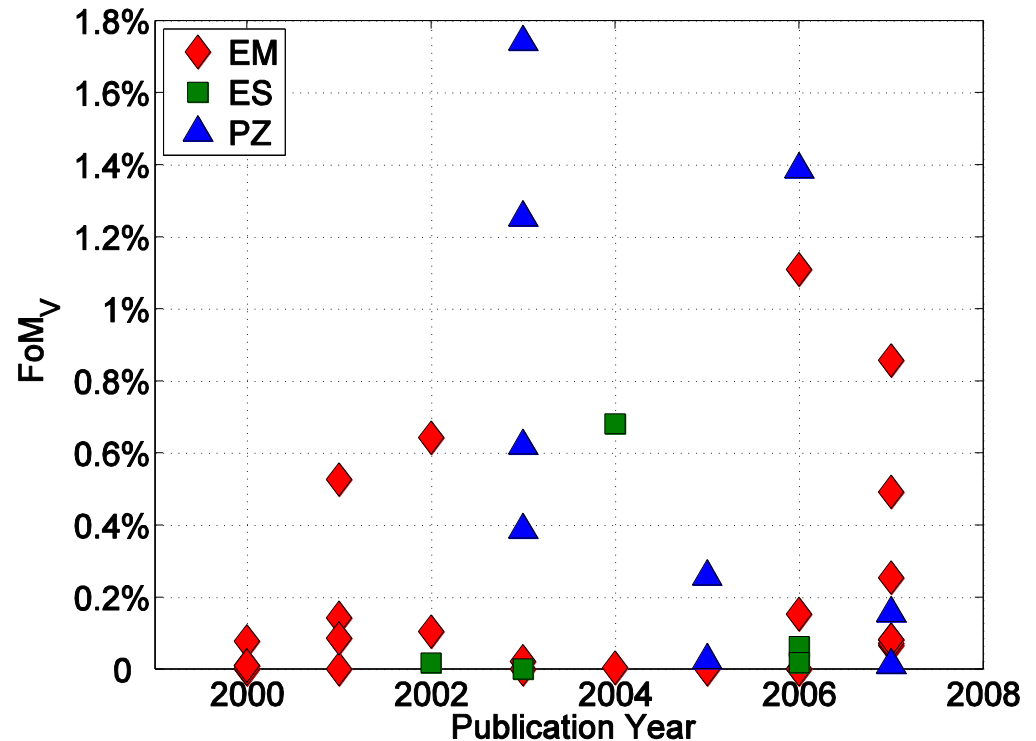
Effectiveness of Previous Harvesters

Volume Figure of Merit
defined as:

$$FoM_V = \frac{\text{Useful Power Output}}{\frac{1}{16} \rho_{Au} Vol^{4/3} Y_0 \omega^3}$$

- Represents ratio of output power to that of idealised generators on slide 7
- Best devices to date achieve only about 2%
- However, thermoelectric devices can reach 70%

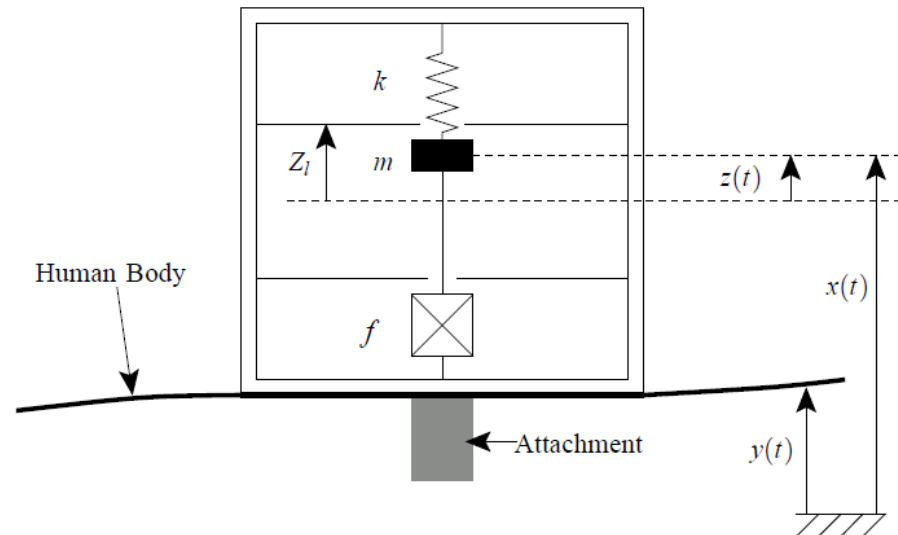
(V. Leonov et al, 5th European Conference on Thermoelectrics, 2007)



(Mitcheson P.D., Yeatman E.M., Kondala Rao G., Holmes A.S., Green T.C., "Energy harvesting from human and machine motion for wireless electronic devices", Proc. *IEEE* 96(9), (2008), 1457-1486.)

