TRANSDUCERS

Minster

ABSTRACT

Generally, the term transducer means a device that converts one form of energy to another (Webster). A sensor converts a physical measurement to an electric output. The purpose of this lab is to apply theory of biomechanical transducers, the strain gage and force sensing resistors. Students performed calibration process and confirmed the nonlinearity of transducer due to the saturation limit. Students used strain gages and FSR measure the force or pressure applied to a sensor which has Wheatstone bridge. Wheatstone bridge provide a way to convert resistance to voltage. Also it provides a means to cancel out thermal effects. It provides a way to amplify output up to four times as original signals. Foot switch is a good example of FSR's application due to the stance and swing phase of a gait. Bonded strain gage that students used in the lab has 1% typical deviation from linearity. The results fall in the region of the deviation from linearity. Normal people have 62% of stance phase and 38% of swing phase. Cerebral palsy patients would have less percentage of stance phase than normal people due to lack of control. Thus, analyzing a gait with foot switch and using FSR is very important to biomedical engineers.

INTRODUCTION

The purpose of this lab is to apply theory to experience with two common biomechanical transducers, the strain gage and Force Sensing Resistors (FSR). Students can learn calibration process and can use the transducers, quantify mechanical crosstalk and transducer nonlinearity. Also students can use a FSR as a foot switch to determine temporal characteristics of a pattern of moving.

Equations are used in the lab are followings:
Momentum = Moment Arm X Force

When skeletal muscle is stimulated, it is rapidly activated and changes from passive tissue into dynamic tissue capable of developing force. During stimulation, the length of the muscle may decrease, increase, or remain the same, depends on the external opposing forces acting on the muscle. Muscle strain (ε) is changed length (ΔL, $L_f - L_O$) over initial length. Thus, the relationship between muscle tension and muscle strain can represent the dynamic characteristics of skeletal muscle. Therefore, understanding concept of strain gage, learning calibration, and analyzing output of signals are extremely important to biomedical engineers for safety of patients, and users.

Generally, transducer represents a device that converts one form of energy to another. A sensor converts a physical data to an electric output. Sensors are useful to minimize the energy extracted while being minimally invasive. Such as a strain gage, which converts displacement to an electric voltage, sometimes has the sensitivity of the sensor that can be adjusted over a wide range by altering the primary sensing element. Tendon and ligament tension can be monitored with stain gage.

Force Sensing Resistors (FSR) use the electrical property of resistance to measure the force or pressure applied to a sensor (Stilson). The FSR is made up of two parts. The first is a resistive material applied to a film. The second is a set of digitating contacts applied to another film. Figure 1 in the method section shows this configuration. The resistive material serves to make an electrical path between the two sets of conductors on the other film. When a force is applied to this sensor, a better connection is made between the contacts, hence the conductivity is increased. Over a wide range of forces, it turns out that the conductivity is approximately a linear function of force. When forces reach this magnitude, additional forces do not decrease the resistance substantially. Because the first is the abrupt transition which occurs somewhere in the vicinity of tiny force, FSRs are useful for designing switches of analyzing forces or pressures that act on body parts.

In order to measure strain with a bounded resistance strain gage, it must be connected to an electric circuit that is capable of measuring the minute changes in resistance corresponding to strain. A Wheatstone bridge is usually employed in strain-gauge sensors because the Wheatstone bridge converts the gauge's strain-induced resistance changes into a differential voltage (Brendel). A Wheatstone bridge is a divided bridge circuit used for the measurement of static or dynamic electrical resistance. The output voltage of the Wheatstone bridge is expressed in millivolts output per volt input. The Wheatstone circuit is also well suited for temperature compensation.

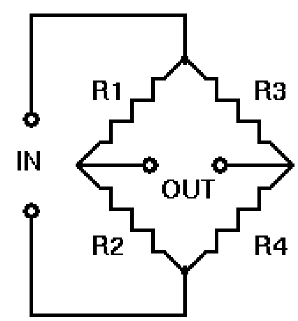

Figure 1. Wheatstone Bridge[1]

When the force sensor is unloaded, its resistance is very high. When a force is applied to the sensor, this resistance decreases. The resistance can be read by connecting a multimeter to the outer two pins, then applying a force to the sensing area. The voltage increases with force because the non-inverting input of the op-amp is driven by the output of the divider. At zero force, the output of the op-amp will be low. When the voltage at the non-inverting input of the op-amp exceeds the voltage of the inverting input, the output of the op-amp will toggle high. The triggering voltage and therefore the force threshold, is set at the inverting input.

Hysteresis represents the history dependence of physical system. The hysteresis acts as a debouncer that eliminating any multiple triggering of the output that might occur. When a material is cyclically loaded in the elastic range, a small amount of energy is dissipated during each loading cycle which causes the loading and unloading curves to be

[1] http://www.play-hookey.com/dc_theory/wheatstone_bridge.html

no coincident. Also, the voltage output in this lab decreases over time so students should read voltage output when they put weights on the FSR.

A change of resistance (R) is proportional to the strain sensitivity (S) of the wire's resistance. When a strain is introduced, the strain sensitivity, which is also called the gage factor (GF). FSRs are polymer thick film device which decreases in resistance with an increase in the force applied to the active surface. Its force sensitivity is optimized for use in human touch control of electronic devices. Even though FSRs have similar properties, FSRs are not suitable for precision measurement. Thus, if sensitivity is too high, then the results will pick up noises, other frequencies which can be errors.

Crosstalk is a disturbance that caused by electromagnetic interference along a circuit or a cable pair. A telecommunication signal disrupts a signal in an adjacent circuit and can cause the signals to become confused and cross over each other. Electromagnetic interference can cause errors of data because FSR measures very small values of changes. Thus, FSR uses op-amps to eliminate noise of signals that are caused by electromagnetic interference. Also because of the small values of output, FSR amplifies the signals to eliminate the noise with filter.

METHODS

There are three parts for this lab. First one is about strain gages, second one is about force sensing resistors (FSRs), and the third one is about the FSR application, for example, foot switch.

1. Strain Gages

Students used gage amplifier, figure 2, to understand about bending moment with different axis. Students turned on the strain gage amplifier and allow it to warm up for fifteen minutes before taking any readings. Then put the 50 pounds load cell (MB-50, Interface, Inc.) in the calibration jig.

