Unobtrusive Integration of Magnetic Generator Systems into Common Footwear

by

Jeffrey Yukio Hayashida

Submitted to the Department of Mechanical Engineering in
partial fulfillment of the requirements for the degree of

Bachelor of Science

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2000

Signature of Author: _____
Department of Mechanical Engineering
May 18, 2000

Certified by: _____
Joseph Paradiso
Principal Research Scientist, MIT Media Lab
Thesis Supervisor

Accepted by: _____
Ernest G. Cravalho
Chairman, Undergraduate Thesis Committee

Unobtrusive Integration of Magnetic Generator Systems into Common Footwear

by

Jeffrey Yukio Hayashida

Submitted to the Department of Mechanical Engineering
on May 22, 2000 in Partial Fulfillment of the
requirements for the Degree of Bachelor of Science in
Mechanical Engineering

ABSTRACT

A power generating system was designed to passively harness some of the kinetic energy available during walking. The system included a rotary arm extending down from the sole, which ultimately drove a pair of small electrical generators through a stepped-up gearbox. A one-way clutch mechanism was used to transmit torque to the gearbox. This allowed for additional spin following the initial impact of a step, also preventing lockup due to rotary inertia in the gears. The entire generator system was designed to fit in the heel of a standard running shoe, with the rotary arm compressing once during each heel strike.

The final system produced a peak power of 1.61 Watts during the heel strike and an average power of 58.1 mW across the entire gait. To maximize power transfer, an ideal load was determined for the two DC generators connected in series. While the average power generated was below the desired 250 mW, initial calculations show this level can eventually be reached or exceeded with the addition of a flywheel to each generator shaft, or a spring to store more energy from the heel-strike.

Thesis Supervisor: Joseph Paradiso

Title: Principle Research Scientist, MIT Media Lab

Acknowledgements

First and foremost I'd like to thank my thesis advisor Joe Paradiso for his tremendous assistance and support throughout the last year. What can I say, he knows everything! I'd also like to thank him and the MIT Media Lab for giving me the opportunity to do my Mech E thesis at the Media Lab. The resources available there will always amaze me. Many thanks to the rest of the crew in Responsive Environments, especially the Ari's, for their help and guidance throughout this project. And last but not least, I'd like to thank my group of loyal friends that I live with, who literally kept me under lock and key until I finished this project.

Chapter 1

Introduction

1.1 Background Information

In today's world, computers, as well as electronic devices, are becoming more and more integrated into everyday life. These seamless integrations focus on mobility, but at the same time strive to be unobtrusive to the end user. With the introduction of personal data assistants (PDA's) and advanced cellular phones capable of searching the web, true mobile computing is closer than ever. Unfortunately, battery technology, which powers most of these mobile connectivity solutions, has not kept up the same pace of improvement. Single-use batteries continue to be bulky, expensive, and unreliable, in addition to costing millions to dispose of each year. And, while impressive gains have been made in rechargeable battery technology over the past decade, these types of reusable energy sources are still struggling to reach single-use levels.

One alternative to carrying relatively large-capacity batteries is to harvest the energy of everyday human motion and use it to power mobile devices. Examples of human powered objects range from, eggbeaters, to bicycles, to hand-crank flashlights[1]. However, only a relative few, such as the Swatch Autoquartz™, Seiko AGS™, and Seiko Thermic™ watches, actually make passive use of everyday motion and energy produced by the body.

By tapping into the many complex functions the human body performs daily, a relatively large amount of power could be produced. The following are

estimates[2] of the power that could potentially be generated through common movements: breathing – 0.42 W, blood pressure – 0.37 W, exhalation – 0.40 W, footfalls – 5 W.   Most notably, the available power from footfalls would be more than enough to quickly charge a battery or continuously run devices such PDA's, cellular telephones, and even wearable computing devices. It is likewise the easiest, least obtrusive, and potentially least dangerous to tap.

Methods of actually producing this power range from piezoelectric inserts to rotary as well as linear electromagnetic generators. To date, neither method of power conversion has been totally successful, as each method has tradeoffs. Piezoelectric insoles[3] tend to be unobtrusive, yet achieve a relatively low average power output of up to 10mW. Recent attempts to equip shoes with actively-driven piezoceramic stacks[4] and electropolymers[3] are promising, but as there are still major unsolved issues in power conditioning and mechanical integration, they are still in the research phase. On the other end of the spectrum, electromagnetic generators, capable of converting a sufficient amount of power, are hard to properly integrate into footwear and tend to be obtrusive to the user's motions.

1.2 General Overview

The goal of this thesis is to ultimately design a relatively high-power, yet reasonably unobtrusive power-generating shoe module. The research focused on the design and implementation of a permanent-magnet/inductance device due to its potential robustness, simplicity, and efficiency. In addition, methods of

extended energy storage, such as flywheels or springs, would be taken into consideration for use with the generation source. While it was desired that this device produce close to a Watt in power, its integration into a standard shoe took precedence. In other words, the first priority was to constrain the power generating to module to fit seamlessly into the heel of a shoe, then optimize the design to produce the greatest amount of output power.

Chapter 2

Design and Methodology

2.1 Initial Concepts

In order to narrow down the possible means of generating power through a heel strike, one method of power conversion was picked. This entailed a permanent magnet – coil setup, whether it be through rotary or linear means. Various concepts that were explored also included adding mechanical energy storage, such as springs or flywheels.

Linear Vibration System

This system simply entails a magnet suspended by springs, surrounded by a voice coil. Here, the method of power generation is essentially the opposite of power consumption by conventional speakers. Audio drivers take in various frequency signals representing music, and convert them to linear motion in the cone. This method of generation takes linear motion, via a heel strike, and converts it to electrical power. When the heel hits the ground, an impulse is sent

into the suspended magnet, causing it to oscillate within a coil. Because of the changing magnetic field within the coil, power is produced. In order to produce appreciable power however, a relatively large magnet would be needed both generate a high magnetic field and provide a large inertial proof mass. A sizeable cavity within the shoe's heel would also be required for the excursion of the suspended magnet. For these reasons, this method was not pursued.

Rotary Methods

A more efficient route to power generation would be to directly drive the magnet during the heel strike, instead of letting it react inertially. Rather than oscillating the magnet in one dimension, it is much more efficient to rotate the magnet or surrounding coil (Figure 2.1).

Figure 2.1 – Rotary Power Generation in Heel

Two-Way Rotary

A rotary generator is thus used in a system that converts a linear heel strike into rotary motion through the use of a rotating arm. The arm compresses by a

centimeter, which has little effect on the gait of the user[5]. The converted rotary

motion is miniscule however, and must be stepped up mechanically with a

gearbox in order to turn a generator at normal operating speeds. This method is

termed "Two-Way," because it utilizes a spring, also compressed during the heel

strike, to produce power on the return stroke of rotating arm. The negative

voltage produced by the generators on the return stroke could easily be rectified

with diodes, theoretically doubling power output.

