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DYNAMOMETER – THE NEW ACTIVITY MONITOR

NSF Summer Undergraduate Fellowship in Sensor Technologies
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ABSTRACT

Activity monitors are convenient tools for extracting empirical information about a person's physical activity patterns, which may be the source of various health issues. The purpose of the "dynamometer" under development in this research effort is to monitor physical activity that impacts on the emerging issue of childhood obesity, and which also can be related to the development of bone deficiencies such as osteoporosis. The dynamometer consists of a piezoelectric sensor that is embedded into a shoe insole and is connected to a microcontroller for data acquisition and analysis. The analysis of the signal results in information about the magnitude, frequency, and duration of a child's actions such as running and jumping. An amplifier circuit amplifies the signal produced by the sensor. The full implementation of signal processing by the microcontroller was not completed due to time constraints.

A sensor calibrator was designed and fabricated to provide a standard stimulus to test the sensors. The results of testing indicated that although noise was present in the amplified signal, the output was reproducible and clean enough to provide accurate results regarding the sensor response to various forces.

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1. INTRODUCTION

The lack of physical activity has become an increasingly serious concern in today's society, especially among children. From this deficiency stem a variety of health issues and the question of how to either prevent or eliminate these concerns. These issues range from obesity to osteoporosis. According to the American Obesity Association, the proportion of obese American children over the past 25 years has risen from 4.3% males and 3.6% females to 16% and 14.5% respectively [1]. It is reasonable to assume that there is a relationship between a person's physical activity patterns and his or her overall health; hence a means of quantifying activity would be a step toward understanding these interactions. While the subject of obesity has been explored to a limited extent, the related issue of how physical activity impacts the strength and density of bones has not yet been extensively addressed. Much as physical exercise is beneficial for one's health with respect to obesity and overall cardiovascular condition, physical activity is also important for children to gain bone mass. Specifically, it would be valuable to know whether it is the maximum force or the accumulation of all forces that affects the quality of a person's bone structure. These findings may be relevant in diagnosing the causes or influences behind the onset of osteoporosis.

Activity monitors would be an integral part of any effort to learn more about these health issues. Empirical information about physical activity would be best obtained through the use of an unobtrusive, but precise activity monitor. These devices should also be sufficiently versatile and adaptable so that they can be easily modified or expanded to address a variety of physical activity by extracting the desired physical measurements.

The current project addresses this issue by developing a device to measure the energy output (specifically, the magnitude, frequency, and duration of physical activity) of children between the ages of 4 and 8. This age group is targeted since it is hypothesized that the roots of many adult health problems originate during childhood. The proposed device, referred to as a dynamometer, is based on a piezoelectric PVDF sensor that responds to the forces arising on the soles of the feet of children as they go about their normal daily activity. The electrical output of the pedometer is fed into a signal processing circuit consisting of a preamplifier, a microcontroller and data storage unit. The microcontroller can be programmed in either C or Assembly language to extract the desired information, such as the overall or the maximum force generated by the child during normal activity. Other software can then process the signals to extract the energy expended.

It is essential that the device be thin and comfortable enough to fit within a child's sock. Another issue is processing the continuous stream of data to extract a timeline of the child's activity patterns. The computational capabilities of the electronics and related software determine how much data analysis can be carried out locally. Lastly, wireless communication is needed between the measuring circuitry and a central data storage site in order for a child to be able to function freely while wearing the device. Although the device is being designed for a very specific goal, it can be easily adapted to address a number of similar problems. Combining sensors with microcontrollers has significant technological implications, particularly those in the health-related research, since much physical data can be collected using such devices at a low cost.

2. BACKGROUND

2.1 Overall

The basic design of the pedometer is shown in Figure 1. It consists of a sensor feeding into an amplifier circuit that outputs a signal to the analog-to-digital converter in the microcontroller. Once the data is converted by the microcontroller, they can be processed and locally stored in the memory of the microcontroller or output to a remote location using a wireless transmission.

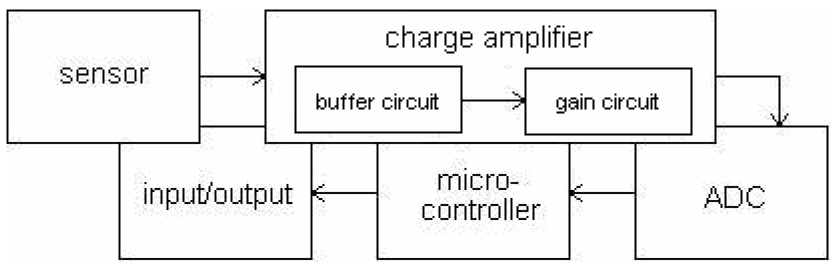

Figure 1. Dynamometer Flowchart

2.2 Piezoelectric Sensor

Sensors can be categorized as active sensors or passive sensors, and then further divided into more specific categories depending on their characteristics and functions [2, p.2]. These functions include, for example, sensing temperature changes, detecting movement using infrared beams and measuring liquid flow.

The sensor material used for the dynamometer is polyvinylidene fluoride, or PVDF in the form of a thin sheet that has electrically conductive nickel copper alloy electrodes deposited on each side.

An electrical current is generated when forces are applied to the piezoelectric material. Consequently no external source is needed to power the sensor [2, p.1]. The piezoelectric response is due to the strains arising in the piezoelectric material when a force is applied to it. The result is a displacement of atomic (or molecular) charges that the observed external currents. The electrical signal is amplified, processed, and converted to digital format for further analysis.

There are various advantages to using piezoelectric sensors instead of other types of sensors. Because this type of transducer possesses a wide measuring range of over 10^8 Newtons, it is able to handle a correspondingly wide range of force inputs. The outputs are stable and reproducible. Piezoelectric sensors are also generally insensitive to the effects of electromagnetic fields and radiation [2, p.2]. On the other hand, it is unable to measure static forces. Time varying force data must be collected and analyzed immediately [1, p.3]. Because piezoelectrics are excellent dielectrics, they retain their charge after the application of a constant force, depending on the capacitance and leakage resistance of the element.