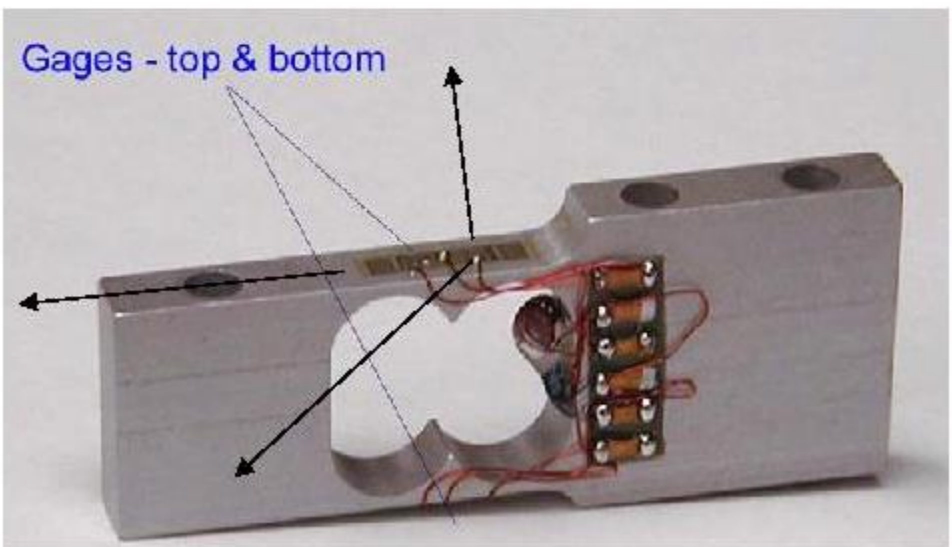

Figure 2 Strain gage amplifier

Students connected the gages to the measurements group P-3500 bridge amplifier which is from Dr. Harris of Marquette University. It has four gages become the four active arms of a Wheatstone bridge. The box amplifies the raw and unfiltered bridge output to plus minus 2.5 voltage output of the bridge. Then students loaded the gage along its axis of positive and negative direction of x, y, and positive z axis. Students loaded two pounds weight until 20 pounds maximum and unloaded the transducer in two pounds increments. The output is the voltage. Y direction is along its axis, X is transverse axis, and Z is bending moment axis. Students need to measure the distance from the neutral axis to the point that force is applied to calculate the bending moment. Students are going to loading and unloading for the combination of direction and axis.

After students are done with all the axis and directions, they calibrate the wire attachment location (jig). Students connect two wires along the Y axis at the same time but in opposite directions. They should try to keep the same condition from the previous experiment as much as possible. Students used weights of two pounds and ten pounds for different magnitudes. They took the positive Y wire off and attach it below the neutral axis then measure output. After that, they took the positive Y axis wire off the place the same weight pulling in the positive Z axis and then measure the output.

2. Force Sending Resistors (FSR)

Students connected the leads on a circular FSR to the multimeter to measure resistance. The group loaded FSR in two and half pounds for the first time and then loaded two pounds for increments from 0 pounds until 20.5 pounds. After reaching the 20.5 pounds, students unloaded weights. Students need to keep wire steady as much as they can to prevent other causes of bending moment. Students repeat this same procedure for a square FSR. Students carefully connected an unmounted FSR to the multimeter to understand the changes while bending FSR. Students saw the changes of resistance while bending FSR and while it is flat. Students also tested the resistance at room temperature and the heated conditions with same FSR.

3. FSR application

Students used the FSR as a foot switch, which the resistance output of gate during loading and unloading converted to voltage. Students performed a calibration of FSR. Students connected the multimeter to measure voltage this time across the ground and output of the force-to-voltage converter. Then they loaded the FSR to 18 pounds in approximately two pounds increments. When reading does not show up, it is saturated. Students unloaded the FSR in approximately two pounds increments. After students performed the calibration, they collected subject's data.

Students used LabVIEW program to open program for foot switch. The scan rate is 500 Hz and the number of scans to 2500 which is 0 to 5 seconds. The range of A/D card is -10 to 10Volts (V). Students put the FSR to toe and hill with tape and they can measure heel strike and toe off while the subjects are walking. Collect data from other volunteer. The configuration of FSR used for the foot switch was circle and small as figure 3.

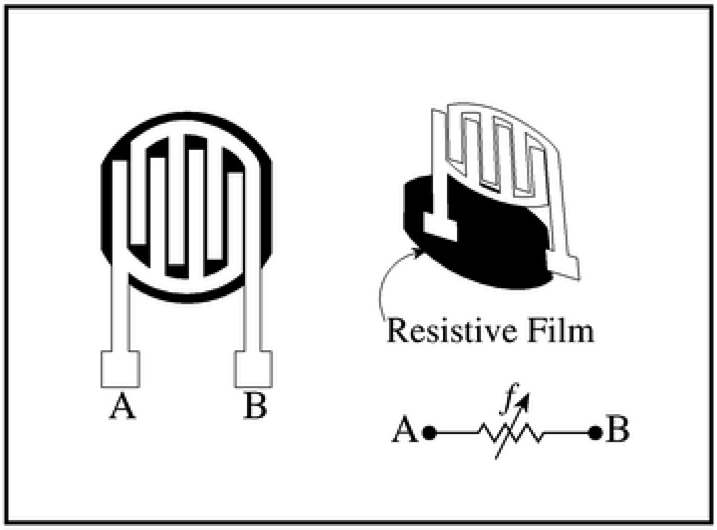

Figure 3 Diagram of a force sensing resistor (Circle shape).

RESULTS

Load (lb)	Loading (mV)	Unloading (mV)
0	-928	-928
2	-940	-939
4	-950	-950
6	-960	-959
8	-970	-969
10	-980	-978
12	-989	-987
14	-998	-996
16	-1007	-1004
18	-1015	-1013
20	-1022	

Table 1. Y+ loading gage axis bending versus voltage output

Load(lb)	Loading(mV)	Unloading (mV)
0	-930	-927
2	-944	-940
4	-956	-952
6	-967	-964
8	-978	-975
10	-990	-980
12	-999	-999
14	-1010	-1010
16	-1020	-1021
18	-1030	-1031
20	-1040	

Table 2. X+ loading transverse axis versus voltage output

Load (lb)	Loading (mV)	Unloading (mV)
0	-926	-928
2	-937	-939
4	-946	-950
6	-960	-960
8	-970	-971
10	-981	-981
12	-991	-991
14	-1001	-1001
16	-1011	-1021
18	-1021	-1031
20	-1031	

Table 3. Y- loading transverse axis versus voltage output

Load(lb)	Loading(mV)	Unloading (mV)
0	930	931
2	945	946
4	960	960
6	973	973
8	985	986
10	998	999
12	1011	1011
14	1022	1023
16	1034	1035
18	1046	1046
20	1057	

Table 4. X- Loading transverse axis versus voltage output

Load(lb)	Loading(mV)	Unloading (mV)
0	-822	-818
2	-602	-603
4	-396	-391
6	-185	-180
8	27	35
10	237	246
12	448	459
14	663	670
16	874	882
18	1087	1091
20	1299	

Table 5. Z+ loading bending moment versus voltage output

Experiment	Direction/Load(lb)	Direction/ Load	Values(mV)
A	-Y/ 10lb	+Y/-2lb	-995
B	-Y/10lb above neutral axis	+Y/2lb Below neutral axis	-954
C	-Y/10lb above neutral axis	+Z/2lb below neutral axis	-613

Table 6. Calibration of the jig with several applied loads.