Steps to Improve Performance of Inertial Harvesters

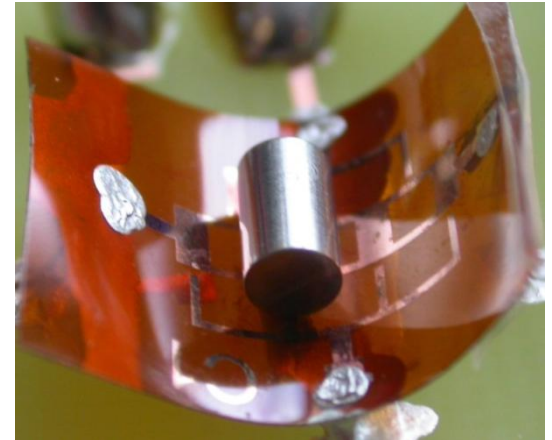
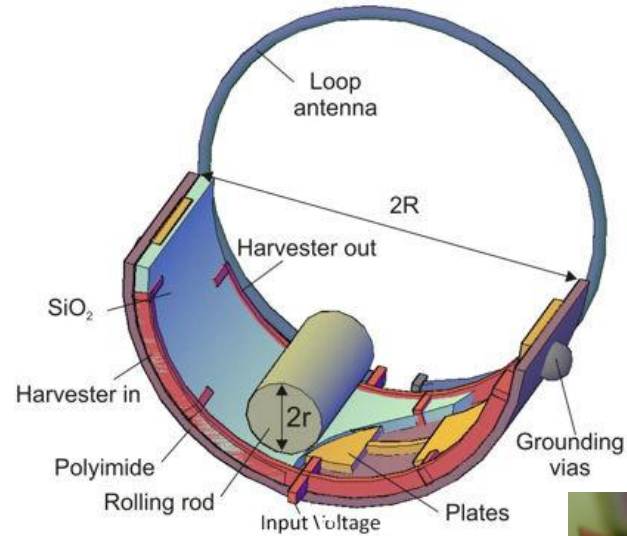
$$P_{\max} = \frac{1}{2} Y_0 Z_l \omega^3 m$$



- Power is proportional to proof mass and the cube of excitation frequency
- We can do little with excitation amplitude in the human body, but a 1cm³ device requires approximately 0.5cm³ of proof mass
- How do we achieve this in MEMS?
- Can we reduce voltages generated by electrostatic harvester?

Proposal for Large Proof Mass, Lower Voltage

- Potentiometric sensors including thermopiles, electrochemical cells as precharge
- Rod-plate capacitor
- Curved polyimide film plane
- Extra capacitance gained from conformal plane
- Repeated charge and discharge reduces maximum generated voltage

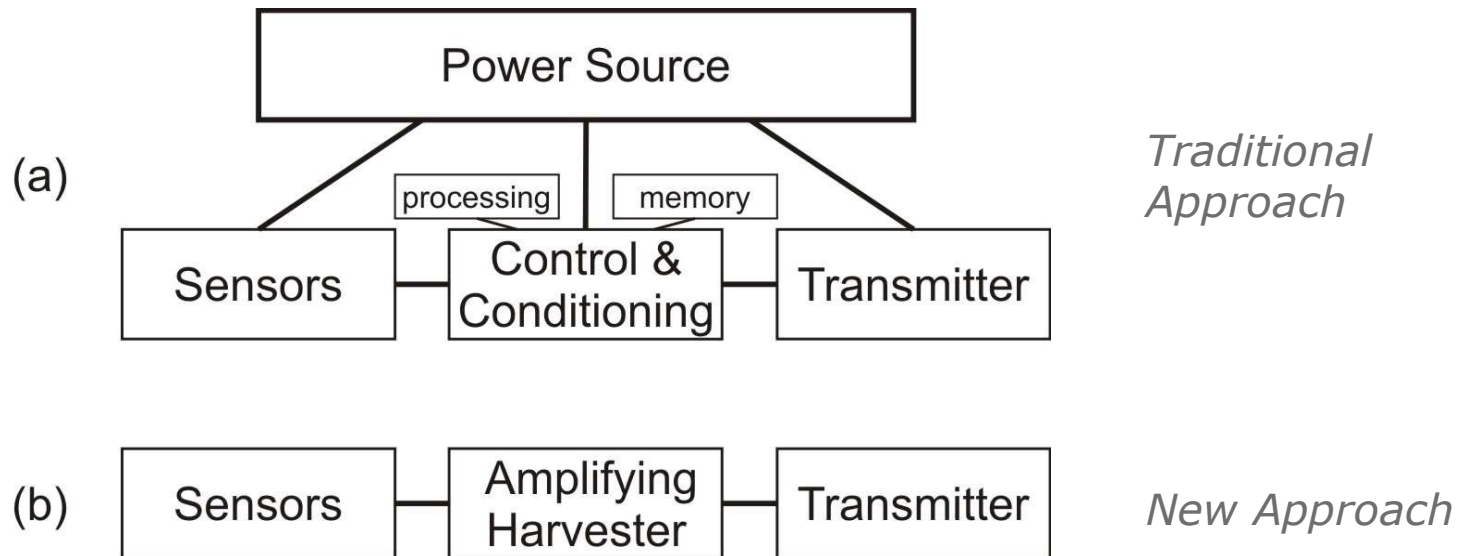


Ref:

C. He, M. Kiziroglou, D.C. Yates and E.M. Yeatman, "MEMS Energy Harvester for Wireless Biosensors", Proc. 23rd IEEE Conference in Micro-electro-mechanical Systems (MEMS 2010), Jan. 24-28, 2010, Hong Kong, pp. 172-175.

Additional Benefit

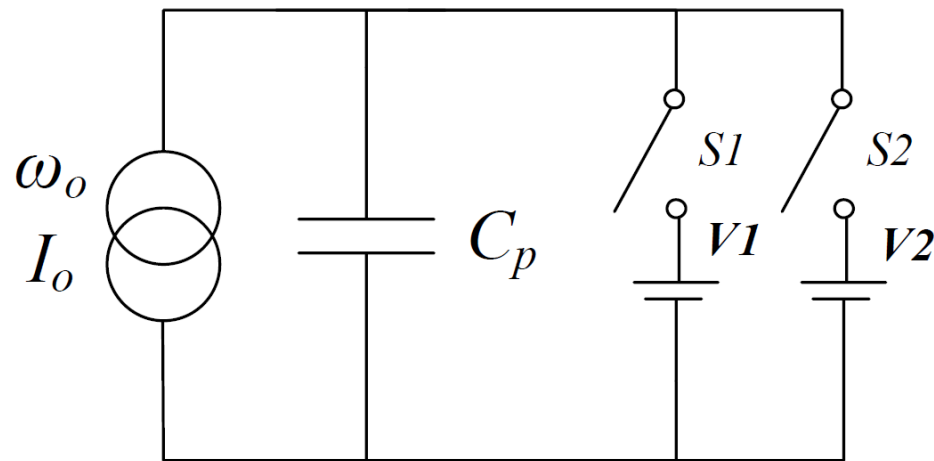
This is a novel architecture of WSN node