   A large problem encountered when further investigating this system deals

with the rotary inertia within the step-up gearbox. On the compression side of the

cycle, the gears spin in one direction, while spinning in the opposite direction

during release. This abrupt change in the direction that the gears are spinning,

would lead to a decrease in the life of the gears, if not a complete lockup and

failure.   Also, because of the rotary inertia in the gears, energy must be

consumed to slow them down and ultimately change their direction of rotation,

leading to a reduction in power output. A possible solution to this problem would

be to design the return stroke such that it actuates the gearing in the same

direction as the compression stroke. A mechanism like this would add

complexity as well as size to the overall system, and because of this was not

explored further.

Rotary Clutch

   The rotary clutch system was the design that was ultimately decided upon. It

is extremely similar to the two-way rotary system, however does not make use of

the rotating arm's return stroke to generate power. Instead, a clutch system

transmits torque through the arm in one direction, and allows for free spinning in the opposite direction.   Since a change in the direction of the gearbox is no longer an issue, an increased rotary inertia in the gearbox can now be utilized to produce additional power.   Based on estimations, it was determined that enough additional power could be produced to offset the fact that the return cycle is no longer used.

2.2 Design Process

In order to further the concept that was decided upon, additional research and experimentation needed to take place. Various one-way clutch designs were sorted through, as size constraints were a key issue. In addition, a wide range of miniature DC motors were bought and tested for both efficiency and power output.   Conventional motors are known to reach 20-90% mechanical-electrical efficiency when working as generators. Several calculations also needed to be made, including the approximate duration of heel compression for the system. From this, a corresponding initial angular velocity was found.

Motor Selection

To select the proper generator for the system, each DC motor (used as generators) was tested for its power output. A tachometer jig (Figure 2.2) was made by placing a slotted optical wheel between a driving motor and generator. The driving motor and generator were then coupled together. To determine the rotational velocity, the slotted optical wheel spun through an infrared emitter-detector pair, whose output was read on an oscilloscope.   The output of the

generator was then connected to a load, with the resulting voltage recorded at various speeds. The load connected to each generator was initially set to be equal to the impedance across the generator leads. Using the following equation, power versus speed curves were generated.
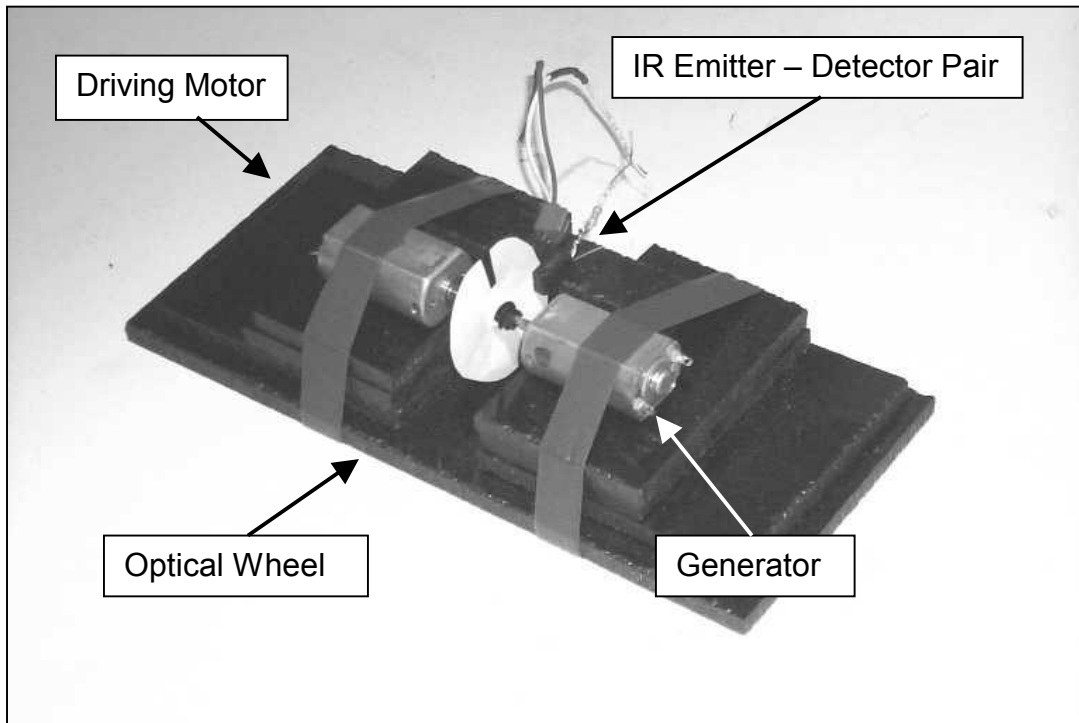

Figure 2.2 – Generator Tachometer Jig

To equalize the various generators tested, physical size was also taken into account. For instance, one of the larger generators tested produced more power than a single pager motor. However four pager motors, fitting in the same volume as the large generator produced a greater amount of total power.

The normalized power versus angular velocity curves were then used to determine which generator would produce the most power at a given angular velocity. The reference velocity was based on the initial calculation for angular

velocity obtainable from a heel strike (Appendix A). From this, it was decided that a pair of 12-Volt DC motors, rated at 10,000 rpm, were the most efficient out of the sample set for producing power at this velocity.

Gearbox Design

To begin the design of the gearbox, specific design parameters were first set. The major requirements were:

- Total length of gearbox < 2 inches
- Gear diameters to fit in heel of shoe < 0.75 inches
- Smaller gear able to fit on 1/8 inch shaft
- Low rotational resistance
- Rigid enough to take weight of average human
- To avoid critical stress on gear teeth, gear ratio < 1:50