Load (lbf)	Loading(KΩ)	Unloading(KΩ)
0	infinity	Infinity
2.5	Infinity	Infinity
5	0.392	0.386
7.5	0.332	0.350
10	0.299	0.305
12.5	0.295	0.265
15	0.262	0.237
17.5	0.228	0.232
20	0.210	0.213
22	0.212	0.200
24	0.202	0.202

Table 7. Circle Force Sensing Resistors (FRS's)

Load (lbf)	Loading (KΩ)	Unloading(KΩ)
0	Infinity	Infinity
2.5	Infinity	0.355
5	0.396	0.198
7.5	0.348	0.188
10	0.341	0.176
12.5	0.197	0.172
15	0.200	0.140
17.5	0.158	0.138
20	0.156	0.135
22	0.148	0.131
24	0.130	0.130

Table 8. Square Force Sensing Resistors (FRS's)

Load(lb)	Loading voltage (V)	Unloading voltage (V)
0	0.130	0.130
2.5	0.810	1.000
4.5	1.560	1.380
6.5	1.750	1.690
8.5	1.940	1.880
10.5	2.060	1.940
12.5	2.130	2.000
14.5	2.190	2.130
16.5	2.380	2.060
18.5	Saturated	Saturated

Table 9. Calibration of FSP application

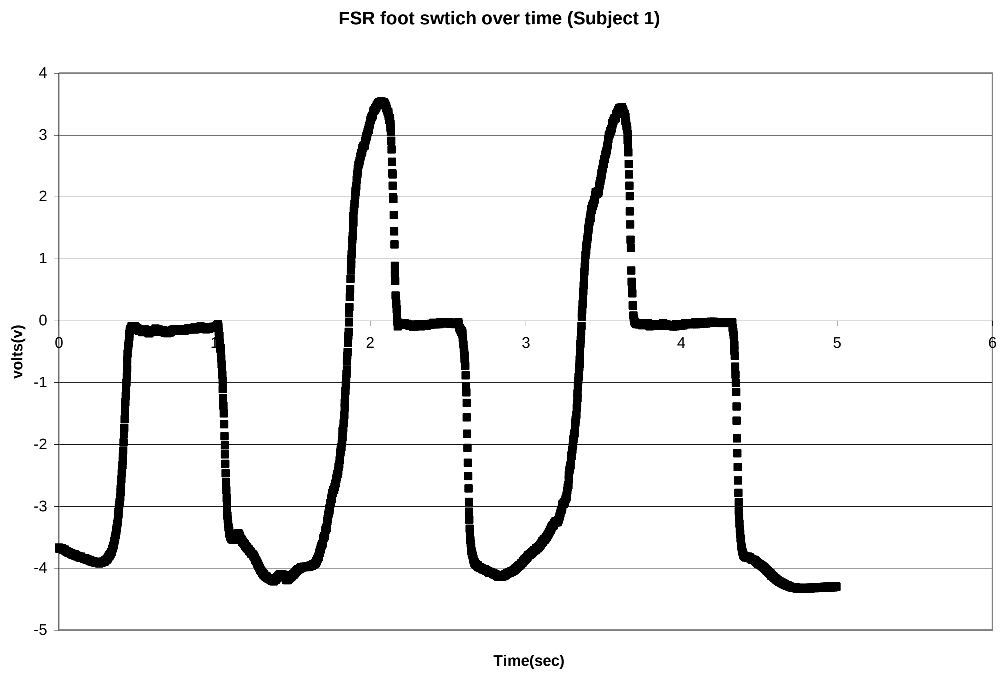

Figure 3 FSR output (Volts) versus Time(seconds) Subject is Chris.

