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RUNNING SHOE PEDOMETER

By

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Final Report for 4600:497 Senior/Honor Design, Fall 2022

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Abstract

This report documents the design process for making a pedometer that is integrated into a running shoe. This pedometer can tell the user when their shoes are worn out and need to be replaced. This helps prevent injury from running in old shoes. The report focuses on the economics of the device, the competitors, the market for the product, how to power the device, the intricacies of the circuit design, and the options for the output communication of the Pedometer. The end result of this paper is a working prototype.

Contents

1. Introduction	1
1.1 Sales Pitch	1
1.1.1 Shock Absorption	1
1.1.2 Obesity	2
1.1.3 Common Injuries	3
1.1.4 The Solution	4
1.2 End Goal	5
1.3 Metrics for Success	6
1.4 Competing Products.....	6
1.4.1 Nike Tesla	7
1.4.2 Adidas “1”	7
1.4.3 Nike + iPod Sports Kit.....	8
1.4.4 Nike + Adidas Micropacer	8
1.4.5 Apple Patent (US7911339B2)	9
1.4.6 Smart Watches.....	10
1.4.7 Strava	10
1.4.8 Sensoria.....	11
1.4.8 Conclusion.....	12
1.5 Polling Data	12
1.5.1 Shoe Wears Out	13
1.5.2 Favorite Brand of Running Shoe	14
1.5.3 After Shoes are Worn Out.....	15
1.5.4 Tracking Shoe Life	16
1.5.5 The Target Market	17
2. Design.....	19
2.1 Battery Considerations	19
2.2 Energy Harvesting	22
2.2.1 Foot Power	25
2.2.2 Types of Passive Foot Power.....	27
2.2.3 Radio Frequency Power Generation	28

2.2.4 Triboelectric Power Generation.....	30
2.2.5 Capacitive Power Generation	32
2.2.6 Piezoelectric Power Generation	34
2.2.8 Energy Harvesting Conclusion.....	40
2.3 Circuit Design	41
2.3.1 Expected Power Generation	41
2.3.2 Smart vs Dumb Circuits	43
2.3.3 Rectification and Voltage Regulation.....	44
2.3.4 Latching Circuits	48
2.3.5 Prototype Circuit Decisions.....	49
2.3.6 Diode Selection	50
2.3.7 Power Capacitor Selection	51
2.3.8 Micro Controller Selection	54
2.4 Visual Indicators.....	59
2.4.1 E - Ink.....	60
2.4.2 Electrochromism	60
2.4.4 Electrochemistry	61
2.4.5 Liquid Crystal Displays.....	62
2.4.6 RFID and Bluetooth	64
2.4.7 Conclusion.....	64
3. Design Verification	66
3.1 Breadboard Testing.....	66
3.1.1 Rectification Circuit.....	66
3.1.2 Latching Circuit.....	67
3.1.2 Arduino ATMEGA328	67
3.1.3 Conclusion.....	67
3.2 Chemical Indicator Testing.....	68
3.3 PCB Design	68
3.4 Plastic Cover.....	73
4. Costs.....	74
4.1 Parts	74
4.2 Labor	75

5. Conclusion.....	76
5.1 Accomplishments.....	76
5.2 Uncertainties.....	77
5.4 Future work.....	77
6.1 Introduction References	78
6.2 Design References.....	Error! Bookmark not defined.
Appendix A: Requirement and Verification Table	Error! Bookmark not defined.

1. Introduction

Running shoes, like anything else, wear out and need to be replaced. A quality running shoe, from a reputable manufacturer, can last between 300 and 500 miles (106). After thousands of impacts, the foam of the shoe begins to deteriorate and deflate. The shoe will begin to lose its bounce and will no longer cushion the impacts of the wearer. This issue might seem trivial to non-runners or even avid runners who are healthy, however, running in worn out shoes can be detrimental to the wearer's health (60). With the average cost of a pair of shoes being \$115-\$120 (32), it can be easy to justify using worn out shoes. However, running in worn out shoes can cause long lasting injuries. This issue is especially relevant because of the growing popularity of the sport of running as well as the growing numbers of overweight or obese runners.



Figure 1: This figure shows a very worn-out pair of running shoes (69).

1.1 Sales Pitch

In order to market the device, a sales pitch was devised.

Running is one of the most popular sports in the world and was participated in by over 60 million people this year (108). These people are at risk of injury if they are running in worn out shoes. Old running shoes have reduced cushioning and increase the impact forces on the runners' joints. This is complicated by the fact that it is hard to determine if running shoes are worn out. The most accurate way to track shoe life is by recording the number of miles ran in a pair of shoes. Creating a convenient way to count the number of miles ran in a shoe would protect runners from injury. The Running Shoe Pedometer is a step counter that determines when a shoe is worn out. It can be built right into a pair of running shoes or retrofitted into an existing pair. This device is single use and is made to be cheap, durable, accurate, and unobtrusive. With the Running Shoe Pedometer runners can stay healthy and be confident in their shoes.

1.1.1 Shock Absorption

It has been proven that the shock absorption qualities of a shoe diminish with use as evidenced in figure 2 below. This is important because there is a direct correlation between amount shock absorption, the wear on the shoe, and the frequency running related injuries (58). When running, every

step exerts 2-3 times the force of the body on the shoe, foot, and leg (71). This means that when running, the foot has 4-6 times more impact than standing still on both feet. For every footstep, the change in momentum, the Impulse, stays constant because the mass of the leg stays the same and the change in velocity stays constant. Velocity stays constant because the leg will go from having vertical motion to no vertical motion. Without the shock absorption of the shoe, the impulse time of the collision is reduced, and the peak force is much higher. This force is absorbed in the arch of the foot and the knee of the runner causing injury.

$$\Delta p = m * \Delta v = F * \Delta t \quad (1)$$

“In general, the shoes retained approximately 75% of their initial shock absorption capability after 50 miles of simulated running, and approximately 67% after 100 to 150 miles. Between 250 and 500 miles the shoes retained less than 60%.” (58)

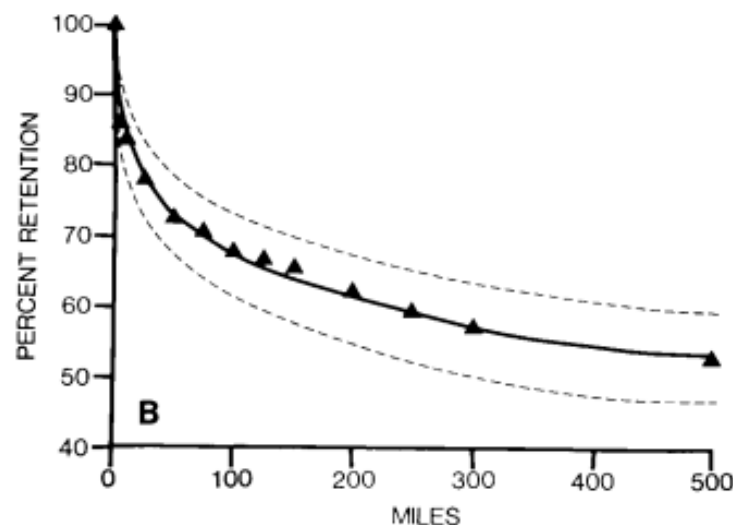


Figure 2: This figure shows the percentage in energy retention in running shoes relative to how many miles they have been run in. It is clear that the shock absorption of the shoe decreases as the shoe gets used (58).

1.1.2 Obesity

It has been proven that more shock absorption leads to lower rates of injury (58)(90). This is especially relevant today because of the growing rates of overweight and obese adults. When people get heavier, and every stride exerts 2-3 times their body weight, injury is far more likely. These more forceful foot strikes wear out shoes much faster and therefore shoes need to be retired more often and after less miles to keep injury at bay. It is especially important for groups at risk such as overweight and obese runners as well as recovering athletes to know when it is time for a new pair of shoes.



Figure 3: This figure shows an overweight person running (10).

Share of adults that are overweight or obese, 1975 to 2016

A person is defined as overweight if they have a body-mass index (BMI) equal to or greater than 25. BMI is a person's weight in kilograms divided by his height in metres squared.

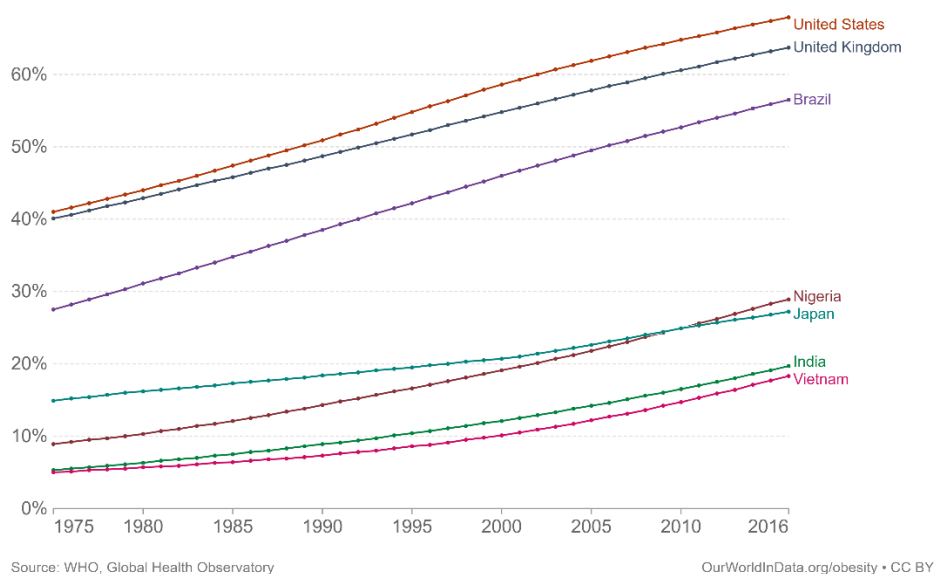


Figure 4: This chart shows the obesity trends in adults over the past 50 years. It can be seen that obesity is on the rise (89).

1.1.3 Common Injuries

There are several common injuries associated with running and running in worn out shoes. About 50 to 75% of all running injuries appear to be overuse injuries due to the constant repetition of the same movement (110). It is estimated that 65% of regular runners get hurt each year (120). It is also estimated that 42% of all running related injuries affected the knee. Of these injuries, stress fractures, plantar fasciitis and Osgood-Schlatter are the result of the high impact forces that could be reduced with better padding or newer shoes. It is also important to consider the cascading effect of injuries. It is common for a runner to ignore an injury and continue to run while favoring a leg or limping. This altered stride causes hip and ankle injuries. Many injuries can be an indirect result of poor padding and worn-out shoes. It is predicted that “a regular runner is expected to get 2.5 to 12.1 injuries per 1000 hours of running” (110). Some of the more common injuries include Plantar Fasciitis, Patellofemoral Syndrome (Runner’s Knee), Shin Splints, IT Band Syndrome, and Osgood-Schlatter(60).

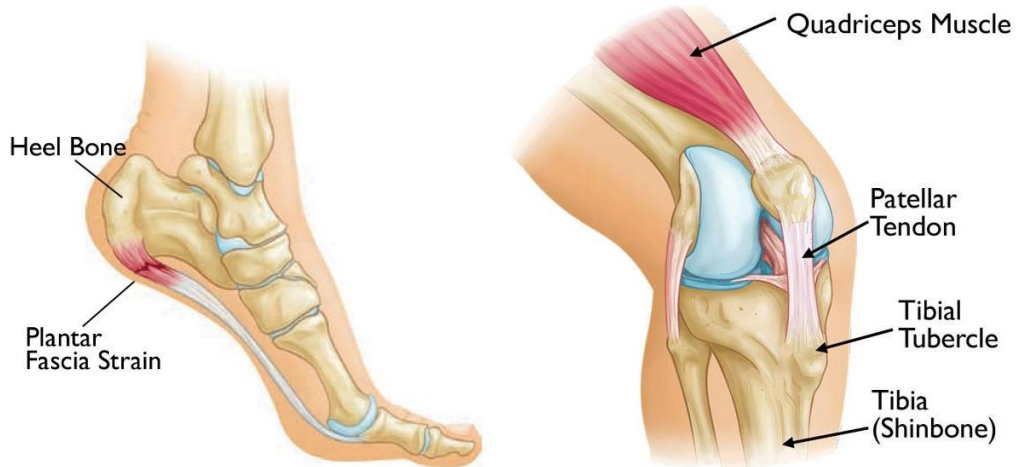


Figure 5: This figures shoe plantar Faucitis (left), and Osgood Schlatter (right). These are both common injuries that arise from using worn out running shoes (73)(81).

1.1.4 The Solution

Even if you could be convinced to buy new running shoes when your old ones were worn out, how would you know they were worn out? Odds are that unless you are a world class runner you have no idea how much life is left in your shoes.

The solution is a pedometer for your running shoes. The integrated, lightweight, cheap, disposable pedometer counts the number of steps you take and lets you know when it is time for a new pair of shoes without any doubt. Using a product only as long as its lifespan is a common practice when it comes to food, tires, clothes and medicine and it needs to become common practice with running shoes as well.

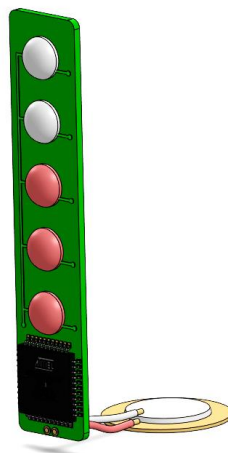


Figure 6: Concept design of Running Shoe Pedometer

1.2 End Goal

When designing the pedometer, it will be important to know what the end goal of this project truly is. A product that is designed for mass production will look very different than a prototype that will be needed to obtain a patent.

Sell Patent

If the prototype works, one of the potential options of the Running Shoe Pedometer would be to sell the patent to a shoe company such as New Balance, Nike, Adidas, Hoka, Brooks, or Saucony. The companies would then own the trademark, branding, and the rights to produce the pedometer. This would be a hands-off way to get a one-time payment. This would involve less risk and would ensure that the pedometer is well integrated into the shoe.

Manufacture Product

Another possibility for the Pedometer would be to manufacture and sell the idea by myself. This would require funding and a high degree of risk but will also have the highest reward. It would involve working with foreign manufacturers, for low cost, and patenting the device internationally. To do this, a company would have to be formed along with a website, tooling, packaging, insurance, distribution, storage, and maybe a few employees (123). This option would also mean that people would have to buy it separately from their shoes and install it themselves. While the device could be designed in a way that it is easy to install with an adhesive back or included tools, it is not guaranteed to work well and look professional. The product would have to be sold online or at sporting goods stores. It would involve advertising, warranties, UL certification, CE certification, EPA certification and would be extremely costly.

License Patent

If the prototype works, one of the potential options of the Running Shoe Pedometer would be to license the idea to a shoe company such as New Balance, Nike, Adidas, Hoka, Brooks, or Saucony. The companies would rent the idea from me or pay me per shoe produced with the Running Shoe Pedometer inside. This would be a hands-off way to make passive money. This would involve less risk and would be well integrated into the shoe. However, if the product were to never take off, there would be little financial gain.

Conclusion

Manufacturing the product by myself is the least desirable option. It involves too much risk and isn't the ideal environment for the product. Selling or leasing the patent to another company is the most appealing. It wouldn't make as much money, but it would remove a lot of the risk. There would still be the costs to prototype and to patent the shoe and trademark the name which could cost around \$7,500 total, but that would be the extent of the spending (122). The manufacturing option has the potential to require a lot of money and get out of hand quickly. With those considerations, this device will be designed with the goal of patenting a working device. This means the device can be designed more

robustly with less focus on pinching pennies initially. A working device will be much more important than a cheap device.

1.3 Metrics for Success

For the Senior Design Project evaluation, the metrics of success for this project must be well defined. This gives a clear criterion before the project begins so that the project can be evaluated as a success or failure. All of these metrics must be tangible and testable.

Cost Effective

In order for the Running Shoe Pedometer to be a success, the product must cost less than \$10 when produced at large scales. Because the product would be disposable, anything more than \$10 would be cost prohibitive.

Durable

The device must hold up to the elements such as rain, snow, water, and mud. Running shoes take a lot of abuse depending on the wearer. The device needs to be at least as durable as the shoe and last 500 miles in demanding trail running conditions. The device must be able to be submerged in water for 24 hours as well as frozen for 24 hours. The device must hold up to accelerated UV testing for the equivalent of 24 hours in direct sunlight. Lastly, the pedometer must be abrasion resistant and withstand sand abrasion.

Accurate

The pedometer needs to be accurate when counting steps. If it were to lose count or miss every other step, the device would be useless and counterproductive. In order to gain the trust of the consumer it must count every step. To be defined as accurate it must read within $\pm 5\%$ accuracy of a regular pedometer or watch.

Unobtrusive

The pedometer must be easily concealed within the shoe and not be immediately obvious by look or feel. A target volume of less than 5 cubic centimeters must be obtained.

Style

The device also needs to be attractive and complement the shoe well. Running shoes are a form of fashion in the community so the pedometer must be sleek and desirable to have commercial success. To achieve this, the device must either be clear or available in multiple PCB colors to match the shoes.

1.4 Competing Products

While this is an admirable problem to solve, it is only thorough to make sure that no such product already exists. If the patent for the proposed device were already held, then the Running Shoe Pedometer could never be commercially viable. Additionally, it must be decided that there is no product that outperforms the Running Shoe Pedometer that already exists.

1.4.1 Nike Tesla

In April of 2015, Nike announced their new “Nike Tesla” shoe. This shoe has integrated piezoelectric sensors in the sole to gather and store energy scavenged from walking/running (124). This shoe would collect the energy and transmit it to the Nike Fuel band in order to charge the phone of the user. The device claims to allow the user to completely power devices on the go. This product never made it to market, most likely because of the impracticality of the wireless energy transmission over distance which still hasn’t come to fruition in 2022. The device also claims to have sensors that could relay information back to the user about heart rate and gait of the wearer. The device does not hold a patent and a patent is not enforceable because the technology was never developed. While Nike Tesla appears related to the Running Shoe Pedometer, they are completely different and serve different purposes.



Figure 7: This figure shows the Nike Tesla shoe (124).

1.4.2 Adidas “1”

In 2004 Adidas unveiled a shoe called “1”. This shoe claims to use “intelligent cushioning” to change the spring characteristics of the heel of the shoe (116). The device used a battery, motor, screw, and microcontroller to measure the stride of the wearer and adjust the cushion of the shoe to improve the efficiency of the runner. The device lasted 100 hours of running and was superseded a year later by a shoe called “Intelligence Level 1.1” which had a motor with more torque. Though this has a microchip in a shoe, it is unrelated to the Running Shoe Pedometer.

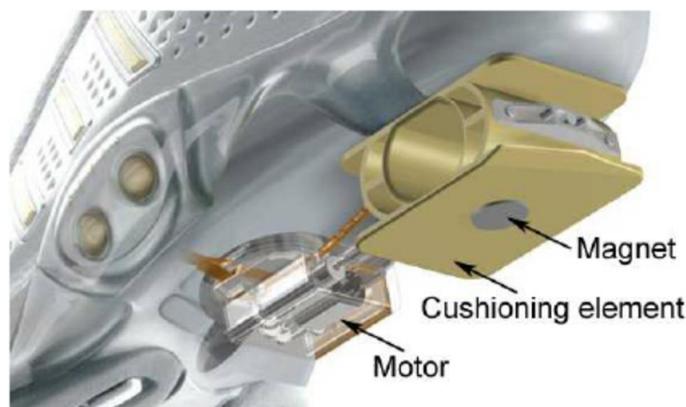


Figure 8: This figure shows the Adidas 1 shoe (68).

1.4.3 Nike + iPod Sports Kit

In 2006 Nike and Apple teamed up in order to create the Nike + iPod sport kit. This device is a two piece kit, one part is plugged into an iPod, the other is placed in a running shoe (26). The device claims to turn your shoe into a very sophisticated pedometer. The device only cost \$25 and uses a nonreplaceable battery to power the sensors and communicate the data to the iPod. The battery was rated to last up to 1,000 hours or about 1 year for an avid runner. Considering that a pair of running shoes typically doesn't last 500 miles, the sport kit would last for 2-3 different pairs of running shoes. It operates using a piezoelectric accelerometer that can track how long a shoe stays planted for during the gait cycle. Because the single support time during running is directly related to pace, the app can figure out the pace of the wearer. Additionally, if the user enters their weight, the app can guess the calories burnt. This device does directly compete with the proposed Running Shoe Pedometer. However, this device is more expensive than the Running Shoe Pedometer, requires the user to purchase an expensive phone, then to run with a heavy and bulky phone. Additionally, there are no current features to record the end of life for shoes. If a runner were to use multiple shoes there would be no way to know when each one is worn out. Most of the functions of this device have also been incorporated into smartwatches such as Samsung, Apple, and Garmin.



Figure 9: This figure shows the Nike + iPod Sport Kit (99).

1.4.4 Nike + Adidas Micropacer

In 1984, Adidas released the Micropacer shoe. This shoe had an integrated pedometer on the front that was battery powered (18)(20). This pedometer could be cleared at the start of each run and count to 9999. It used an LCD screen to display the count and was a typical pedometer miniaturized and strapped to a pair of shoes. This device doesn't let the user know when the shoes are worn out and requires heavy and bulky electronics. For these reasons, it doesn't compete with the Running Shoe Pedometer.



Figure 10: This figure shows the Adidas Micropacer shoe (20).

1.4.5 Apple Patent (US7911339B2)

In 2013, Apple filed a patent for a “sensor and alarm system that can be embedded into footwear” (15)(36). The sole purpose of this device was to let users know when their foot ware was worn out and needed to be replaced. The patent starts by recognizing the importance of a good pair of shoes and the potential for injury that can occur when shoes wear out. Their device uses a sensor to detect steps, a microprocessor/controller to count the steps, and an alarm. Their patent covers devices using piezoelectric sensors, accelerometers, and pressure sensors. The device also has allowances for a sensor called a “body bar” that could detect repetitive motions during weightlifting. The patent specifies an alarm of an LED, a display, a speaker, or a wireless interface to communicate with the wearer. The patent outlines that the electronics would be stored in the sole while sensors could be placed anywhere in the shoe. Lastly, the device will be powered by an integrated battery or some form of electromechanical generator. This device is very similar to the Running Shoe Pedometer. With a focus on the end of the shoe’s life, and a patent covering multiple output styles as well as sensors and technologies, this patent might make the sale of Running Shoe Pedometer difficult. Let's discuss patent law and the options available for the Running Shoe Pedometer.

Wait it Out

It is important to remember that the patent is valid for 20 years and although the patent is held, they have never brought a product to market. So, if the Running Shoe Pedometer is insufficiently dissimilar and therefore covered by the Apple patent, in 10 years the Apple patent will be expired, and the Running Shoe Pedometer can be brought to market.

Buy the Patent

If the Running Shoe Pedometer has commercial value, the patent could be purchased or leased from Apple. This would be a large expense, but If Apple was reasonable, it is a viable option. It is clear that Apple had no intention of bringing this product to market and only acquired the patent to sell it later. Hopefully, this means they would be reasonable about the sale of the patent.

Little Guy Approach

Another approach to circumventing this patent would be to ignore it entirely and hope to not get sued. If the pedometer gathers enough traction in the running world, I could win in the court of

public opinion. A massive billion-dollar company suing a 21-year-old college student out of his idea would be bad publicity for Apple. Additionally, a patent filed 10 years ago that never became a commercial product is easily forgotten and chances are this patent was forgotten long ago.

