Biomechanical Energy Conversion: Challenges in Power Electronics and Electromechanics

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Sponsored by Office of Naval Research

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Human-Portable Energy

- Proliferation of Portable Electronics:
  - mobile phones
  - mobile computers
  - ‘wearable’ computers
  - personal digital assistants

- Others to come?
  - very low power electronics - mW and below - with new technologies
Batteries

- Primary source of man-portable energy
- Storage
  - lead acid: 30 W-h/kg
    - 40 kg human; suppose 4 kg of batteries (10 %)
    - 120 W for 1 hour
    - computer, roughly 50-200 W
    - cell phone, up to 30 W
  - NiMH, Li-Ion: 30-100 W-h/kg
- Rechargable
- Relatively ‘clean’ energy
Other Significant Options

- Combustibles
  - small jet fuel engines (JP8)

- Fuel Cells
  - $$$ (at least for now)
  - far more complex than advertised
  - ‘clean’, but fuel still ultimately limited
Biomechanical Energy Conversion

- Relatively new, untapped option
- Goal: harvest energy from otherwise wasted human motion
  - ‘clean’ energy- no doubt
  - renewable (food consumption)
  - unlimited energy
    - relatively limited power
    - less limited for bursts
  - quiet
Commercially Available, Human Powered

- Shavers
- Radios
- Flashlights
- Wristwatch
  - vibration/flywheel mechanism
- Night vision scopes
Mobile US Marine Power

- About 8 W continuous power
- Up to 25 W bursts
Conceptual Portable Energy System

Biomechanical Energy Converter (BMEC)

Biomechanical Motions → Electromechanical Devices → Energy Conversion Circuitry

Point-of-use Loads
- Battery
- Fuel Cell
- BMEC

Central Energy Processing

Base Load

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6/24/2014
### Potential Sources?

<table>
<thead>
<tr>
<th>Activities</th>
<th>Available Power</th>
<th>Conversion Eff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body Heat</td>
<td>116 W</td>
<td>3%</td>
</tr>
<tr>
<td>Breath</td>
<td>1 W</td>
<td>40%</td>
</tr>
<tr>
<td>Blood Pressure</td>
<td>0.9 W</td>
<td>2%</td>
</tr>
<tr>
<td>Upper limb motion</td>
<td>24-60 W</td>
<td>few %</td>
</tr>
<tr>
<td>Heel strike</td>
<td>67 W</td>
<td>7%-50%</td>
</tr>
<tr>
<td>Body waste</td>
<td>1-5 W</td>
<td>50%</td>
</tr>
</tbody>
</table>

according to Prospector IX: Human Powered Systems Technology, Space Power Institute, Auburn U., 1997
Identifying Potential Sources

- Present data very insufficient
- For now, focus on relatively large power
- Work with biomechanics experts
  - Prof. Xudong Zhang and students, MIE, UIUC
  - identify and quantify the best candidate motions for power
  - quantify the fatigue factor for candidate motions
  - carry out experiments on human subjects
Typical Biomechanical Link Model

- Model, calculate force, speed, and power for motions
- Estimate fatigue under given loads
- Confirm with data from our biomechanics laboratory
Human Subject Database

- Perform calculations based on prior data collected regarding size and strength

\[ H = \text{height} \]

\[ 0.135(H) \quad 0.2(H) \]

(average)

(case study: Prof. Chapman)
Test and Measurement

- Biomechanics lab
  - 5-camera digital capture system
  - reaction force platform
  - electromyography (raises controversy for muscle fatigue measurements)

- Two human subjects experiments planned
Challenges in Electromechanics

- Evaluate materials
- Identify, evaluate topologies
- New generator designs
  - construction, placement on body
- Construction and testing
Materials

- Better known
  - Piezoelectric
  - Electrostatic
  - Magnetic

- Research level
  - polymers
  - other exotic materials
Piezoelectric

- Compression/tension movements
- Compact, lightweight
- Form fitting possible
- Subject of most biomechanical energy conversion work
  - heel strike energy recovery
Piezoelectric, Heel Strike

- Heel strike is the most obvious high power movement
- Groups at MIT have built prototypes
  - focus on piezoelectric material itself
  - little power recovered
    - did power a transmitter
  - did use power electronics to improve the energy use
- Electromagnetic generators largely dismissed
Effective Mass; Heel Strike