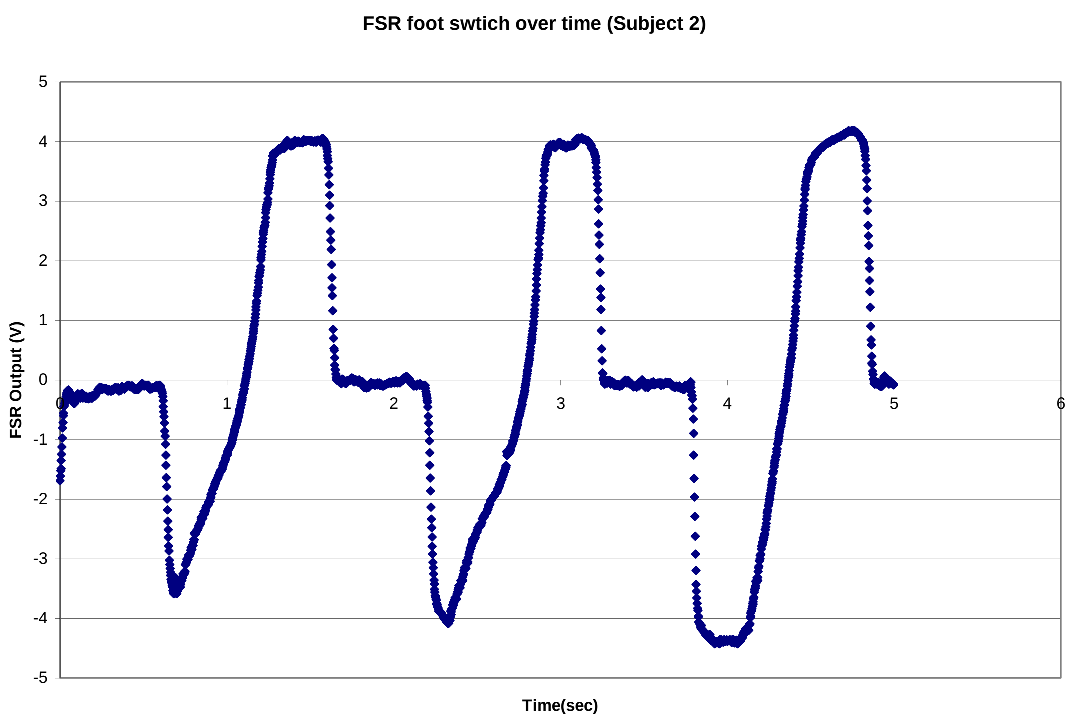

Figure 4 FSR output (Volts) versus time (seconds) Subject is Sarah

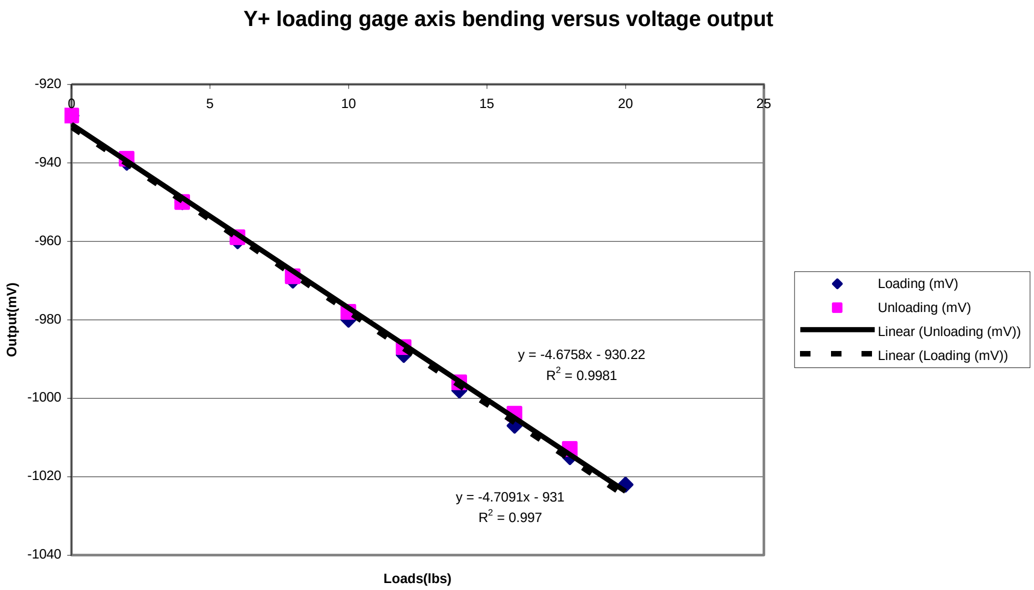

Figure 5. Y+ loading gage axis bending versus voltage output

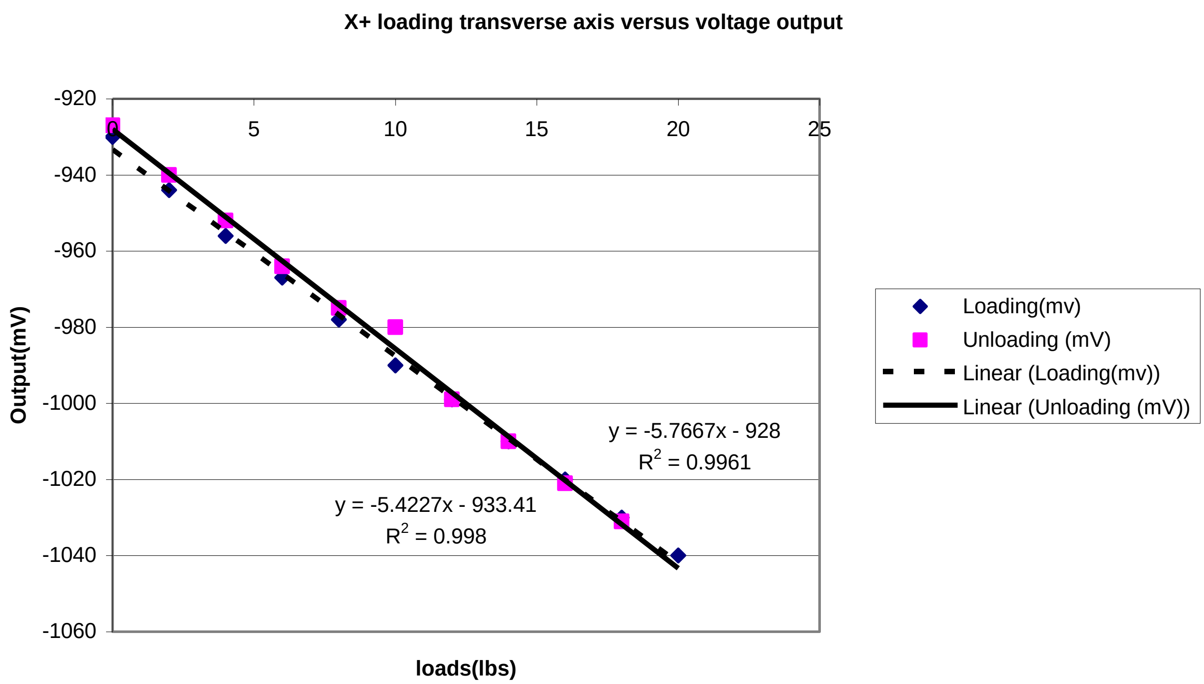

Figure 6 X+ loading transverse axis versus voltage output

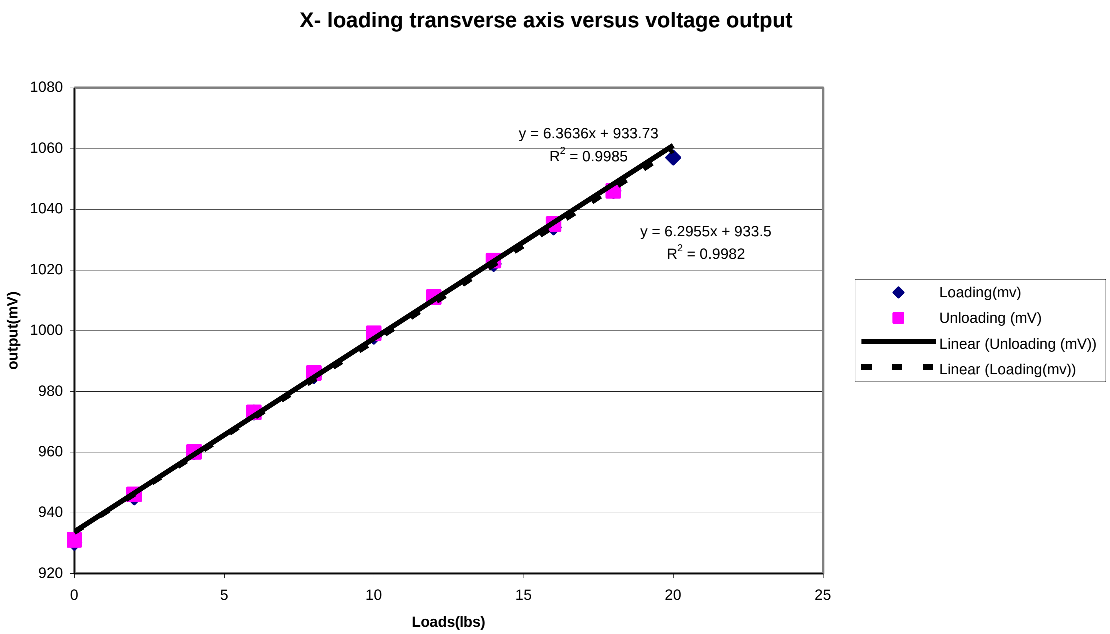

Figure 7 X- loading transverse axis versus voltage output

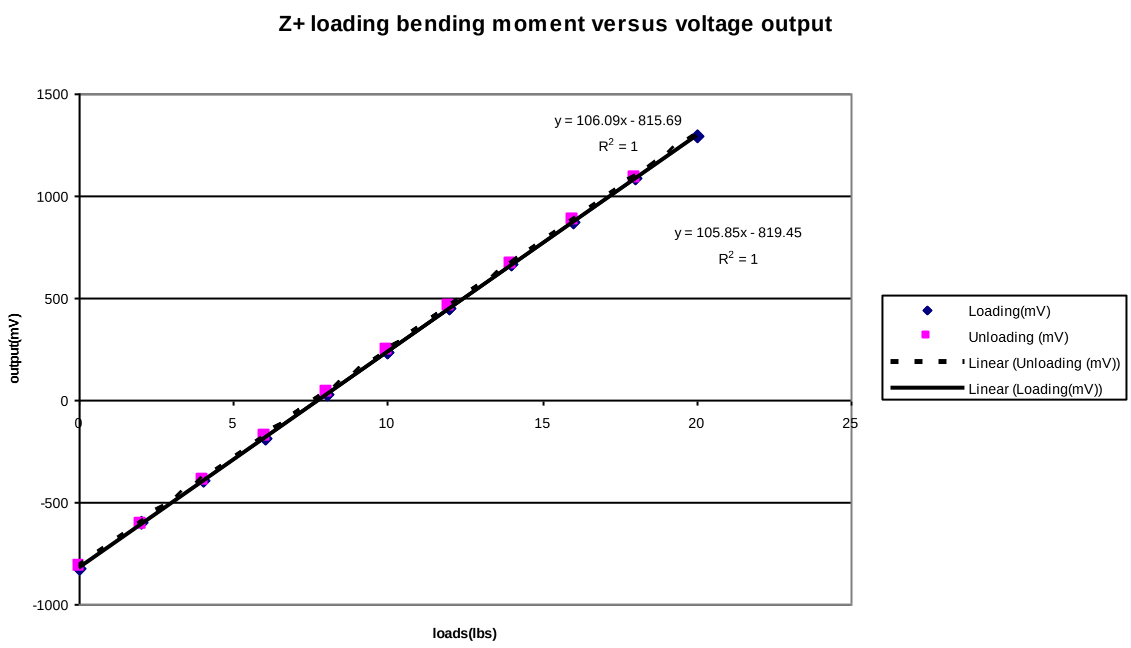

Figure 8 Z+ loading bending moment versus voltage output

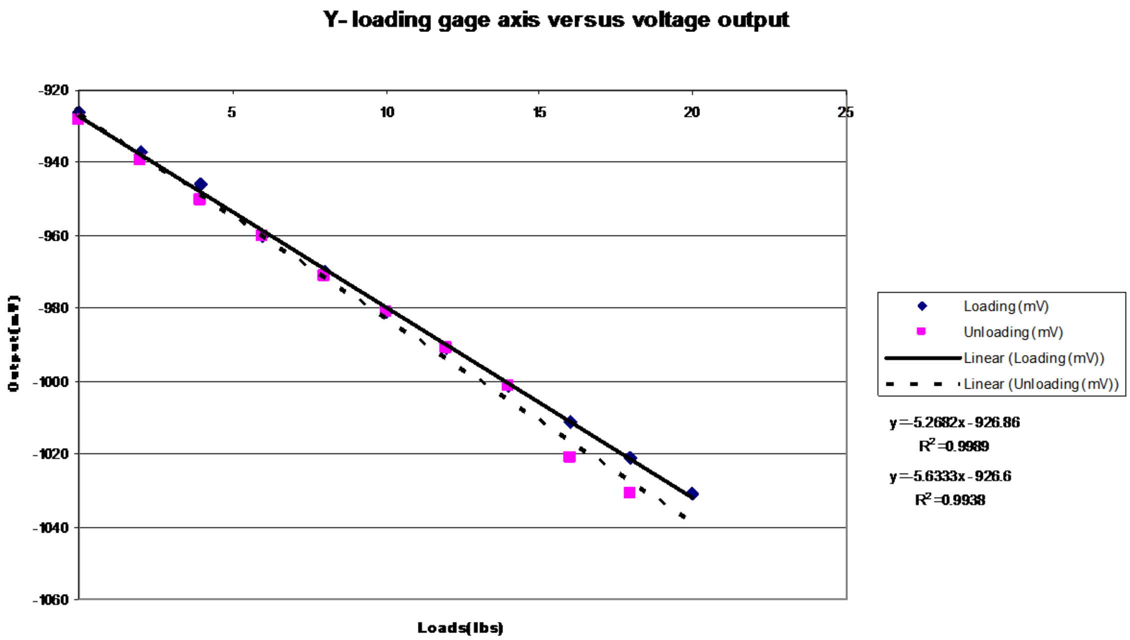