Very simple and power efficient

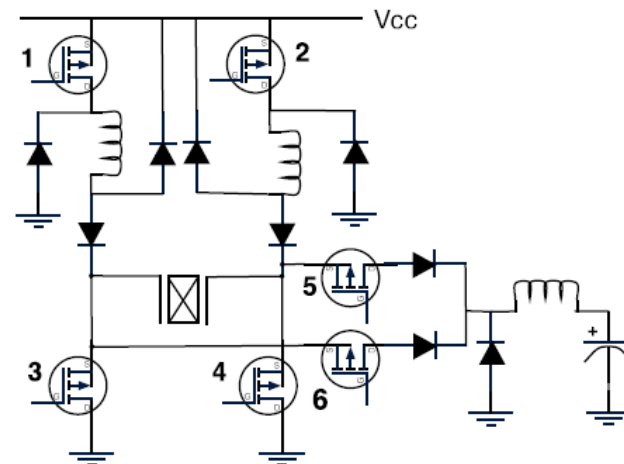
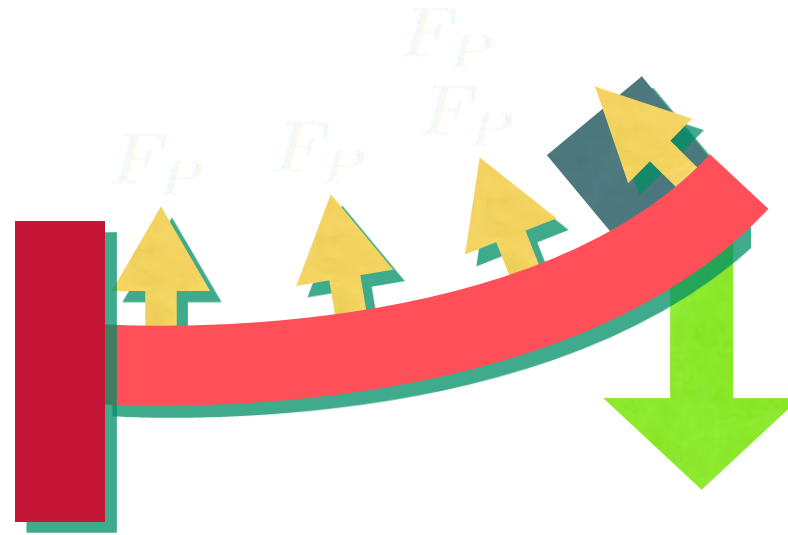
Improve Power Density of Piezo – “Prebiasing”

- With an increased mass we need to increase the transducer force
- Hard in the electrostatic case as size increases....
- What about piezoelectric?
- Force the current source to work into a high voltage...



Holistic approach – Piezoelectric Pre-biasing

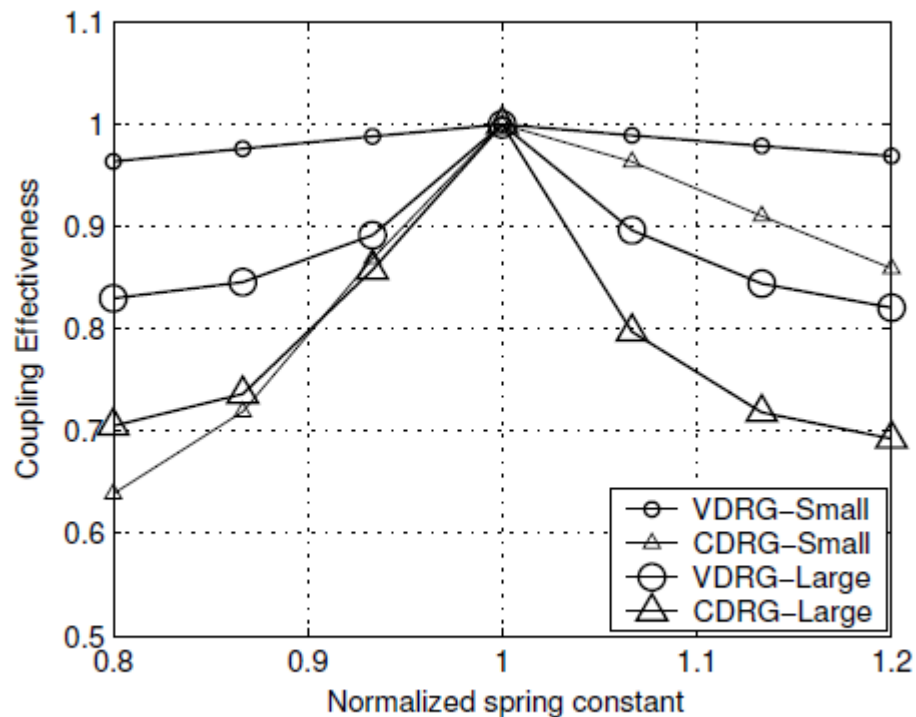
- Put a bias charge on piezo before it moves
- Thus more work can be done against it when it does move
- Technique demonstrated giving power output increase of 20 times over resistive load



Dicken J, Mitcheson PD, Stoianov I, et al, Increased Power Output from Piezoelectric Energy Harvesters by Pre-Biasing, PowerMEMS 2009, Pages: 75-78,