Based on these parameters and the availability of specific gears, it was decided that an overall ratio of 1:42 would be used. This ratio was found after several iterations through both gear layout and sizing. The final gears selected are shown below (Figure 2.3).   The gear pitch of 48 was chosen because it was the smallest pitch (least rolling resistance) that could handle the amount of loading seen by the system. Ball bearings were chosen as rotational supports for the drive train because of their resistance to wear, as well as to minimize friction. The rotational arm, which was originally constrained to compress 1 cm, was finally set to compress 3.2 cm in order to alleviate any excessive force felt by the user. This compression distance is relatively large however, and will be reduced to the recommended 1 cm[4] in further design revisions.
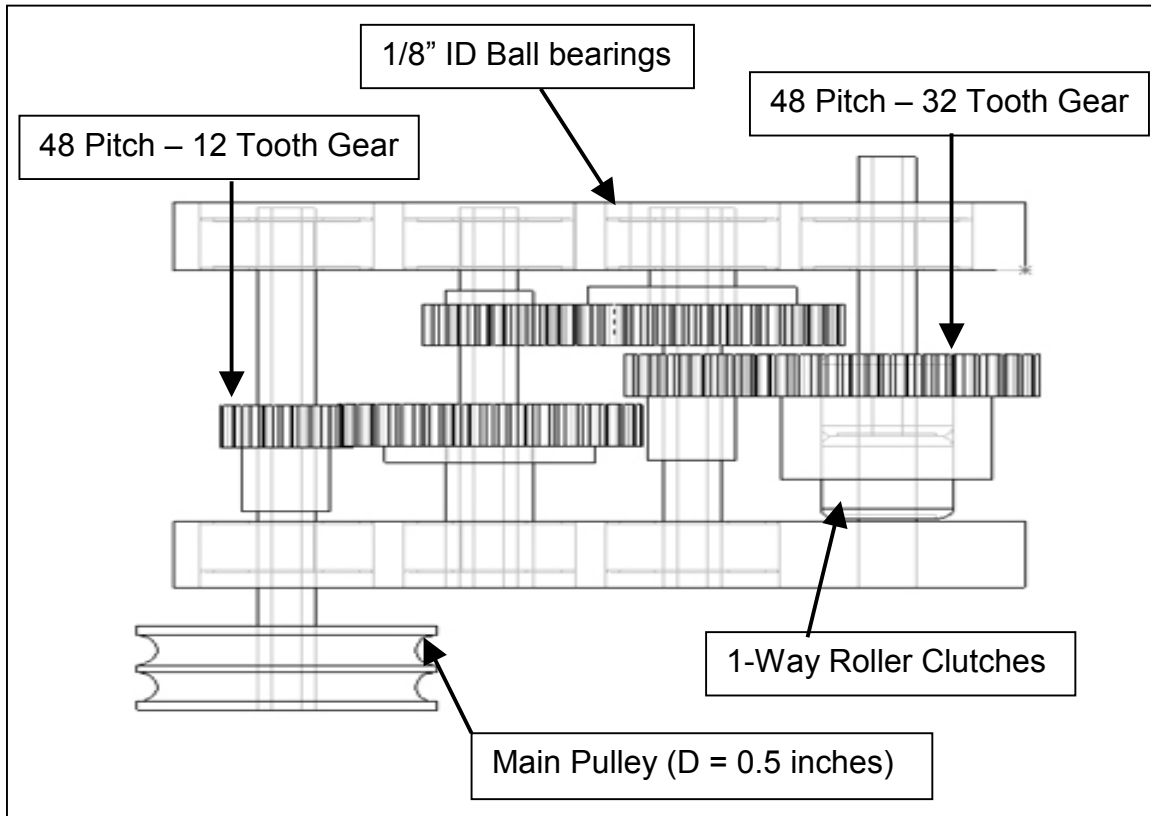
Figure 2.3 – Final gearbox layout

Clutch Mechanism

The main goal of the clutch mechanism was to provide torque transmission to the gearbox in one direction only, while allowing free spinning in the other direction. This was achieved through the use of two roller bearing clutches, coupled together. The input of the rotating arm fed directly into the roller clutch, which transmitted torque to the rest of the gearbox. In order to allow the rotating arm to return to its original position, a torsional spring was fitted to it, and anchored to the outside of the housing. Figure 2.4 shows the final layout of this drive stage.
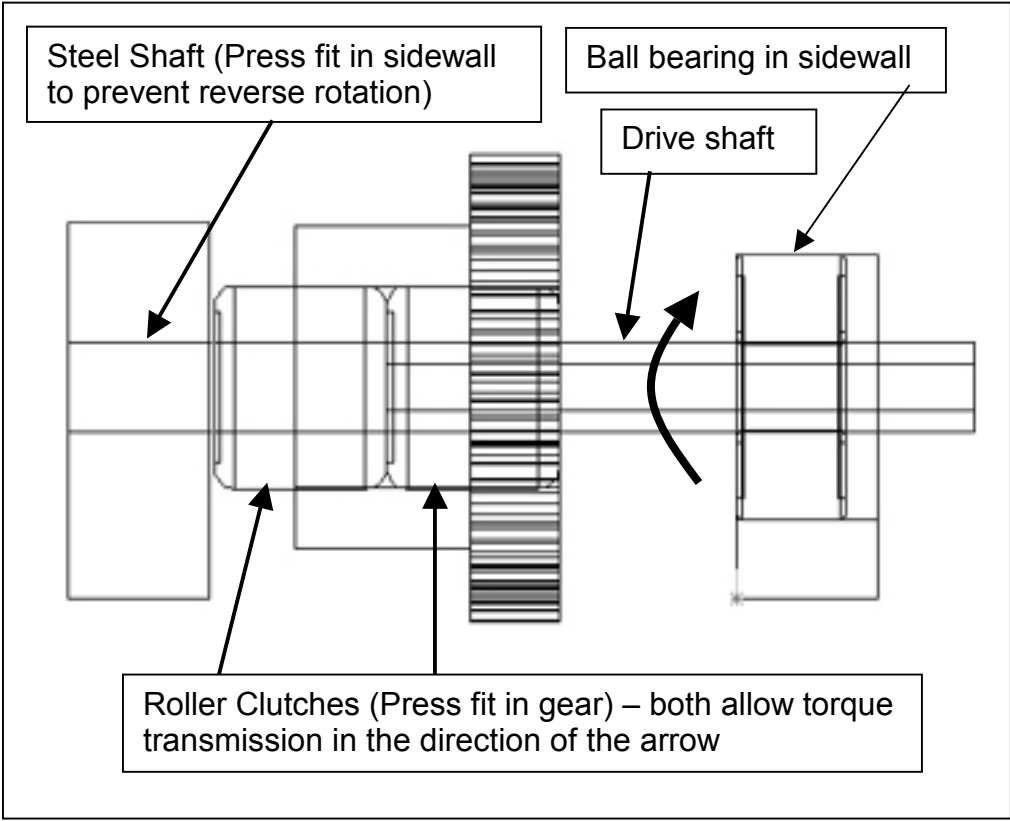
Figure 2.4 – Roller Clutch assembly

Steel Shaft (Press fit in sidewall to prevent reverse rotation)

Ball bearing in sidewall

Drive shaft

Roller Clutches (Press fit in gear) – both allow torque transmission in the direction of the arrow

Chapter 3

Part Production and Assembly

3.1 Gearbox Assembly

Prior to any machining or assembly, the entire design was modeled using Solidworks™. This ensured that critical dimensions, such as gear spacing, were correct, and also helped in the final integration of the gearbox into the sole of a New Balance™ running shoe.

The first parts of the gearbox to be made were the aluminum sidewalls. These were made out of 0.2" thick aluminum, because of the low weight and high rigidity of aluminum. A CNC mill was then used to drill the holes that ball bearings would eventually be press fit into.

The next step in assembly involved making the various gear subassemblies. First the gears were cut down to their proper widths, then soldered onto the main brass shaft. Telescoping brass rods were used for the main shafts in order to account for the different sized holes in the gears. Because they were telescoping, the brass rods fit into each other with a very small clearance gap, and allowed for the easy fabrication of spacers.   Next, one of the 32 – tooth gears was drilled and reamed in order to press fit both of the roller clutches into it.

Prior to final assembly of the gearbox, the rotating arm was manufactured and installed. This arm was made out of 1/8" stainless steel rod, chosen for its

hardness, which was necessary, since it was to be used within one of the roller clutches.