Figure 9 Y- loading gage axis versus voltage output

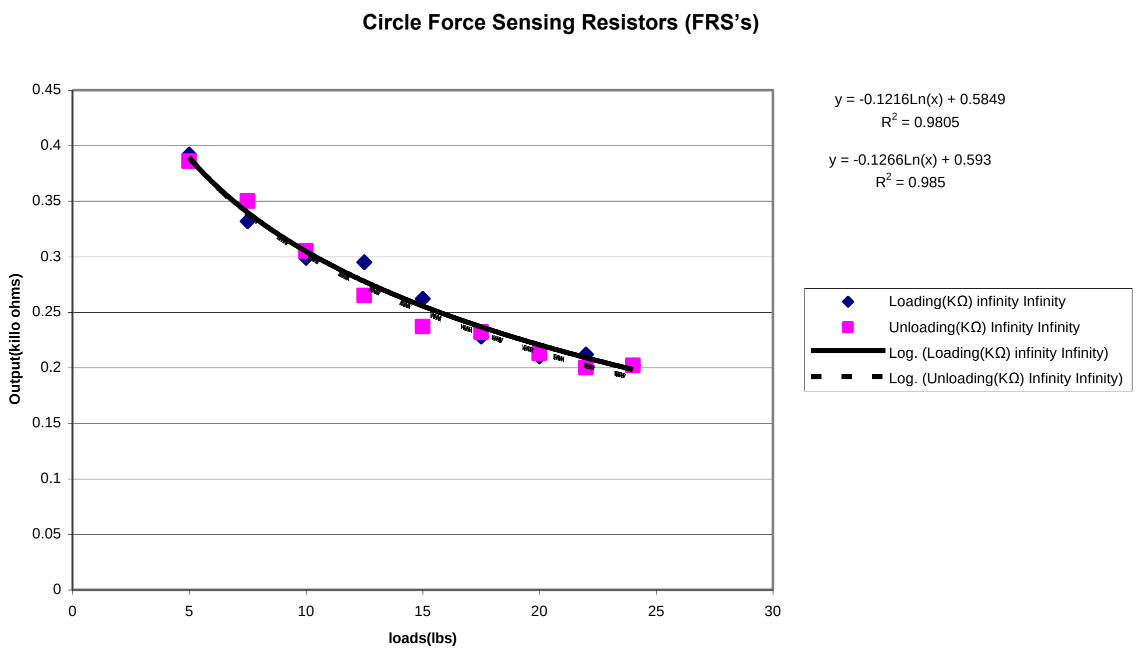

Figure 10 Circle force sensing resistors

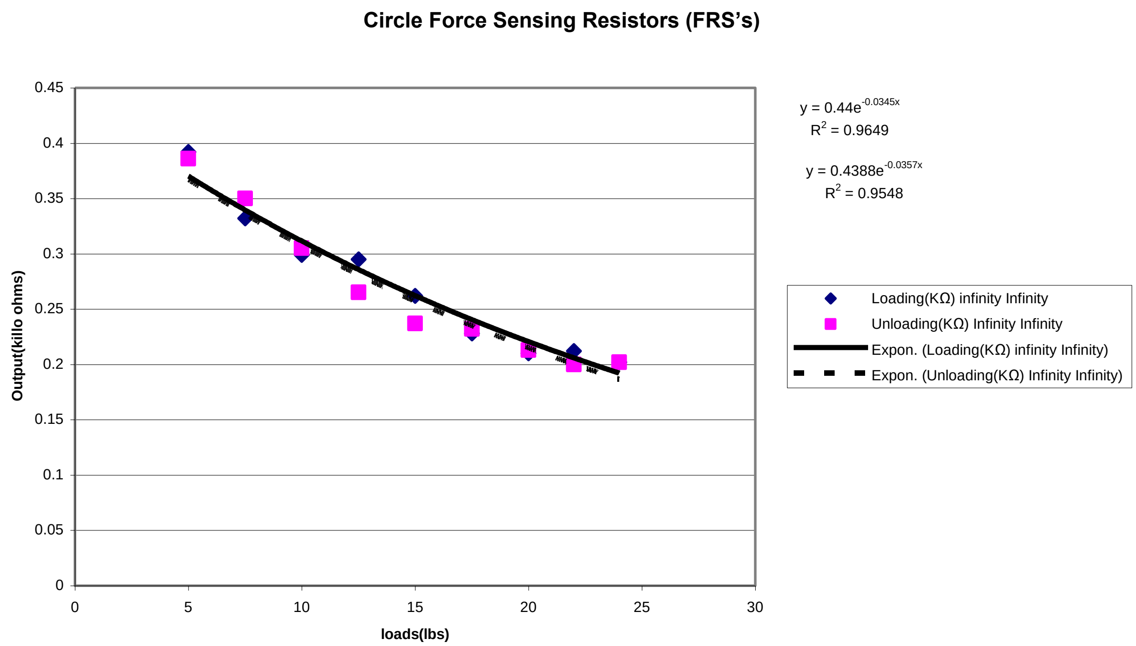

Figure 11 Circle force sensing resistors

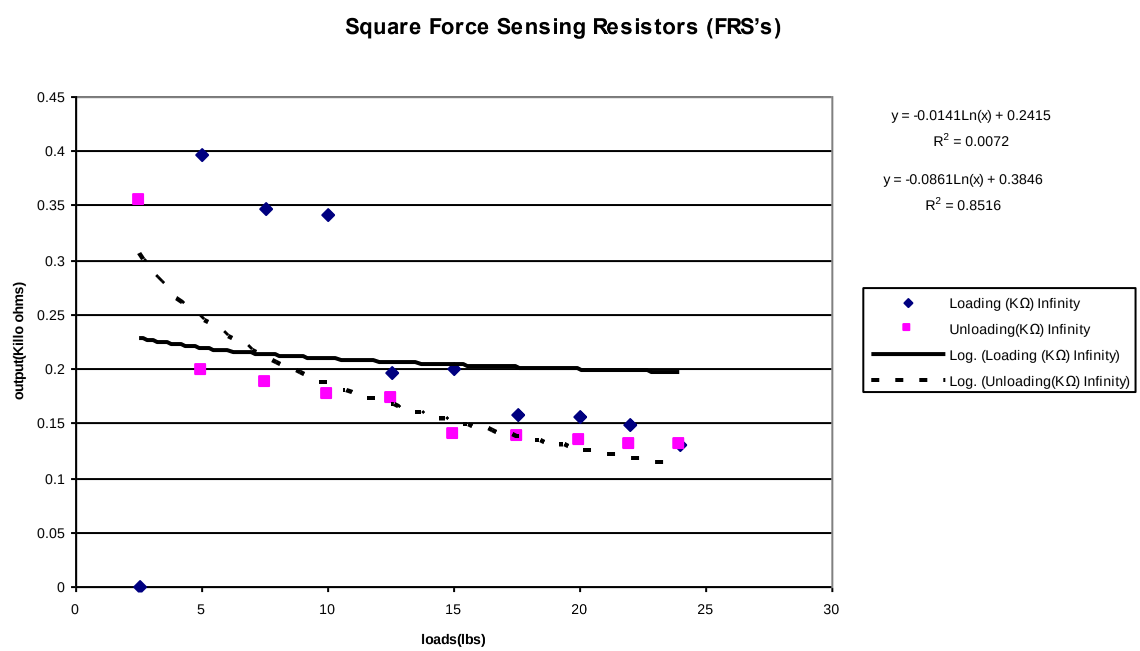

Figure 12 Square force sensing resistors

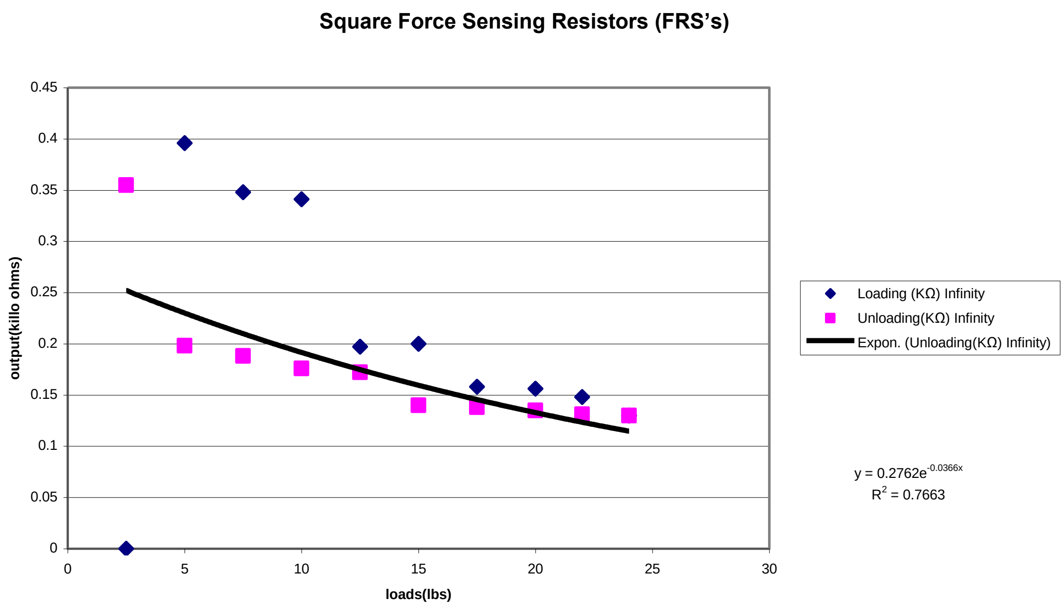

Figure 13 Square force sensing resistors

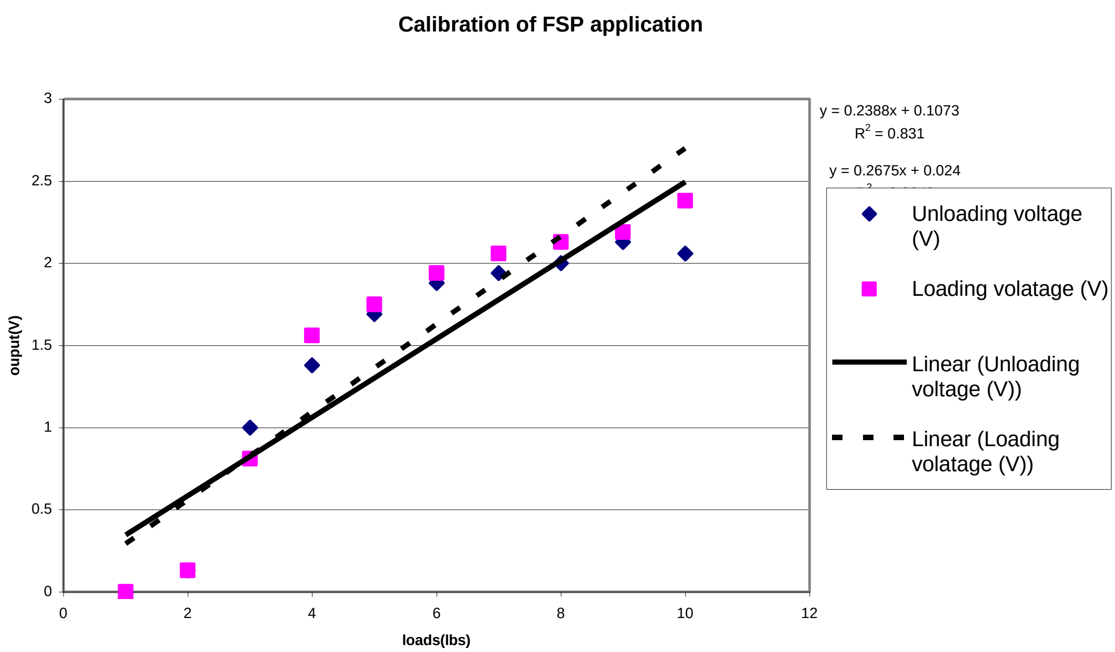

Figure 14 Calibration of FSR application

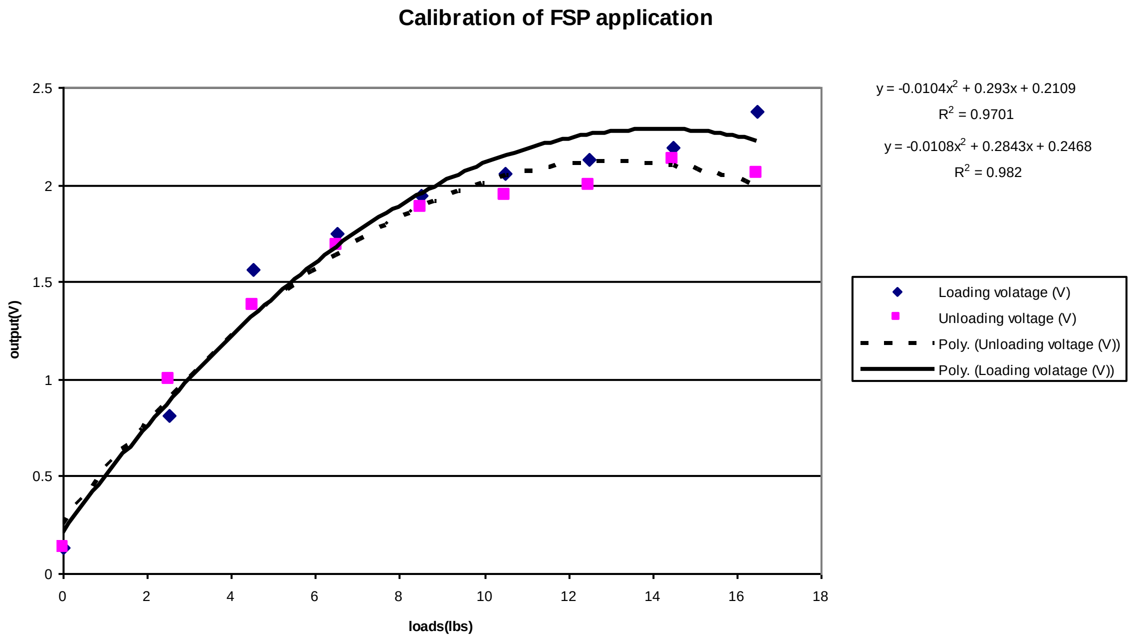

Figure 15 Calibration of FSR application

	Loading	Unloading	Sensitivity of loading	Sensitivity of unloading