Adaptability

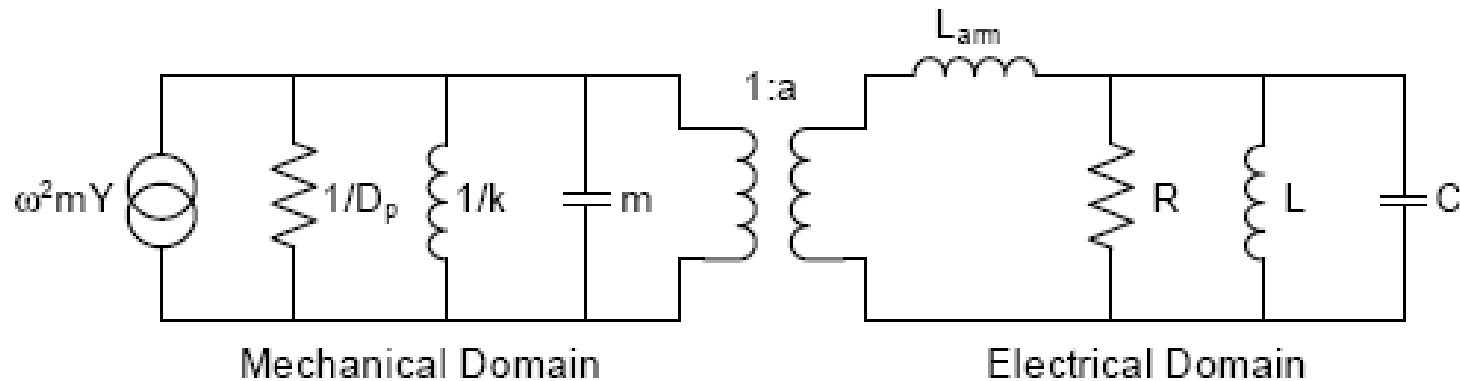
For different activities we could benefit from resonant frequency tuning



Von Bueren, T. Mitcheson, P.D. et al, Optimisation of inertial micropower generators for human walking motion, IEEE Sensors Journal, 2006, vol 6, Pages 28-38

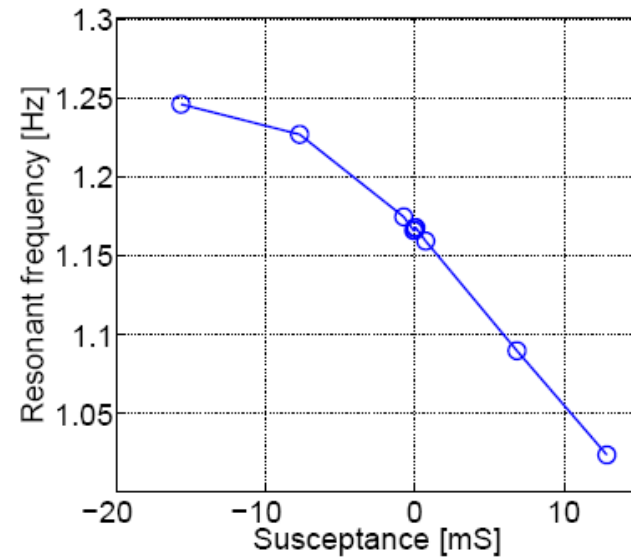
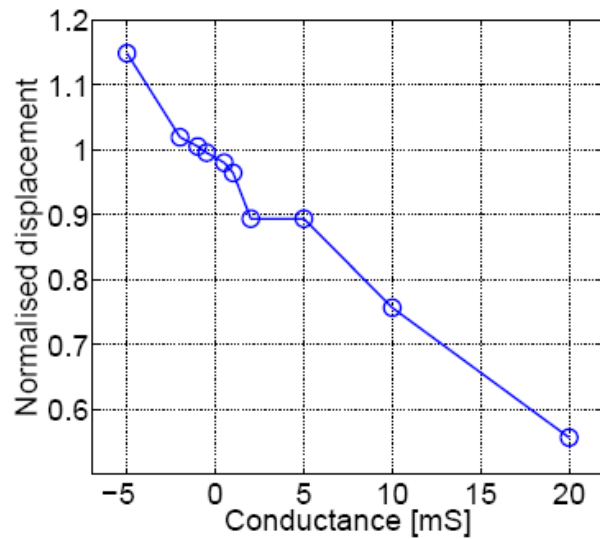
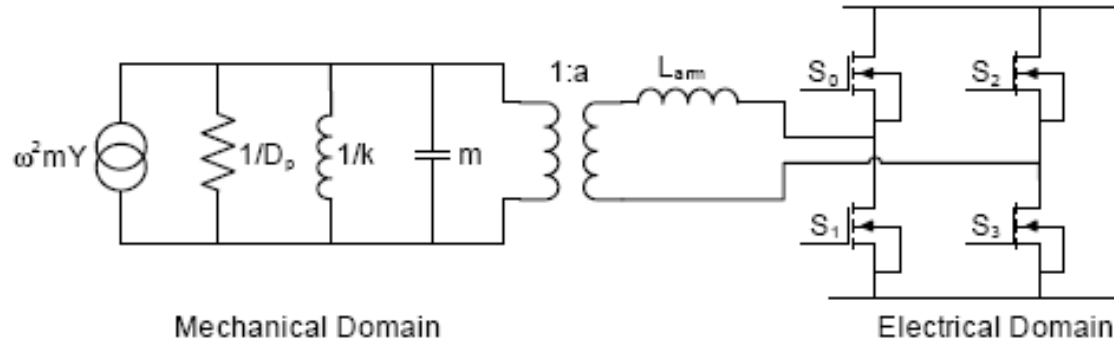
Adaptability of Harvester

How do we make a device tune resonant frequency and damping?