Following the final assembly of the gearbox, the motor mounting bracket was made and the motor mounted within it. The drive shaft of each motor was trimmed to the proper length, in order to accept the press-fit pulleys. This sub-assembly was then aligned and bolted to the gearbox. Finally, belts were made in order to transmit power between the main pulley and two motors. The material used for the belts was 18 gauge nylon rope, burned at each end, and then melted together. After cutting away residue near the weld line in the ropes, the belts ran exceptionally smooth and the power generating module (Figure 3.1) was complete. Pictures of the final assembly are contained in Appendix B.
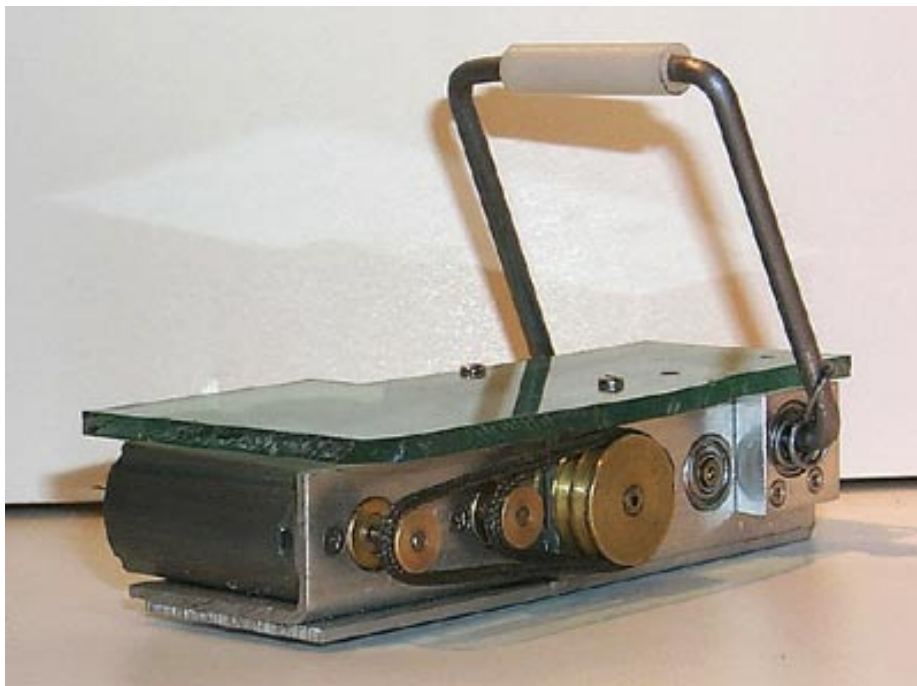

Figure 3.1 – Final assembly of power generating module

3.2 Integration Into Shoe

The final integration of the power generating device into the heel of a shoe, entailed cutting the hard rubber sole off the shoe, then carving out the softer foam beneath it. A template was then made in order to assure that the cutout was in the proper location, as well as to the proper dimensions. An Exacto™ knife was used to perform the cutting, with all the material under the template being removed up until the cloth layer beneath the heel.

Electrical leads were soldered to the generators and passed up the side, in between the inner and outer layer of the shoe.   With the gearbox-generator system pressed into the shoe, a Plexiglas cover was added in order to protect the gears from foreign objects, in addition to adding aesthetics to the assembly (Appendix B).   As a final assembly step, the harder rubber sole, removed earlier, was replaced. Before this however, small sections were cut out of it, in order to allow for easy viewing of the mechanism through the heel (Figure 3.2).

Figure 3.2 - Completed power generation in heel of shoe

Chapter 4

Experimental Results

4.1 Load Matching

In order to produce as large an output voltage as possible, the two DC generators were wired in series. From there, the output of the generators was tested with numerous resistive loads (Figure 4.1) in order to find the load that allowed for maximum power delivery.
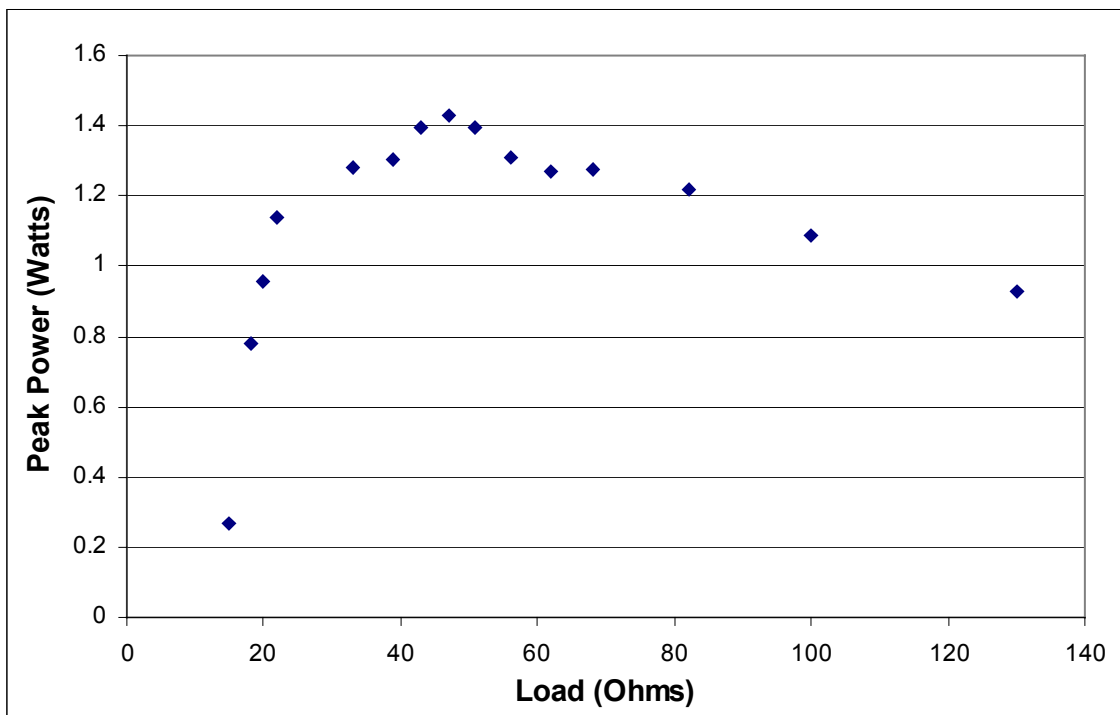

Figure 4.1 – Peak Power Output versus Load across Generator Leads

From the data (Appendix C) it was determined that the ideal resistive load across the two generators was approximately 47Ω. All consequent output power measurements were hence made using a 47Ω resistor as the load. Notably, this

ideal load was only a little higher than the impedance across both generators at $\omega=0$.