Novelty

The last and best outcome for the Running Shoe Pedometer would be if my idea was deemed a novelty that was not infringing upon the Apple patent (54). I would argue that the Running Shoe Pedometer novelty is the entirely passive/scavenged piezoelectric energy generation along with the chemical style alarm/indicator. Using a different power source and “alarm” should make the Running Shoe Pedometer sufficiently dissimilar and unrelated to the Apple patent. Additionally, the low cost and disposable nature of my device would make it different than Apple’s.

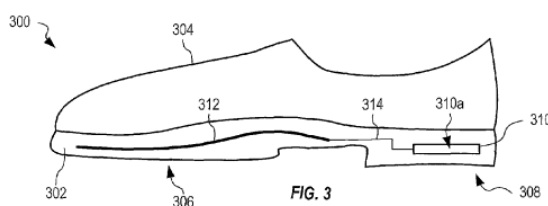


Figure 11: This figure shows a concept sketch from the Apple patent(36).

1.4.6 Smart Watches

Smart watches are another product that could serve to usurp the Running Shoe Pedometer. There are many running/smart watches on the market by brands such as Garmin, Apple, Samsung, Fitbit, Oura, Coros, and Polar (125). While these watches are all very different, the key purposes are those of a traditional watch such as a stopwatch, timer, and clock, as well as some newer functions such as heartrate monitoring, GPS tracking, and logging workouts. Any one of these brands could include an app/feature that would allow the user to choose which shoes they ran in that day and track the life of the shoe. These watches could also incorporate a 3rd party app such as Strava.



Figure 12: This figure shows the Garmin Forerunner Smart watch. This watch is the premium watch on the market and costs \$390 (126).

1.4.7 Strava

Strava is the running social media app which allows users to post their runs for their friends to see. Though the app started as a cycling app it quickly expanded into the running community. This app

has a feature which allows users to enter the gear that they run in including their shoes (127). The app then tallies up the number of miles run in each pair of shoes and shows that number to the user. The app will also give notifications when your shoes hit certain milestones that indicate they need to be replaced. This is the largest threat to the Running Shoe Pedometer especially in younger markets. Strava has 95 million active users with the majority of users between the age of 25-34 (102)(103). Though data can be manually input into the app, most Strava users use a GPS device such as a watch or phone while they run.

Though these apps and watches could let users know when their shoes are worn out, it would be only slightly more convenient than writing down the milage on a piece of paper and adding it up. It still takes time and effort and is not automatic. People also forget to wear or charge their watches which would lead to plenty of miles not recorded on the shoes. Lastly, this is an expensive alternative. These watches can cost as much as a phone with the average price being around \$300. This is a high barrier to entry. Additionally, some runners, such as myself, don't enjoy running with a watch.

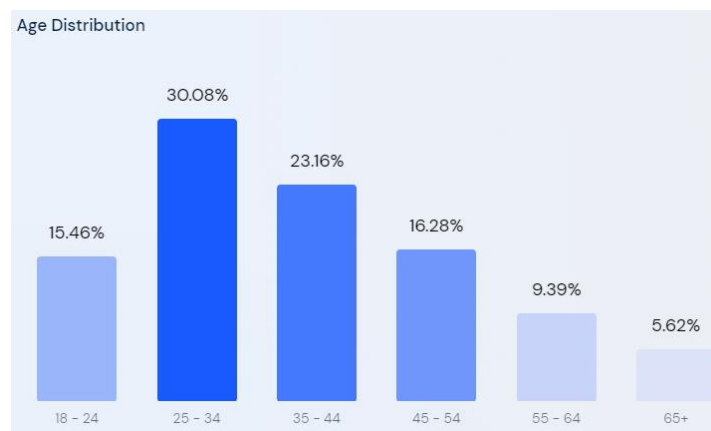


Figure 13: This figure shows the age demographic of Strava users. It clearly has a younger demographic but has a surprising amount of reach into the older generations considering the demographics of runners in general skews younger (103).

1.4.8 Sensoria

Sensoria was founded in 2010 and introduced a smart sock that could monitor a runner's foot pressure distribution (97). Their product uses a mesh of sensors built into their proprietary socks to measure various characteristics of the runner. It must be used in conjunction with their smartphone app and can count steps, speed, calories, altitude, and distance tracking, as well as track cadence, foot landing technique and the impact score generated. Though their device is unique and brilliant, it doesn't serve the same function as the Running Shoe Pedometer.



Figure 14: This figure shows the Sensoria Smart Sock V2.0 and two Sensoria Core microelectronic modules(128).

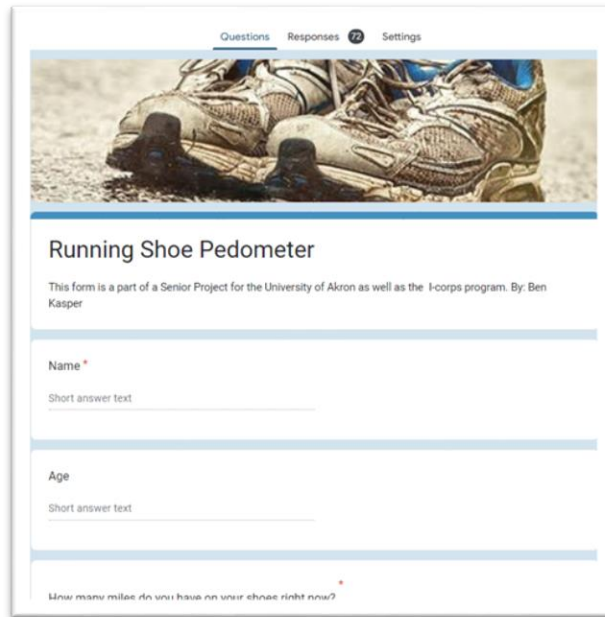
1.4.8 Conclusion

While this product market is certainly not a new frontier, no other product on the market serves the precise function of the running shoe pedometer. The super minimalist and lightweight design, as well as the simplicity of the device and disposable nature make it perfect for people who care about their shoe life without feverishly recording their mileage after every run or lugging around a smart phone or watch while they run. A similar device doesn't appear to already be on the market or be covered off by any patents. The largest threats to the commercial viability of the pedometer are the Apple patent and Strava.

Additionally, the copyright for the "Running Shoe Pedometer" appears to be open if I were to decide to trademark the name. I am not necessarily committed to the name; it could be rebranded later but for now, it is the clearest and most concise way to explain the product to others.

1.5 Polling Data

To better understand the needs of runners, market research was done with a google form. This form was given to two University level amateur running clubs as well as two high schools cross country teams and posted on two online forums for runners. Though all of this data does skew younger due to the nature of the poll, the younger generation was the initial target audience of the project. 70 responses were recorded, and the results were analyzed. The goal of this research was to find trends within runners who might be the most receptive to this product.



The image shows a screenshot of a Google Forms poll titled "Running Shoe Pedometer". At the top, there is a navigation bar with "Questions", "Responses" (with a count of 22), and "Settings". Below the navigation bar is a header image of a pair of worn, brown and blue running shoes. The title "Running Shoe Pedometer" is displayed in a large, bold font. Below the title, a subtitle reads: "This form is a part of a Senior Project for the University of Akron as well as the I-corps program. By: Ben Kasper". The form contains three questions, each with a "Short answer text" input field. The first question is "Name *", the second is "Age", and the third is "How many miles do you have on your shoes right now?". The form is styled with a clean, white background and blue accents.

Figure 15; This figure shows the poll that was given to several groups to gather data about the target audience of the product.

1.5.1 Shoe Wears Out

This is the critical question for the Running Shoe Pedometer. Data shows that the foam sole and therefore the cushioning of the shoe is the most likely to fail. However, if most runners don't believe this is the part that breaks first then they won't understand that they need this product. It can be easy to see if the upper fabric breaks or the treads wear down, but it can be much harder to determine if the foam is deflated.

This poll indicates that most people agree with the scientifically accepted results that the foam is the first thing to break on most shoes. This means that the target audience has already admitted that the Running Shoe Pedometer might serve a need that they have already identified.

What Part of the Shoe Wears Out First

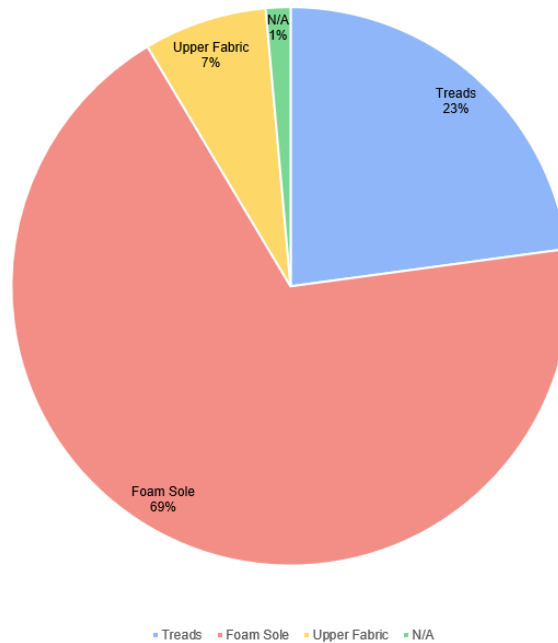


Figure 16: This figure shows the breakdowns of responses to the question, “what part of the running shoe wears out first”.

1.5.2 Favorite Brand of Running Shoe

This question is critical to the goals of the running shoe pedometer. The current goal is to partner with a brand to sell the pedometer as integrated into the shoe instead of a standalone insertable pedometer. If the data comes back with many preferred brands, then I could be limiting my horizons by partnering with just one brand.

The results of the data show that runners have diverse tastes and that many brands contribute to the overall market. Partnering with just one brand might severely limit the potential of the pedometer. It is also good to keep in mind that Nike’s popularity has increased dramatically since the invention of their Alpha Fly ultra-performance shoe. Perhaps if the pedometer was well received, it could pull market share away from other brands and towards the brand that I am partnered with.

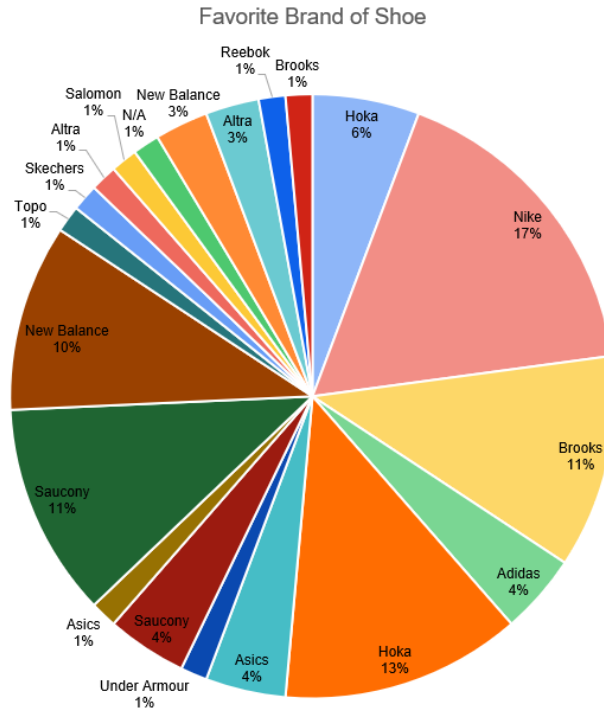


Figure 17; This figure shows the breakdown of the responses to the question, “what is your preferred brand of running shoes”. **NOTE:** Some brands are duplicated on the pie chart, read carefully.

1.5.3 After Shoes are Worn Out

This question isn’t as critical as the first few but does allow insight into the mind of the consumer which could be valuable and paint a more well-rounded picture.

It appears that most people continue to wear their shoes after they are “worn out”. It should be considered if the device can be designed in a way that it can be removed from the shoe easily to allow the shoes to be worn as regular shoes more easily.

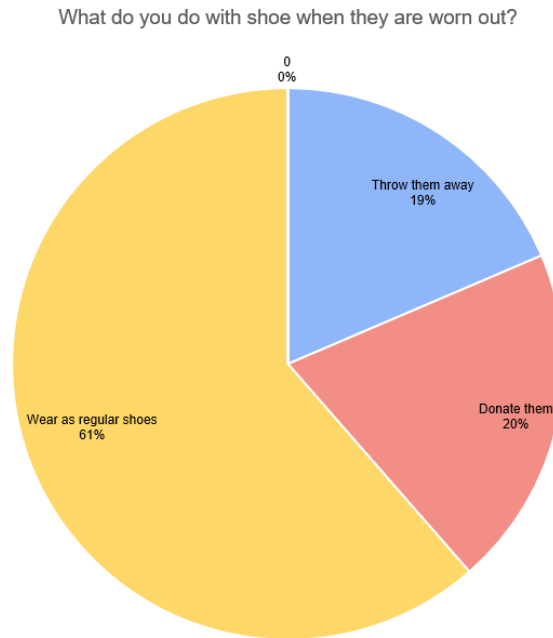


Figure 18: This figure shoes a breakdown of the responses to the question, "what do you do with your shoes when they are worn out".

1.5.4 Tracking Shoe Life

This question is the most critical question from the poll. If the data comes back that most people already track the life of their shoes in a more convenient method than the pedometer, the pedometer will be entering a contested market.

From the results of the poll, it appears that most people that I interviewed already track the life of their shoes in some way. This potentially limits the marketability of the pedometer but perhaps the pedometer could be a secondary method to track shoe life. The categories which could be served by the pedometer are the "I don't", "write it down", and "rough guess" categories. These total 28% of the surveyed group. Considering the size of the running market, 28% of the market would still be 16 million people.

It is also important to consider that the average age of the survey respondents is 27 years old. This age range is the most likely to use technology and Strava. If this demographic is already having their needs met by an app, my efforts should be redirected towards a more middle aged to older demographic and perhaps could also be redirected from a more avid runner to a more moderate/occasional runner.

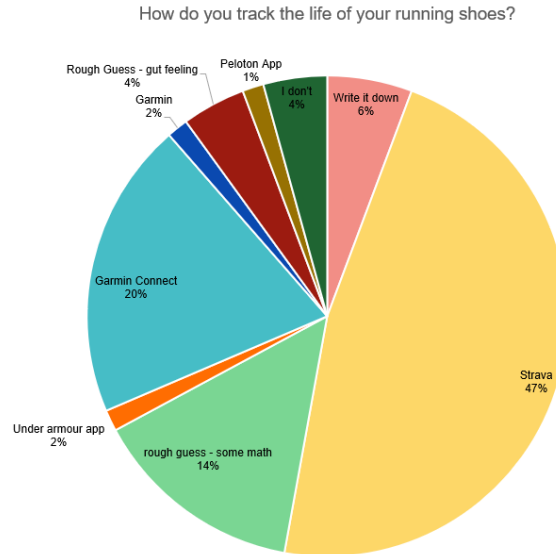


Figure 19: This figure shows the breakdown of the responses to the question, "how do you track the life of your running shoes'.

1.5.5 The Target Market

At the beginning of the project, the target audience for this product was assumed to be avid runners who ran more than 5 days a week and were young and accepting of new technologies and ideas. I predicted older runners were more likely to be purists who were stuck in their ways and wouldn't want to mess around with technology in their shoes.

The research suggests that most young and avid runners use apps to keep track of their milage and wouldn't necessarily need the Running Shoe Pedometer as their primary milage tracking method. More casual runners were more likely to forget when they bought their shoes and how many miles they had run in them. This research creates a few categories of runners that the Running Shoe Pedometer should target.

Injured

People who are habitually sustaining running injuries are more diligent of their shoe life and are more likely to use the Running Shoe Pedometer. Avid runners will do anything if they think it will keep them healthy.

Young and Growing

A common trend in the interviews was that people got injured when running in middle school and high school as their bodies and proportions were changing and they didn't know that shoes wore out. This group is very injury prone and might be more receptive to an injury prevention device.

Obese

If the running shoe pedometer is going to change its marketing tactics and becoming an injury prevention device, then another group that should be targeted is overweight and obese people. These

runners wear out shoes in drastically different ways than professional marathoners and would have a hard time tracking their shoe life by the traditional milage metrics.

Old and Old Fashioned

The last group of runners who might be interested in this product is running purists and older folks. These people might not like running around with fancy technology and using apps. This might be the share of people who reported that they record the milage of their shoes by writing it down.

2. Design

The figure below shows the overview of the technical design. The first part of the design will focus on the power of the system and whether a battery should be used or if passive power will suffice. Then the design will focus on turning that energy into useable energy. The next step will be to design the counting circuitry including selecting the microcontroller and programming it. The last task will be to design the visual output of the pedometer. If all of these steps are completed, then a device which can count steps and output the results will be created.

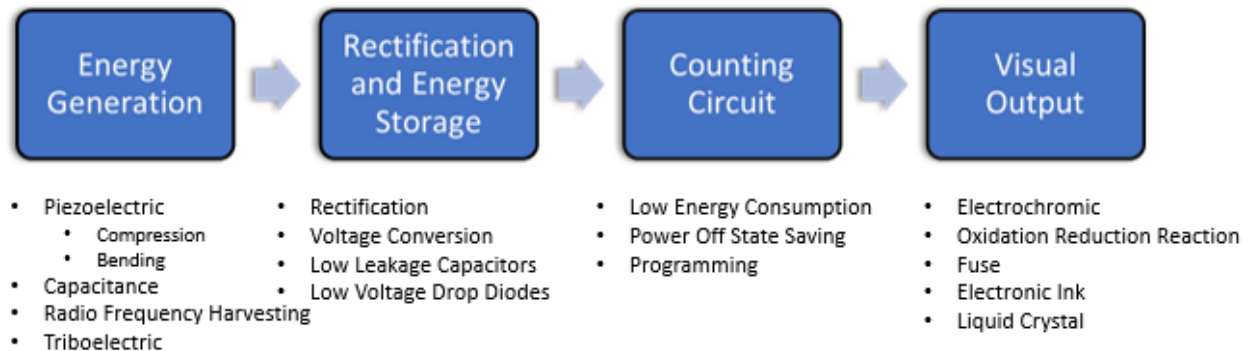


Figure 20: This chart shows the basic idea of the running shoe pedometer and how the systems interact. Each one of these systems must function properly for the pedometer to work.

2.1 Battery Considerations

In an effort to reduce complexity and weight, it was decided from the onset that the device wouldn't be battery powered. Let's investigate if battery power is feasible and if it is a good backup plan for the main power source for the Running Shoe Pedometer.

Component Reduction

One of the main concerns with battery power is that there will still be a piezoelectric sensor required to determine if a step has been taken. Though it is possible and easy to use an accelerometer to detect steps, it adds complexity and requires the shoe to be always on and monitoring the output of the accelerometer. This means that a battery powered pedometer would still need a piezoelectric sensor. The battery would remove the rectification circuit, the zener diode and the possible voltage multiplier. These components are cheap and would probably cost the same as a single coin cell battery.

Shelf Life

One of the considerations with battery power is the shelf life of the battery. Most consumer electronics make the user add batteries or remove a plastic tab to complete the circuit. Having a battery in a completed circuit, even when the circuit is not powered on can drain the battery (129). A plastic tab on one of the battery terminals creates an open circuit until the Pedometer is ready to be used. This would increase the shelf life of the pedometer but would need to be integrated into the design of the pedometer.

Durability

Another concern with battery power is the need to seal it off entirely. A battery in a watch needs to be behind several O-rings to prevent corrosion and short circuits caused by the water. This would add complexity, size, and weight. Instead of just adding a battery to the circuit, which may not be too difficult, the battery needs to be enclosed and sealed off.

Novelty

Another concern with using battery power is the novelty of the idea. Part of the reason this avoids other patent infringement is that it utilizes energy harvesting. If the device were battery powered, it might fall under the Apple Patent.

Now that all of the cons of battery power have been investigated the actual power output of the battery should be investigated. From this, it can be determined how large a battery is needed both in terms of weight and size, and how much that battery will cost.

Power Draw

The first step to determining how much power will be needed is to determine how much power will be drawn. This will be difficult considering that the circuit hasn't been designed yet and a microcontroller hasn't been picked. To get an accurate estimate of the power draw I will use a patchwork power draw approach by stitching together several constants that are already known. The power draw of the microprocessor will use the data from the MSP430F2001 which is one of the microcontrollers in contention. These calculations will be conservative and use the values that will draw the most power.

Assumptions

Step Frequency: 1.0 Hz

Power Consumption in Active Mode: 220 μ A

Time to write to EEPROM: 50ms (40)(59)

Operating Voltage: 3.6V

Power Consumption in Standby Mode: 0.5 μ A

Number of steps in mile: 2000 steps

Number of miles: 1000 miles

Calculations

$$\begin{aligned} \text{Total \# of Steps} &= \text{number of miles} * \text{steps in mile} * .5 = 1000 * 2000 * .5 \\ &= 1,000,000 \text{ steps} \end{aligned} \quad (2)$$

$$\text{Total Operating Time} = 1,000,000 \text{ steps} * \frac{1}{1 \text{ Hz}} = 1,000,000 \text{ seconds} \quad (3)$$

$$\text{Percent of Cycle in High Power Draw} = \frac{50 \text{ ms}}{1000 \text{ ms}} = 0.05 = 5\% \quad (4)$$

High Current Draw

$$= 0.05 * 1,000,000\text{sec} * 220\mu\text{A} = 11000000\mu\text{A} = 11000000\mu\text{A} \quad (5)$$

$$* \frac{1\text{A}}{10^6} \mu\text{A} = 11\text{A} * \text{sec}$$

Low Current Draw

$$= (1 - 0.05) \quad (6)$$

$$* 1,000,000\text{sec} * 0.5\mu\text{A} = 475000\mu\text{A} = 475000 * \frac{1\text{A}}{10^6} \mu\text{A} = 0.475\text{A} * \text{sec}$$

$$\text{Total Power Draw} = 0.475\text{A} + 11\text{A} = 11.475\text{A} \quad (7)$$

$$\text{Total Power Draw} = 11.475\text{A} * \text{sec} * \frac{1\text{ hr}}{3600\text{ sec}} = 0.0031875\text{A} * \text{hr} = 3.1875\text{mA} * \text{hr} \quad (8)$$

It appears that the running shoe pedometer can be powered by almost any commercial coin cell battery (52)(83). However, this doesn't account for the energy used for the output chemical reaction. That reaction could draw a large amount of power if improperly designed.

Nevertheless, it looks like even under the worst circumstances, a battery could potentially supply enough power to meet the needs of the pedometer. For all of the complication's batteries bring, they would make the design a lot simpler. It would be smart to design the prototype to easily accept a battery in case issues with the piezoelectric arose. At large volumes, these batteries can cost about 60 ¢ which may offset the cost of the voltage regulation components (74).

It is important to remember that temperature and pulse effects also hurt the life of the battery. Also, a battery might have enough mass to be picked up on a metal detector. This could make flying with shoes equipped with the pedometer more complicated because of the invent of shoe bombs. However, it didn't appear like any of the Adidas shoes with integrated electronics caused any issues in airports. The inclusion of a battery could also lead to environmental concerns about the disposable nature of the product.

If a battery is a serious consideration, it would also be wise to analyze the inner working of a typical pedometer and revisit the more manual style counting circuit described 2.3.2.

Battery	Rating (mAh)	Rating drain to 2V
CR 1025	30	68K Ω (~43uA)
CR 1216	34	62K Ω (~46uA)
CR 1220	40	45K Ω (~64uA)
CR 1616	55	30K Ω (~97uA)
CR 1620	79	30K Ω (~97uA)
CR 1632	130	15K Ω (~190uA)
CR 2012	58	30K Ω (~97uA)
CR 2016	90	30K Ω (~97uA)
CR 2025	163	15K Ω (~193uA)
CR 2032	240	15K Ω (~190uA)
CR 2320	135	10K Ω (~290uA)
CR 2430	290	10K Ω (~290uA)
CR 2450	620	7.5K Ω (~390uA)

Table 1: This table shows the mAh rating for various energizer lithium coin cell batteries (52).