The sensor samples used for this research were provided by Dr. Mitch Thompson, Director, Development Engineering, Piezo Sensors Division, MSI Sensors, Inc., Wayne, PA 19087. Some preliminary testing suggested that the laminated LDT1-028K model would be the most appropriate sensor to use for the project since it was small enough to be less sensitive to bending than a longer sensor, yet large enough to be able to cover a suitable surface area under the foot. The overall dimensions of the sensor are 16mm x 41mm x 205µm.

It is necessary to calibrate the sensors to insure reliable data [4].

2.2.1 Measurement

The output current generated is a result of applying a force (stress) to the material. This force-current relationship arises from the thermodynamic free energy relation between the factors of strain, stress, electric field, and displacement. These relationships can be used to show that the current, when integrated over time leads to the total force exerted over the time period of interest. The current going into the amplifier is:

$$I = V/R + C\, dV/dt,$$

while the magnitude of the charge is:

$$Q = CV$$
$$Q = 10^{-8} \text{ F} * 12 \text{ V} = 1.2*10^{-7} \text{ Coulombs.}$$

The main question is whether the maximum force or the accumulation of the forces impacting the skeletal tissue determines how the bone adapts to these pressures. The maximum forces, the duration of the forces, and the frequency of the forces are all valuable pieces of information that need to be extracted from the signal.

The oscilloscope probe has an internal resistance of 1 MΩ, which shunts the small piezoelectric sensor current; hence, a much higher input resistance is needed.

Some noise problems arose in obtaining the signal. Part of this was due to problems with the ground reference point for the electronic components such as the power supply, oscilloscope, and amplifiers. This resulted in a large noise signal. In addition, 60-Hz pick-up was an issue because of the lack of proper shielding.

2.3 Amplifier

In order to successfully extract and analyze the signal output by the sensor, a simple high input impedance amplifier was designed and constructed to interface between the piezoelectric film and the other electronics (in this case, the microcontroller).

A LT1112CN8 op-amp was used in the actual amplifier circuit, while a LT1012ACN8 was used in the simulation. All simulations were done using MultiSim software to observe the effects of changing certain components in the amplifier design without potentially burning out the chips. The op-amps were powered by ±12 volts from a dual power supply.

Specifically, there are two parts of the amplifier circuit (see Figure 4). The first stage uses a buffer circuit, and the second stage consists of a gain circuit.

2.3.1 Buffer circuit

The buffer circuit (shown in Figure 2) acts as a unity gain impedance transformer, meaning that the gain of the output does not change. Although the input and output voltages remain the same, the circuit converts a very high input impedance into a very low output impedance, on the order of tens of ohms. As shown in Figure 2, the input impedance of the buffer is 1 MΩ, although in practice a 100 MΩ resistance would be used. The low impedance output from this first stage insures that the second stage can track the buffered signal without additional delays.

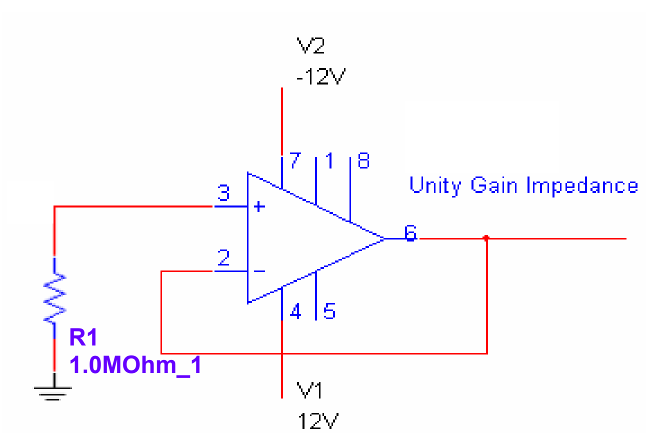

Figure 2. Buffer Circuitry (Stage 1 of the Amplifier Circuit)

2.3.2 Gain circuit

The purpose of the gain circuit (see Figure 3) is to amplify the buffered signal. The significance of this circuitry is that high gain can be achieved without decreasing the bandwidth of the signal. The gain can be calculated using the following formula:

Gain = Rg + Rout / Rout

This effect is demonstrated in Figure 5. So if more gain is desired, the feedback resistor can be increased.

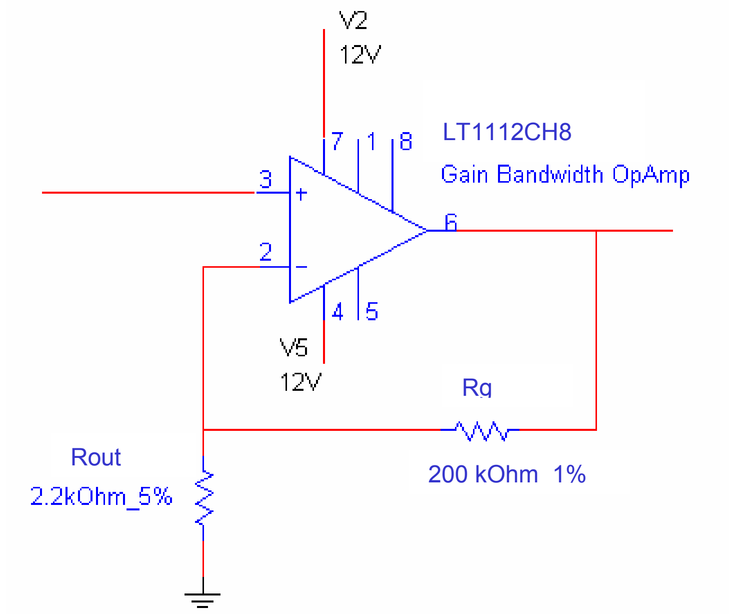

Figure 3. Gain Circuitry (Stage 2 of the Amplifier Circuit)