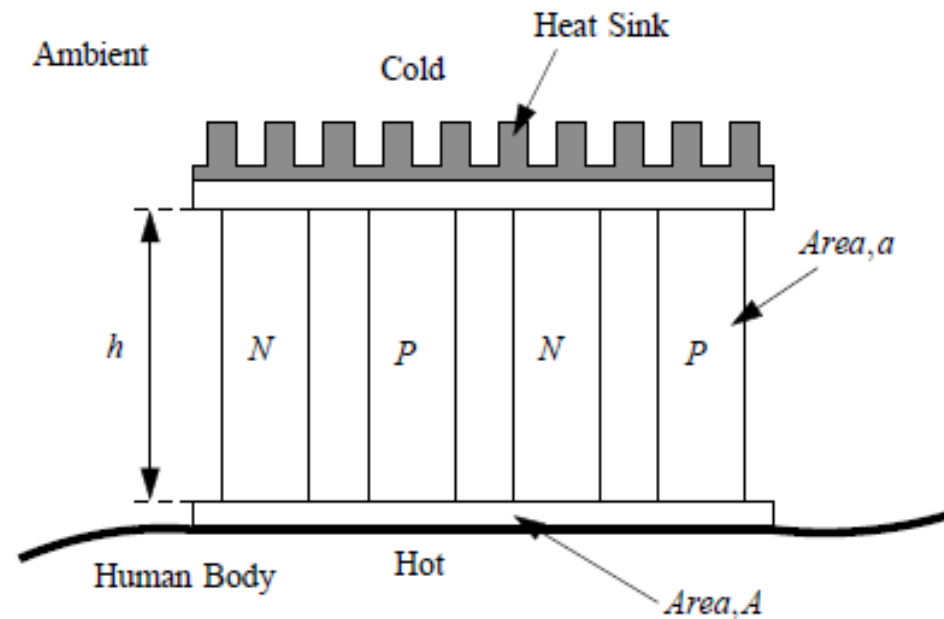
- *We can modify the mechanical system (primary side)*
- *We could modify the electrical side*
- *Can we do that in a continuous way?*
- *Not clear which approach is best*

Power Electronics for adaptability – damping and resonance



Thermoelectric Devices

- IMEC/Holst Centre working on these devices
- Use Seebeck effect of a thermal gradient to generate a potential difference
- Basic principle is that charge carriers on hot side of junction diffuse more than on the cold side.
- This leaves behind ionised atoms creating a voltage
- Achieved with alternating n and p-type silicon thermally in parallel and electrically in series

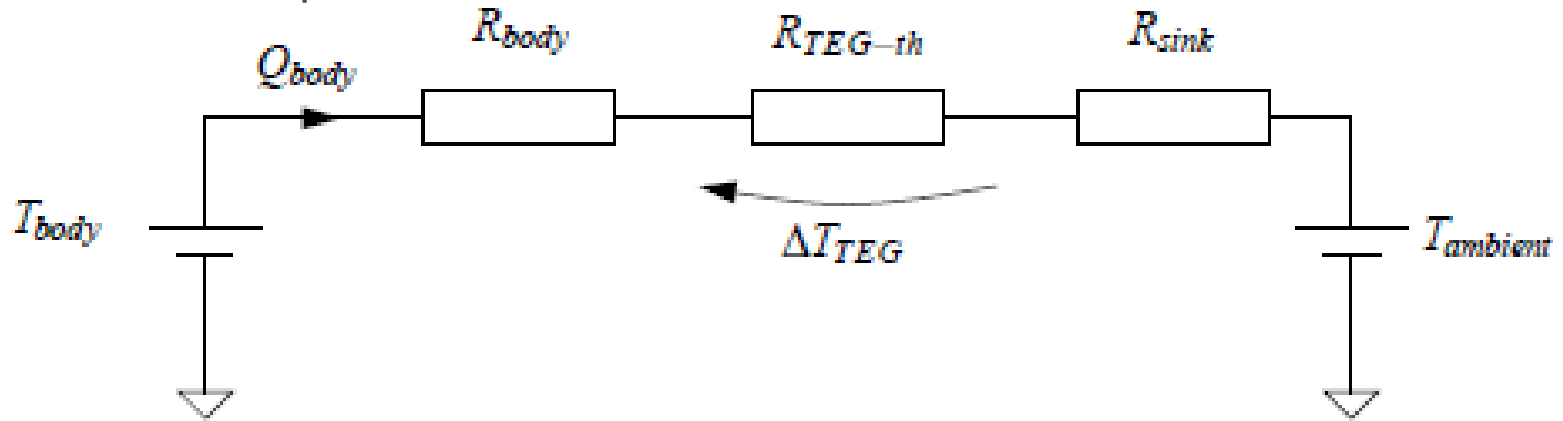


$$V = n\alpha\Delta T_{TEG}$$

If we make $R_{TEG-th} > R_{body} + R_{sink}$ we get maximum voltage across the TEG...