Shoe with Implants

PIECOELECTRIC INSERT

METAL SPRING

ALTERNATIVE GENERATOR SYSTEM

Starner, “Human Powered Wearable Computing,”
IBM Systems Journal
Piezoelectric Energy Recovery

- Lead zirconate titanate (PZT)
  - for compression, requires too much force to get reasonable energy
  - for bending, little range
- Polyvinylidene fluoride (PVDF)
  - much more flexible and more easily shaped
  - given 116 cm$^2$ PVDF, deflected 5 cm, 68 kg, every 5 sec $\Rightarrow$ 1.5 W
    - condition approximated heel strike
    - perhaps up to 5 W, considering both feet and brisk pace
- Open to debate - more data needed
Electrostatics

- Use compression/tension between parallel plates
- Use ambient or intentional vibration to cause relative motion between plates
- Electrostatics tractable only if very small air gaps (microns) due to field breakdown
  - limited to 40 J/m³ for macroscopic application
Results reported thus far

- Microelectromechanical systems (MEMS) approach out of MIT
  - use MEMS capacitors (micron airgaps)
  - very sensitive to vibrations
  - power conversion circuit recovers current due to changing capacitance
  - mW or μW power levels, but enough for some applications
Magnetic machines

- Clearly the best for macroscopic applications
  - 1 T field $\rightarrow$ 400 kJ/m$^3$
  - Widespread use, covering nearly all electric machinery
- Standard rotary configurations not straightforward to adapt to this application
- One of the heel-strike papers shows an example, but not carefully engineered at all
Topologies

- Magnetic should probably be the main focus
- Which paradigm of machines is best?
  - reluctance, induction, permanent magnets, combinations
  - match to motion
  - mass
  - cost and performance tradeoffs
Range of Motion, Degrees of Freedom

- Rotary or linear?
  - depends on movement
- Why not both?
- Why not multiple degrees of freedom?
Induction machines

- Force comes from interaction between currents on movable and stationary members
- Difficult to justify in stand-alone applications
- Inexpensive, well understood
Reluctance machines

- Force comes from change of inductance
- Even simpler than induction
- Again, tougher to use in stand-alone conditions
- Position synchronization required
Permanent magnet machines

- Force occurs due to interactions of current on stationary member with magnets on rotary member
- Relatively high cost, though an active research area
- Most straightforward to use for stand-alone electric generation
- Position synchronization may be required
Design Methods

- New machine topologies demands new design methods
  - take specs from biomechanical data
- Can’t use ‘cookie-cutter’ approach
- Finite elements? 3-D likely.
- Magnetic equivalent circuits?
Construction and Testing

- Not straightforward to build
  - custom approaches
- Testing torque and speed with dynamometer is not likely
  - few watts
  - torque and speed not so continuous
  - random motions, large variations between human generators
- Develop benchmarks specific to biomechanics
Electromechanics Synopsis

- Most work to date by people seeking an application for their own technology
  - piezoelectric and MEMS in particular
- Essentially no published work by electromechanics and biomechanics experts
- Little use of the best electromechanics materials: steel and copper
Challenges in Power Electronics

- Energy source is unconventional
  - uncertainty
  - variable frequency, signal level
  - current source if electrostatic generator
- Low power
  - at most, 10’s of watts
  - at low end, mW
- Low signal level, possibly
  - Switch drops comparable to voltage levels
- Control and power for control circuit
Simple Designs

- Diode bridge rectifier + filter
  - three-phase rotary generator
  - match voltage generated to converter
- Emphasize generator design over electronic design
  - involves tradeoff of silicon versus steel
- Heel-strike work to data largely shows simple diode-capacitor bridges, linear regulators
More Sophisticated Designs

- Design the generator for maximum power output
- Rely on converter to give the correct voltage and current
  - equivalent of power factor correctors, ac/dc converters
- Requires more control, more power devices
  - perhaps part of a central power processing system
Other Caveats

- Can biomechanical energy conversion improve human experience?
  - cause heel strike to have less negative impact
  - reduce the burden of constant circus of recharging batteries

- Can the conversion be beneficial in motoring as well as generating?
  - help physically disabled persons
  - performance booster for athletes, military
Summary

- Biomechanical energy conversion can have a large impact on the low power, portable electronics.
- Significant obstacles are present for electromechanics, power electronics, and biomechanics.
- Little prior work has been done, none of it comprehensive = wide open research area.