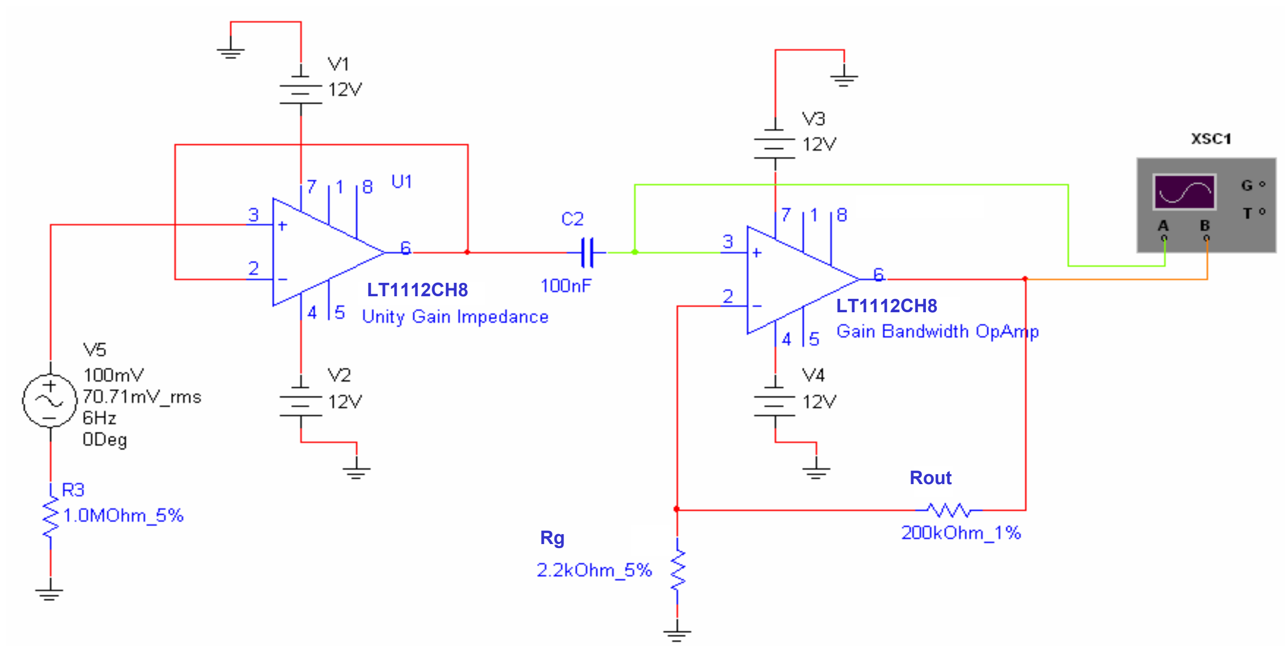

Figure 4. Amplifier Circuit. R3 represents the high impedance necessary to shunt the input, V5 represents the piezoelectric sensor input, the first op-amp represents stage 1 of the circuit, and the second op-amp represents stage 2 of the amplifier.

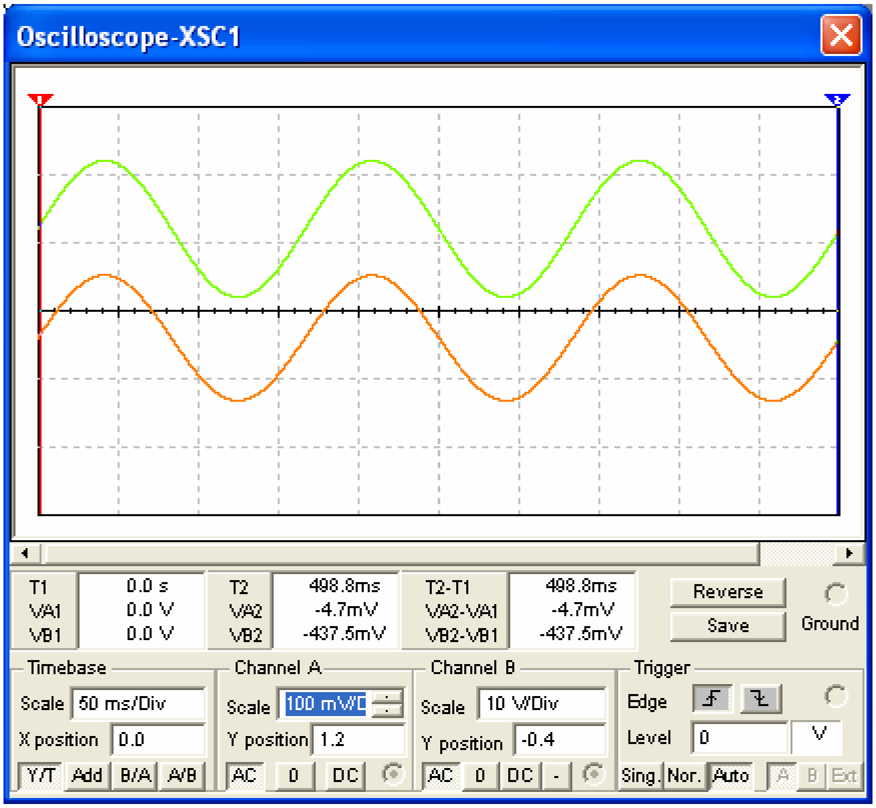

Figure 5. Input into stage 2 (green) and Output (orange) of overall Amplifier Circuit

2.4 Microcontroller

The PicMicro 16F876 microcontroller was chosen for this project since it was a compromise to achieve both an affordable price and simple functionality. The 14-bit core peripheral interface controller (PIC) was programmed and compiled using the CC5X B. Knudsen C compiler as an extension of the MPLab 6.5 software.

Some smaller programs were written to test the relationship of the microcontroller with both digital and analog inputs. The digital signal was generated by a function generator, while an analog signal was obtained by connecting the output of the sensor into the microcontroller. The bi-functionality of the IO ports allowed us to specify whether the pins acted as inputs or outputs by setting the TRIS function to the appropriate bits. As a test, a simple 5-volt sine wave, offset by 2.5 volts, was sent into one of the input ports. The microcontroller was then programmed to output the same value it received. By using the PORTC registers as outputs with each pin representing one of 8 bits of the output value, we were able to use the oscilloscope to determine that the lowest bit was represented on Pin 11. Pins 12, 13, 14, 28, 27, 26, and 25 represented increasingly higher bits since high bits are represented by waves of lower frequency, while the low bits are represented by waves of higher frequency. Basically, the registers store the value of the wave ranging from 0 to 5 as a hexadecimal value from 2 to 255 (see Appendix C for pin diagram).