ENERGIZER CR1025



Industry Standard Dimensions

mm (inches)

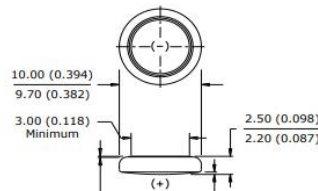


Figure 21: This figure shows the dimensions for the CR1025 battery. The battery is 10mm in diameter and 2.5 mm thick (83).

2.2 Energy Harvesting

In order to count the number of steps that the wearer takes, electronics must be used. In order to power the electronics and the counting circuit, some type of energy must be extracted from the wearer. While a battery may be able to provide enough energy, it adds weight, complexity, and environmental impact. Therefore, a battery is not the desired power source. Another option is energy harvesting. Energy harvesting (also known as power harvesting or energy scavenging) is the process in which energy is captured from a system's environment and converted into usable electric power (16).

It might be tempting to dismiss energy harvesting as an unviable option, however, energy harvesting technology is becoming more and more prevalent in our lives as we have become more dependent on electricity. Marketable products have been made from wind up or shake style flashlights as well as wind up emergency radios (104)(119). There is even a market for human powered phone charges (14)(84)(130). The best known of these technologies is the self-winding watch. These watches use mechanical motion to slowly charge themselves and stay powered. Since it is seen that products using energy harvesting do exist, how much energy can a human actually generate?

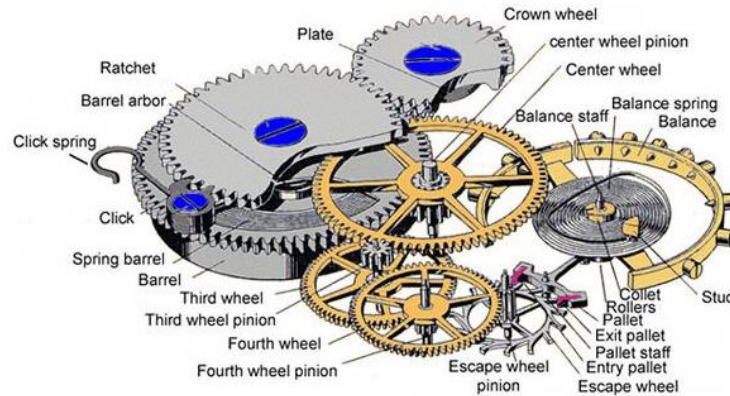


Figure 22: The figure above shows the ratcheting and flywheel mechanisms that power the self-winding watch (131).

Active Energy Generation

Active energy generation involves making an effort to produce power. The shake flashlights and wind-up radios are powered intentionally and take exertion. Pedaling a bike at a reasonable pace can generate 100 watts of power (35). Active power generation won't work for the running shoe pedometer because it is undesirable for the user to have to carry or hold anything they normally wouldn't. For the device to be unobtrusive, per the metrics for success, passive energy generation will be required.

Passive Energy Generation

To power the running shoe pedometer, passive energy generation must be used. This means that the energy is generated in a way that the user wouldn't notice, similar to the self-winding watch. The wearer doesn't have to shake their wrist at a particular frequency or angle to wind the watch. They just go about their lives only to find that their watch never dies. The running shoe pedometer must be similar. It must harvest energy that the wearer was already going to exert in a non-assuming way.

The running shoe pedometer is focused on counting steps taken in running shoes to show wear. To understand how to turn walking and running into power. It must first be understood how the body behaves during running and walking.

"The simplest model of the human gait can be described as an inverted pendulum (pendulum with its mass above its pivot point) where one leg is swung from one position to the next while the other foot remains in contact with the ground during the transition from one inverted pendulum to the next (132). The stance phase can be divided into three sub-phases: from heel strike to foot flat (initial contact period), from foot flat to heel off (mid-stance period) and from heel off to toe off (propulsive period) as illustrated in Figure 2.3" (16).

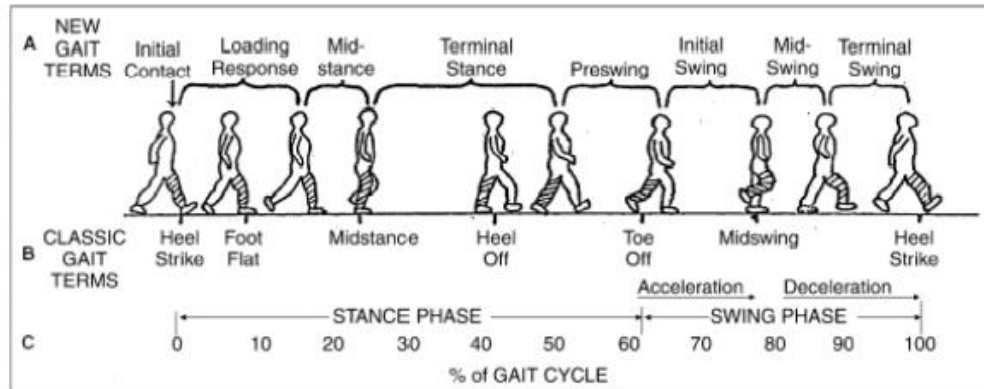


Figure 23: This figure shows the gait cycle broken up into phases and the relative duration of each part of the gait (16).

Motion While Running

Head: A runners' head should stay relatively still while running.

Arms: While running, the arms rotate about the shoulder and swing back and forth.

Chest: While running, the chest expands in and out while the person breathes. The chest also moves up and down relative to the running surface. The center of mass moves with a motion similar to a sine wave with an amplitude of 2.5 cm (16).

Legs: The runners' legs also swing back and forth about the hips. The knees also bend with each step

Feet: Lastly the feet move up and down and back and forth in the air and strike the ground with force.

All human activities take some sort of energy, and because nothing is perfectly efficient, there is always waste energy that can be recovered and used for something else. "In this field of research, the areas of most interest on the body are the upper body, the legs and finally the feet"(16).

Activity	Conditions	Power
Walking (heels)	3.5 mph 68 kg human	67 W
Walking (ankles)	3.5 mph 68 kg human	57 W
Walking (knees)	3.5 mph 68 kg human	31 W
Walking (hips)	3.5 mph 68 kg human	32 W
Walking (shoulders)	3.5 mph 68 kg human	1.8 W
Walking (elbows)	3.5 mph 68 kg human	1.8 W
Bicep curl	1 sec per curl 1 arm	6 W
Overhead arm lift	2 sec per lift 1 arm	11 W

No .	Research	Body Source	Generated Voltage	Generated Power	Volume/ Area	Freq	Amplitude	Power Density
15	Gaistrom [5]	Center of Mass	-	45.6 mW	-	-	100 lbs. Load	-
16	Niu [11]	Center of Mass	20 V	50 – 80 mW	-	-	1 kg Load	-
17	Elmes [16]	Center of Mass	-	0.86 – 21.15 W	-	1.5 Hz	1.7 cm Amp 11.3 kg Load	-
18	Rome [21]	Center of Mass	-	5.6 – 7.4 W	-	4 – 6.4 km/hr	4.5 cm Amp 38 kg Load	-
19	Kim [53]	Center of Mass	18 – 198 mV	-	-	0.5 – 8 Hz	-	-
20	Arakawa [53]	Center of Mass	-	6 μ W	-	10 Hz	1 mm Amp	-
21	Amirtharajah [54]	Center of Mass	-	400 μ W	-	2 Hz	-	-
22	Feenstra [80]	Center of Mass	-	176 – 400 mW	-	2.75 Hz	50 lbs. Load	-
23	Niu [81]	Center of Mass	-	95 mW	105 cm ³	0.75 m/s	4 kg Load	-
24	Khaligh [102]	Center of Mass	-	6 + 37 mW	49 cm ³	2 Hz	3 cm Amp	-
25	Farmer [103]	Center of Mass	3 V	-	482.6 cm ³	1-2 Hz	-	-

No .	Research	Body Source	Generated Voltage	Generated Power	Volume/ Area	Freq	Amplitude	Power Density
1	Thermolife [3]	Body Heat	1.5 – 3.0 V	40 μ W	0.5 cm ²	-	5 °C	-
2	eTEG [3]	Body Heat	-	16 – 36.5 mW	-	-	10 K	-
3	Tashiro [43]	Breathing	-	36 μ W	-	6 Hz	180 bpm	-
4	Leonov [46]	Body Heat	-	62 μ W	-	-	-	-
5	Leonov [46]	Body Heat	-	2.8 mW	76.8 cm ³	-	-	-
6	LPTG [50]	Body Heat	4.0 V	20 μ W	-	-	20 K	15 μ W/cm ²
7	ZnO Nanowire [52]	Breathing	-	-	-	-	-	2.7 – 11 mW/cm ³
8	Flipsen [53]	Body Heat	-	-	-	-	1 °C	13 μ W/cm ²
9	Review [54]	Body Heat	0.25 - 2.3 V	1 μ W -184 mW	-	-	-	-
10	Carmo [97]	Body Heat	-	1.5 mW	-	-	-	-
11	Yang [98]	Body Heat	-	1 – 2 mW	-	-	-	-
12	Lossec [99]	Body Heat	-	-	-	1.4 m/s	-	7 – 30 μ W/cm ²
13	Hoang [100]	Body Heat	-	40 - 520 μ W	-	-	3 – 15 °C	-
14	NanoRibbons [101]	Breathing	-	0.01 μ W	1 cm ²	32 Hz	-	-

Tables: 2, 3, 4: These tables show collections of energy scavenging studies as well as the area of focus of the study and the amount of power that was generated and the volume of the device (16).

In the upper body, research has primarily focused on the motion of the center of mass and human vibration. This might be able to generate sufficient power, but there will be no way to easily transfer this power from the upper body to the foot. For research concerning human power generation using the legs, energy is usually harvested from the leg joint rotations. Some type of knee brace is used that generates the required power. This is quite cumbersome and would still need to be transmitted down the leg to the shoe. Lastly, there has been broad research into energy harvesting using the foot. This is the area of research that will be explored because the running shoe pedometer is on the foot. Any power that is generated from the foot will not have to be transported to another area of the body and will already be near the shoe. While we may be able to generate more power elsewhere on the body, it would be too cumbersome.

2.2.1 Foot Power

Energy harvesting from passive power from the foot can be subdivided into two groups: energy that is generated from acceleration and energy that is generated using force or pressure.

Acceleration

Foot Swing: This type of energy harvesting involves using the lateral motion of the foot. During walking nearly 20 G's of acceleration can be generated (30).

Foot Strike: This type of energy harvesting involves using the impact of the foot on the pavement. During walking nearly 50 G's of acceleration can be generated (30).

Pressure

Weight Transfer: This type of energy harvesting involves using the weight of the person to generate electricity. Throughout the gait cycle, the shoe goes from zero pounds of force to the wearer's weight, and back to zero again. During walking, the force exerted on a shoe can be 130% of a person's weight and during running the force can be 250% of a person's weight (71).

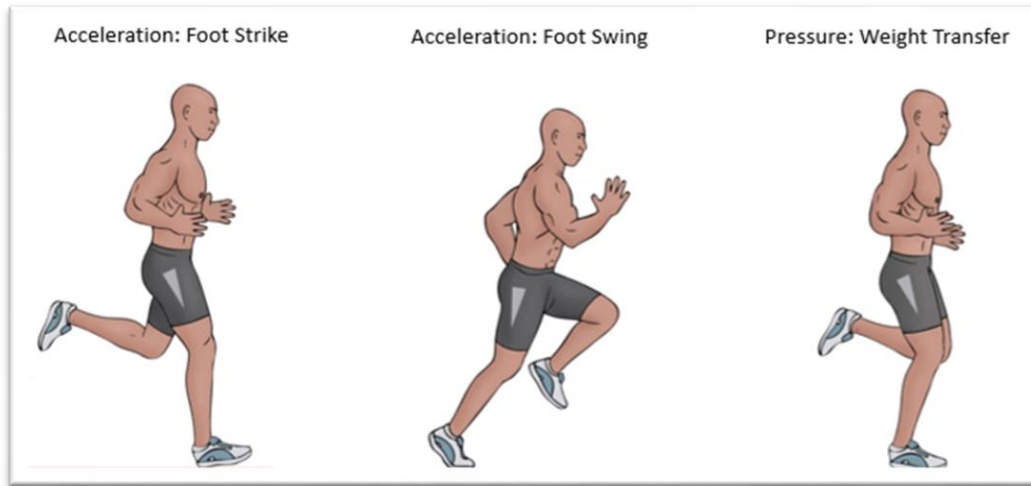


Figure 24: These figures show the different types of foot power that can be harvested when running (34).

2.2.1.1 Acceleration due to Leg Swing

Energy generation from foot swing uses the changing motion and acceleration that a foot does when walking or running. The swinging motion of the foot has horizontal as well as vertical motion. These motions have been investigated successfully with the primary energy generation method being inductance. Multiple papers have been written about energy harvesting that involve magnets moving through coils of wire located on the outside of the shoe or within the heel to generate power. Though these devices do show promise for walking, these devices have all been bulky and clumsy which is not appealing for the minimalist nature of running. The weight of magnets and coils as well as the motion of the magnet mid stride, and the space requirements make all of these designs impractical. The research community has generally focused on peak power numbers rather than functionality. In conclusion, generating power from the acceleration of the leg swing is impractical for the running shoe pedometer.

Author	Volume	Power
Niu and Chapman	N/A	80 mW
Carrol	18 cm ³	14 mW
Ylli K and Hoffmann	21 cm ³	0.81 mW
Zeng and Stankovic	10 cm ³	59.05 mW

Table 5: This table shows research done involving energy harvesting from acceleration of the leg swing. These papers have all been able to generate impressive power outputs at the cost of practicality (16)(121).

2.2.1.2 Acceleration due to Heel Strike

Energy generation from heel strike uses the spike in acceleration when a foot slams into the ground when walking or running. This area was explored successfully before using piezoelectrics that are attached to masses and then excited and allowed to vibrate at their natural frequencies. This area has also been successfully investigated using induction in vertically mounted magnets and coils as well as a multitude of impractical rotational designs including the US army's SPARK and MIT's rotary magnetic generator(121). While these designs have been able to generate some power they have been obtrusive. By definition, these devices are not static and require free space and volume. In conclusion, energy harvesting from the acceleration of the heel strike is impractical.

Author	Volume	Power
Pillatsch P, Yeatman	125 cm ³	2.1 mW
MIT (Kymissis)	2 cm ³	1.1 mW
Ylli K and Hoffmann	48 cm ³	4.13 mW
US ARMY (SPARK)	N/A	2.5 W

Table 6: This table shows research done involving energy harvesting from acceleration of the leg swing. These papers have all been able to generate impressive power outputs at the cost of practicality (16)(61)(62)(75)(121).

2.2.1.3 Foot Pressure

Energy generation from foot pressure has long been the simplest solution to energy harvesting. It involves using the cyclic loading and unloading of weight on the shoe to generate electricity. This has conventionally been done with piezoelectrics, but energy has also been generated using capacitance style designs. This design is the least intrusive and can be easily incorporated into the shoe. It also generates the least amount of power. While most of the foot pressure designs focus on the heel or the ball of the foot, there is also significant research into the bending of the sole as a method for energy generation. Energy harvesting from the foot pressure is the most practical of the three because of the solid-state nature.

Author	Volume	Power
Fourie [89]	43 cm ³	0.06 mW
Mateu et al [90]	3 cm ³	0.018 mW
Wang [88]	48 cm ³	5.04 mW
MIT (Kymissis)	21 cm ³	2.3 W

Table 7: This table shows research done involving energy harvesting from foot pressure. These papers have all been able to generate medium amounts of power but are more practical (16)(75).

2.2.2 Types of Passive Foot Power

There are many ways to harvest power passively. To save time in analyzing all of these methods, a brief explanation of each of these will be given and some of the less feasible power generation

methods will be discarded. Green headers indicate a viable option, and a red header indicates a less viable option.

Radio Frequency Harvesting: This involves using an antenna to pick up stray or intentional radio signals. These signals can be converted into electricity and if multiplied correctly can generate enough power to be useful especially in burst usage scenarios. This option is well researched, cheap, durable, and lightweight. This is an option worth considering.

Triboelectric: The triboelectric effect refers to harvesting energy from static electricity or pulling electrons off of surfaces. Running is a sport that involves rubbing of materials and friction, so this is an area worth exploring.

Photovoltaic: Photovoltaic energy generation involves using solar cells to generate electricity. This would be a promising option considering that the feet are usually exposed to sunlight but there are too many scenarios where this won't work such as running inside, running at night, muddy shoes, cloudy weather.

Thermoelectric: Thermoelectric energy generation involves using temperature differences to generate electricity. However, typically temperature differences of at least 20 degrees are required. This is not a viable option even in cold weather.

Inductance: Electromagnetic induction is the production of an electric current across a conductor moving through a magnetic field. This usually involves some type of magnet and motion to generate hysteresis. This has been done successfully by many (16)(121) but involves too much weight, space, and moving parts to ever be used in a running shoe.

Capacitance: Capacitance based energy generation relies on changing the distances between parallel plates of a capacitor to induce a current. This would work well for a shoe because as the foam in the shoe gets compressed with each step the capacitance would change allowing for energy generation. This would also be robust, lightweight, and simple.

Piezoelectric: Piezoelectric energy generation involves compressing or bending a piezoelectric material. This material when compressed or bent causes a voltage difference on either side because of the unique properties of the crystals. This is well researched, durable, cheap, and lightweight and merits further consideration.

2.2.3 Radio Frequency Power Generation

Radio frequency energy generation relies on both stray and deliberate radio signals such as those for AM radio, FM radio, VHF television, and UHF television, and Wi-Fi signals. This concept relies on an antenna that becomes charged due to the radio waves. That charge can then be multiplied, collected, and stored to be used at a later time. For safety and warning broadcast reasons, the Federal Communications Commission (FCC) specifies a minimum strength of signal in a radio station's broadcast range. They specify at least 60 dB μ received signal strength which translates to electromagnetic field with 1.0 millivolts per meter strength. In the worst-case scenario, a single quarter wave monopole

antenna would generate 0.75 millivolts (50). However, much higher voltages could be achieved through the use of multiple antennae with longer lengths. This can get the voltage up to 3-4 millivolts. However, this is still not nearly enough for CMOS logic. In order to get to CMOS voltage levels of 2-5 volts, the voltage must be multiplied.

Typically, to multiply voltages, active type switching components are used similar to those in rectifiers and boost converters. These allow for much more efficient voltage boost but require constant power. Because this device won't have a battery, a passive style boost circuit must be used such as a Cockcroft-Walton voltage multiplier.

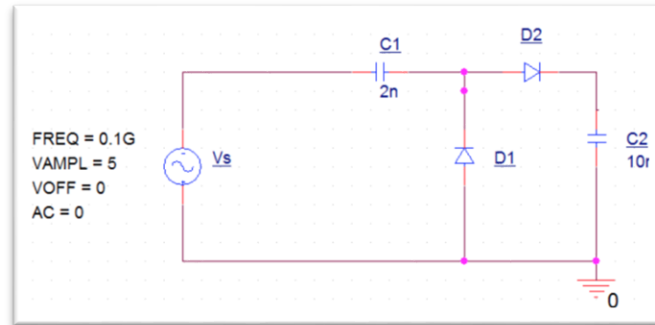


Figure 25: Pictured is a single state Cockcroft-Walton voltage doubler schematic. This circuit charges capacitor C1 to Vmax on the negative half of the sine wave. Then on the positive half of the sine wave, the voltage source and capacitor C1 work together to double the voltage. Capacitor C2 and diode D2 work together to reduce the voltage ripple in the output. The voltage is never truly doubled because the capacitors and diodes aren't ideal (50).

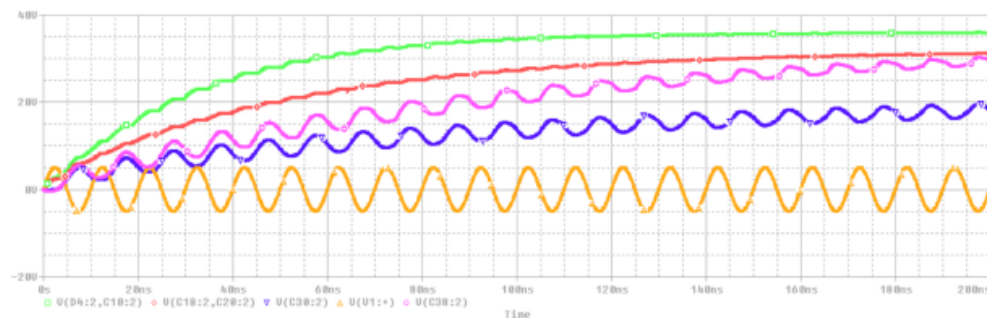


Figure 26: This figure shows the output voltage relative to time of different setups of voltage multipliers. These variations of multipliers include arithmetic capacitance and uniform capacitance as well as an 8 stage multiplier compared to a 4 stage differential multiplier (50).

After doubling the voltage 8 times, there is enough voltage to reach CMOS logic levels. Even though this approach may be able to provide enough power, there are too many other obstacles for RF energy generation. One of the issues facing the RF design is the location of the antenna. It may have been possible to use an antenna in a flexible PCB on the upper and toe of the shoe, or some type of wire around the shoe, but this would have left it vulnerable to being ripped and torn and would not be conducive to running. It may be further explored for casual or walking shoes, however. Another issue with the RF design is that the device would not work as well indoors or in remote regions, which is critical for running. This type of design is also not conducive to small form factors. Lastly, the RF design is too technical for my skill set and requires much more training in electrical engineering.

Even though radio frequency might not be a viable power source, the radio frequency approach to electronics that involves voltage multipliers, heavy simulation, impedance matching, and careful component selection can be applied to the rectification circuit that powers the rest of the device. It might also be an interesting supplemental device to the primary power source, or it could be an undesired side effect that should be avoided. Lastly, another sensor would still need to be incorporated in the device to count the steps taken.

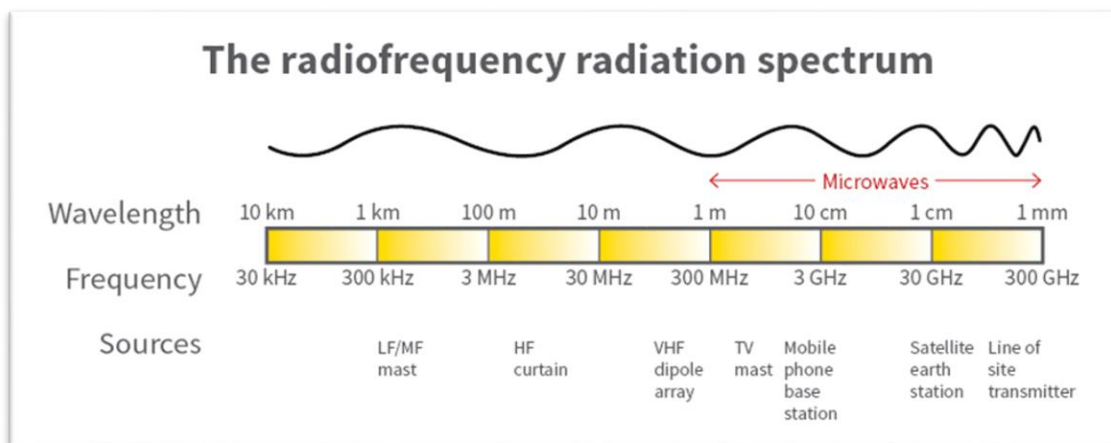


Figure 27: This figure shows a breakdown of the radio frequency spectrum in the radio frequency category. Devices such as AM radio, FM radio, VHF television, and UHF television, and Wi-Fi signals all use radio signals (85).