Thermoelectric devices – optimisation on body

But not maximum power...



$$P = \frac{n\alpha\Delta T_{TEG}^2}{4R_{TEG-el}}$$

*If electrically
impedance matched*

$$R_{TEG-th} = \frac{h}{K_{TEG} \cdot na}$$

$$R_{TEG-el} = \frac{\rho nh}{a}$$

$$P_{max} = \frac{\alpha\Delta T^2}{16\rho K_{TEG}(R_{body} + R_{sink})}$$

Thermoelectric Devices – optimisation on body

- Bismuth Telluride is a good thermoelectric material at these absolute temperatures (high figure of merit)

$$P_{\max} = \frac{A\Delta T^2}{2500(R_{body-pa} + R_{sink-pa})}$$

- The thermal resistance of the body changes depending on location on body activity etc, but we can assume around 0.05 m²K/W (at rest) to 0.01 m²K/W (heavy exercise)

(V. Leonov et al, Proceedings of BSN 2009)

*Holst Centre Human++
program,
thermoelectric powered
EEG and hybrid
thermo/solar EEG*



Other Harvesting Methods

We mentioned:

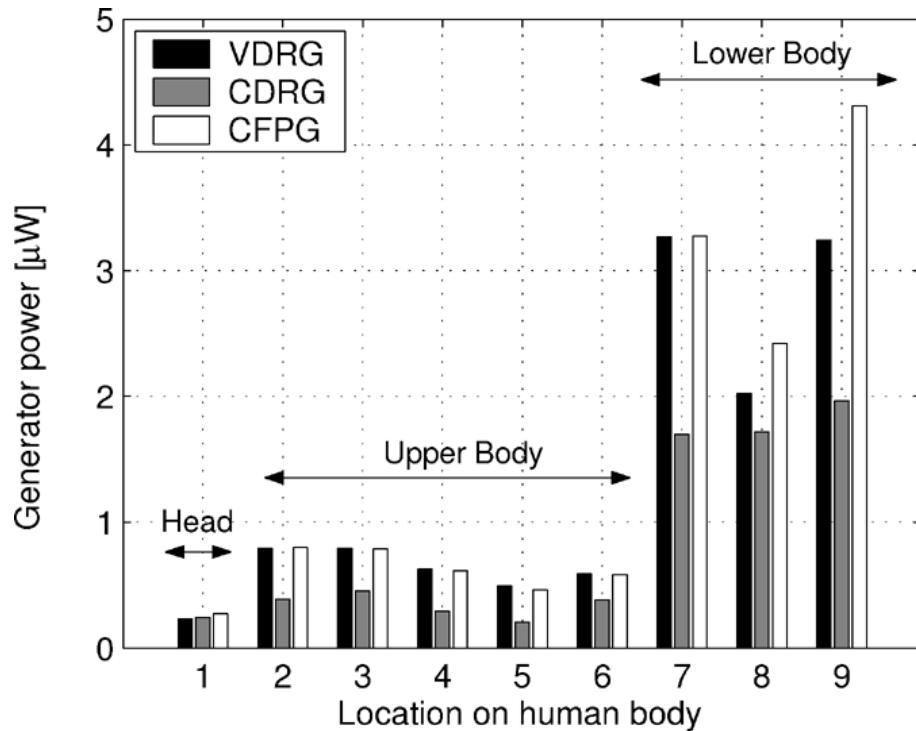
- Vibration
- Thermal
- Solar
- RF
- Fuel Cell (eg from blood sugar)

As usual the available harvesting methods are application dependent. Fuel cells could not be hermetically sealed and there is no light in implanted applications.

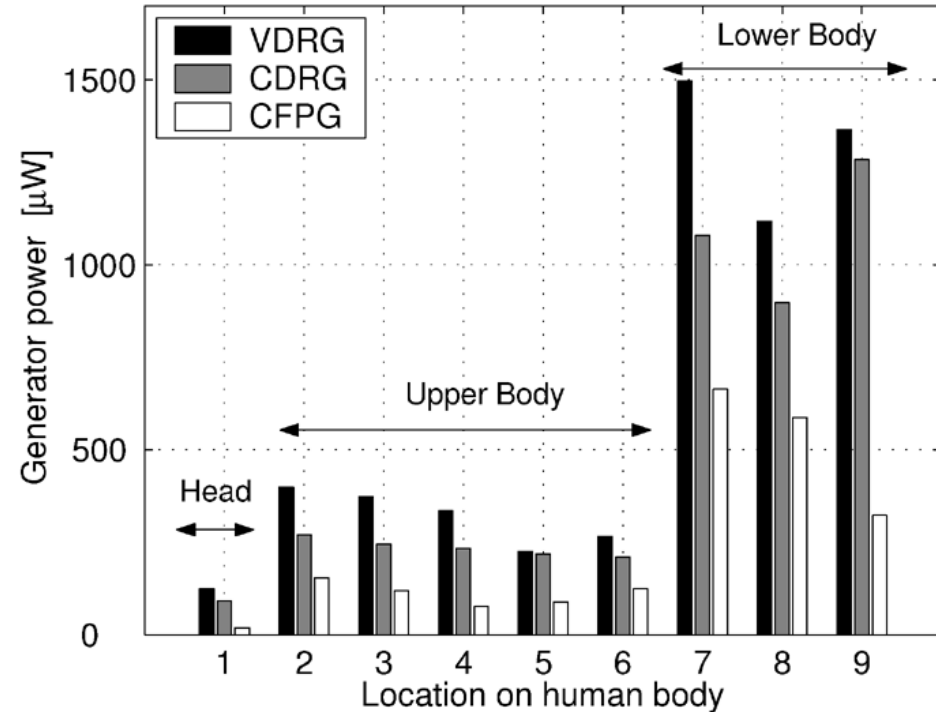
RF may be possible if a specific source is introduced, but then this is not harvesting but the power density would be very low

Which is best... thermal of vibration/motion?