2.4.1 ADC (Analog to Digital Converter)

The ADC is located on pins 2 and 3 of the PicMicro 16F876. The purpose of this feature is to convert the analog signals (the varying forces exerted) into signals that can be read and processed digitally by the microcontroller. The resolution of the ADC determines how many units a reading can be broken down into; in the case of the PIC, the ADC is 10-bits wide. This means that an analog input signal can be digitized and read in as a value between 0 and 1023, since $2^{10} = 1024$. Working with 10-bit values can get complicated since 10-bit values need to be processed as 16-bit words, so it is common to use 8-bit values represented as 8-bit words. Dividing the input into a smaller number of units also reduces the size of the program required to handle the numbers involved and the amount of processing required. On the other hand, choosing to use 8-bits over 16 bits is throwing away a factor of 4 in resolution, i.e. 256 instead of 1024. That is 0.4% resolution instead of 0.1%, which could be a problem if the data required is of high resolution.

2.4.2 Functions

The desired functions of the microcontroller are to be able to find the maximum signal and to integrate the area under the signal to extract the overall force exerted by the child. Some secondary outputs are the duration of activity, which can be obtained by isolating a block of activity and subtracting the start time from the end time, and the frequency of activity.

3. SENSOR CALIBRATOR DESIGN

In order to be able to test the electronics and the output of the sensors, a standard stimulus was designed; it was fabricated in the Physical Sciences Machine Shop located in David Rittenhouse Laboratory (see Appendix A). The design of the sensor calibrator cyclicly stressed the sensor with a period of approximately 3 seconds. As a result, a prescribed periodic force could be applied to the different sensors, thereby providing calibrated and detailed measurements of the signals. Hence, when the sensors are attached to an insert of a shoe, it would be possible to calculate the force that generated the observed charge.

3.1 History of ideas

The initial inspiration for stamping a cyclical pattern onto the sensor stemmed from the repetitive nature of many toy movements. For example, using a mechanical wind-up toy or a battery-powered car on a racetrack seemed like an inexpensive and quick means of obtaining a calibrator. However, a more efficient calibration technique would feature a stationary device.

One option was to use the switching power of an electromagnetic relay to simulate the up and down movement necessary to vary the force of a mass on top of the sensor. The problem was that the electromagnetic forces induced would not be sufficiently strong to lift a large mass comparable to a child's weight since relays are usually very small and a huge current would need to be drawn to create an electromagnetic field of the appropriate strength.

For simplicity, the next idea involved simply attaching the sensor to a foot-like structure and pushing it off a fixed height to calibrate the sensors. Although the height would be calibrated, the exact force exerted on the sensor would vary depending on how the "foot" hit the floor. Also, it would not be possible to attain a cyclical motion from this type of design.

Linear motors were researched since the unidirectional movement of such a device would be ideal for inducing a repetitive response onto the sensor. The main problem with this idea was the high cost of such devices.

The final approved idea was to use an oscillator in conjunction with a spring to vary the weight of a fixed mass on top of the sensor to be tested. Specifically, a spring with spring constant K was attached to an oscillatory driver on one side and fixed on the other to a mass M that was large enough so that the maximum lifting force exerted on it when the spring is displaced by +A cm is less that Mg, the weight of the mass. The spring displacement is given by $A(t) = A*\sin(2\pi*f_o*t)$. Hence the force will vary by $\pm KA$ and because $KA<Mg$, the weight remains stationary but the force is not (see Figure 7).

The forces are affected by the following parameters, where M is the mass of the weight, A is the displacement of the spring, and k is the spring constant:

$$F_{total} = Mg - kA(t)$$

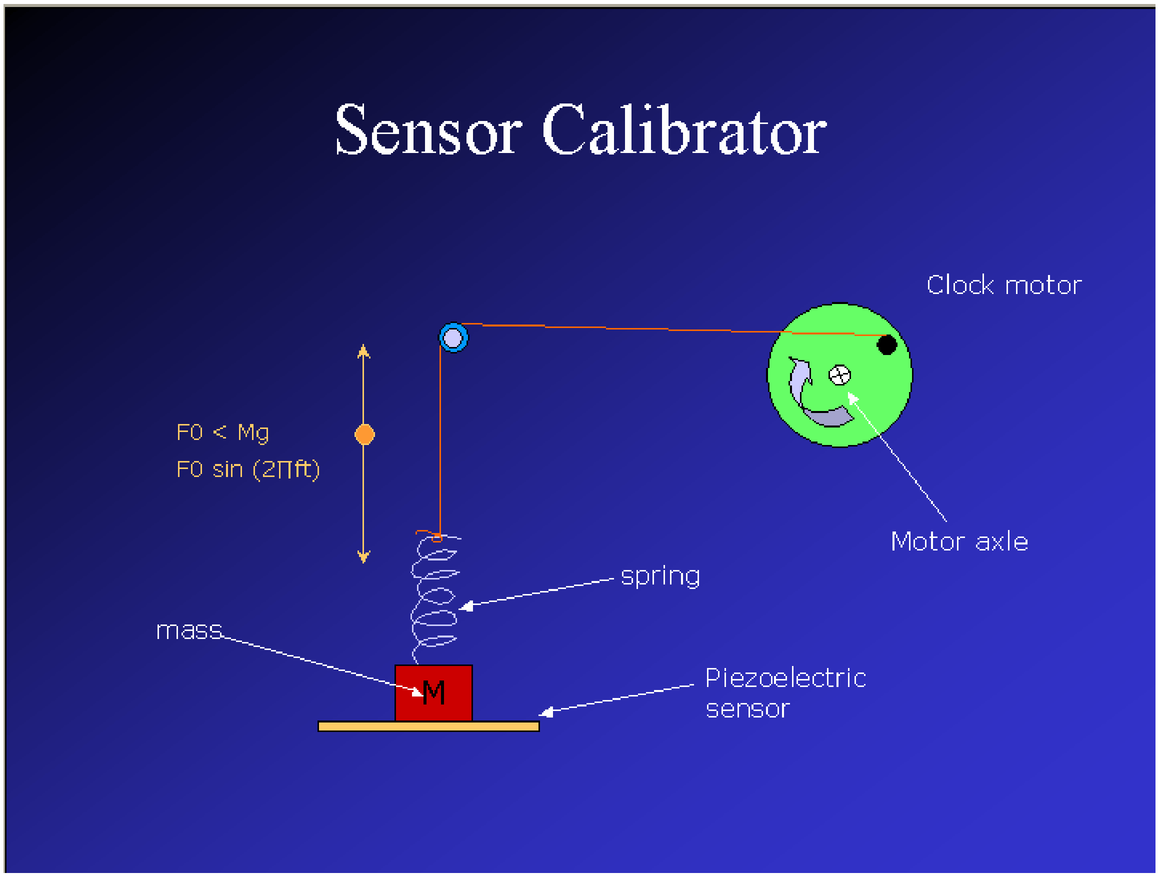

Figure 7. Diagram indicating varying forces of the spring-mass system

The design process required that the spring displacement be calculated in order to decide the necessary size and radial position of the drive wheel. It is important that the drive wheel have enough clearance to be able to turn without any obstructions while also rotating enough for the desired spring displacement. The greater the spring displacement, the greater the range of force values exerted onto the sensor. PowerPoint, Canvas 9, and AutoCAD were used to share the ideas and receive critiques, as well as to draw out the final blueprints for the machine shop to fabricate. (Canvas 9 is a technical drawing software program primarily used to create blueprints.)

3.2 Parts

Aluminum was used for the calibrator since this material is strong and relatively cheap. A clock motor with a low speed of 16-RPM CCW was chosen since the 25-lb in toque specifications would be sufficient to lift a mass the weight of a small child. A tubular instrument scale was selected for its reasonable force constant and its ability to handle up to 25 kg (approximately 55 lbs). Additionally, a pulley with bearings was ordered to change the direction of the wire holding up the mass from left-to-right to up-and-down. The mass used was about 21.5 pounds.

4. RESULTS

Before testing the effectiveness of the sensor calibrator, steps were taken to solve the problems with the raw information produced by the sensor (see Figure 8). After grounding the motor, the oscilloscope, and the sensor to the same reference point used by the circuitry, the signal showed fewer signs of interference from external factors (see Figure 9) than when the circuitry was not connected to ground.

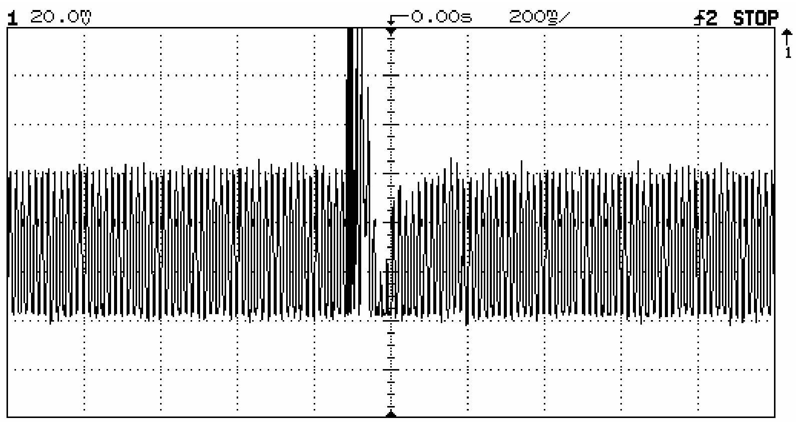

Figure 8. Signal before grounding the electronics. The amount of noise (pick-up) present in the signal is evident.

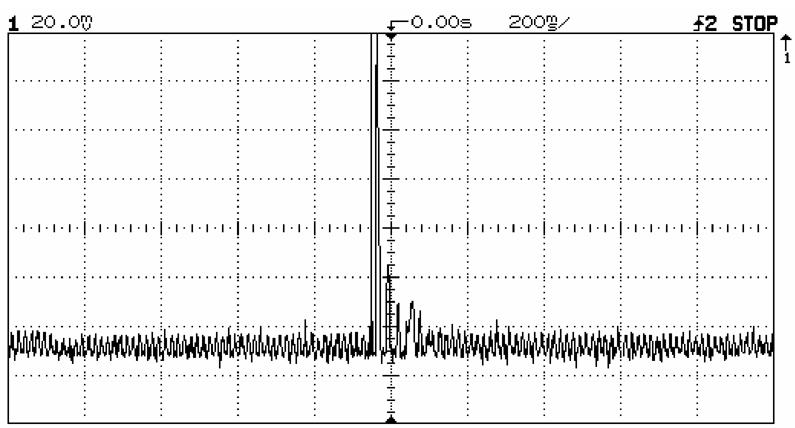

Figure 9. Signal after grounding the electronics (some noise eliminated)

Next, the sensor calibrator was used to check for the response of the sensors. A 9.75 kg (21.5 lb) weight was attached to the spring to allow the oscillatory motion of the calibrator to vary the forces of the weight on the sensor. The outputs of the sensors (see Figures 10 and 11) confirmed the reproducibility of the force-sensor relationship, since the measurements taken at different times resulted in similar output behaviors.

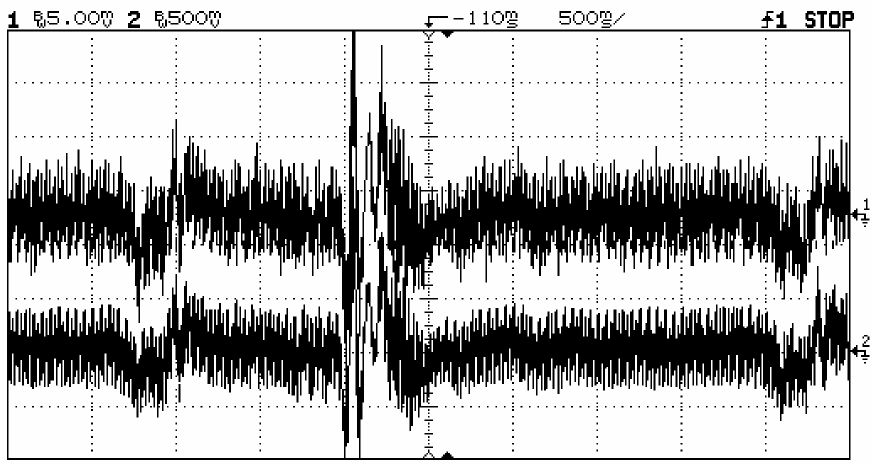

Figure 10. Output of Sensor using Sensor Calibrator (Scale 5.00mV/500mV)