2.2.4 Triboelectric Power Generation

Triboelectric energy generation is the process of energy generation using static electricity and friction. More specifically, this process uses triboelectrification and electrostatic induction. This relies on a material's natural affinity to become positively or negatively charged. A classic example of this is a Ebonite and fur set as well as a nylon and silk friction rod set. These are classics physics demonstrations that are typically used in conjunction with an electroscope.

When two materials of opposite charge affinities are forced together, the opposite polarities accumulate on the surface of the materials. When the materials are separated, however, they remain oppositely charged. This charge, if hooked up to a circuit, will cause a flow of electrons that can be stored and used for power generation. This is similar to walking around on a cool dry day and getting shocked by a doorknob.

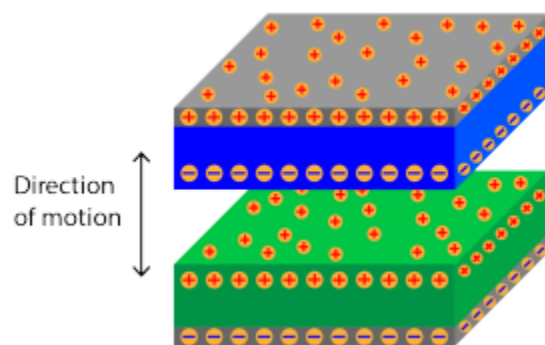
This type of energy generation typically results in high voltages and low currents which can be problematic for CMOS circuits (16)(17). Energy generation with the triboelectric effect will require very carefully designed voltage regulators or transformers to create usable power. Another issue with triboelectric energy harvesting is the exotic materials that are required. These materials are not yet cost effective or necessarily conducive to long service life and comfort for the wearer. These systems can be combined very easily with other piezoelectric harvesting schemes to boost their power output. Minglu Zhu was able to create 1.73mW of power with a triboelectric and piezoelectric sock.

This is a promising field but, to date, triboelectric energy generation hasn't been converted into any actual products. Making a runner use a particular sock everyday will be expensive and require investment into the triboelectric ecosystem. There are other concerns such as chaffing and wet weather which also make triboelectric energy generation a promising possibility in the future, but not viable for a product coming to market soon.

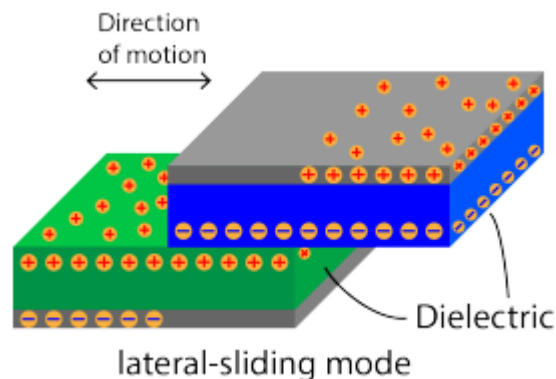
Triboelectric	Charge affinity [nC/J]	
Polyurethane foam	+60	↑
Hair, oily skin	+45	
Solid polyurethane	+40	
Nylon, dry skin	+30	
Machine oil	+29	
Glass (soda)	+25	
Paper	+10	
Wood (pine)	+7	
Cotton	+5	
Nitrile rubber	+3	
Wool	0	0
Polycarbonate	-5	↓
Acrylic	-10	
Epoxy	-32	
PET (mylar) solid	-40	
Polystyrene	-70	
Polyimide	-70	
Silicones	-72	
Vinyl: flexible	-75	
Polypropylene	-90	
PVC (rigid vinyl)	-100	
Latex (natural) rubber	-105	
PTFE (teflon)	-190	

Table 8: This figure shows a combination of mundane and exotic materials and their charge affinity. By choosing triboelectric materials with the greatest difference of charge affinity the most energy can be easily generated (17).

(1) VERTICAL CONTACT SEPERATION



(2) LATERAL SLIDING MOTION



(3) SINGLE ELECTRODE MODE

(4) FREE STANDING TRIBOELECTRIC LAYER MODE

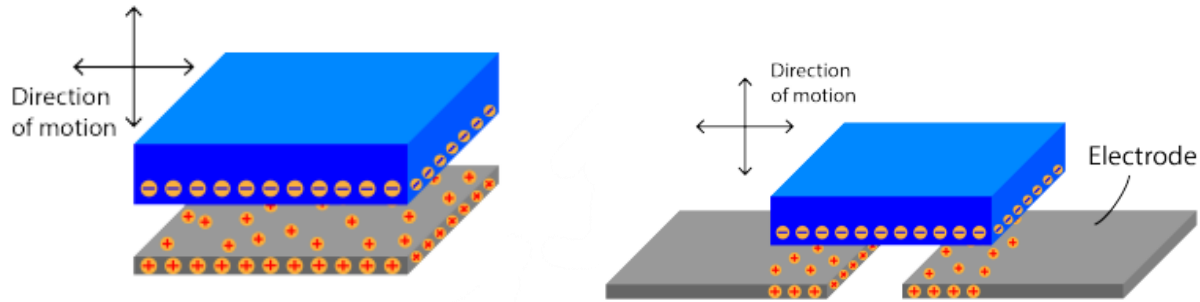


Figure 28: These figures show all of the types of triboelectric motions. The relative motion between the surfaces results in unequal charges. These charges can then be captured and stored. The easiest mode of motion for energy scavenging is mode 1, vertical contact separation (17).

2.2.5 Capacitive Power Generation

Similar to triboelectric energy harvesting, capacitance energy relies on electrostatic electricity to scavenge energy. This involves utilizing the flow of electrons created when the capacitance of a system is continually changed. However, having a system with changing capacitance presents a unique design challenge, all CMOS systems rely on capacitors with fixed values. In order to utilize capacitive energy generation, a flexible and variable capacitor must be designed. In order to change the capacitance of a system, an active and a ground electrode must be used. There are two approaches that can be taken, a stacked electrode approach and a coplanar electrode approach.

Stacked Electrode: To change the capacitance of a system using stacked electrodes, an active electrode is placed above the ground electrode with dielectric layers both in-between and on top (17). This is very similar to a typical parallel plate capacitor. Then, when a another “ground” such as a finger, moves closer to the active layer, the electric field of the capacitor will be split between the ground layer and the finger. This will cause electrons in the ground layer to flow. This electron flow can be scavenged.

Coplanar Electrodes: To change the capacitance of a system that utilizes coplanar electrodes, an active electrode is placed adjacent to a ground electrode with a dielectric layer in-between (17). In this case, there is a small capacitance between the plates where they are closest due to the dielectric, but the overall capacitance is very small. When a finger or other ground electrode is placed near these plates, its capacitance helps facilitate the electric field between the two plates and changes the capacitance of the system. This causes the electrons in the ground plate to flow which can be scavenged.

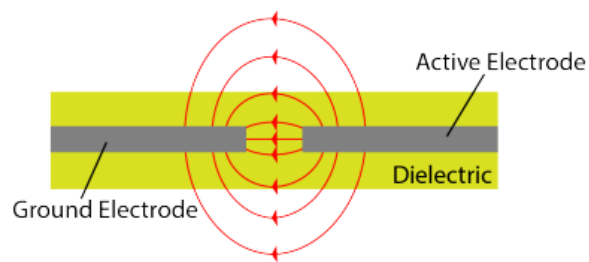


Figure 29: This figure shows a coplanar electrode configuration (17).

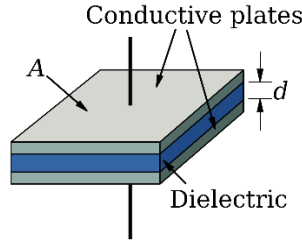


Figure 30: This figure shows a parallel plate or stacked electrode capacitor (33).

$$Q = CV$$

$$\frac{dQ}{dt} = C \frac{dV}{dt} + V \frac{dC}{dt}$$

$$E = \frac{1}{2} CV^2 = \frac{1}{2} QV$$

Figure 31: This figure shows some of the relevant equations of electrostatic conversion theory. Charge(Q) can be related to capacitance(C), voltage(V), and Energy(E) (17).

These flows of electrons can be scavenged using a half or full bridge rectifier. From there, the energy can be stored and used for later. One of the key drawbacks with this design is the need for an active layer. There would be no capacitance between electrodes of equal charge such as two ground layers. The active layer must have a charge. This charge must be maintained via an external capacitor. In an ideal system, this wouldn't be terribly inconvenient. With one charge at the beginning of the pedometer's life, it will be able to produce its own electricity forever. However, the running shoe will not be used in an ideal environment, the capacitor and diodes that stores the charge for the active layer will leak current resulting in no energy generation. This means that the circuit will have to be recharged with energy periodically. This means that this type of circuit is perfect for a device that already uses electricity and has a battery such as a smartphone. The variable capacitance could help keep the phone alive, but nobody would expect it to keep the phone charged forever.

Capacitive energy generation systems have merit and have been used to generate energy from ventricular wall motion (133) as well as evaporative forces in synthetic leaves (134). However, because of the reliance on an initial bias voltage, and the need to periodically replenish the system, this will not be a viable power generation solution for the running shoe pedometer. However, it might be a good system to use in conjunction with other methods. A triboelectric or piezoelectric energy source could help make sure the active layer stays charge allowing for multiple modes of energy generation. These combined approaches show merit and might improve the energy yield. However, because the pedometer is required to be lightweight and as cheap as possible, we will not explore combinations of energy generation systems.

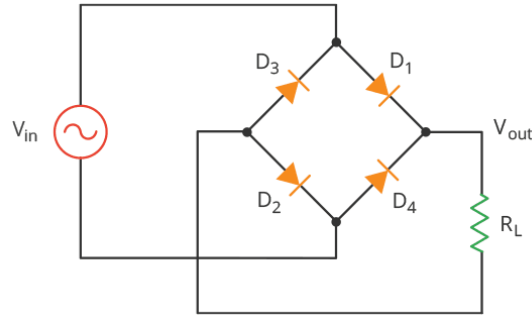


Figure 32: This figure shows a typical diagram of a full bridge rectifier that is used to turn the AC current into a DC current that can be used for circuits (51).

2.2.6 Piezoelectric Power Generation

Piezoelectric energy harvesting uses unique materials with a particular crystalline structure. These crystalline structures are comprised of positively charged and negatively charged molecules arranged in a lattice structure. When the crystals are placed under stress, the lattice structure deforms moving the positive molecules towards one end and the negative molecules towards the other. This creates a polarization and produces a net charge across the crystal. This charge can be connected to a circuit and scavenged to produce electricity. Through the direct piezoelectric effect, crystals turn mechanical force into electricity (57). Similarly, if a voltage is applied to piezoelectric materials they will deform, this is known as the converse piezoelectric effect. Using the direct piezoelectric effect, very accurate sensors can be produced, or electricity can be harvested. Using the converse piezoelectric effect, actuators, motors, fans, and buzzers can be made.

Piezoelectric energy generation works in a similar way to capacitive energy generation except that the materials are naturally “charged” so there is no need for an initial bias voltage. These piezoelectric materials are the most thoroughly explored area of energy scavenging. They are commonly used in sensors in many industries including the accelerometer in your phone. They have also found use in trigger style lighters. In this style of lighter, you squeeze the trigger until it suddenly snaps and lights the flame. This snap is a hammer hitting a piezoelectric quartz crystal(APC). This generates tens of thousands of volts. This voltage is carried down the barrel of the lighter where it lights the butane gas (112). This incredibly cheap ignition method doesn’t have any wear components like a flint and steel striker and should never wear out.

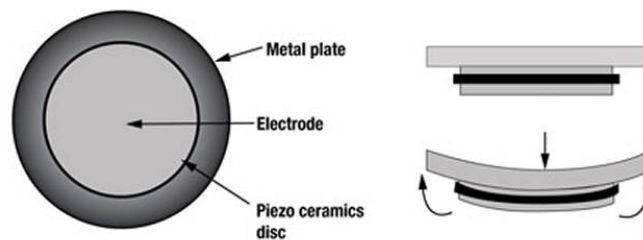


Figure 33: This figure shows a bimorph piezoelectric bender. This consists of a metal plate with two layers of piezoelectric material separated by an insulating substrate layer. This substrate layer allows the energy harvester to generate voltages

both in bending and in compression. A unimorph bender only be able to generate a voltage in simple compression will generate a net zero voltage under bending (79).

2.2.7.1 PZT vs PVDF

In order to optimize the energy generation of the pedometer, the piezoelectric material must be carefully chosen. While there are hundreds of piezoelectric materials such as Lead Zirconate Titanate(PZT), Polyvinylidene fluoride(PVDF), bone, quartz, Barium Titanate, Potassium Niobate, Sodium Tungstate, alumina, glass sapphire, silicon, and many more, choosing the correct one will be vital (16).

After investigating all of the mechanical properties, two characteristics will define our search, the coupling constant, and the density. The coupling constant is the efficiency at which the material converts mechanical energy to electrical energy. This is important because we want to generate as much energy as possible which will require high conversion efficiency. There is also a focus on the physical characteristics of the materials such as the density because of the low volume and lightweight requirements of the design. After sorting the list of potential piezoelectric materials by this criterion, the search ends with the two most commonly used piezoelectric materials, PZT and PVDF.

Property	Units	PVDF	PZT
Density	g/cm ³	1.78	7.6
Relative Permittivity	ϵ/ϵ_0	12	1700
Elastic Modulus	10 ¹⁰ N/m	0.3	4.9
Piezoelectric Constant	10 ⁻¹² C/N	d ₃₁ =20 d ₃₃ =30	d ₃₁ =180 d ₃₃ =360
Coupling Constant	CV/Nm	0.11	k ₃₁ =0.35, k ₃₃ =0.69

Table 9: This figure shows the comparison of the traits of PZT and PVDF piezoelectric materials (16).

Although the lighter density and increased flexibility of PVDF materials are more suitable for embedding in the shoe sole, its conversion efficiencies are almost one order of magnitude smaller than that of the PZT. This can be analyzed through the piezoelectric constants. However, this does not tell the full story because piezoelectrics can be excited in multiple ways.

2.2.7.2 Mode 31 and Mode 33

To optimize the material for the running shoe pedometer, the different ways that a piezoelectric can be stressed must be investigated. Certain materials are more efficient or practical in different modes. Because of the lattice structure, any piezoelectric material has two polarization directions.

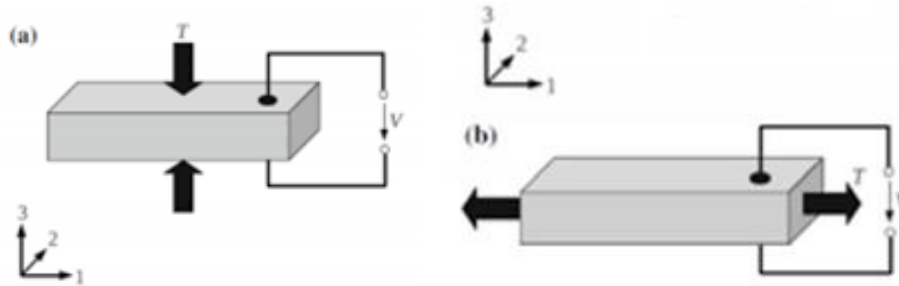


Figure 34: This figure shows a piezoelectric material being activated in mode 33. This is referred to as compression and known as a Parallel Compression Generators. This figure shows a piezoelectric material being activated in mode 31. This is referred to as tension and is known as a Transversal Tension Generators.

On paper, the most efficient mode of energy generation is mode 33 for a PZT material. However, after applying the relation $\Delta H = FH / AY$ where h is height, Y is elastic modulus, A is area, and F is the applied force, under the weight of a man running only a very small deflection, in the order of ten thousandths of an inch, is achieved. Additionally, the efficiency increases with the force applied which isn't ideal for walking on well-padded running shoes that are designed to reduce impact forces.

When examining the efficiency of mode 31 excitation, we can see that a film of PVDF will give the better mode 31 efficiency because this material can be made with an extremely low width. A PVDF film can generate thousands of times more electricity in mode 31 than mode 33 (16).

	Mode 31	Mode 33
V_o	$g_{31}(F_1/W)$	$g_{33}(F_3/WL)H$
q	$d_{31}(F_1L/H)$	$d_{33}F_3$

Table 10: This figure shows the relationship between charge(Q) and voltage(V) of piezoelectric materials and the mode they are excited in. G is the piezo stress constant, d is the piezo strain constant, F is force, L , W , and H are the dimensions of the piezo (16).

Lastly, we must take a look at how bending affects a piezoelectric. When using bending, especially in a bimorph, see figure 25, the practicality of mode 31 can be used with a more efficient and denser PZT material. The bending stretches the top layer of piezoelectric and compresses the bottom layer. This will result in opposite charges on either side of the bender. This can be a more efficient way to use mode 31 on a PZT material. Though this may be more efficient, it can be harder to implement. The piezo needs to be attached in a way that promotes bending such as being compressed over a fulcrum. It can be imagined that a flat piezoelectric bender placed in the bottom of a shoe might bend and cup around the shape of the heel throughout the gait cycle. While this may result in higher efficiency for mode 31 PZT's, it is substantially harder to predict the behavior of the piezoelectric and is best understood through advanced modeling such as FEA. These complexities make this excitation mode unsuitable for an undergraduate project. There are other downsides to bending the piezoelectric such as the potential for cracking the piezo if unexpected forces like heavy landings or jumps are applied to the

shoe. Because the bender is too difficult to use, and could prove to be unreliable, the search can be narrowed down to mode 31 and mode 33 excitation again.

Now that we understand that a mode 33 PZT provides the most electricity but requires impractical forces, and that bending is the most efficient, but requires too much risk, mode 31 must be analyzed. Mode 31 requires a material to be stretched or pulled. While it is possible to use mode 31 excitation in compression along the longitudinal axis, the risk of bucking is too great. In order to implement mode 31 with PVDF materials tension must be used. Throughout the gait cycle, the sole of the running shoe bends in half and gets longer as a person pushes their foot off the ground. The ball of the foot stays planted on the ground while the heel starts lifting in the air, bending the sole. In the past, MIT researchers have covered the sole of a shoe in PVDF film and used the bending to activate the piezoelectric in mode 31. This creative solution was designed to satisfy the long length and thin width characteristics that suit the PVDF films. However, the researchers at MIT prioritized power generation over practicality. This design is massive and uncomfortable and not at all subtle. The PDVF stave produced 20mW of power which exceeds the needs of the pedometer so perhaps a paired down version of this design would work well for the pedometer.

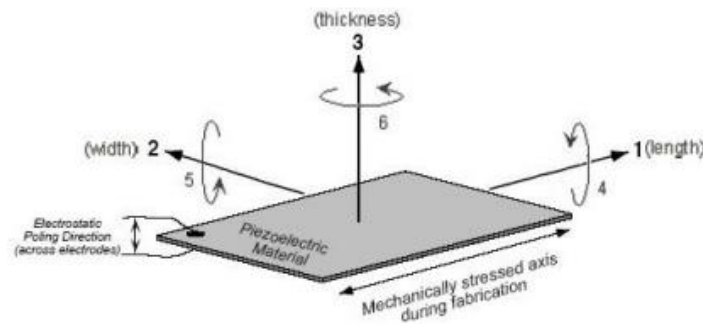


Figure 35: This figure shows the length width and height of a piezoelectric material relative to the modes of activation.

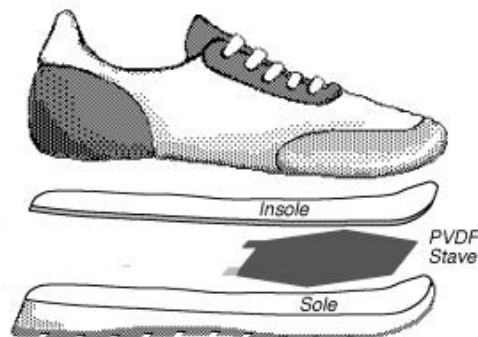


Figure 36: This figure shows a sketch of the PVDF stave made by MIT researcher John Kyminsis and his team. This design utilized bending to use the more efficient and practical mode 31 to scavenge energy.

In conclusion, mode 31 always benefits PVDF materials whereas mode 33 is always more efficient for PZT materials. However, achieving true mode 31 stretching is near impossible in a running

shoe. Therefore, using bending as a workaround for true mode 31 materials is acceptable only for PVDF because of the increased flexibility and durability of the plastic polymer. Using bending on a PZT ceramic risks shattering and is not an acceptable risk.

From this, a more condensed PVDF mode 31 generator similar to miniaturized version Kymissis's generator is a viable option(16)(75). Another viable option is mode 33 generation using PZT materials. While both of these options are likely to be cost effective in the long term, the mode 33 PZT material is likely to be the least obstructive to the user due to the power density per weight and the low volume. This design can also be incorporated deep in the blown rubber of the heel or underneath the insole of the shoe. Due to the limited movement and sensitivity of the heel, it can likely be incorporated unknowingly into the shoe whereas the PVDF stave design will be placed under the more sensitive ball of the foot and is more likely to be detected by the wearer.

As for the impractical forces necessary to use the PZT, this issue can be mitigated through the use of voltage multipliers. If the piezo produces voltages that are too low, due to the low force per area, we can use a voltage multiplier to achieve CMOS voltage levels. Additionally, a smaller PZT placed on a larger platform will allow the force to be concentrated increasing the voltage. Lastly, multiple of these piezoelectric disks can be stacked together to double the voltage from any step. These piezo stacks will still be light and thin enough to be easily concealed in a running shoe.

Additionally, PZT pads are readily available on the internet because of their wide use in everyday objects as microphones , sensors, and buzzers. This will make testing cheaper and easier than a custom PVDF film.

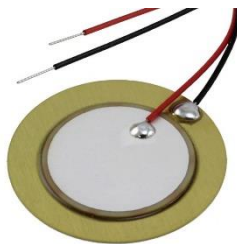


Figure 37: This figure shows a commercially available PZT piezoelectric element attached to a brass disk (5).

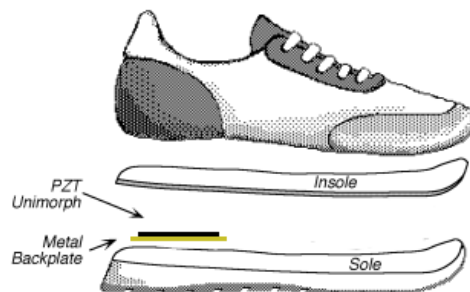


Figure 38: his figure shows a PZT unimorph piezoelectric element inserted in a running shoe under the heel beneath the insole.

2.2.7.3 Piezoelectric Durability

Piezoelectric materials might be able to generate the power necessary and be concealed easily enough, but that won't matter if the piezoelectric crystals break when they get wet or fail after the first thousand cycles. To decide if the proper mode of energy generation for the running shoe pedometer is piezoelectrics, their durability must be investigated. There are three essential factors that affect the operating life of a piezoceramic in harvesting applications; humidity, temperature, and operating voltage/force applied (87).