4.2 Power Output of Generators

A moderate walking pace entails a heel strike every half second, or the same foot hitting the ground once per second. This was the approximate rate at which the completed system was tested. Figure 4.2 shows an average voltage spike produced across a resistive load of 47 ohms.
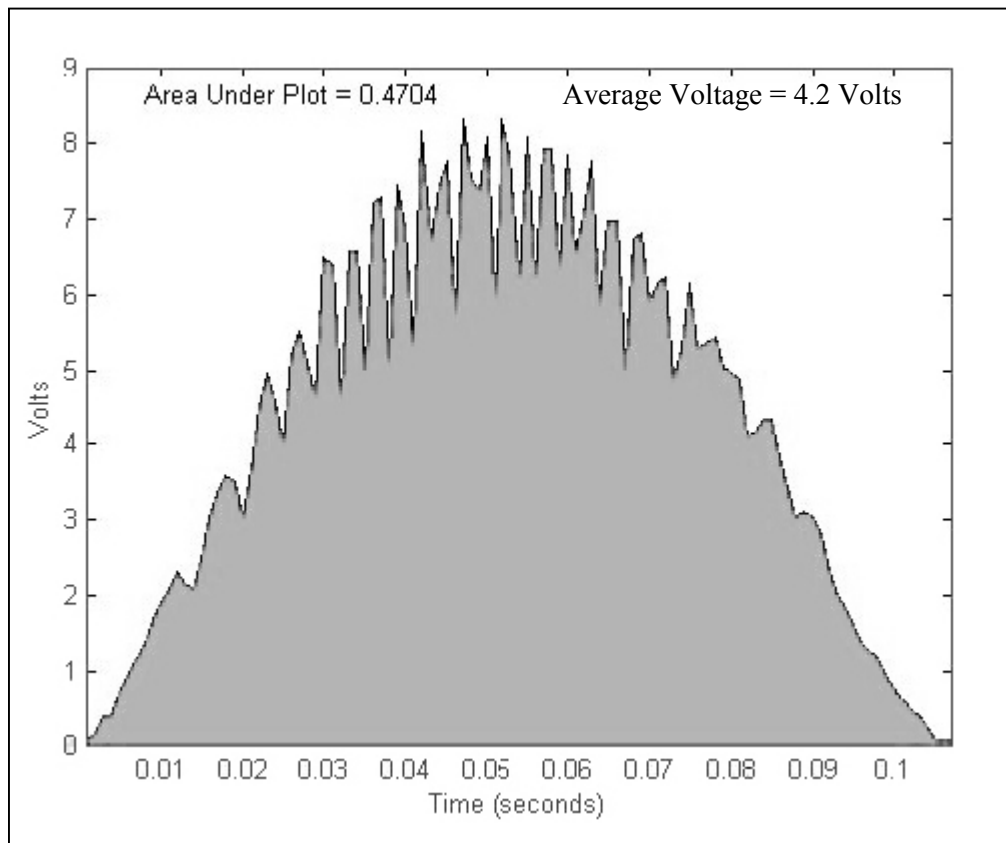

Figure 4.2 – Average Voltage Spike Produce by Generators

During the heel strike, the multiple peaks in the above plot came from the DC commutator switching in the generator. In order to calculate average power, a plot of V^2 versus time was generated. The area under this curve was calculated

using Matlab and divided by the integral period in order to find an average V^2 value. The average power generated over three consecutive steps was then calculated using Equation 2.1.   This value was found to be approximately 58.1 milliWatts, with the peak power reaching 1.61 Watts. Figure 4.3 depicts power output of the system over three consecutive steps, and shows the relative length of pulses versus the cycle time. The width of the pulses averaged about 110 milliseconds in length.
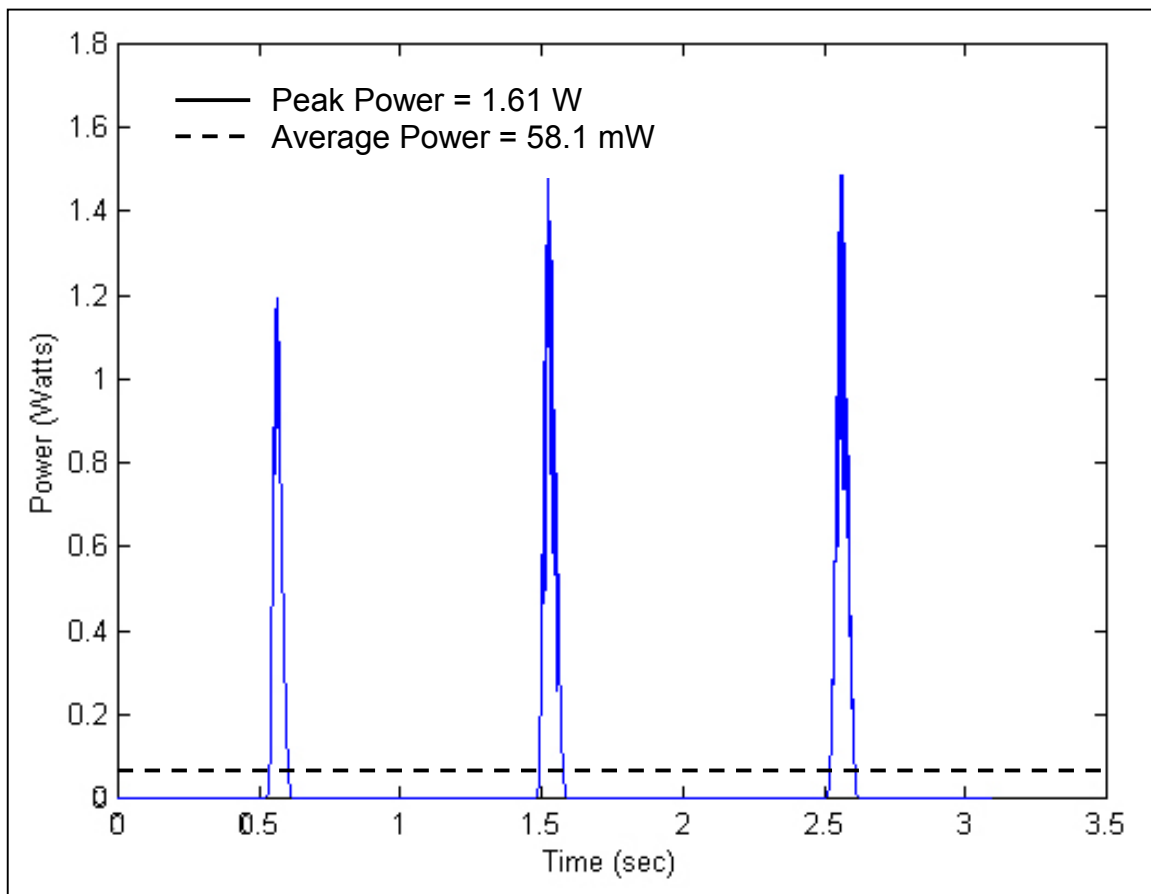
Figure 4.3 – Power Spikes Produced by Three Consecutive Steps

Chapter 5

Discussion

5.1 Discussion of Experimental Results

The peak power output of the shoes proved to be quite high at over a Watt. However, the average power fell significantly short of an initial goal of 0.25 Watts continuous. This initial goal was demonstrated in the group's earlier work with an essentially unwalkable, proof-of-concept prototype[6]. This dramatic difference in power production is largely due to the short pulse width in which power is actually generated. For close to 90% of the stride, no power is being generated by the device. At the same time, when only the width of the pulse is being taken into account, the average power produced is approximately 0.59 Watts. This indicates that there is the potential for a much higher average power output as elaborated below.

Other factors such as rotational friction and inefficiencies in power transmission, while decreasing the power output, did not play as large a role in the low average power output. Slight improvements could be made in the further reduction of frictional losses, however only with great expense. This additional cost would far outweigh any minor gains in power production. The most feasible way of increasing the average power output would be to tap the heel strike for additional energy and mechanically store it in onboard energy storage devices such as flywheels or springs. This way, the generators are driven to maintain power production through most of the walking cycle, instead of only $1/10^{th}$ of it.