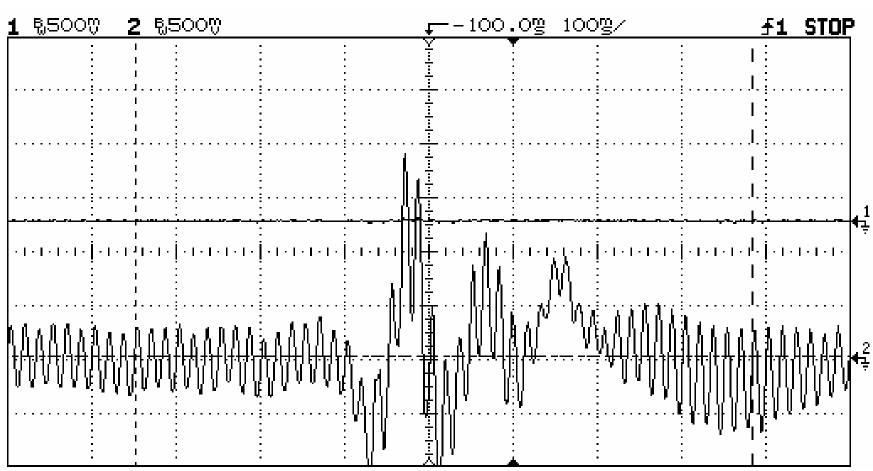

Figure 11. Output of Sensor using Sensor Calibrator (Scale 500mV/500mV)

The microcontroller aspect of the project was started; however, the microcontrollers failed before the functions written could be tested and debugged. The framework of various functions was outlined (see Appendix B). These functions included the calculation of the maximum value of the signal, the initialization of the analog-to-digital property of the microcontroller, as well as the conversion of a digital signal to an analog value.

The sensor calibrator appears to work well giving reproducible signals. Despite the presence of 60-cycle noise, it is clear that the peaks from both figure 7 and figure 8 correspond to the same maximum force applied. This suggests that the signals produced could be directly related to a person's activity. It is also evident that the amplifier is behaving correctly since the output of the sensor (represented by channel 2) has a gain of approximately 100 over the original signal (represented by channel 1). The actual gain is 92.

5. RECOMMENDATIONS

5.1 Issues

The sensitivity of the sensors to bending affects their ability to exclusively measure forces. Since larger sensors are more sensitive to this property, it is recommended that smaller sensors be used for the dynamometer, while still maintaining a large enough surface area to be able to collect the force data. The issue of noise can be dealt with by shielding the system in order to reduce the presence of unwanted frequencies.

5.2 Microcontroller

The Texas Instrument family of microcontrollers provides much superior, smaller chips that could be used in place of the PicMicro 16F876 chip. Its main advantage is that it is smaller than the PicMicro, which would make it easier to design a desirable, unobtrusive dynamometer device. Some of the device's key features include high-performance analog (ideal for precise measurement), in-system programmable Flash, which permits flexible code changes, and pricing as low as $0.49 per unit. One of the intended applications of this microcontroller is for intelligent sensing, which encompasses the goals of the dynamometer. [5]

5.3 Wireless

Wireless technology should eventually be incorporated into the design of the dynamometer in order to be able to continually transmit data from the microcontroller to a remote location using the serial ports of the microcontroller. The Bluetooth SiPs (Systems-in-a-Package) are ideal modules to introduce wireless functionality to the activity monitor. These Bluetooth SiPs take up an area as small as 49 mm^2, coexist with 802.11 WLAN, and require only an external clock source and antenna for operation [6].

On the other hand, the microcontroller could store up to 5 kilobytes locally, so if wireless was possible, the microcontroller could transmit data every time it was in close proximity to a wireless hub. An EEPROM chip can also be connected serially to the microcontroller for additionally memory storage, since this memory is not directly mapped in the register file space. This function is categorized under the role of the special function registers [7].

5.4 Prototype

The goal was to have a working prototype that a child can wear comfortably while collecting data. Clearly, a child's activity patterns will not represent normal activity if the device worn is obtrusive with wires hanging out. In fact, if the child is unwilling to wear the device, data cannot even be collected. Most likely, all the circuitry other than the actual sensor will be encased in a small box that can be strapped onto the child's ankle. The design of the box is not a trivial matter. A child's interests must be considered when choosing the size and shape of the box containing the electronics (see Appendix D).

5.5 Testing on Children

Drs. Babette Zemel and Dr. Anne Buison, a post-doctoral Fellow, have agreed to handle the human testing aspect of the device. Once they confirm the type of data they want to collect, the microcontroller can be modified to extract this type of information. Ideally, the data collected about a child's activity will be useful in determining what types of activity promotes the level of bone growth and strength. This data can then be used to reduce the number of cases of osteoporosis occurring in adults by targeting childhood prevention.

6. CONCLUSIONS

The idea of a pedometer is relatively simple, but the implications are huge. If obesity or other health issues can be monitored, significant health benefits may be achieved for a very low cost. Specifically, it would be possible to learn more about bone development and the relationship between activity and bone strength, which has significant implications for osteoporosis is diagnosis and prevention.

The sensor-microcontroller design is extremely versatile. For one, it can be used in an unlimited number of places since the sensor is thin and wearable. This surpasses the functionality of a force plate, which is too large to be moved around with a person during their daily routine. The design is also easily adaptable to serve other functions as long as the signals produced by the sensors can be captured. The microcontrollers used can be modified to collect different data, depending on the type of data desired and the type of sensor used. For example, if the desired data is the speed of a runner, an accelerometer sensor could be used and attached to the athlete's wrist or leg.

7. ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. Jay N. Zemel, for his all his guidance and advice regarding not only my research project, but on planning for my future career. I would also like to thank all the faculty, administration, and researchers involved with the SUNFEST program for making this summer an unforgettable experience—especially Dr. Van der Spiegel for devoting so much time in planning the program, Dr. Tamar Granor for critically editing my final paper, Sid for always playing the devil's advocate to my ideas, and the lovely ladies of Moore 203 for sharing their microwave. A special thanks to Rob Callan for his invaluable assistance in helping me tackle the microcontroller aspect of the pedometer and Alex Chang for keeping me sane by introducing me to the idea of taking breaks. Finally, I would like to thank the National Science Foundation and Microsoft Corporation for their financial support of this REU Program.

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APPENDIX A:
Blueprints for Sensor Calibrator

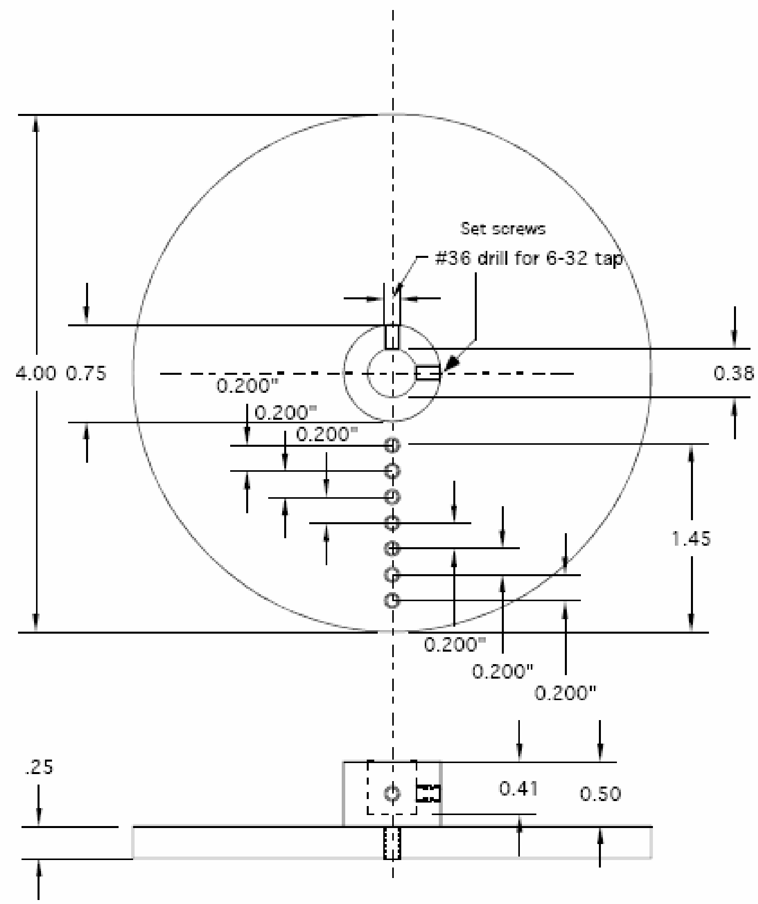
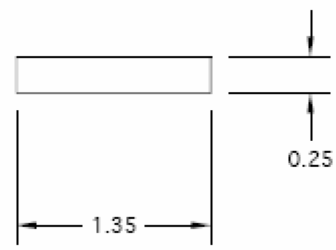


Figure 5
mild steel Stock
±0.010
A 7 holes 6-32 tapped

Drive Wheel of Calibrator



Pin for pulley. Round ground stock

Press fit to the 0.250" in hole in the Motor Mount on one side and to the pulley on the other. To be aligned with the cord.

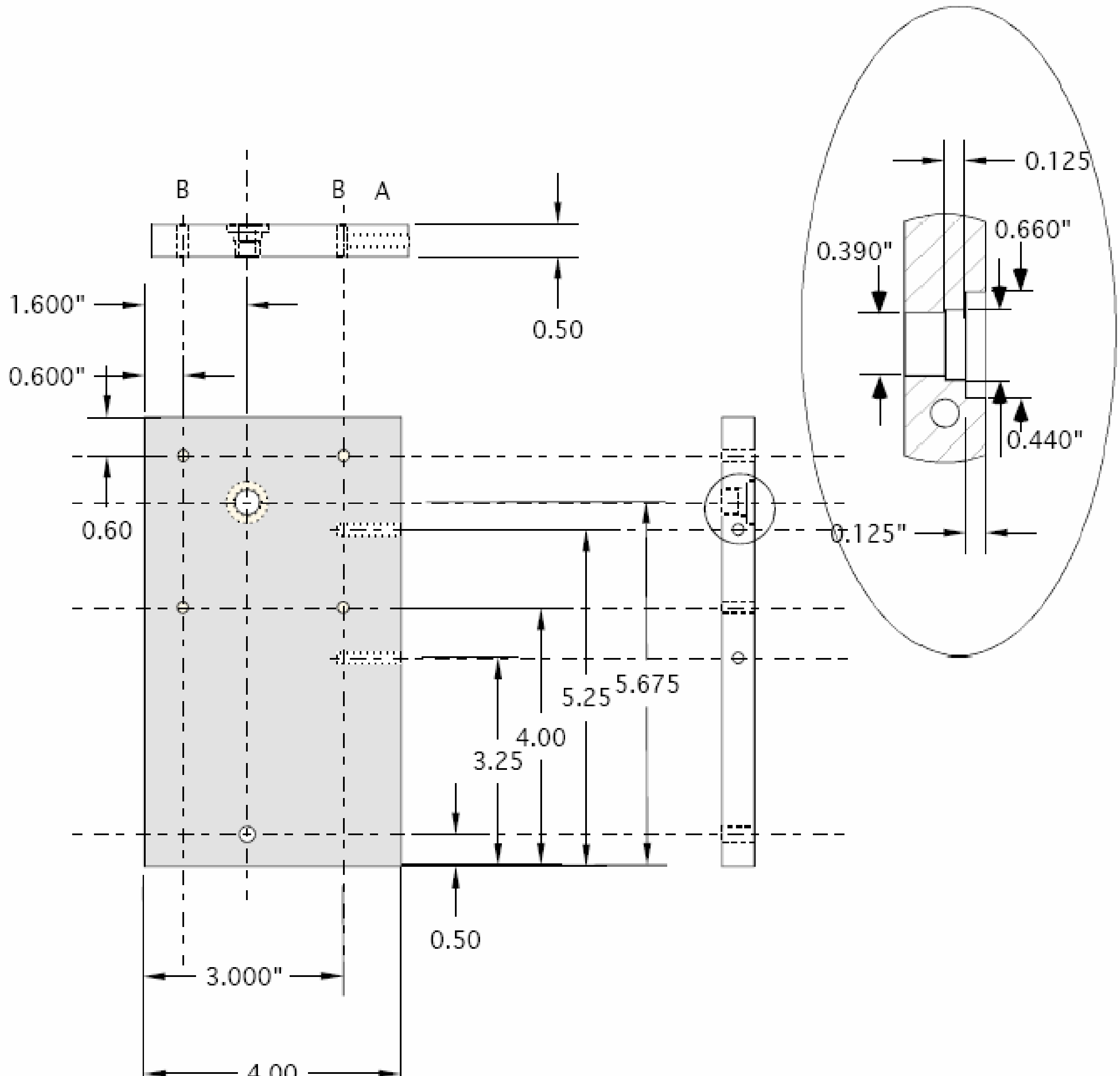
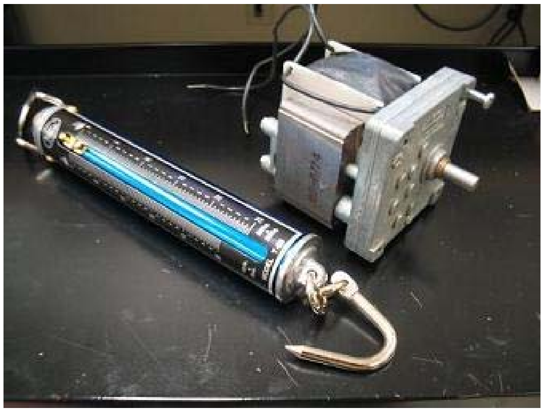