Humidity

Humidity and moisture can affect the piezos because of their reliance on electrostatic interaction. Water will create a short circuit between the top and bottom of the disk as well as reduce the electric potential from within the coarse crystalline structure itself. Luckily, water is unlikely to do permanent damage to the piezo, if it were to get wet, being thoroughly dried would bring the piezo back to life. Besides that, the piezo could be encased in a flexible plastic or rubber that would prevent water ingress. To prevent failure by humidity the piezo could be inserted into the blown rubber of the midsole or be encased in rubber and hidden under the insole. Because the motion of the piezoelectric is so minute, any rubber or plastic shield would have a very long life. Besides from this, the piezo can be covered with a specialty ceramic coating such as that used in the PICMA actuators to resist water (86).

Temperature

While temperature is known to affect the life of a piezo, this constraint applies to industrial uses such as NASA's mars rover where temperatures can be blisteringly hot. Normal PZT piezos will start to degrade after 300°C. This means that the piezos will be able to stand up to the boiling water of the spin cycle at around 100°C and being put through the dryer at around 57°C with ease. As for cold temperatures, piezos are rated well below frostbite inducing cryogenic temperatures. In a running shoe, the piezo crystals shouldn't face harsh enough temperatures to affect their life.

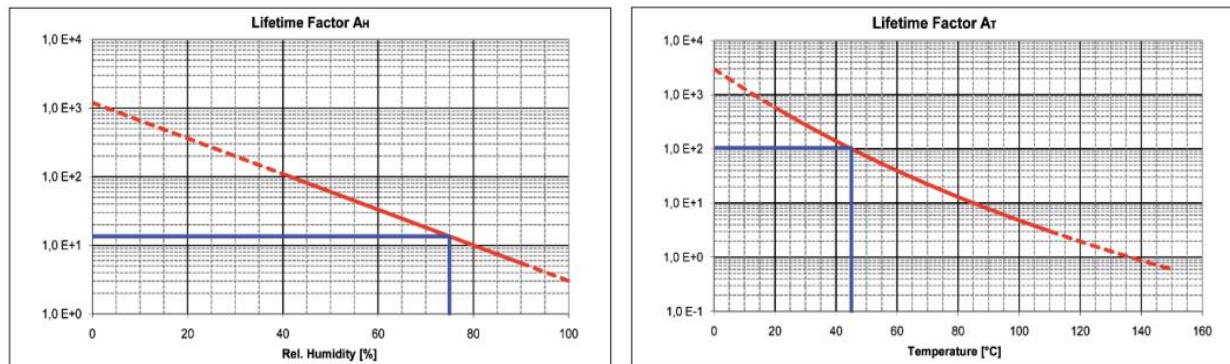


Figure 39: These figures show how the lifetime factor of the piezoelectric is related to the temperature and the humidity. Note that the Y axis is not the number of cycles but a factor which when multiplied with the other factors shows the total number of hours to product is expected to last. Under typical running conditions the piezo will outlast the shoes by a factor of 100 (86).

Operating Voltage/Force Applied

Lastly, the piezos must not have forces greater than they are specified for applied to them. This can crack the lattice structure and cause the piezo to break. However, as previously mentioned, mode

33 PZT's are most efficient under very high forces, higher than we can hope to apply. Breaking the PZT via pure compression will be impossible. However, if the shoe is improperly designed, the cupping of the heel and the shoe might cause the piezo to bend and crack under moderate loads. To avoid this, a stiff plate is added behind the PZT to distribute the force evenly and mitigate the risk of breaking from bending.

Conclusion

The investigation yielded that when used properly, PZT piezoelectrics can last 10 billion or even 100 billion cycles (46). This is because of their solid-state nature. There are no bearings gears, grease or moving parts. Similar to the silicon used in computer chips, they must degrade on a molecular level or be placed in undo circumstances in order to break. With humidity being the only cause for concern, the final product must be fitted with a plastic or rubber housing to dispel water. It would also be beneficial to investigate the ceramic and polymer coatings that can be applied and embedded in the ceramic to fight the effects of humidity.

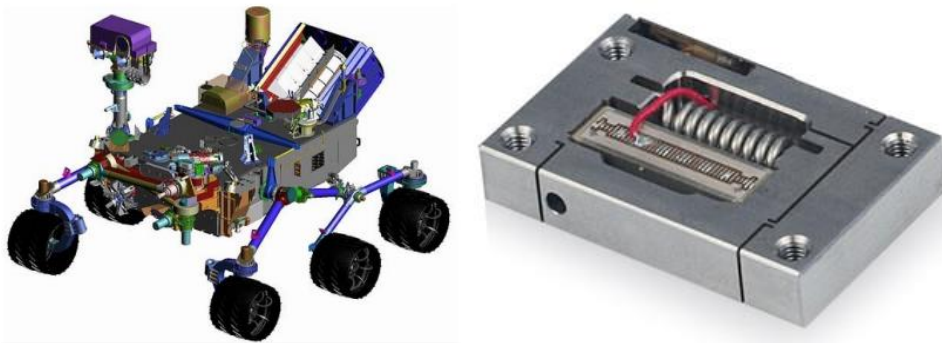


Figure 40: The figure on the left shows 100 Billion Cycles: PICMA® actuators were life tested by NASA/JPL before they were sent to the Mars. No failures were seen after the extensive tests (46). This figure on the right shows a piezoelectric flexure.

This is a very precise positioning system that achieves micro-meter accuracy levels. These flexures are used in the most precise optical applications as well as grinding and machining at very high tolerances (47)(48).

2.2.8 Energy Harvesting Conclusion

For energy scavenging in a running shoe, several power generation methods were investigated, including radio frequency, triboelectric, photovoltaic, thermoelectric, inductance, capacitance, and piezoelectric. Of these methods, the most promising were radio frequency harvesting, triboelectric, capacitance, and piezoelectric. After each of these were studied extensively, only piezoelectric harvesting remained as the most promising alternative.

Radio frequency harvesting couldn't work indoors and couldn't have provided enough power. It would have required very complex circuitry and needed a separate system to count steps. Triboelectric has not been investigated and vetted enough to become a product yet. It might struggle under certain weather conditions and would require special clothing by the runner. Capacitance based charging systems need an applied voltage from an active source such as a battery which would defeat the purpose of generating energy. Each of these might be a good secondary or supplemental power source because they have complimentary shortfalls, but for the sake of simplicity and cost, piezoelectric power

generation is the most promising and thoroughly explored area of energy scavenging. Piezoelectrics were found to be cheap and durable.

The advantages and disadvantages of piezoelectric energy generation align well with the goals of the running shoe pedometer. Special care will have to be taken to impedance match the circuit as well as rectifying the energy for CMOS use.

Methods	Advantages	Disadvantages
Piezoelectric	No external voltage required [39] Large power density [39] High voltage output [39] Macro and micro fabrication [39]	Requires accurate impedance matching [82] Material fatigue [15] Not compatible with standard CMOS Wide range of efficiency depending on material
Electromagnetic	High output currents [82] Long life span [82] Macroscale robustness [114] No external voltage required	Very low output voltages [39] Limited miniaturization [39] Difficult to integrate with other fabrication processes [18] Expensive materials [82] Strong damping forces [114] Works better at high frequencies [15]
Electrostatic	High output voltage [82] Easy to miniaturize [82] Inexpensive [82] Integrates easily with CMOS and MEMS fabrication	External voltage required [39] Parasitics reduce efficiency [15] Electrets suffer charge decay [21]
Triboelectric	Very high voltages [25] Higher efficiency in low-frequency range [1] Inexpensive materials [182] Wide variety of materials [42] Flexible and biodegradable	Susceptible to humidity, stability, and surface damage [98] Lifetime reliability uncertain [25] Electrification mechanism still not fully understood [182] Not compatible with standard CMOS

Figure 41: This figure from, “Charge Pumping with Human Capacitance for Body Energy” (17), shows the advantages and disadvantages of each energy generation method. Note that capacitance style energy generation is referred to as “Electrostatic” (16).

2.3 Circuit Design

To create a circuit that is optimized for a piezoelectric power source, the expected output from the piezoelectric must be calculated. After the theoretical output is predicted, it can be compared to experimental results.

2.3.1 Expected Power Generation

Before too much research is done on the power rectification and voltage regulation. A cursory analysis of the expected power generation is necessary. This analysis will be done using a PZT piezoelectric material that is excited in mode 33. The analysis begins by applying the relation $\Delta H = FH / AY$ where h is the height, Y is the elastic modulus, A is the area, and F is the applied force. We can substitute values for a typical man running with a single PZT unimorph plate in his shoe.

$$\Delta H = \frac{F * H}{A * y}$$

$$\Delta H = \frac{(195 \text{ lbf} * 2.5 * 0.01 \text{ in})}{(1.5 \text{ in}^2 * 4.9 * 10^{10} \frac{\text{N}}{\text{m}^2} * \left[\frac{0.000145 \frac{\text{lbf}}{\text{in}^2}}{1 \frac{\text{N}}{\text{m}^2}} \right])} = 1.4729 * 10^{-5} \text{ in} \quad (9)$$

From this, it can be determined that a very small deflection would occur. From there we can calculate the expected energy generation.

$$V = \frac{G_{33} * F_3 * H}{A}$$

$$V = \frac{24.8 * 10^{-3} \frac{\text{Vm}}{\text{N}} * 2168.5 \text{ N}}{0.531495^2 * \pi} = 23.99 \text{ V} \quad (10)$$

This should provide a peak voltage that can theoretically be generated. This means that if the circuit is designed correctly, there should be no need for voltage multiplication but only for voltage regulation. Though this value can be generated, the voltage drops from the rectifying diodes, the capacitance of the system, the resistance of the system, and the discontinuous nature of the pulse means that the experimental setup cannot generate voltages that high.

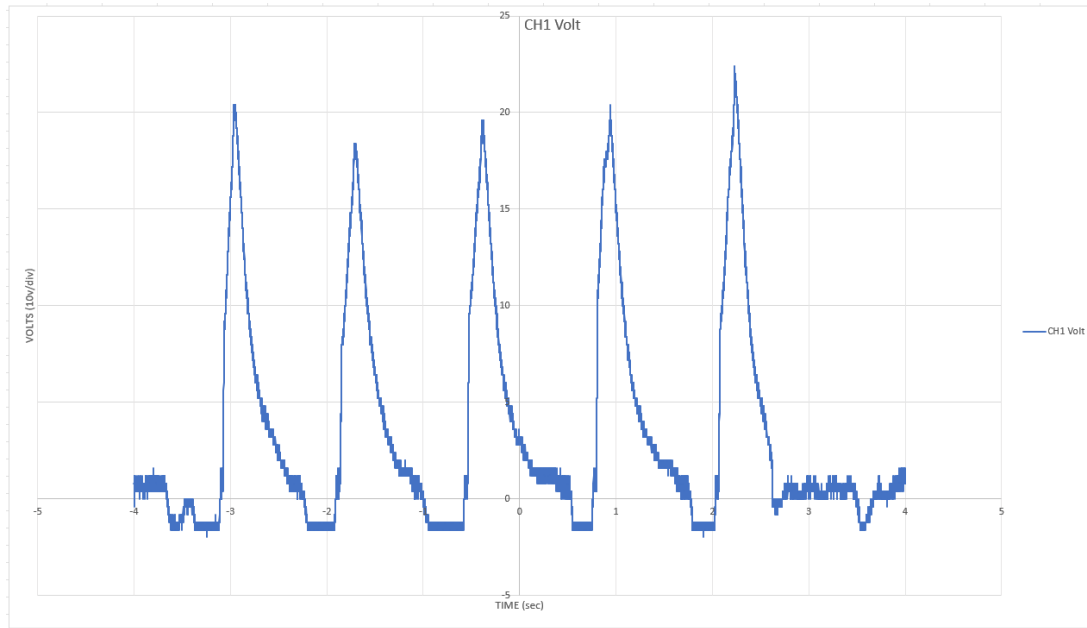


Figure 42: This figure does show, when connected to just an oscilloscope, the piezo was able to generate voltages almost as high as was predicted by equation 10.

In reality, the peak voltage isn't nearly as important as the slope of the curve. The slope of the curve and the fall time of the piezoelectric represents an RC circuit. This negatively sloped curve shows the resistance and capacitance of the and the oscilloscope and piezoelectric. From this, losses from the oscilloscope could be calculated and neglected so that just the expected power output could be found experimentally. Instead of doing these calculations, this will be taken as reassurance that the

piezoelectric behaves as predicted and further theoretical analysis is likely to be accurate as well. Now the total expected power can be approximated.

$$P = \frac{V^2}{R}$$

$$P = \frac{44mV^2}{55\Omega} = 0.0000352 \text{ W} = 0.0352 \text{ mW} = 35.2 \mu\text{W} \quad (10)$$

This means that the circuit should be designed to be well within the 35.2 μW power limit. This is a pretty stringent target goal. If the circuit requires more than the power than can be supplied, then the number of piezoelectric pads in the shoe will have to be increased. This will add cost and weight could make the shoe less comfortable but might be necessary. If this becomes too much then the inclusion of a battery could be the only alternative.

2.3.2 Smart vs Dumb Circuits

Now that the energy source has been narrowed down to piezoelectric, and the power limit has been determined, the next step might appear to be to create CMOS power that can be used by the microcontroller. However, that completely skips the choice of a logic circuit. Once upon a time, not everything relied on a processor. Circuits used to be designed using transistor logic and still are for simple applications today.

Transistor Logic

Transistor logic might be a viable solution to the Running Shoe Pedometer. A bank of transistors, when set up correctly, could make a very low-cost counting circuit. The asynchronous counting circuit would ideally be composed of a series of JK flip flops and a Schmitt trigger. Once the value of voltage from the piezoelectric crossed a threshold voltage, when a step was taken, the clock pulse would be sent, and the circuit would count the pulse as a step. Other than just counting, the circuit needs to be able to create an output when it has counted high enough. This could be done with a few “AND”/“OR” gates. If the counter had counted above a specified number, the gate array would dump the stored energy into the output device to make a visual indicator. This would be the most cost-effective route in the long term. If the product were to be a commercial success, a custom chip could be made with the required transistor array. Also, a commercially available chip can be programmed so that it behaves as a bank of transistors arranged like the pedometer required.

The issue with the transistor logic device is the intermittent power being generated by the Running Shoe Pedometer. Every time the shoes are not being used, and there is no power supplied, the transistor logic circuit would lose count or become “floating” and inaccurate. To date, a Non-Volatile Flip Flop (NVFF) has not been invented. Technically, the ferrite rings arranged in a grid that were used as memory storage in an early computer can be used in such a way (1), but these aren’t practical for a Running Shoe Pedometer. Trying to create an NVFF has been a big research topic. A chip that can keep count in such a way, a type of flip-flop and F-RAM combination, would be critical for sensors and medical devices. Typically, for a water meter, the counting circuit is hooked up to a battery so that if power were to lapse, the count wouldn’t be lost. A nonvolatile counting circuit would be a perfect substitute for this battery backed sensors, but this technology hasn’t been invented yet.

Microcontroller

Because the Non-volatile Flip Flop that I proposed has not yet been invented/isn't commercially available. The only other option is a microcontroller.

2.3.3 Rectification and Voltage Regulation

Now that the power source has been decided, the focus should be on creating CMOS power that can be used by the microcontroller. CMOS power means DC power that is between 3-5 volts. "One of the main limitations of all energy harvesting methods is the need to efficiently convert the generated AC power into usable DC power. "Microscale electromagnetic and piezoelectric generators have a major obstacle to overcome as the generated voltage is in the mV range and thus require very efficient AC/DC conversion techniques in order to produce usable DC power" (62). AC to DC power conversion is one of the most studied areas in Electrical Engineering. Power can be transported long distances very efficiently as AC energy but needs to be converted to DC to be used for electronics. Once the electricity is converted to DC, the voltage also needs to be adjusted to be used for logic level devices. The order of voltage correction and rectification can be switched around to improve efficiency depending on the application.

Voltage Adjustment then Rectification

In most consumer electronics such as computers and phone chargers, the voltage is changed before the signal is rectified. This is typically done using a transformer. Transformers can have extremely high efficiencies from 95%-99%. Then once the voltage has been stepped down to an acceptable level, typically 5 volts or 12 volts, then it can be rectified to DC. This is the most efficient for normal appliances because the AC energy from the wall is steady and predictable. However, if the voltage from the wall was to drop even 10%, the rectifiers would lose efficiency and the electronics wouldn't work.

Rectification then Voltage Adjustment

The process of rectification before voltage adjustment is typically done to AC signals with lower voltages. This order of operations is typically done on power generators that don't reach steady states or that may vary in voltage. This can be seen on self-charging flashlights, very small hydroelectric generators, or car alternators. This will method used for the Running Shoe Pedometer for a few reasons. First of all, there will not be room in the shoe for a heavy and bulky transformer. Also, the "AC" signal from the shoe isn't a true AC signal at all. Each time a person takes a step a pulse that resembles AC occurs. The frequency of the AC would vary from person to person and the speed at which the person is running. Peak voltage of the AC wave would also change depending on the physical characteristics of the runner. Because the AC waveform is so hard to predict and won't be constant, it makes more sense to rectify the current before the voltage is stepped up or down.

2.3.3.1 Active vs Passive Rectification

In order to rectify the AC waveform, two types of rectifiers must be investigated; active rectifiers, and passive rectifiers. Passive rectifiers are powered by AC current that they are transforming, and active rectifiers are controlled from another energy source. "When compared to other power

generation methods, piezoelectric generators require additional circuitry to rectify the output power from the unsteady high impedance source to a stable low impedance supply” (16).

Active Rectifiers

An active rectifier uses an external energy source to rectify the signal. These include BJT's, mosfets and transistors arrays such as a bidirectional switch. These mosfets arrays can be up to 99% efficient when used on high voltages. This is because the forwards voltage drops are much lower across the gate of a transistor when compared to the voltage drop across two diodes. When the input is a steady and predictable AC waveform, the mosfets turn on and off at specific times as the direction of the AC is switching. This provides maximum efficiency.

The issue with active rectifiers is that they require an external power source and control circuitry. While this leads to great efficiency at high voltages, at lower energy levels/voltages, “the power required to drive the mosfet gate cancels the efficiency gained from the reduced forward voltage drop” (16). To control the active rectifier an Op-Amp must be used. An active rectifier may not improve efficiency, will require external power that cannot be stored or spared, and will add complexity.

Passive Rectifiers

The two categories of passive rectifier are the whole wave and half wave rectifier. The full wave rectifier will require slightly more diodes but by definition is twice as efficient as a half wave rectifier. A full wave rectifier will maximize the energy provided by the piezoelectric as well as improve the efficiency of the voltage regulator. A full wave rectifier relies on four diodes oriented in a way that allows the positive and negative parts of the AC input to produce current in the same direction. The full wave rectifier also minimizes the ripple of the output voltage.

The biggest challenge with the full wave rectifier in a piezoelectric application is the forward voltage drops produced by the diodes. These diodes can have a drop of 0.3 volts to 0.7 volts. This will greatly hurt the efficiency of the device and may require multiple piezos in series to generate enough voltage to overcome these losses. Component selection to minimize losses from diodes will be crucial.

There are also schemes on how to use mosfets as a full bridge rectifier such as those in Peters et al. (135) and Roa and Arnold (136). These schemes appear to use the best of both worlds and use a second stage active diode to stop current flow back. However, these schemes are only efficient over 20Hz with continuous AC. That means they won't work for the running shoe pedometers predicted 0.75-1.5Hz variable frequency input.

2.3.3.2 Active Voltage Regulation

Linear Regulators

“A linear voltage regulator utilizes an active pass device (such as a BJT or MOSFET), which is controlled by a high-gain operational amplifier. To maintain a constant output voltage, the linear regulator adjusts the pass device resistance by comparing the internal voltage reference to the sampled output voltage, and then driving the error to zero.” (111)

These regulators are highly efficient, cost effective, and only require two small capacitors. The issue with linear regulators is they can only step power down and convert a high voltage to a lower

voltage. This might be applicable to the pedometer depending on the load exerted by the microcontroller. If the resistance of the microcontroller is very small, then the voltages of the piezoelectric will be high, and a linear voltage regulator may be called for. If the resistance of the microcontroller is higher, then the voltage will need to be stepped up and not stepped down.

Switching Regulators (Buck Boost Converter)

Switching regulators are more efficient and are more versatile for their voltage range. These regulators can have up to 95% efficiency and can also step-up voltages as well as step-down voltages. “A switching regulator circuit is generally more complicated to design than a linear regulator, and requires selecting external component values, tuning control loops for stability, and careful layout design. They may also require additional external components, such as inductors, capacitors, FETs, or feedback resistors.” (111).

All of these active regulators are not ideal because they require steady input voltages and constant power. They will also take up space and add cost. They play a valuable role in consumer electronics but do not fit the disposable and low-cost nature of the Running Shoe Pedometer.

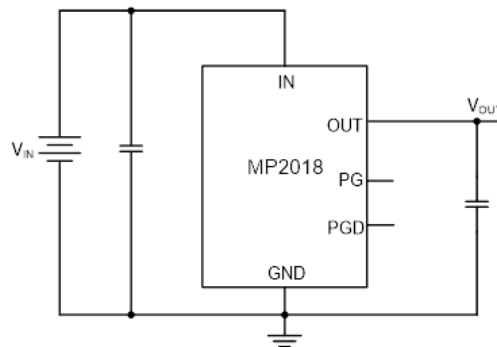


Figure 43: This figure shows a linear voltage regulator using the MP2018 chip (111).

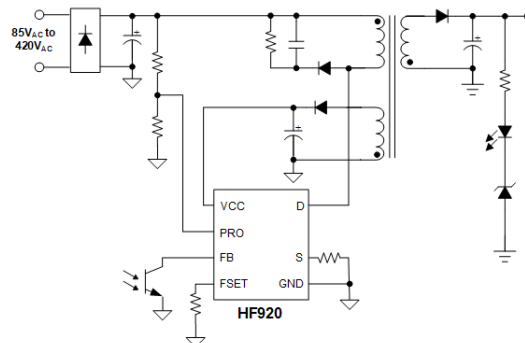


Figure 44: This figure shows a switching voltage regulator using the HF920 chip (111).

2.3.3.2 Passive Voltage Regulation

Passive rectifiers are powered by the currents that they are transforming and don't require an outside DC power source.

Zener Diode

If the voltage only needs to be stepped down, the easiest and most reliable way to regulate the voltage is a Zener diode. When a voltage is applied in the reverse direction across the diode, the diode will only permit voltages above a certain level to pass through. This is called the avalanche breakdown. It is not the most efficient if V_{in} is much greater than V_{out} . These diodes can be purchased at different reverse voltage levels.

To use the zener diode as a voltage regulator, the diode must be placed in parallel with the load. A current limiting resistor must also be used in series with the diode as seen in figure 45 below. For the most efficient design, the resistor values are carefully chosen to minimize the current through the zener diode. A zener diode value will be chosen on the upper voltage limit of the microcontroller. If the microcontroller has a voltage range of 3-5V then an ideal zener diode value would be 4.5V. This design is very cheap with no active components. It is not the most efficient way to regulate the voltage, and it can only reduce the voltage.

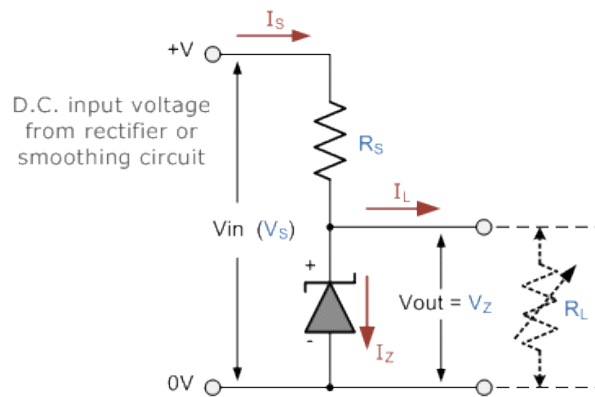


Figure 45: This figure shows a typical schematic for a zener diode voltage regulator. This design only requires a single zener diode and current limiting resistor (6).