5.2 Future Improvements

As mentioned previously, the greatest improvement to this power generating system would come in the form of an additional energy storage device. Both a flywheel and torsional spring would allow for power generation to take place long after the initial impulse, if not through the entire cycle. The magnetic device of the previously mentioned prototype[6] used a relatively large flywheel, however had to be mounted inconveniently outside of the shoe.

One possible improvement involves a relatively stiff rotational spring placed in the secondary stage of the gearbox, after the clutch. The secondary gears would be coupled through the spring, allowing the energy from a large impulse to be stored within the spring. In order to make use of this stored impulse, an additional stage in the gearbox could be added, thus increasing the overall step up ratio. As it is now, the presence of the current device is barely noticeable when walking. The force used to compress the rotational arm is already so small that it is not detectable. Adding an additional energy storage device to the power generation system would undoubtedly increase force needed for compression. However, if designed properly, a large increase in power, perhaps in the vicinity of a Watt (Appendix D), could be could be achieved, without any noticeable increase in pressure to the user.

The other possible method of extending power generation after the initial impulse would be through the use of a flywheel. The flywheel should be placed on the final stage of the gearbox, where the angular velocity is greatest. This is

because energy storage, thus power generation, is directly proportional to angular velocity squared. The flywheel should be designed to have a maximum radius, width, and mass while still fitting within the constraints of the shoe's heel. It is estimated that an additional 150-250 mW of power could be generated if properly sized flywheels were attached to each generator in the system (Appendix E). These estimate takes into account the electro-mechanical conversion efficiencies of the generators.

5.3 Conclusion

The current system produces approximately 59 mW of average power, and 1.6 Watts of peak power. In this current state, the power output is attractive, but still a bit low to justify regular use, considering the added mechanical complication. However, it was successfully demonstrated that relatively large amounts of peak power could be produced, through the use of traditional rotary generators placed in the heel of a shoe. By using simple mechanical energy storage systems, it is possible to lengthen the amount of time during which power is generated through the initial impulse. These storage systems can provide up to an additional Watt of power with a spring, and 250 mW with flywheels, while using common components that still fit in the shoe sole. Other methods of increasing the average power output of the system can include increasing the peak voltage, instead of pulse width. The latter method is preferable however, as it distributes power generation over a longer period of time, reducing peak mechanical stresses within the system.

Appendix A

Output Velocity Calculation Sheet:

Average foot strike velocity V_s **= 0.4 m/s**

Desired angle of rotation Θ **= 40 degrees**

Desired compression distance L_c **= 0.03175 m**

Gear ratio **G** = 1:42
The gear ratio was determined based on the following criteria:

- Gear diameters able to fit in heel of shoe
- Smaller gear to fit on 1/8" shaft
- Total length of gearbox < 2" (worst case scenario, to allow for motors)
- Readily available gear sizes

Rotational arm Length **L_a**:

$$L_a = \frac{L_c}{\sin(\Theta)} = 0.0495 m$$

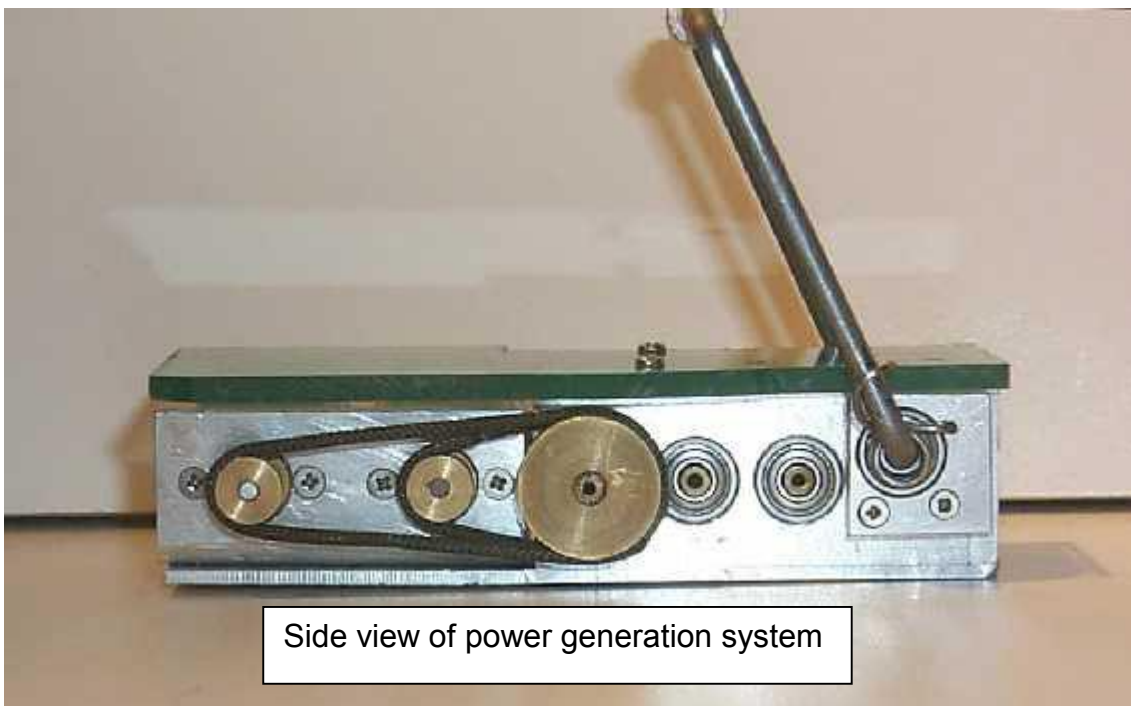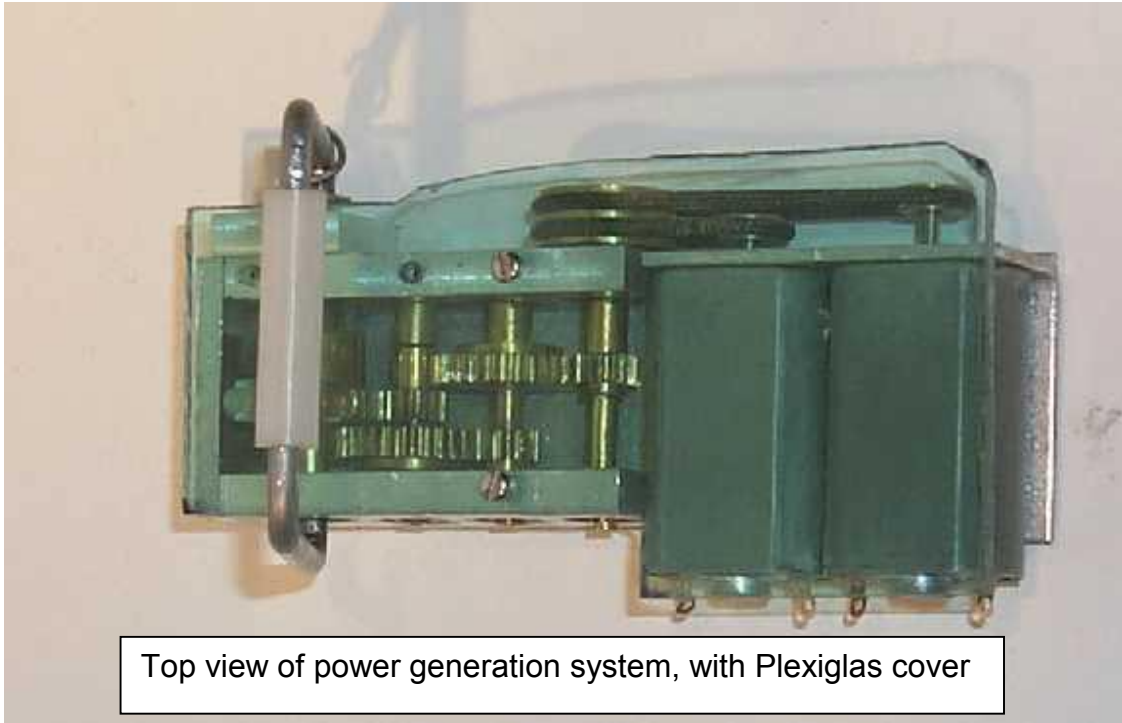Compression time **t_f**:

$$t_f = \frac{L_c}{V_s} = 0.08 \sec$$
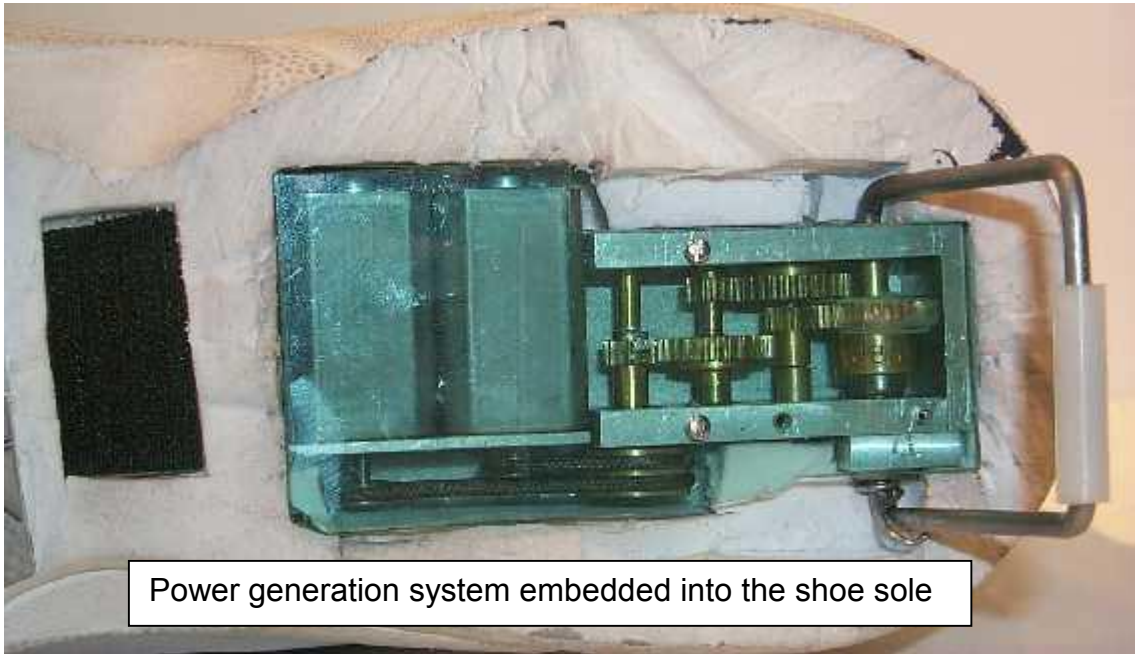
Rotational velocity of output shaft **ω**:

$$\omega = \frac{\Theta(\frac{2\pi}{360})}{t_f} \bullet G = 367 rad/\sec$$

Appendix B:

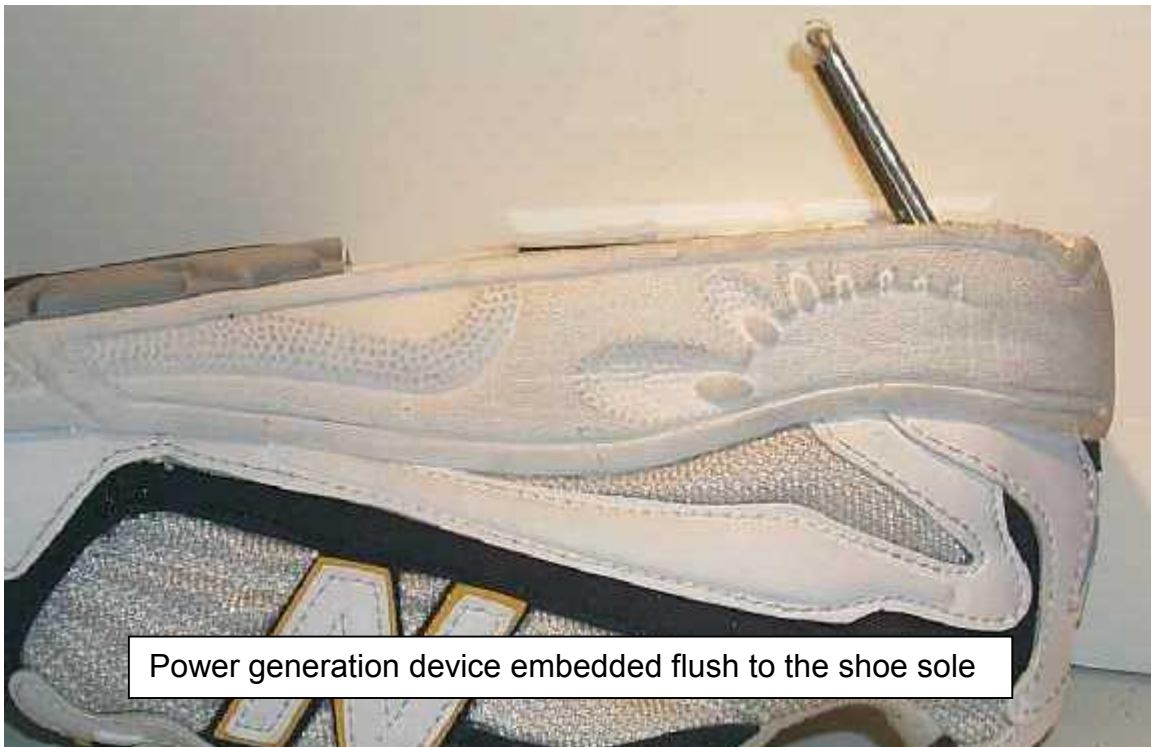**Photographs of Completed System:**

Top view of power generation system, with Plexiglas cover

Side view of power generation system

Power generation system embedded into the shoe sole

Power generation device embedded flush to the shoe sole

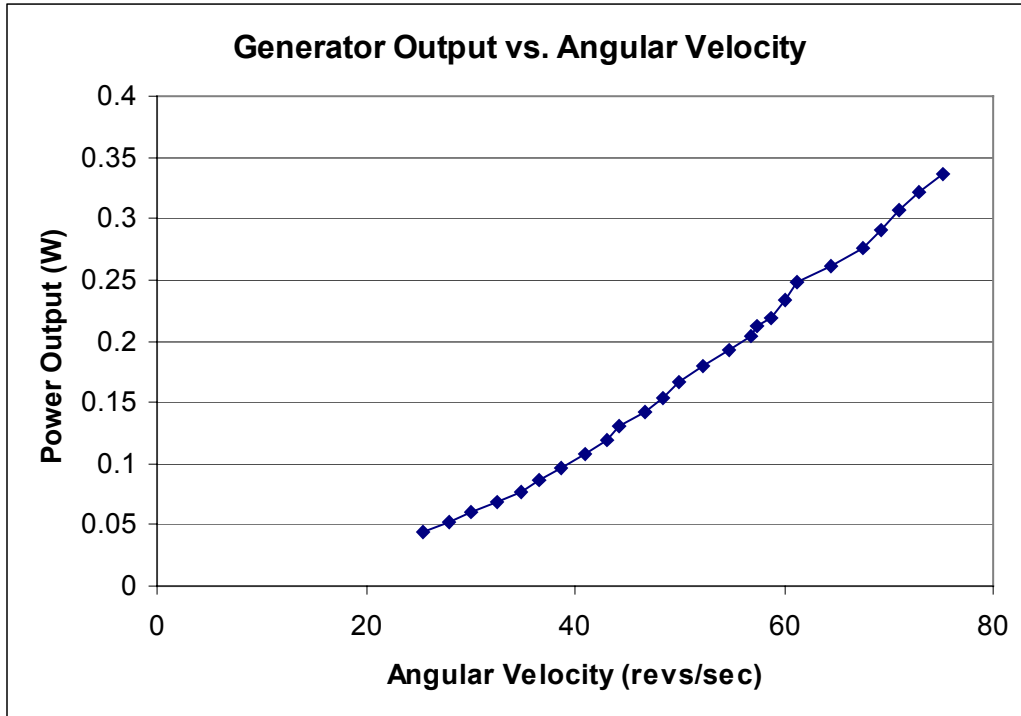View of final system embedded in shoe heel, with rubber sole

Electrical generator leads exiting top of shoe
– to be replaced with 1/8" jack

Appendix C

Raw Data of Output Power versus Load:

Voltage	Resistance (Ohms)	Peak Power (Watts)
2	15	0.266666667
3.75	18	0.78125
4.375	20	0.95703125
5	22	1.136363636
6.5	33	1.28030303
7.125	39	1.301682692
7.75	43	1.396802326
8.188	47	1.426454128
8.43	51	1.393429412
8.563	56	1.309374446
8.875	62	1.270413306
9.313	68	1.275470132
10	82	1.219512195
10.44	100	1.089936
11	130	0.930769231

Appendix D

Extended Energy Storage/ Power Production:

Additional Power Developed with use of a rotational spring:

Angle of rotation Θ = 40 degrees

Input angular velocity ω_l = 8.74 rad/sec

Rotational arm length L_a = 0.0495 m

Estimated power conversion efficiency η_c = 0.35

Maximum Torque transmitted through clutch τ_{max} = 2.83 lb-in = 0.323 Nm

Additional power generated:

$$Power = \eta_c \tau_{max} \cdot \omega_l = 0.988W$$

Maximum force felt by user:

$$F = \frac{\tau_{max}}{L_a \cos(\Theta)} = 8.52N = 0.869kg$$

Appendix E

Extended Energy Storage/ Power Production:

Additional Power Developed with use of flywheel

Outer Diameter of Flywheel D_o = 0.75 inches = 0.0191 m
Inner Diameter of Flywheel D_i = 0.60 inches = 0.0152 m
Width of Flywheel L_f = 0.50 inches = 0.0127 m
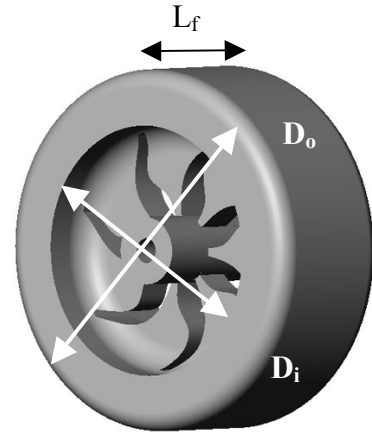Cycle Time Interval t_c = 1 second
Peak Angular velocity ω = 367 rad/s
Density of Lead ρ_l = 11340 kg/m3
Density of Depleted Uranium ρ_u = 19050 kg/m3
Estimated power conversion efficiency η_c = 0.50
Note: While uranium is not commonly available, it
      was used to demonstrate the increase in
      power available with maximum mass.

Mass of Flywheel:

$$m_l = \pi \rho_l L_f \left(\frac{D_o^2}{4} - \frac{D_i^2}{4}\right) = 0.0151 kg$$

$$m_u = \pi \rho_u L_f \left(\frac{D_o^2}{4} - \frac{D_i^2}{4}\right) = 0.0254 kg$$

Rotational Inertia of Flywheel:

$$I_l = \tfrac{1}{2} m_l \left(\frac{D_o^2}{4} + \frac{D_i^2}{4}\right) = 1.12e^{-6} kg \cdot m^2$$

$$I_u = \tfrac{1}{2} m_u \left(\frac{D_o^2}{4} + \frac{D_i^2}{4}\right) = 1.89e^{-6} kg \cdot m^2$$

Additional Power Produced (Note: 2 flywheels total, one per generator) :

$$P_l = \eta_c \frac{\Delta K}{t_c} = \eta_c \frac{\tfrac{1}{2} I_l \omega^2 - 0}{t_c} = 0.076 Watts$$

$$P_u = \eta_c \frac{\Delta K}{t_c} = \eta_c \frac{\tfrac{1}{2} I_u \omega^2 - 0}{t_c} = 0.123 Watts$$

References

[1]   http://www.winduppower.com/

[2]   Starner, T., "Human-Powered Wearable Computing," IBM *Systems Journal*, Vol. 35, No. 3&4, 1996, pp 618-629.

[3]   Kymissis, J., Kendall, J., Paradiso, J., Gershenfeld, N., "Parasitic Power Harvesting in Shoes," *Second IEEE International Conference on Wearable Computing (ISWC)*, October 1998.

[4]   Hagood, N., et al., "Development of Micro Hydraulic Transducer Technology," in Proc. of the 10th *International Conference on Adaptive Structures and Technology (ICAST '99),* Paris France, Oct. 10-13, 1999.

[5]   Marsden, J.P. and Montgomery, S.R., "Plantar Power for Arm Prosthesis using Body Weight Transfer," in *Human Locomotor Engineering*, Inst. Of Mechanical Engineers Press, London, 1971, pp. 277-282.

[6]   Kendall, C.J., "Parasitic Power Collection in Shoe Mounted Devices," BS Thesis, Department of Physics and Media Laboratory, Massachusetts Institute of Technology, June 1998.