Figure 5
Material: Stock Aluminum
±0.005"
A 2holes 8-32 tapped
B 4 holes 8-32 tapped

Motor mount of sensor calibrator: Holds up the pulley pin and motor attached to the drive wheel.



Calibrated Spring and Clock Motor

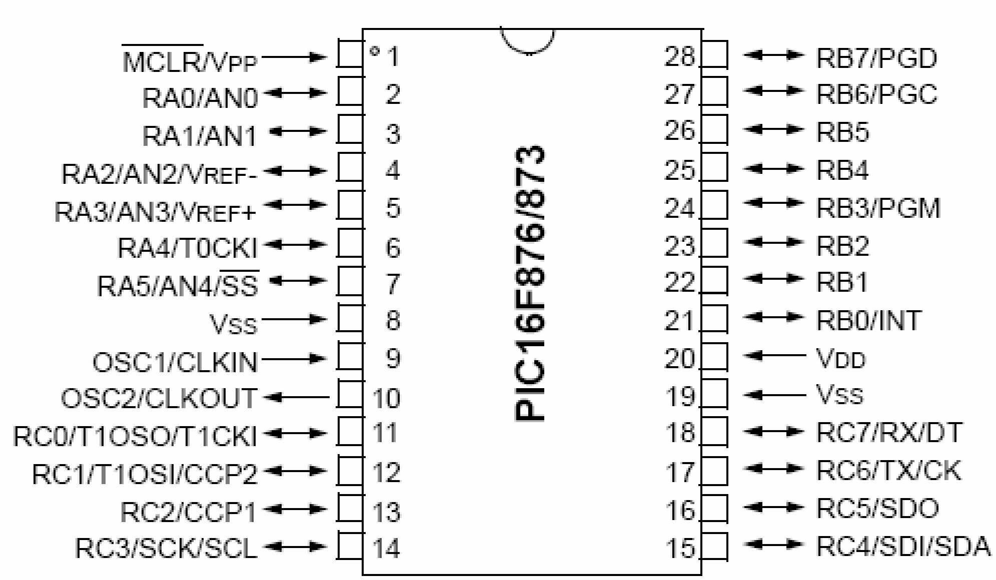
Drive Wheel and Pulley

Calibrated Spring and Mass with Dynamometer prototype

APPENDIX B:
Microcontroller C Code

```
/* function written by Rob Callan: setup for ADC */
uns8 get8BitADC(){
	ADCON0.0= 1;  //	0=TURN ON Analog
	ADCON0.2= 1;  //	2=MAKE CONVERSION
	while(ADCON0.2==1);		// while incoming signal
	return ADRESH;
}

uns8 getIntegration(uns8 y, uns8 samplerate) {
	uns8 sum, area;
	sum = 0;
	while ( // more samples to be read in, or reach cutoff) {
		area = y * samplerate;		// y * deltax (small)
		sum += area;
	}
	return sum;
}

uns8 getMax (uns8 y) {
	uns8 max;
	max = 0;
	if ( y > max)
		max = y;
	return max;
}

/*	function written by Rob Callan: set-up for DAC		*/
void setupPWM(){
  CCP1CON&= 0xf0;
  CCP1CON|= 0x0c;
  CCP2CON&= 0xf0;
  CCP2CON|= 0x0c;
  PR2= 0xff;
  T2CON&= 0xf8;
  T2CON|= 0x00;
  T2CON.2= 1;
}

/*	function written by rcallan: output for DAC	*/
void setOutputOfPWM(uns8 toOutput, uns8 outputReg){
  if(outputReg==1)  CCPR1L= toOutput;
  else			CCPR2L= toOutput;
}

void main( void) {
	uns8 temp, temp2;
	PORTC = 0b.1111.1111; /* out = 1 */
	TRISC = 0b.0000.0000; /* xxxx 0001 */
	setupPWM();

	/*while(1) {
		PORTC = 0xff;		// set all ports to high
		temp = get8BitADC();		// get input from fxn gen
	}*/

	setOutputOfPWM(51,1);		// 51 -> 1 V		//128 approx 2.5 V
	while(1);
}
```

APPENDIX C:
Pin diagram for PicMicro 16F876



APPENDIX D:
Device Prototype