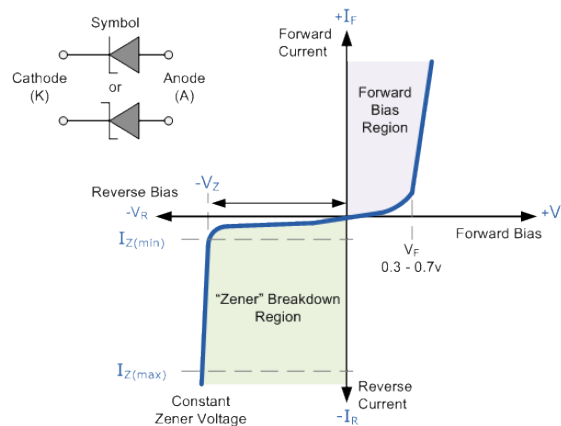


Figure 46: This figure shows a the I V diagram for a zener diode. When used in the reverse orientation, there is a voltage where a large amount of current is allowed to flow called the breakdown voltage (6).

The zener diode might work if the output voltage it high enough. But how could the voltage of the pedometer be boosted if need be.

Cockcroft-Walton

The most basic form of the Cockcroft-Walton voltage multiplier is the single-stage voltage doubler. This voltage multiplier can be used to increase the voltage in an AC circuit. It uses a series of diodes and capacitors to add and subtract charge from the negative and positive peaks of the AC wave. The result is higher differences between capacitors.

The shortcomings of the Cockcroft-Walton multiplier are that the capacitors and diodes aren't ideal. From a noncharged state, it can take many cycles of the AC waveform to charge the capacitors of the system especially in large multipliers. The voltage multiplier is also hindered by the "unideal diodes" that have voltage drops. These voltage drops increase the charge time of the capacitors and set a theoretical maximum multiplied voltage. At some number of voltage multiplier stages, the voltage will stop increasing.

In order to reduce charge time and output voltage ripple, specific capacitor values must be determined. While most Cockcroft-Walton voltage multipliers can use the same capacitors for each stage, it is more efficient to arrange the capacitors in an arithmetic progression[8, Case 3] (50). This means that the smallest capacitor will be the last stage and the preceding stage will have a doubled capacitance value. The size of the capacitors is also inversely proportion to the frequency of the input signal [9][10].

Lastly, the stages can also be connected in parallel or series, if the stages are connected in series, then the impedance and equivalent resistance of the circuit is higher. This means that the multiplier will consume more power. The advantage to the series connection is that the components only need to be rated to double the amplitude of the input voltage. In a parallel stage arrangement, the impedance is much lower, and the circuit is more efficient. The disadvantage of parallel stages is that for high voltage, multi-stage multipliers, the capacitors and diodes will have to be rated to higher values. However, because the Running Shoe Pedometer is in the tens of volts range, the parallel arrangement is more beneficial. The capacitor values and diodes will have to be carefully selected to optimize for efficiency if the voltage needs to be multiplied.

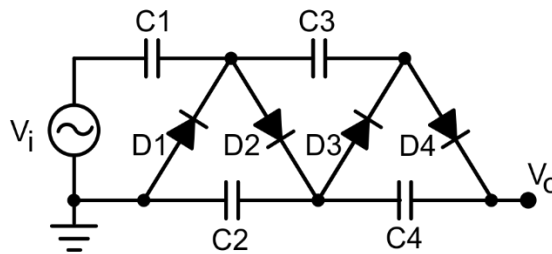


Figure 47: This figure shows a series style voltage multiplier (50).

2.3.4 Latching Circuits

If the best course of action appears to be to keep the microcontroller off most of the time, and then wake it up when needed, a latching circuit will be required.

No matter if the power source is a battery or energy harvesting, a latching circuit (Auto Power Off Circuit) (11) may need to be used to dose the power to the microcontroller. If the microcontroller

was always on, it would drain the capacitor/ battery all the way down when the shoes weren't being used. For this reason, a latching circuit will be used to completely disconnect the power storage from the microcontroller when the shoes are not in use. This means that the initial steps and energy generation from the piezoelectric will turn on the microcontroller, the microcontroller will keep itself on until the step has been saved into the microcontroller memory and then turn itself off. This will prevent a power loss from interrupting the microcontroller and losing the count altogether. Though there are several types of latching circuits, a transistor style latching circuit will be used for the running shoe pedometer because of the small size, low cost, and low power draw.

In figure 48 below, the battery and the switch will be replaced by the pulsing piezoelectric. Then once a pulse of energy wakes up the microcontroller via Vin and a GPIO interrupt, the microcontroller will set pin 2 to high in order to keep itself powered on. Then once this step has been counted, the microcontroller will set pin 2 to low and turn itself off.

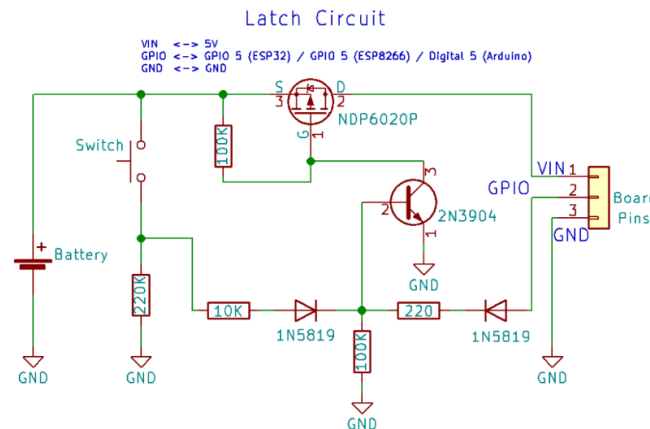


Figure 48: This figure shows a transistor base power latching circuit. This circuit requires a P channel mosfet as well as a BJT NPN transistor as well as a few diodes and resistors. This is the exact latching circuit that was used on the Pedometer (11).

2.3.5 Prototype Circuit Decisions

Creating a prototype will involve careful decision making and calculation. As can be seen above, there are many options for circuit, and it will be hard to tell what is necessary without many iterations and prototypes. Now that some of the major options have been discussed, some decisions about the design will be made.

The first thing is that the prototype circuit board must have the ability to connect multiple piezoelectrics in series or parallel depending on the need that is decided. This means that a series of pads must be available that can be jumpered together in certain ways. The next thing that the circuit will need is several rectification circuits. This will allow for the testing of multiple types of diodes and capacitors without desoldering. These should be switched with toggle switches. It should also be set up in a way that allows for the testing of parallel vs series rectification and rectification on each piezo. Next, a latch circuit should be integrated into the circuit, there should be jumpers to bypass the latch circuit if it is deemed unnecessary. This will allow for testing of a low power mode vs a power off mode. Then, it would be wise to include the possibility of a zener diode to reduce the voltage as well as prevent

overcharging of the capacitor. The prototype circuit should be designed to allow for voltage multiplication as well. Next, the microcontroller options. This too should be able to accommodate multiple types of microcontrollers so that a few can be tested. Next, a few types of oscillators should be available to connect to each microcontroller including internal and external oscillators. Lastly, there should be a spot to connect an output device such as an electrochromic or electrochemical solution or display. This prototype PCB should also be designed to accept oscilloscope clips to make testing convenient. This means that the prototype will not resemble the final product at all. It will be designed for versatility and experimentation.

2.3.6 Diode Selection

Multiple types of diodes must be compared to find the type of diode that yields the highest efficiency. Diodes prices shouldn't vary significantly between types, so price won't be included in the analysis. The forwards voltage drop, and the reverse leakage current will be the main values analyzed. The switching times of the diodes also don't play a large role because of the low 1-1.5Hz demands of the pedometer. Below are excerpts from papers that outline their decision-making process for diode selection for a similar low power rectification circuit.

"In particular, the models listed in Table 1 are identified as having the lowest values of both ON voltage and reverse leakage current; and for a given current the PMEG1020 has the lowest ON voltage. However, it has a much higher reverse leakage current than the PMEG2010 and this causes significant power loss during the diode OFF times, which Chapter 5: AC/DC Circuit Modelling 133 for these wearable generator voltages typically constitutes more than 50% of the voltage waveform period. The PMEG1020 conducts a slight negative current during the negative pulse of the source voltage, and the relative magnitude of this negative current is increased as the load is increased. Therefore, the rate of discharge of the output rectified voltage is larger (when compared to the PMEG2010) during periods in between the source voltage pulses. The PMEG2010 diode model was assumed in all remaining circuit models and simulations described in this chapter." (16)

Table 5.1: Parameters of the Various Diode Models Investigated

Diode Type	Reverse Current (mA) Max:	Reverse Voltage (V)	Forward Current (mA)	Forward Voltage mV ($I_F = 0.1\text{mA} - 1000\text{mA}$)	Power Dissipation mW
PMEG2010EH [209]	0.04 – 0.2	20	0.1- 1000 0.1 -1000	Typ: 90 – 420 Max: 130 – 500	375 - 830
PMEG1020EH [210]	2 - 3	10	2000	Typ: 100 – 350 Max: 130 – 460	375 - 830

Figure 49: This figure from Carrol Phd shows the diode values he was concerned with when designing a low power rectification circuit for energy scavenging (16).

"A typical silicon diode will have a forward voltage drop of about 700 mV while forward biased. This is an unavoidable result of silicon pn-junctions. Germanium diodes fare somewhat better with an approximate 300 mV forward voltage drop [4, pp. 187][5, pp. 204]. The forward bias voltage drops of these types of diodes are too high to support extremely low voltage applications. Schottky Diodes promise a much better alternative. Due to their metal-semiconductor contacts, as opposed to

semiconductor contacts, Schottky diodes can have a forward voltage drop as low as 120 mV. In addition, Schottky diodes typically have much faster reverse-recovery times [6, pp. 70]. This allows Schottky diodes to work at very high frequencies, which is expected for the RF energy harvester. A Schottky diode was found with a forward voltage drop of 120 mV at 10 mA [7]. If the current through the diodes is kept under 10 mA, the forward bias voltage drop can potentially be kept under 100 mV.” (50)

Another paper on energy scavenging rectification mentioned that the diode that best suited their application was “a commercially available off-the-shelf low-leakage diode the BAS116 from Nexperia”. (17)

It might be surprising that all of these papers came to a different conclusion about the diode that best suited them. This is most likely due to the astronomical number of options on the market and the slight differences between the applications. Because the running shoe pedometer’s primary purpose is not to write a book on diode selection, we will test each of the diodes that these more knowledgeable researchers have determined to be optimal. It might be worthwhile to simulate these diodes before testing all of them as well. The options are:

Option 1: Germanium diodes.

Option 2: PMEG2010 diode a Schottky diode.

Option 3: BAS116 a small signal low leakage switching diode.

Option 4: 1N4004 a typical silicon rectifier diode.



Figure 50: This figure shows a 1N4004 generic use diode (4).

2.3.7 Power Capacitor Selection

The correct capacitor selection will be the most important decision of the whole pedometer. For that reason, data gathered by PhD level electrical engineers for their own energy harvesting systems was used heavily for the Running Shoe Pedometer analysis. Combined, the primary papers that are referenced use the word capacitor nearly 700 times.

Capacitance Value

Too large of a capacitor value will take too long to charge resulting in too many steps to be missed at the start of each run. Too large of a capacitor value will also increase the size and cost of the pedometer. A value based on how much power it takes to write to EEPROM with a factor of safety should be picked. It is difficult to know just how much power the microcontroller will draw from theory alone. For that reason, an oversized capacitor will be used during testing which can be reduced before

mass production. There is also the possibility of under sizing the capacitor. A capacitor that is too small will not hold enough charge for a single write too EEPROM and will not count any steps. Additionally, it is hard to determine how much current the visual output will require. This will be sized based roughly on formula below.

Capacitor Physical Size

“Conventional capacitors cannot achieve such a large capacitance in an area suitable for integration into a shoe sole. To achieve such large capacitance in a small-scale package supercapacitor technology was investigated.”(carrol phd)(16)

A supercapacitor might be the only option for the power to weight to size required for the pedometer. This can be further determined after testing to make sure that a much cheaper capacitor is not a viable option.

5.3.3 Constant Power Capacitor Choice

In order to produce a DC voltage with a voltage ripple level (ΔV) of approximately 10% for example (which is at least required since the output voltage level is low), a very large capacitor is required due to the very low frequency of the input voltage, at 1 Hz. This can be estimated by:

$$C = \frac{V_{O_Max}}{R_{Load} \times f \times \Delta V} \quad (5.39)$$

Figure 51: This figure from Carrol PhD (16) shows how to size a capacitor based on the frequency and power draw of our system as well as the input voltage and the required low voltage (16).

Equivalent Series Resistance (ESR)

“However, one of the main criteria on the output supercapacitor is that the large capacitance is available with a small ESR (equivalent series resistance). A large ESR in the output capacitor of the AC/DC conversion circuits will increase output voltage ripple and reduce generator DC performance.” (16)

This is another way of saying that if the impedance is too high the capacitor won't function as desired.

Impedance Matching

To determine the impedance of the capacitors, the frequency of the average runner must be decided. For a 1-mile run, a tall fit runner takes around 900 steps in 6 minutes whereas a shorter less fit runner takes around 2000 steps and runs a mile in 12 minutes. It is important to keep in mind that these numbers are for steps taken by both feet. Therefore, the number of steps for one foot must be divided by two for the calculations below.

$$\begin{aligned} f &= \frac{\text{steps}}{2 * \text{min}} * \left[\frac{1 \text{ min}}{60 \text{ sec}} \right] \\ f_{Fit} &= \frac{900}{(2 * 6 \text{ min})} * \left[\frac{1 \text{ min}}{60 \text{ sec}} \right] = 1.25 \text{ Hz} \\ f_{Not Fit} &= \frac{2000}{(2 * 6 \text{ min})} * \left[\frac{1 \text{ min}}{60 \text{ sec}} \right] = 1.38 \text{ Hz} \end{aligned} \quad (11)$$

It is intuitive that these frequencies are similar based on the human gait. For safety, the impedance calculations will be done with a frequency of 1-1.5 Hz. In order to continue the impedance calculations, the desired capacitance C must be determined. This will be based on the energy requirements of the system. The system will be designed with a 1mA current draw at 3.3 volts. This equates to 0.0033 watts. Then the capacitance can be calculated.

$$V = I * R \rightarrow R = V/I = (3.3 \text{ V})/(1 * 10^{-3} \text{ A}) = 3300 \Omega \quad (12)$$

$$C = \frac{V_{0Max}}{R_{Load} * f * \Delta V^2}$$

$$C = \frac{5.0 \text{ V}}{3300 \Omega * 1 \text{ Hz} * 1^2} = 0.001515 \text{ F} \quad (13)$$

“Thus, the output capacitor required for this generator design must have a high capacitance (>0.1 F), in a small-scale package and with a low ESR. A number of commercial options are available that achieve all three requirements, including “BestCap” ultra-low ESR high power pulse supercapacitors from “AVX” which provide high power pulse characteristics due to the combination of very high capacitance and ultra-low ESR together with extremely low leakage current [216]. Capacitance values ranging from 10 mF to 560 mF are possible with ESR values in the region of 25 to 500 mΩ depending on the case size and voltage rating of the capacitor. However, it is the family of supercapacitors available from Cap-XX [214] which provide the best output capacitor solution for any of the conversion circuits considered. This is due to their very small size (thickness < 3mm), high capacitance (90 mF to 2400 mF) and very low ESR (26 mΩ to 200 mΩ). The closest value in the Cap-XX range to the required 0.1F is the GW209F which has a capacitance of 0.14 F and an ESR of only 70 mΩ. This supercapacitor was integrated into all constant power conversion circuits described throughout the remainder of this thesis unless otherwise specified.” (17)

Because the value of the resistive load cannot be determined easily because the microcontroller will bounce between high and low energy states and because the output voltage of the piezoelectrics after rectification cannot be accurately determined and the required voltage ripple level is not known, the formula in Figure 51 will only provide a rough guess for the required capacitance. This required capacitance value can be narrowed down through experimental testing, through simulation, or analytically after the other values have all been determined experimentally. The rough guess that was calculated yielded a capacitance of 0.001515 F. However, for the first prototype it should be oversized. According to Carrol PhD’s recommendations, the capacitor should be closer to 0.1 F. However, the microcontroller should have a super low power draw when it is in the sleep state. For that reason, the 1mA current should be very conservative. A 1.5mF capacitor should be able to meet the needs of the pedometer easily.

$$Z = \frac{1}{2 * \pi * f * C} \rightarrow Z_{1\text{Hertz}} = \frac{1}{(2 * \pi * 1 * 0.001515 \text{ F})} = 1.050 \Omega \quad (14)$$

2.3.8 Micro Controller Selection

Now that the rest of the circuit has been decided, the most important part, the microcontroller can be selected. First, the governing criteria will be laid out and then several microcontroller options will be investigated.

Low Power Consumption

The Running Shoe Pedometer relies on human power generation. This means that the device needs to have an extremely low power draw if it is to turn on and count after only a few steps.

Onboard Memory

To count the number of steps taken this device will need some form of onboard memory to store the count so that when power is removed it doesn't lose count. This could be avoided if a coin cell battery was used that would continuously power the device but under the current design criteria that is not an option.

Counting

If we say that the average pair of running shoes is for sure very worn out at 1000 miles, then we can determine how high the circuit must be able to count to. While walking or running slowly, the average person takes around 2000 steps per mile.

$1000 \text{ miles} * 2000 \text{ steps per mile} = 2,000,000 \text{ steps} \approx 2^{21}$

These would be steps taken on both feet. Each shoe only needs to count half of this number so around 1,000,000. That means that a counter would need to count to around 2^{20} . To allow for counting to higher numbers in the future, the circuit will be designed to count to 2^{21} . This should be easily achieved by any microcontroller on the market.

Voltage Range

Because this is a low power application, where the voltage source may not be the most stable. It will be important to have a low and wide operating voltage range. This means that a strictly 3.3 volt or 5 volt MCU won't be an option.

Number of Bits

The number of bits is the word length that the microcontroller thinks in. An 8-bit microcontroller can only easily represent values from 2^8 or 0-255. A 32-bit microcontroller can represent numbers up to 2^{32} . The running shoe pedometer must be able to count to 2^{20} . However, this doesn't mean that an 8-bit microcontroller can't count to 2^{21} . With the use of threading and registers an 8-bit MCU can count much higher. When programming a 32-bit unsigned integer must be used.

Oscillator Speed

The oscillator creates the clock that causes the microcontroller to run. This is a steady stream of 1s and 0s that allow the transistors to move and receive data in a predictable way. The faster an oscillator is the quicker the whole circuit runs. However, this typically takes more energy. For the running shoe pedometer choosing an MCU with a lower speed will be important to energy savings.

Brown Out Detection

Leakage by the MCU, capacitors, and diodes means that this circuit will not always have power. It is important to select a microcontroller that is built to lose power in a predictable way and leave the controller ready to be powered on again.

Watch Dog Timer

A watch dog timer monitors the CPU and makes sure that it is still operating correctly. If the controller is not operating correctly, it can reboot the system. This may not be necessary for my application because of the constant power losses experienced by the system. If an error were to occur the counter would be unable to count that run or walk and then reset for the next use.

Sleep Features

Different sleep features allow low power consumption for microcontrollers. These features typically involve removing certain functionalities of the system such as peripherals, ram, watch dog timers, brownout detection, or lowering clock speed. These will be extremely important to limit the power consumption of the MCU. These can also be difficult to compare as each brand calls the features different names such as sleep, halt, idle, doze, deep sleep, standby mode, low power sleep, low power run, and wait.

2.3.8.1 Sleep Modes

Turn Off

Typically, a microcontroller can't turn itself on from a complete power off state. However, because the piezo provides a burst of power, the piezo would be able to turn on the microcontroller if the rest of the circuit was designed accordingly. One possibility for the pedometer is that it would power cycle itself each time a step is taken. This could be done by the previously mentioned latching circuit. The piezo burst would turn on the microcontroller, then the microcontroller could keep itself powered on via the latching circuit while it reads the count and adds 1 to it. Then, the microcontroller would turn itself off via the latching circuit until the next step is taken and it is woken up again.

Sleep

The sleep scenario for the microcontroller would be to have it wake up when the capacitor is charged for a certain value, read the EEPROM write to the EEPROM, and then go into a super low power consumption state. Then when the next step is taken the microcontroller could wake back up and add 1 to the count in the volatile SRAM and then go back to sleep. The difference being that the EEPROM wouldn't need to be read and written nearly as often. The EEPROM only needs to be bothered once every 10 steps or when the running stops.

Conclusion

In order to use this "turn off strategy", a latching circuit must be used which will add components and therefore cost and complexity. This strategy would also require wear leveling the

EEPROM which can only withstand 100,000 or so cycles before degrading. This too would add complexity. Lastly, writing to EEPROM is energy intensive and would hurt the efficiency of the device. Some of these concerns could be mitigated with the much less energy intensive, stable, and durable Ferroelectric Random Access Memory (FRAM). For that reason, FRAM integrated microcontrollers will be investigated.

However, it appears that the “sleep strategy” will be the most traditional and cost effective and reliable counting method. This may appear to be more coding related topic, however, just like everything else on the pedometer, decisions like this have cascading consequences on other areas such as the hardware. No decisions can be made in a vacuum without consideration for the whole device.

2.3.8.2 FRAM vs EEPROM

At this time, it appears that only Texas Instruments has managed to incorporate FRAM into a microcontroller. They have also wisely chosen to integrate the FRAM into their ultra-low power lineup of MSP430FRxxxx microcontrollers (53). Also surprisingly, the costs are dramatically low in large volumes and can cost as low as 35 cents depending on how much storage is needed. They have also incorporated this chip into a miniscule 24-pin VQFN(RLL) 9 mm² 3 x 3 which makes it perfectly small for the pedometer. Considering the low cost, small size, incredible efficiency, and durability of this microcontroller, the previously discussed “turn off strategy” might actually be remarkably viable. This microcontroller could be used for both the “sleep” and “turn off” strategies which makes it a great contender for the pedometer prototype.

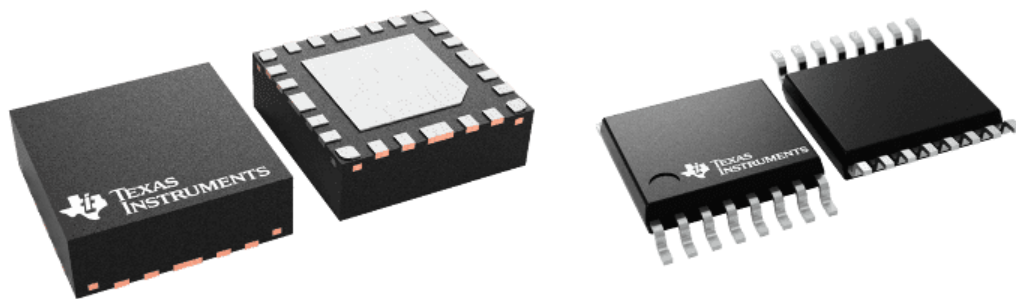


Figure 52: The figure on the left shows the MSP430 MCU in the 24 pin VQFN(RLL) 9 mm² 3 x 3 package. The figure on the right shows the MSP430 MCU in the 16 pin TSSOP(PW) 22 mm² 5 x 4.4 package (67).