Detailed study on Power available from human motion



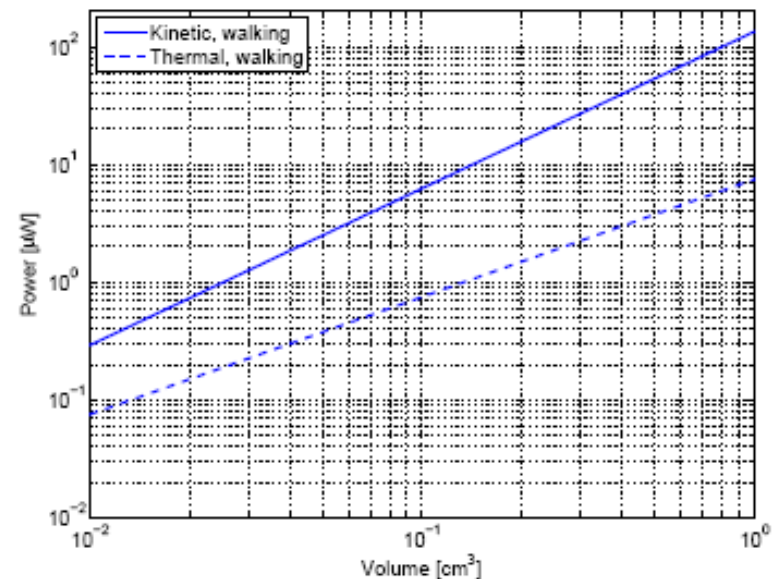
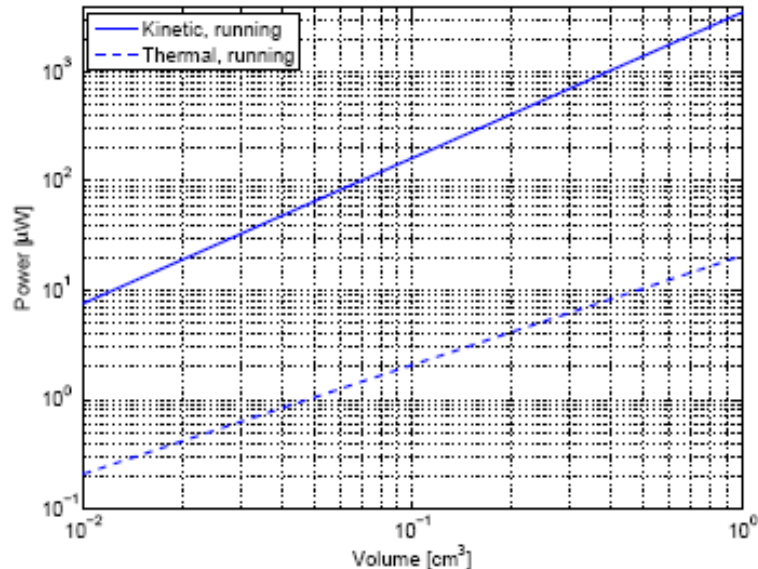
0.3g mass, $Z_I=0.25\text{mm}$ (approx 10mm^3)



2g mass, $Z_I=2\text{cm}$ (approx 1cc)

Von Bueren, T. Mitcheson, P.D. et al, Optimisation of inertial micropower generators for human walking motion, IEEE Sensors Journal, 2006, vol 6, Pages 28-38

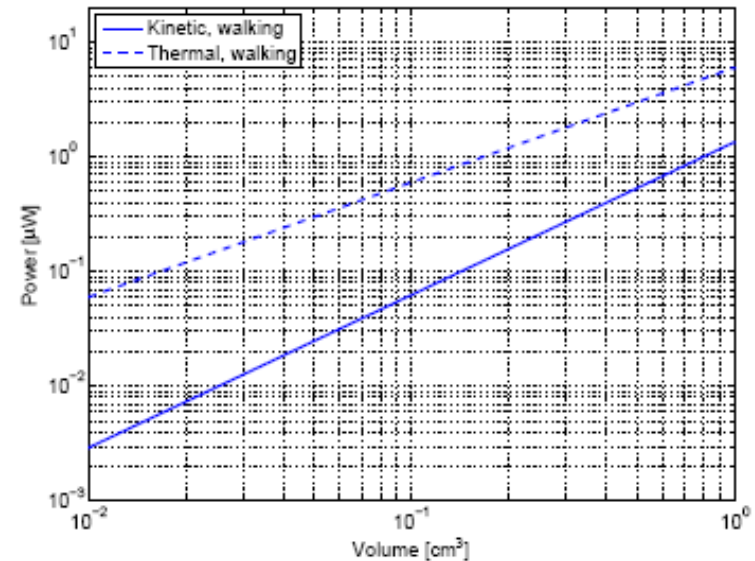
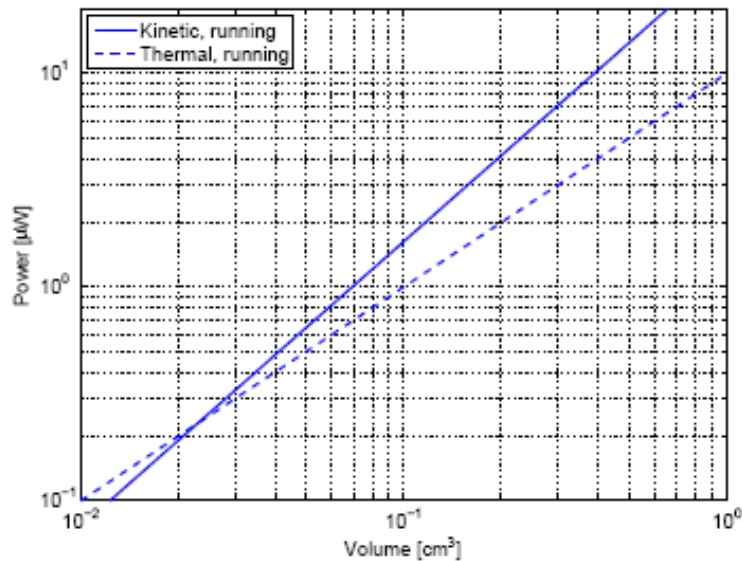
Comparison – Ultimate limits



- Kinetic devices are one to two orders of magnitude better per unit volume – and improve faster with increased size
- Expect up to 2 mW/cm³ from kinetic as an upper limit (running)
- Expect 20 μW/cm³ from thermal as the upper limit (running)

How close can we get to these ultimate limits?