X-	y = 6.3636x + 933.73	y = 6.2955x + 933.5	0.9985	0.9982
X+	y = -5.7667x - 928	y = -5.4227x - 933.41	0.9961	0.998
Y-	y = -5.2682x - 926.86	y = -5.6333x - 926.6	0.9989	0.9938
Y+	y = -4.7091x - 931	y = -4.6758x - 930.22	0.997	0.9981
Z+	y = 106.09x - 815.69	y=105.85x - 819.45	1	1

Table 9. Trendline equations and sensitivity values for loading and unloading situation of strain gage. Function Y represents Voltage output (v) and X represents force.

	Logarithm (Loading)	Exponential (Loading)	Logarithm (loading)	Exponential (Unloading)	Sensitivity Logarithm loading	Sensitivity exponential loading	Sensitivity Logarithm unloading	Sensitivity exponential unloading
Circle force sensing resistors	y = -0.1216Ln(x) + 0.5849	y = 0.44e-0.0345x	y = -0.1266Ln(x) + 0.593	$y = 0.4388e^{-0.0357x}$	0.9805	0.9646	0.985	0.9548
Square force sensing resistors	y = -0.0141Ln(x) + 0.2415	N/A	y = -0.0861Ln(x) + 0.3846	$y = 0.2762e^{-0.0366x}$	0.0072	0.8516	N/A	0.7663

Table 10 Trendline equations and sensitivity values for loading and unloading situation of force sensing resistors. Function Y represents resistance output and X represents force.