2.3.8.3 GPIO vs Analog Interrupts

If the “sleep” strategy is pursued, then the way that the microcontroller wakes up from hibernation is important. The way that the MCU wakes up is known as an interrupt. There are two main types of interrupts; analogue and digital.

Analogue Interrupts

An analogue interrupt would check an analogue input such as the voltage that the capacitor is charged up to. It would measure this value and if it was too low it would keep the microcontroller asleep and if it was high enough it would wake the MCU up. Not all MCU's have analogue interrupts so if this route is taken it could limit microcontroller options.

GPIO Interrupts

A GPIO stands for General Purpose Input/Output. It essentially means that it is designed for signals at the operating voltage. Because we don't care about the particular analog value, just if it is above or below the threshold, an external voltage comparator could be used to convert the analog signal to GPIO signaling. Once again, not all MCUs have GPIO interrupts, but most should have at least a limited number of pins that can.

2.3.8.4 Internal vs External Oscillator vs Resonator

A microcontroller operates on a clock pulse that keeps the whole processor in sync. The clock pulse allows for the absence of voltage to be read as a 0 and the presence of voltage to be read as a 1. There are three options when it comes to the clock pulse of a circuit; an internal oscillator, an external oscillator, and a resonator. An internal oscillator is often located inside the MCU and uses a resistor capacitor circuit as well as a series of amplifying transistors to create a steady pulse. Typically, due to the amplification nature of these circuits, there are inherently not very frequency accurate. This isn't a concern for the Pedometer because it does not have a Real Time Clock (RTC) and doesn't need to interface with other circuitry. The downfall of the internal resonator is the relatively high power draw. The next option is the resonator. This is a 3 pin external component that uses a PZT piezoelectric and the inverse piezoelectric effect to resonate at a certain frequency. The advantage of these is their smaller package size and their cost effectiveness. They have better accuracy than an internal resonator but require extra work to implement and are not especially accurate (92). However, their power draw still cannot match the traditional quartz crystal. These quartz crystals are used in external oscillators, they are very frequency accurate and have extremely low power draw. Their main disadvantage is their relative cost (a few cents) and their size. A small external oscillator is the size of a small pill which might be size prohibitive for a small smart watch but not for the running shoe pedometer. Because the main target is to reduce power draw, the external crystal oscillator is the best option for the Running Shoe Pedometer.

2.3.8.5 Texas Instruments: MSP430

The MSP430 family of microcontrollers is one of the front runners in the microcontroller comparison. This is due to the incorporation of F-RAM or Ferromagnetic Random Access Memory directly into the MCU (66)(67). This means that instead of writing to the power intensive and short lived EEPROM or Electronical Erasable Programmable Read Only Memory. Though the MSP430 might not have the lowest possible listed power draw Microcontroller, the power draw of writing to EEPROM can be substantial.

Model Number: MSP430F2001

Operating Voltage: 1.8 V to 3.6 V

Power Consumption in Active Mode: 220 μ A

Power Consumption in Sleep Mode in Standby Mode: 0.5 μ A

Power Consumption in Sleep Mode with Memory Retention: 0.1 μ A

Operating Frequency: 32 kHz

Flash Memory: 1 Kbytes

SRAM Memory: 128 B

EEPROM: 256B

Bits: 16

Pins: 14

MSP430: World's Lowest-Power MCU

- **Ultra-low power by design**
 - 100nA storage mode, <500nA standby, <1µA RTC mode
 - 0–16MIPS <1µs, agile instant-on clock system
 - Intelligent peripherals reduce CPU load, improve performance
- **A modern transparent family architecture**
 - Compatibility top-to-bottom
 - Consistent performance throughout
 - True embedded emulation
- **Mixed signal processor**
 - 10-, 12-, 16-bit ADC
 - 12-bit DAC, op-amps, comparator
 - Enabling higher performance, low total cost systems

Figure 53: this figure shows the low power draw characteristics of the MSP430 MCU (66).

2.3.8.6 ST Micro Electronics: STM8

The STM8 series from ST Micro Electronics is the best offering that that this brand has in the low power draw MCU market. It has more power draw and more power intensive EEPROM (100). These microcontrollers are an industry staple but are less advanced than some of the other options.

Model Number: STM8L101F2

Operating Voltage: 1.65 V to 3.6 V

Power Consumption in Active Mode: 150 µA/MHz

Power Consumption in HALT Mode: 0.3 µA

Power Consumption in Active Halt: 0.8 µA

Operating Frequency: 16 MHz

Flash Memory: 8 KBytes

SRAM Memory: 1.5 KBytes

EEPROM: 2 KBytes

Bits: 16

Pins: 20

Low power modes

To minimize power consumption, the product features three low power modes:

- Wait mode: CPU clock stopped, selected peripherals at full clock speed.
- Active-halt mode: CPU and peripheral clocks are stopped. The programmable wakeup time is controlled by the AWU unit.
- Halt mode: CPU and peripheral clocks are stopped, the device remains powered on. The RAM content is preserved. Wakeup is triggered by an external interrupt.

Figure 54: this figure shows the low power draw characteristics of the STM8 MCU.

2.3.8.7 Silicon Labs: C8051F99

The C8051F99 from Silicon Labs is the lowest power MCU offered by Silicon Labs. This MCU has an industry leading low power draw (92). It still uses the undesirable EEPROM memory, but it is offset by the low power drawn from the MCU during idle. It may be an even better option than the MSP430.

Operating Voltage: 1.8 V to 3.6 V

Power Consumption in Active Mode: 150 μ A/MHz

Power Consumption in Sleep Mode With Mem Retention: 10 nA

Power Consumption in Sleep Mode With Brownout: 50 nA

Power Consumption in Sleep Mode With LFO: 300 nA

Operating Frequency: 32 kHz to 24.5 MHz

Flash Memory: 16 Kbytes

SRAM Memory: 2 KB

EEPROM: 128 B

Bits: 32

Pins: 20

2.3.8.7 Conclusion

All of these processors are the lowest power options by the major players in the low power MCU space. While all of these microcontrollers seem like good options, and all are far below the maximum power draw needed for the pedometer, further research from a qualified computer engineer should be done to further decide between these options. Because these MCU's are professional grade, programming and incorporating them is far beyond my capabilities. To program these MCUs, special software, special hardware, and a large knowledge base would be required. These microcontrollers would need to be programmed using Spy by Wire and knowledge of computers that goes beyond the hobbyist level. If this product were to be made commercially, a computer engineer would have to be recruited to program the microcontroller. For that reason, the prototypes were made with a high power draw, and easy to program ATMEGA 328U which is the quintessential hobbyist MCU. This MCU can be programmed by most anyone but draws nearly 1000 times more power than the MSP430. That means that this CPU will allow for easy programming and testing but won't be able to be fully powered by the scavenged energy when tested on full runs. If the product were to go into production, a real electrical engineer and computer engineer would have to review the design of the pedometer.

2.4 Visual Indicators

In order for the pedometer to serve its function, it must output a display to the user somehow. It is all well and good to count steps, but the point is to let the user know when their shoes are worn out. There are many different ways to make an "indicator" or "alarm". It can be a visual indicator that changes color, an auditory indicator such as a "beep", a tactile indicator such as a vibration, or a electronic indicator such an RFID or Bluetooth indicator. The most ideal of these would be a visual indicator where the color of the shoe, or part of the shoe, would change color irreversibly so that once the shoe hit the milestone, the state would be forever changed and require no additional power to see.

These visual indicators will be constrained by various criteria that will determine if they are a suitable solution for the pedometer. One of these is temperature. The pedometer might reach well below freezing if the shoes are left outside in the winter. The indicator also needs to be able to withstand the high heat of the desert. The indicator that is chosen needs to be able to withstand both of these extremes. Another constraint is durability. Running shoes are often used hard and the indicator that is selected needs to be able to withstand scrapes and light impacts as well as be abrasion resistant if the user is running through sand or snow. It is difficult to know how the shoes will be used and the indicator might easily be the most vulnerable part of the shoe. Lastly, the solution needs to be chemically safe. Strong acids or dangerous chemicals should be avoided at all costs. It would be advantageous if the indicator were skin safe.

2.4.1 E - Ink

The first candidate for the output of the Running Shoe Pedometer is E-Ink or Electronic Ink. This ink is typically used in E readers such as the Kindle. This ink uses microcapsules which are suspended in liquid (38). These capsules are polarized so that one side is negatively charged and the other is positively charged. Then these capsules are colored so that the negative side is colored black and the positively charged side is colored white(38). Then when an electric field is applied, all of the microcapsules align to produce one color. This way, certain pixels can be turned black or white which creates a monochromatic display. These displays are passively powered and reflect light. This is unconventional when compared with other display technologies such as LCD's which use a backlight to show text. These E-Ink displays, if left undisturbed, would theoretically continually display their last image forever. This would be an appealing option for the running shoe pedometer because once the shoe reached a milestone, say 100 miles, a little dot on the shoe could permanently change from black to white. However, this display technology won't work for the pedometer because of the constant shaking and pounding produced by running. The display would quickly randomize and while running. The display is also not particularly durable and wouldn't hold up to the abuse of running very well.

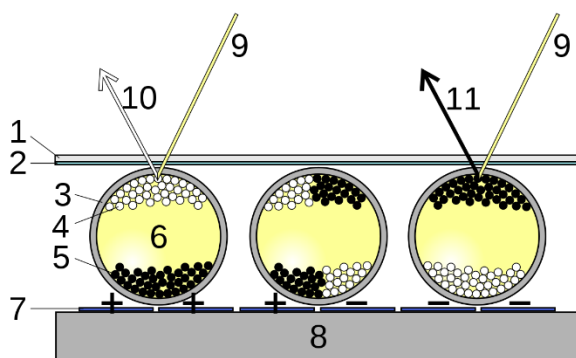


Figure 55: This image shows the inner workings of an E-Ink display.

2.4.2 Electrochromism

Electrochromic materials are those which change color when voltages are applied. These color changes are the result of an oxidation reduction reaction and typically result in a “bleached” or clear state as well as a colored state (113). These displays have found commercial use in automatically tinted

or frosted windows. When a voltage is applied, the windows will change color or opacity. They can be found in airplane windows, fancy conference rooms, and rearview mirrors (29). These displays have extremely low power draws and have remarkable image retention (bistability) after power is removed (45). They involve very specialized polymers such as polyanilines, Viologens, transition metals, or Prussian Blue compounds. Because these displays rely on clear conductive materials, they are paired with conductive polymer laminates or indium tin oxide coated plastics (113). A great deal of research has gone into improving the switching times of these polymers so that they can be incorporated into more applications. However, for the Running Shoe Pedometer, it would be more beneficial to have an electrochromic that only switches one way, from bleached to color, and cannot switch back, even when the charge is removed. In this way, the pedometer would need a “failed electrochromic” material with an irreversible reaction. Because of the large varieties of chemicals and properties of these materials, I am confident that there exists a chemical that is robust enough for use in a running shoe. However, it is extremely hard to research such a vast field and harder still to find an example of a failed material without expert help. Before the Pedometer goes to market, a Chemist or Chemical Engineering should be recruited to further explore this very promising option.

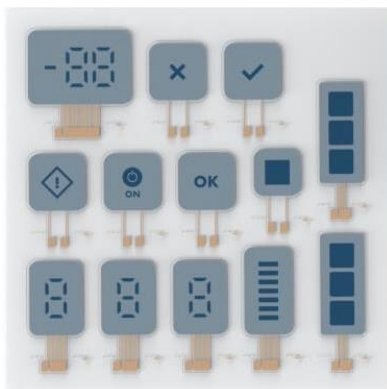


Figure 56: This figure shows an example of a commercially available Electrochromic display (113).

2.4.4 Electrochemistry

Even though electrochromism is a type of electrochemistry, they have been divided into separate categories because of the ways in which they would be used. While an electrochromic material would have an electrode on either side of the liquid/gel reactant that the reaction is observed through, and electrochemical reaction could just have two electrodes on opposite ends. A typical electrochemical reaction would change color due to a Ph indicator that is in solution with an oxidizing/reducing agent. This means that when a voltage is applied, the reactant would oxidize, changing the Ph of the solution, and in the indicator, such as phenolphthalein would change from clear to pink. In this way, a voltage could cause an irreversible color change. The difficulty with an electrochemical reaction is housing the liquid, in order to have 5 separate indicators, for 100, 200, 300, 400, and 500 miles, there must be 5 small pools of liquid attached to the PCB. Unsurprisingly, there is no industry standard for attaching small pouches of miscellaneous liquid to a circuit board. This means that a unique solution would have to be found. The current idea is to take a clear piece of domed plastic, about the size of a pill or contact lens, fill it with the liquid, and then glue it to the circuit board. If the proper plastics and glues are used,

it could be durable enough to be used on the pedometer. Another challenge with the electrochemistry approach is the vast number of options across various fields of chemistry. Solutions to this problem could be found via an acid base reaction, oxidation reduction reaction, or a polymer. It is hard to say which of these fields offers the most promise.

One of the main challenges facing an acid base reaction is their reliance on water as the oxidizing agent. This means that when an acid is in water, and an electric current is applied, the solution will become basic as hydrogen gas and OH^- are produced (28)(76). This will change the pH of the solution and yield a color change but will also produce an undesirable gaseous byproduct. Using water as a base also proves problematic because it will freeze at low temperatures and evaporate at high temperatures. This means that a non-water based electrolyte would need to be used and both the oxidizing and reducing agents would need

One of the upsides of electrochemistry is their low voltage requirements. It is very easy to calculate the required voltages and amperages in electrochemistry. Typically, the voltages are within those used by CMOS logic levels. One of the drawbacks, however, is the high currents that could be required to induce the reaction. Once again, a trained chemist should be able to find a very clever, cheap, safe, and low power chemical reaction that would perfectly suit the pedometer. However, such a broad question is very difficult to answer without years of experience in the field of chemistry.

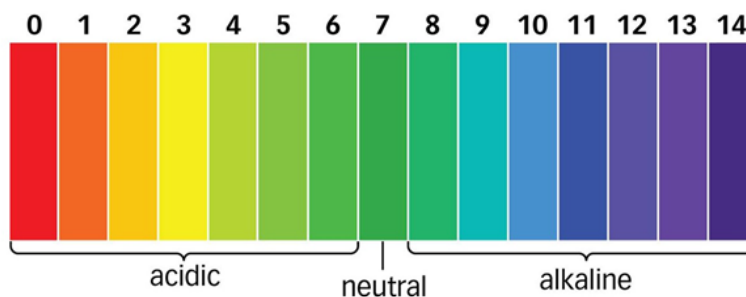


Figure 57: This figure shows the different colors that universal indicator turns based on the pH of the solution (55).

2.4.5 Liquid Crystal Displays

Another chemically based visual indicator option that could be used for the pedometer is a Liquid Crystal Display (LCD). These displays are used in a large variety of displays including computer monitors, calculators, and digital watches (25). These displays operate using long polymer chains that float randomly in a liquid. Then, once a voltage is applied, these polymer chains twist into shape and align so they are oriented in the same direction (115). In conjunction with two polarized layers, the liquid crystal can reflect most of the light that hits it when unenergized and absorb most of the light that hits it when energized (23). These displays can also be combined with backlights so they can be read in the dark. However, the most energy efficient LCD's, such as those used in watches, are reflective and use passive light to convey information.

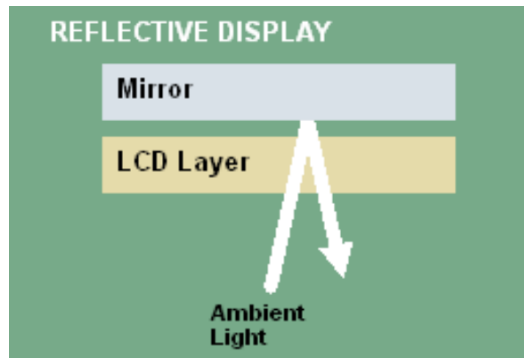


Figure 58: This figure shows the basic operating principle of a Reflective Liquid Crystal Display (23).

The main drawback of this display technology is that they are driven using an AC waveform. Driving the device with a DC voltage could ruin the display and cause “burn in”. This means that extra circuitry may be needed to drive the display from the charge capacitor. However, if the display were to be purposefully used incorrectly, and driven with a DC voltage, then the LCD could be “burned in” intentionally and change state permanently even when power is removed. LCD’s widespread incorporation into low power devices like watches make this a promising option for the indicator of the running shoe pedometer. Research should also be done to see if an LCD could be designed for “burn in” so that even when power was removed, the LCD could still convey information.

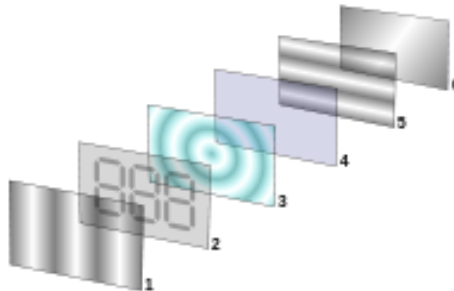


Figure 59: This figure shows all of the layers of an LCD screen. The 1st layer is a vertically polarized film. The 2nd layer is conductive glass coated with Indium Tin Oxide in the desired shape. The 3rd layer is the nematic liquid crystal. The 4th layer is another conductive substrate such as glass covered with ITO. The 5th layer is a horizontally polarized film. The last layer can either be a reflective surface such as a mirror or a backlight (115).



Figure 60: This figure shows a burned in LCD which can be the result of improper use or displaying a static image for too long (27).

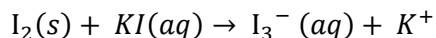
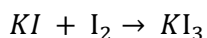
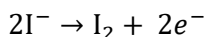
2.4.6 RFID and Bluetooth

Another option as an indicator to the wearer is to use some type of electronics such as an RFID tag or Bluetooth. These options would both require some external way to read the signal. If Bluetooth were used to signal the user about the state of their shoes then the user would need to use a smartphone and an app to track their shoes. This might be fine or even preferable for some users but is prohibitive for others. These apps and devices would need to be continually updated and supported in order to interact with the Pedometer. These devices could also cause trouble in areas where wireless communication is strictly monitored such as in airplanes, hospitals, or testing centers. The power draw of RFID and Bluetooth are relatively low and would suit the Pedometer well but would also require costly and complicated external devices/apps. If external devices are an option, then it would be very easy to make a small handheld reader that could be plugged into the Running Shoe Pedometer and be externally powered. However, all of these devices would require the wearer to periodically check their shoe. The user would have to connect their phone or RFID or external device periodically to make sure the shoes were still okay. The Pedometer is being designed for a running purist, who would prefer to set and forget the Pedometer rather than checking it after every run. For that reason, all of these options are eliminated. The only thing that the user should need to determine that their shoes are worn out is their shoes.

2.4.7 Conclusion

There are a lot of viable options for the running shoe pedometer indicator methods. An electrochromic indicator would be low power, with great retention and easy to integrate into a running shoe but they are difficult to research and prototype on a small scale. An LCD would also be promising low power option, but they haven't been designed for single use yet and would require the user to power on the display intermittently to review the status of the shoes. This isn't the truly passive option that the running shoe pedometer needs. These displays are also difficult to prototype on a small scale with limited funds. The last viable option is to use electrochemistry as the visual indicator. This method will be cheap, easy, and safe but will be challenging to implement. After researching electrochemistry, I

stumbled upon the starch-iodine reaction. This reaction leverages the fact that iodine and starch react to form a blue-black color. A salt of iodine like potassium iodine (KI) or sodium iodine (NaI) is dissolved in a solution of water and starch. This yields no color change because the salts are neutral and dissociate into neutral Potassium and Iodide. Then when an electric current is applied, the iodide is changed into iodine which reacts with the starch (39).



This is an oversimplification of the complexities of the starch iodine reaction. This reaction has been the subject of several papers which document the mechanism (28). It is also an oversimplification to say that the iodide becomes iodine. In reality the reaction involves Hypoiodite (OI-) and potassium triiodide (KI₃) but the net result is the same. When electricity is applied, the solution will irreversibly go from clear to black. The downsides to this reaction are the production of hydrogen at the anode and the possibility that the water would freeze at low temperatures or evaporate at high temperatures. Perhaps this could be solved through the use of additives in the water or perhaps another conductive liquid besides water should be considered. However, for prototyping, the starch-iodine reaction will be good enough for concept validation.



Figure 61: This figure shows the reaction of starch and iodine (137).

3. Design Verification

Before the design goes into mass production a prototype should be made. For the development of the running shoe pedometer, the testing was done on a breadboard using an oscilloscope. This way, the various pieces of the pedometer could be tested and combined incrementally to debug the system.

3.1 Breadboard Testing

A breadboard is a small panel with hundreds of holes in it that allows for reliable and convenient electrical connections. It is the de facto standard for prototyping electronics because it allows the easy connection of microcontrollers, sensors, displays, integrated circuits, and individual components such as resistors and capacitors. The breadboard was used to test all the different parts of the circuit.

3.1.1 Rectification Circuit

The first part of the circuit that needed to be prototyped was the rectification circuit. As discussed in section 2.3.3, this part of the circuit will be the full bridge rectifier that turns the AC generated from the piezoelectric into DC that can be stored and used. The two wires that extend off screen are connected to the piezoelectric mounted in the running shoe.



Figure 62: This figure shows the rectification portion of the breadboard circuit.



Figure 63: This figure shows a piezoelectric pad mounted under the heel of the running shoe that was used for testing.

3.1.2 Latching Circuit

The next part of the circuit that needed to be prototyped was the latching circuit. As discussed in section 2.3.4, this part of the circuit allows a microcontroller to turn itself off when it is done. This saves power because a typical microcontroller can't usually turn itself off.

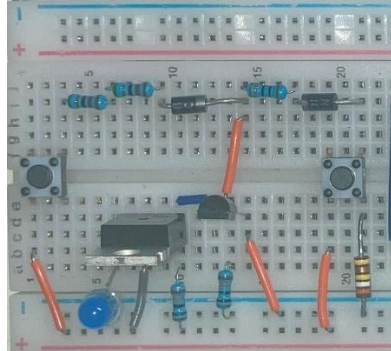


Figure 64: This figure shows the latching circuit that was used for prototyping. This circuit was made to the schematic in figure 48.

3.1.2 Arduino ATMEGA328

The next part of the prototyping was testing and programming the microcontroller. The microcontroller I had on hand was the Arduino Pro Micro which utilizes the ATMEGA 32U4. The focus of the microcontroller testing wasn't the power consumption but rather the code to monitor the voltage of the piezoelectric and try to count the steps that the user was taking. The microcontroller was connected to a computer and the number of steps recorded by the microcontroller was monitored using the serial monitor.