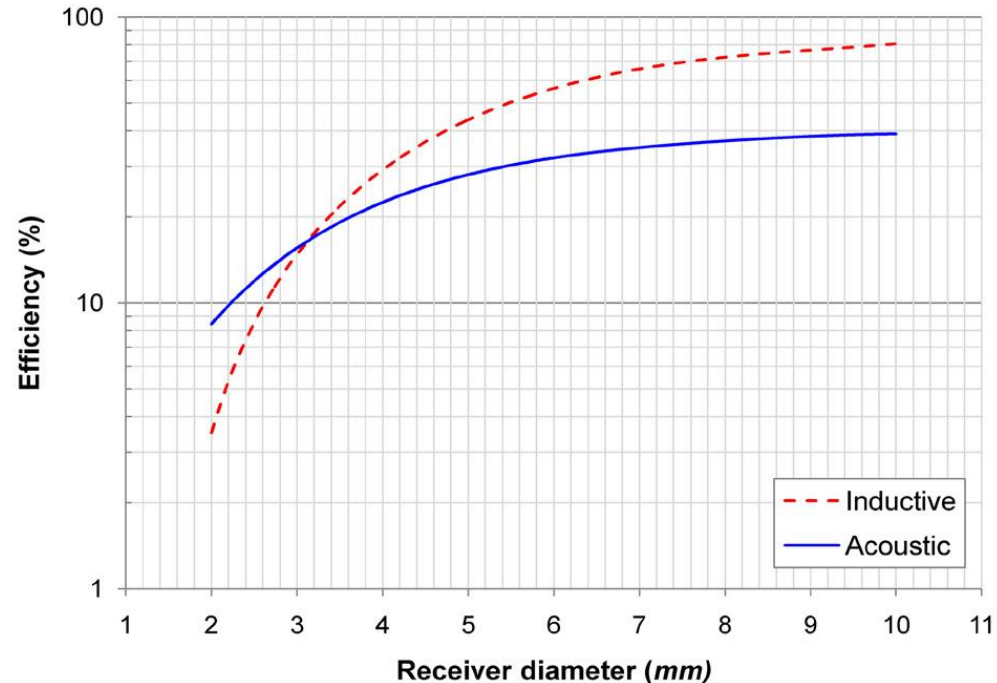
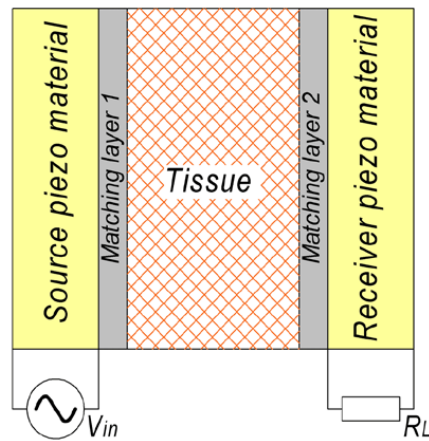
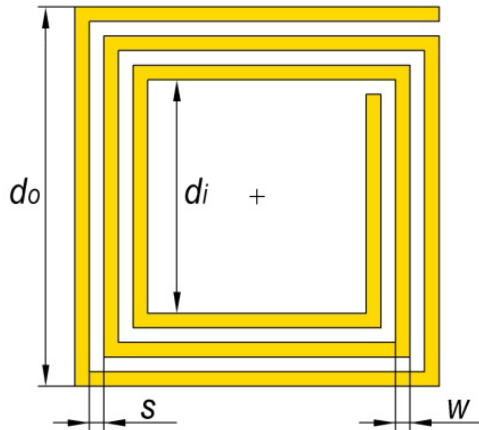
Comparison – Existing performance limits



- Now the optimal choice changes to thermal....
- No moving parts for thermo devices and generally better V to I ratio for power electronics
- Power densities of the order of 10 to $20 \mu\text{W}/\text{cm}^3$ for running
- Power densities of the order of $5 \mu\text{W}/\text{cm}^3$ for walking

Mitcheson, P.D. Energy Harvesting for Human Wearable and Implantable Bio-Sensors, IEEE EMBC Conference, pages 3432-3436, 2010

Non-harvesting methods – Inductive vs Acoustic



- At small dimensions (interesting for the body), acoustic transmission through the skin may be better than electromagnetic radiation
- Inductive is currently used in some implant powering systems

Conclusions – so why are we still using batteries?

- Thermal and kinetic energy harvesters are practical for wearable (and possibly implantable devices)
 - Sealable
 - Single attachment point
 - Other types are less suitable (lack of light and not hermetically sealed)
- Thermo devices already operate close to their ultimate limit
- Presently, kinetic devices are no where near their ultimate performance limits (typically $< 1\%$ effectiveness)
 - Ideas to improve power density with external mass, improved transducer coupling
- Expect power densities around $10 \mu\text{W}/\text{cm}^3$ at the moment
- Can we ever achieve a few mW/cm^3 with kinetic devices?
- We will probably need to if we are to beat batteries...

It is reasonable that we should start to see some ultra-low thermoelectric powered medical devices near term, and possibly kinetic in the long term – which may increase functionality

Challenges

- Reliability (“typical results...”)
- Intermittency (storage)
- Improve efficiency/effectiveness for vibration devices
- Can we improve thermoelectric FoM?
- Adaptability – bespoke vs general approach
 - Overhead of adaptability
- Power Processing interface – major challenge especially in BSN space
- Cost
- Low frequency very difficult – e-health application is hard
- Miniaturisation (power density drops with volume)
- Energy harvester aware load electronics

Acknowledgements

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