	Polynomial (loading)	Polynomial (unloading)	Sensitivity Polynomial loading	Sensitivity Polynomial unloading	Linear (loading)	Linear (unloading)	Sensitivity Linear loading	Sensitivity Linear unloading
Calibration Of FSR application	$y = -0.0104x^2 + 0.293x + 0.2109$	$y = -0.0108x^2 + 0.2843x + 0.2468$	0.9701	0.982	y = 0.2388x + 0.1073	y = 0.2675x + 0.024	0.831	0.8649

Table 11 Trendline equations and sensitivity values for loading and unloading situation of force sensing resistors. Function Y represents resistance output and X represents Force.

	Subject 1 Time(sec)	Subject 2 Time(sec)
Stance	1.93	1.65
Heel Strike	1.44	1.66
Toe off	1.63	1.69

Table 12 Heel Strike, Toe off, and Stance duration for each subject and step over 5 seconds

The orthogonal coordinate system with respect to the gage follows right hand rule. Transverse axis is positive X axis and along gage axis is positive Y axis. Therefore, up direction is positive Z axis.

Table 1 through table 5 show the collected data of strain gages with different axis and directions. According to figure 4 through figure 10, which are plots of data, positive Z direction is the most sensitive because R^2 is 1. Even though positive Z direction shows the most sensitive values, it might be errors in there because it cannot be perfectly performed in this real world.

Figure 4 and figure 5 show the gait analysis with FSR foot switch. The upper strike is heel strike and down strike is toe off. When subjects walk with same force, and time, then the shape should be same for each heel strike or each toe off. Even though graph do not have exactly same gait over a period of time, those are very close to determine heel strike and toe off.

According to figure 11 and figure 12, circle force sensing resistors show better fit with logarithms trendline due to the sensitivity. Logarithm equation shows 0.98 sensitivity but exponential equation shows 0.95 sensitivity.

According to figure 13, and figure 14, square force sensing resistors have poor data compare to other parts of data. When students tried to perform exponential tendline, the Microsoft Excel program did not allow performing trendline for “loading” data because data were very scattered. Even though the sensitivity of loading data is very low, unloading data is much better than loading one.

According to calibration of FSR application, figure 15 and figure 16, show the polynomial is better fit than the linear fit due to the higher sensitivity.

According to figure 4, subject 1 had only two toe off regions and three heel strike regions. According to figure 5, subject 2 had three heel strike and toe off regions.

DISCUSSION

Strain gage sensitivity values are going to be large when the direction perpendicular to gage axis (x, z) because of the bigger moment arm to create bending moment. Moment is equal to moment arm cross product of force. Thus, bigger moment arm gives bigger moment.

Resistance is equal to resistivity time length over area. When force is applied the length of strain gage is changed that causes resistance increases. Gage factor is delta L/L = 1 + 2 x poissson's ratio + normalized resistivity / length term. Therefore, changes of length affect resistance.

The strain gages that students used in the lab have the typical deviation from linearity is 1%. According to sensitivity from graphs, the strain gages fall in the region of typical deviation from linearity of 1%. Even though the sensitivity falls in the region of typical deviation of 1%, there are still factors may have affected to the discrepancy. Pulleys that contact with wire are able to move during loading weights. This might cause the different reading of output voltage of strain gages. Also wires are not perfectly straight and also it stretches while weights are loaded.

The FSR resistance versus load shows the non linear relationship between force and resistance. This is caused by few factors. When students loaded weights to the wires, wires vibrate or have pendulum motion even though they try to keep wires to be still. This can cause the reading of output because the pendulum motion can cause momentum in different directions and different magnitude. Also pulleys have mass and friction. Moreover wires are stretchable. Those can cause the calibration does not show linear relationship. The force is approximately proportional to until a saturation region is reached. When forces reach this magnitude, additional forces do not decrease the resistance substantially.

When students heat the FSR, the resistance decreases. When students bent FST, the resistance decreased This property of FSR may affect data for foot switch experiment. A foot of subject was directly contacted FSR which can cause low resistance output due to body temperature. FSR was bending while subjects were walking. This can cause low resistance output due to bending. To minimize these errors, students could put FSR on their foot for a while so FSR has same temperature as body temperature. Also subjects could walk straight so that FSR is bending same side when FSR contact the floor. In the real world, biomedical engineers use Wheatstone bridge to reduce thermal errors and amplify signals.

The strain gages are force sensor. However, the FST is pressure sensor. Because the area of the FSR affects converting from force to voltage or resistance. Pressure is force per area so area is important for FSR. It is pointless when students use 1 meter^2 square FSR for measuring force over 1cm^2.

There are stance phase and swing phase during a gait. The gait has heel contact, foot flat, mid stance, heel off, toe off, mid swing, and heel contact. About 62% of a gait is stance phase and about 38 % is swing phase. When heel is contact on the floor, FSR on the heel decreases resistance and when it is swing phase FSR on the heel does not sense anything. Cerebral palsy patients would not have 62% of a gait in stance phase and about 38% of swing phase. They would have less percentage of stance phase than normal people due to lack of control.

Therefore, the position of FSR is very important on the heel. When students tried to put FSR, they put FSR little bit back of the heel. However, it did not work very well because when heel's contacting surface is changing, FSR does not fully pick the signals. Thus, students put in the middle of the heel which detects much better than previous trials.

CONCLUSION

This lab is successful because students understand the transducers, for example, strain gages, force sensing resistors, and foot switch. Students also learned how to calibrate strain gages with weight. This lab fully conveyed quantify mechanical crosstalk and transducer nonlinearity and use an FSR as a foot switch to determine characteristics of gait.

The results of this lab show the collected data of strain gages with different axis and directions. According to figure 4 through figure 10, which are plots of data, positive Z direction is the most sensitive because R^2 is 1. Even though positive Z direction shows the most sensitive values, it might be errors in there because it cannot be perfectly performed in this real world. Figure 4 and figure 5 show the gait analysis with FSR foot switch. The upper strike is heel strike and down strike is toe off. Because a gait has 62% of stance phase and 38% of swing stance, the foot switch can be used. When heel is contact on the floor, FSR on the heel decreases resistance and when it is swing phase FSR on the heel does not sense anything. Cerebral palsy patients would not have 62% of a gait in stance phase and about 38% of swing phase. They would have less percentage of stance phase than normal people due to lack of control.

Circle force sensing resistors show better fit with logarithms trendline due to the sensitivity. Logarithm equation shows 0.98 sensitivity but exponential equation shows 0.95 sensitivity. Square force sensing resistors have poor data compare to other parts of data. When students tried to perform exponential tendline, the Microsoft Excel program did not allow performing trendline for “loading” data because data were very scattered. Even though the sensitivity of loading data is very low, unloading data is much better than loading one.

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Reference

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