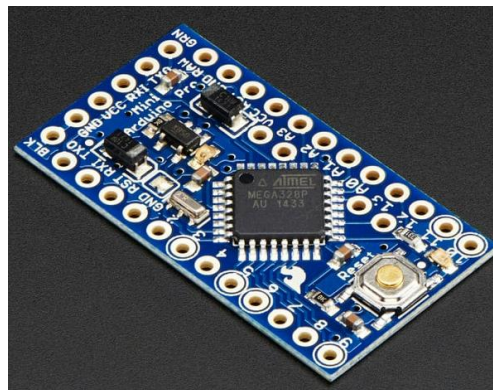
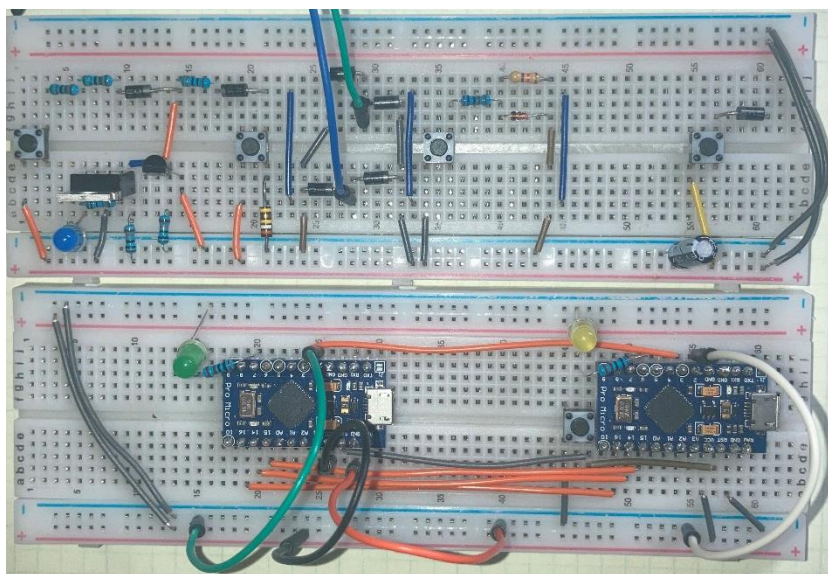


Figure 65: This figure shows the Arduino Pro Micro Microcontroller that was used as a proof of concept.

3.1.3 Conclusion

The result of all the prototyping was a breadboard that looked like this. The circuit in the top right is the charge capacitor and the button near it is to drain the capacitor conveniently so the charging characteristics could be observed. To test the power draw of the rest of the circuit, the capacitor could be charged and discharged using a small 5v power supply. Interestingly, the RC circuit in the 5v power supply would continually drain the charge capacitor. For that reason, the charge capacitor was charged

across a diode so that power couldn't be leeched by the powered off power supply. Also, the additional Arduino microcontroller in the bottom left was not used.



3.2 Chemical Indicator Testing

The next part to be prototyped was the starch iodine reaction. To prototype the reaction a 50ml of 0.5M Potassium Iodide solution was mixed with 5 grams of starch. Then two graphite leads were connected to a 9v battery. Within seconds of emerging the graphite electrodes into the solution, the solution turned from clear to black.

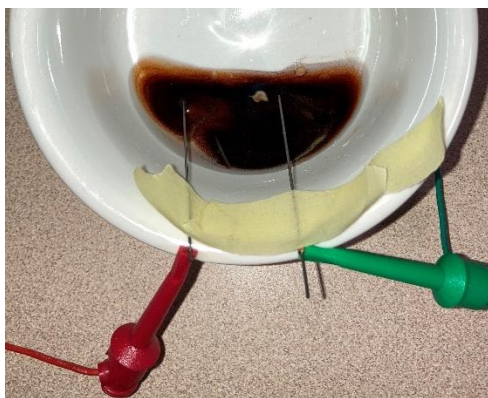


Figure 66: This figure shows the darkened Potassium Iodide solution.

3.3 PCB Design

Now that the electronics and the chemistry have been proved out. The next step is to take the circuit and miniaturize it by making a Printed Circuit Board (PCB). This was done in a free software called EasyEDA. Three different circuits were drawn up so that different prototype ideas could all be tested at once. All of these designs used the same microcontroller and rectification circuits. The first iteration used all through hole and Dual Inline Package (DIP) components. This makes the circuits easy to hand solder and modify later if needed. This version also had several buttons that could be used to reset the

DIP COMPONENTS

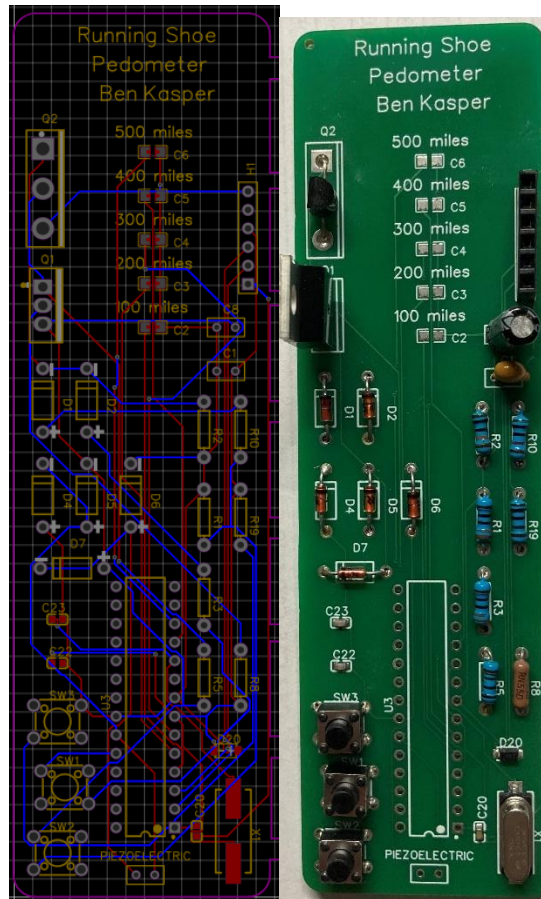


Figure 68: This figure shows the layout of the circuit board as well as the printed circuit board for the through hole component version of the pedometer. Note the microcontroller still needs to be soldered on.

The second prototype for the pedometer was electrically the same as the first but utilized Surface Mount Technology (SMT) components that are much smaller and can be soldered robotically. These prototypes utilized a solder jumper that could be used to reset the pedometer if need be. These pads can be shorted with a pair of to put the pedometer into a programmable mode.

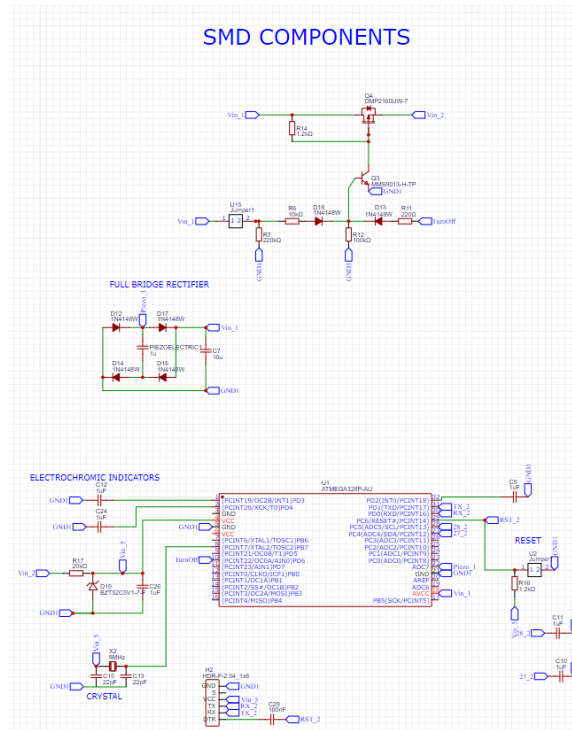


Figure 69: This figure shows the schematic for the SMT component version of the pedometer prototype.

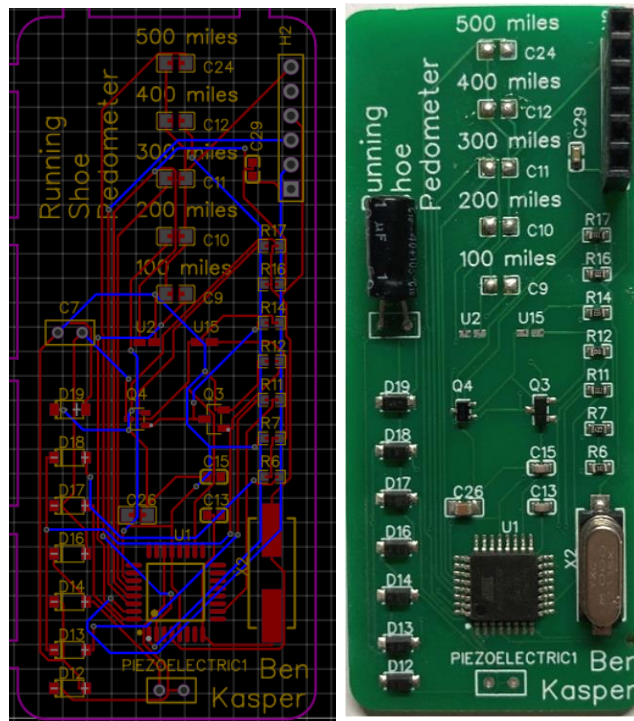


Figure 70: This figure shows the layout of the circuit board as well as the printed circuit board for the SMT component version of the pedometer.

The third and final version of the Pedometer prototype was similar to the second version but lacks the latching circuit. In that circuit, the MCU is connected directly to the power capacitor. This version will be used if the low power draw microcontroller can allow the MCU to stay on in a low voltage state the whole time between the steps.

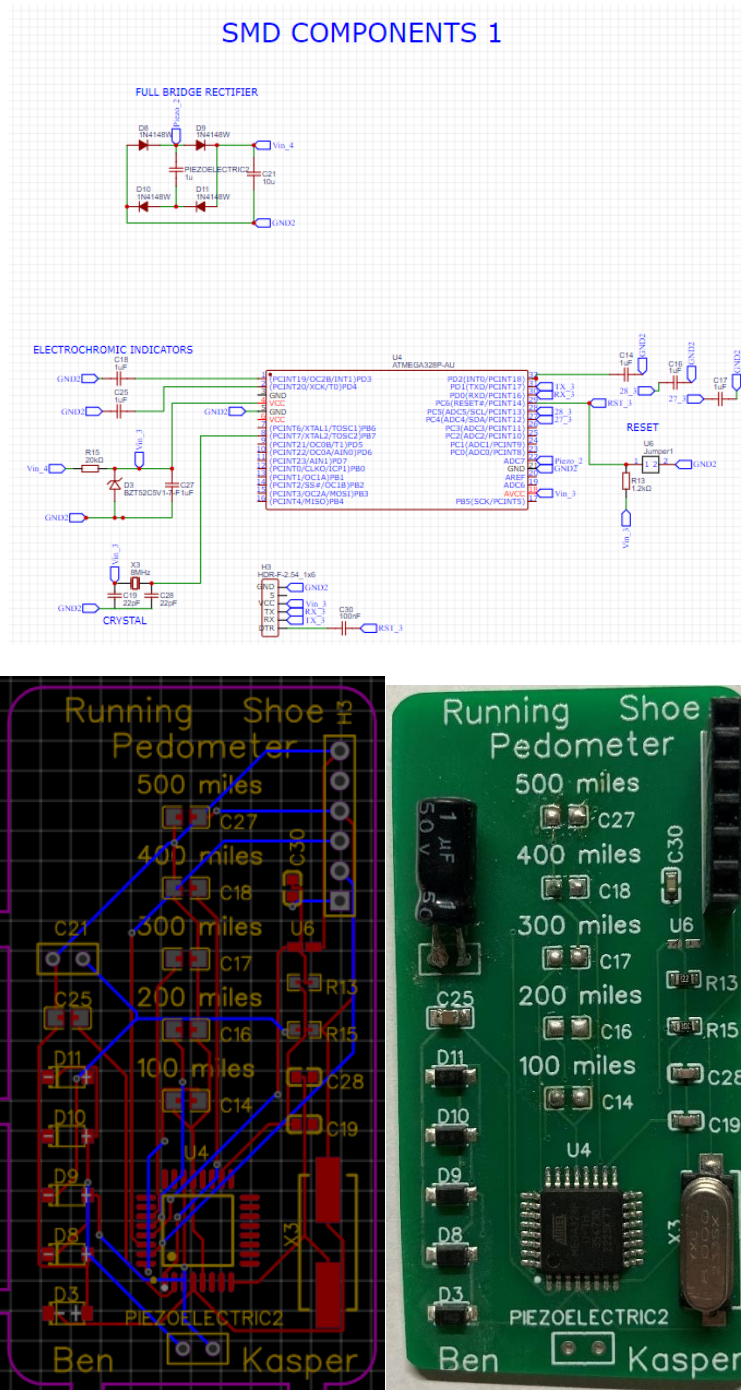


Figure 71: This figure shows the layout of the circuit board as well as the printed circuit board for the SMT component version of the pedometer without the latching circuit.

Through the design of the circuit board, one of the oversights that was almost made was the programming of the MCU. For this reason, a female header was added to each of the prototypes that could be connected to a FTDI to serial converter. In a production model each of the microcontrollers can easily be programmed before they are soldered to the PCB.

The third and most likely version of the pedometer is by far the smallest and the lightest. It only measures 51 grams which is light enough to be incorporated into a running shoe without bothering the wearer. This design is still massive compared to what it could be. The whole design could very easily fit onto the size of a quarter if smaller SMT components were used and smaller QFN packaged MCU were used. The largest part by far would be the visual output of the pedometer.

3.4 Plastic Cover

To house the starch iodine reaction, and to protect the circuitry of the breadboard from the elements, a plastic cover will be attached to the PCB. This cover will have pop outs over top of the electrodes. These can be filled with the starch iodine solution before the plastic cover is glued to the circuit board. Before the plastic selection can be narrowed down, the method from which these covers are going to be made should be determined. It appears that vacuum forming would be the easiest and most cost effective way to make prototype covers for the Pedometers. This forming method will shape to each pedometer individually, so the fit is always ideal and tolerances in the PCB manufacturing and soldering are less important. In order to create the pop out that will hold the liquid, a small bead or bean should be temporarily glued in place to leave a cavity for the liquid to occupy.

Before a plastic could be picked, the necessary characteristics of the plastics were investigated. These characteristics were the plastic's abrasion resistance, clarity, and UV resistance. Several plastics were investigated for use in the cover including Acrylic (PMMA) Acrylonitrile butadiene styrene (ABS) Polycarbonate (PC). Each of these had its merits, but the most promising was polycarbonate because of its impact resistance and UV resistance (138). Polycarbonate is not the easiest plastic to vacuum form, or the cheapest, but in high volumes the cost of the cover will be negligible.

4. Costs

This figure shows the cost breakdown for some of the prototype items used on the running shoe pedometer. This breakdown includes a lot of the breadboard components that were used to prototype. The cost breakdown doesn't include the \$105 spent making the prototype PCB's.

Running Shoe Pedometer Budget Proposal					
ITEM	COST	QUANTITY	TOTAL	VENDOR	USE/JUSTIFICATION
Potassium Iodide (100g)	\$20.00	1	\$20.00	Online Vendor	The potassium Iodide will be necessary to produce the required color changing reaction. This will react with the starch(I will provide) and go from clear to dark brown when an electric signal is applied.
Piezoelectric Buzzers BUZZER ELEMENT STD 2.8KHZ 35MM -(7BB-35-3L0)	\$1.28	5	\$6.40	Digikey / Mouser	The Piezoelectric buzzers will be used as the main source of energy for the device. They will scavenge energy off of the compressive forces on the heel of the foot during running.
Shotkey Diodes DIODE SCHOTTKY 60V 5A DO201AD-(S8560-T)	\$0.47	12	\$5.64	Digikey / Mouser	These diodes will be used for the rectification of the messy AC signal created by the piezoelectrics. They will be arranged in a full wave rectifier in order to minimize loss. They were carefully picked to reduce power draw.
Microcontroller Option 1 Arduino Pro Micro	\$20.00	1	\$20.00	Spark Fun / Ebay / Amazon	The microcontroller will be necessary to count the steps and control the visual output. For this, a very low power microcontroller must be used.
Electrolytic Capacitor Assortment	\$18.00	1	\$18.00	Digikey / Mouser / Ebay / Amazon	To hold the power produced by the piezoelectrics for the microcontroller to use, a capacitor must be used. The value of the capacitor must be tuned to the power draw of the circuit. It must not hold too much or too little power. For that reason, an assortment must be purchased for the research and development of this project.
Clear UV Resistant Plastic Film	\$20.39	1	\$20.39		A clear UV resistant plastic film such as Polycarbonate or polyethylene must be used to house the color changing liquid. This will be thermally formed in the correct shape when heated and stretched over a mold.
Steel for Mold	5	1	\$5.00		This is the material the mold will be made from. Any type of steel should be able to be machined for the proof of concept design.
		TOTAL:	\$95.43		

4.1 Parts

This is the parts breakdown for all of the components used on the PCB. This includes the parts for all three versions. The components for the third version of the PCB added up to \$1.12.

ID	Name	Designator	Footprint	Quantity	Manufacturer Part	Manufacturer	Supplier Part	Price
1	BZT52C5V1-7-F	D3,D19,D20	SOD-123_L2.7-W1.6-LS3.7-RD	3	BZT52C5V1-7-F	DIODES(美台)	C151588	0.037
2	1N4148W	D8,D9,D10,D11,D12,D13,D14,D16,D17,D18	SOD-123_L2.8-W1.8-LS3.7-RD	10	1N4148W	HT	C179717	0.011
3	TF3415	Q4	SOT-23_L2.9-W1.3-P1.90-LS2.4-BR	1	TF3415	TuoFeng	C436874	
4	ATMEGA328P-AU	U1,U4	TQFP-32_L7.0-W7.0-P0.80-LS9.0-BL	2	ATMEGA328P-AU	MICROCHIP	C14877	3.477
5	BC846BQ-7-F	Q3	SOT-23-3_L2.9-W1.3-P1.90-LS2.4-BR	1	BC846BQ-7-F	DIODES(美台)	C526461	0.041
6	100nF	C20,C29,C30	C0603	3	CL10B104KB8NNNC	SAMSUNG(三星)	C1591	0.002
7	HDR-F-2.54_1x6	H1,H2,H3	HDR-F-2.54_1X6	3			C40877	0.072
8	1uF	C9,C10,C11,C12,C14,C16,C17,C18,C24,C25,C26,C27	C0805	12	CS2012X7R105K500NRE	Samwha Capacitor	C516002	0.012
9	22pF	C13,C15,C19,C28,C22,C23	C0603	6	CL10C220JB8NNNC	SAMSUNG(三星)	C1653	0.006
10	10kΩ	R6	R0603	1	0603WAF1002T5E	UniOhm	C25804	0.001
11	220kΩ	R7	R0603	1	0603WAF2203T5E	UniOhm	C22961	0.001
12	220Ω	R11	R0603	1	0603WAF2200T5E	UNI-ROYAL(厚声)	C22962	0.001
13	100kΩ	R12	R0603	1	0603WAF1003T5E	UNI-ROYAL(厚声)	C25803	0.001
14	1.2kΩ	R13,R14,R16	R0603	3	0603WAF1201T5E	UNI-ROYAL(厚声)	C22765	0.001
15	20kΩ	R15,R17	R0603	2	0603WAF2002T5E	UniOhm	C4184	0.001
16	8MHz	X1,X2,X3	CRYSTAL-SMD_L11.5-W4.8-LS12.7	3	X49SM8MSD2SC	YXC(扬兴晶振)	C12674	0.087

4.2 Labor

The Running Shoe Pedometer is a largely circuit based design. It can be divided into three main parts, the circuit board, the plastic cover, and the indicating liquid. The PCB can be easily manufactured in large quantities by hundreds of companies. PCB production scales very well at large quantities and due to the high automation. The vacuum formed covers could all be made to a mold, or they could be made for each Pedometer. This is a very easy to automate, low tech process that costs next to nothing. The last part of the pedometer is the very cheap indicator that can be made in bulk in any laboratory. The most difficult part would be the assembly of these parts. It will be tedious to fill the plastic covers with liquid, then apply the glue, and glue it to the pedometer. In large volumes the running Shoe Pedometer scales very easily and integrates well into automated processes. That means that the total cost of the Pedometer will be a product of the raw materials and electrical components rather than the assembly.

5. Conclusion

In order to make a conclusion about the Running Shoe Pedometer, the metrics for success should be investigated.

Cost Effective

The metric for success that was outlined at the beginning of this project was that the cost for the pedometer would have to be less than \$10. In the high quantities the electrical components cost \$1.12 per pedometer and the PCB cost \$ 0.50. This is well below the target \$10 and leaves more than enough room in the budget for the chemical indicator, the plastic, and the assembly costs.

Durable

In order for the pedometer to be deemed durable, it was determined that it needed to hold up to 500 miles of running as well as being frozen and submerged in water, and being UV tested for the equivalent of 24 hours of exposure to direct sunlight. Only some of these claims got tested before the semester was over. The claims about being frozen and submerged in water were all tested and validated but the UV exposure and 500 miles of use were not validated. This will be counted as a success because the pedometer was designed to meet these UV and durability requirements.

Accurate

For the pedometer to be deemed accurate, it needed to count the steps accurately within 5% accuracy. This claim was validated against a regular pedometer on a single run. On that run the pedometer recorded 6,022 steps and the Running Shoe Pedometer recorded 5,871 steps. This was a 2.5% error which was within the acceptable levels.

Unobtrusive

In order to test if the pedometer was unobtrusive or not a target volume of 5 cubic centimeters was set. This criterion was almost met with the CAD model indicating a 7 cubic centimeter volume. This prototype design was kept fairly large for ease of and soldering the components, but the design could have very easily been designed to be much smaller. When holding the device up to a shoe, it looks large and cumbersome and does not meet the unobtrusive criteria even if the device doesn't weigh much.

Style

It was also decided that the device should be attractive and stylish and complement the shoe well. The metric for success is that the pedometer had to be available in multiple colors. This would be easy to achieve using different colored solder masks or a clear flexible PCB but because this was not done for the prototype, it will be counted as a failure.

5.1 Accomplishments

The Running Shoe pedometer was a success. It was an investigation into practical human power generation. All of the research papers that were written about human power generation were hyper

focused on power rather than practicality. The pedometer proves that an unobtrusive device powered passively is possible and makes sense in certain applications.

5.2 Uncertainties

The pedometer was not optimized in a program such as LT Spice to achieve maximum efficiency. Additionally, while all of the components were investigated for optimum efficiency, the prototype was made using the standard versions of these components rather than the specialized ones that would increase the efficiency. Also, the pedometer efficiency was ever measured. It would be possible to determine how much energy could be generated from the heel strike of an average runner and compare that to the power gathered by the pedometer.

5.4 Future work

The next step in the development of the running shoe Pedometer should be to obtain a patent for the device. This will protect the device in the future, making any further investment more worthwhile, and also making sure that it doesn't infringe on any other patents. If it did compete with other patents then the Pedometer project might need to be stopped entirely. Assuming the patents are granted, the Pedometer should be further developed until the pedometer to make the Pedometer ready for mass production.

The first step in improving the design of the pedometer will be to recruit an electrical engineer. This engineer could review all of the decisions made for the current version of the pedometer and optimize it further. This means that the whole concept should be revisited to see if a microcontroller is the best option for counting the steps and what type of voltage regulation should be used. From there, the microcontroller selection could be reviewed as well as each of the individual components such as the diodes and capacitors. Then the circuit could be simulated in LT Spice to optimize it further. Then consideration should be given to flexible PCB's. A flexible PCB could be sewn right into the shoe and be more easily concealed than a rigid flat circuit board.

The next step in getting the pedometer ready for the mass market will be a thorough review of the visual indicator system by a chemist or chemical engineer. From there, they can determine whether a chemical reaction, and electrochromic device, or an LCD is the best option for the indicator.

There is plenty more improvement that can be done on the pedometer. The main drawbacks from my development were the lack of funding, the lack of time, as well as the lack of knowledge in several advanced fields such as computer engineering, electrical engineering, and chemical engineering. If the project were several semesters long I could have had more time to research those fields more extensively. A project like this involves hundreds of decisions which are all critical to the functionality of the device and some of the more in depth decisions were glossed over so that a working prototype could be made before the end of the semester.

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