Biometric Piezoelectric Sensor

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Motivation

- Non-invasive measurements
- User-friendly for any type of situation/emergency
- Human energy is harvested from respiratory motion
- Monitors the individual's vitals signs in a remote area
- Durability (Water , Dust, and Drop Resistance)

Current Technology

- Electrocardiogram (EKG or ECG)
  - Records/displays an individual's heart rate
- Thermometer
  - Measures an individual's body temperature
- Sphygmomanometer
  - Measures an individual's blood pressure
- Practical Methods
  - Visual and physical monitoring
    - Carotid artery (neck)
    - Chest
    - Wrist
- Heart Rate and Blood Pressure Monitor in one device
  - Comes in a compact or traditional size
  - Wireless technology
    - Able to sync information to phones, tablets, and watches

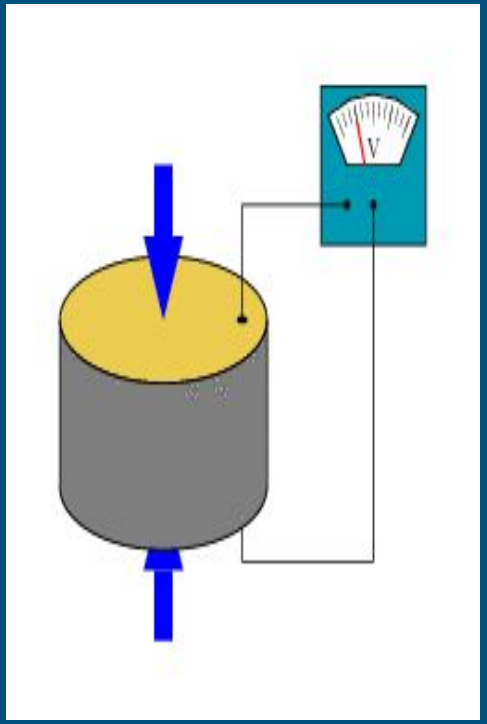
Wireless Blood Pressure & Heart Rate Monitor

Wrist Blood Pressure & Heart Rate Monitor

Limitations With Current Technology

- Singular device
  - Different devices for each vital sign
- Portability
- Convenience
- Accessibility
- Durability
- Affordability
  - Currently any proper devices are too expensive for consumers
- Blood pressure
  - Calculating without cuff
- Development
  - Not enough research is being done with piezoelectricity for a developmental prototype for mass consumption

Background



Piezoelectricity

- Was discovered in 1880 by two French Physicists, Brothers Pierre and Paul Jacques Curie.
- Literal meaning “pressing electricity”
  - Piezein(Greek) “to press”
- Formal Definition
  - “Electricity or electric polarity due to pressure especially in crystalline substance.” -Merriam-Webster
- Crystals by nature have a balanced electrical charge.
- By pressing on the crystal it deforms the crystal structure and therefore creates a net electric charge.

Experimentation

Piezoelectricity

- Experiment 1: Comparison of measurements between piezoelectric materials and control devices for each vital sign.
- Experiment 2: Pulse wave velocity in relation to blood pressure
- Experiment 3: Pulse wave velocity in relation to heart rate, respiratory rate and blood pressure

Arduino

- Phase 1: Preliminary testing
- Phase 2: Narrowing down a setup
- Phase 3: Developing the theory
- Phase 4: Piecing together the final product

PIEZOELECTRICITY

Piezoelectricity

Devices/Software Used To Collect And Analyze Data

- Data Acquisition (DAQ)
  - A system that measures an electrical or physical phenomenon such as voltage, current, temperature, pressure, or sound with a computer.
- Fast Fourier Transform (FFT)
  - Fourier analysis converts a signal from its original domain (often time or space) to a representation in the frequency domain and vice versa.
- Matlab
  - A high-performance language for technical computing. It integrate computation, visualization, and programming in an environment where problems and solutions are expressed in familiar mathematical notation. Typical uses include: data analysis, exploration, and visualization.

Piezoelectricity Experimentation

Experimental Group:

A group of subjects that are exposed to the variable of a control experiment.

- Subject 1
  - Gender: Female
  - Age: 20 years old
  - Ethnicity: Sri Lankan and Mexican
- Subject 2
  - Gender: Male
  - Age: 20 years old
  - Ethnicity: Samoan and Caucasian

Piezoelectric Crystal

PIEZOELECTRICITY: EXPERIMENT 1

Experiment 1

Controlled Experiment:

A scientific test done under controlled conditions, meaning that just one (or a few) factors are changed at a time, while all others are kept constant.

Control Group:

The group in an experiment that does not receive treatment and is used as a benchmark to measure how the other tested subjects do.

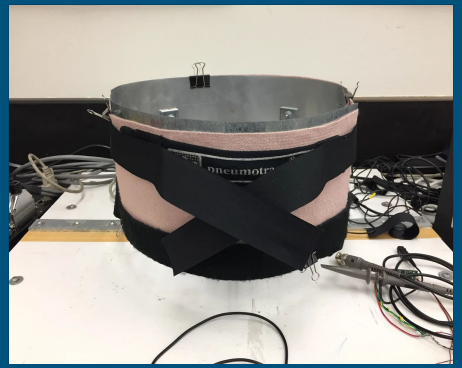
- Finger Sensor
- Respiratory Chest Strap
- Sphygmomanometer

Experiment 1

Control Experiment

- The controls for each vital sign are used on both subjects in multiple trials
- For each trial, the Data Acquisition (DAQ) device reads the voltage from the control in a 30 second interval

Finger Sensor



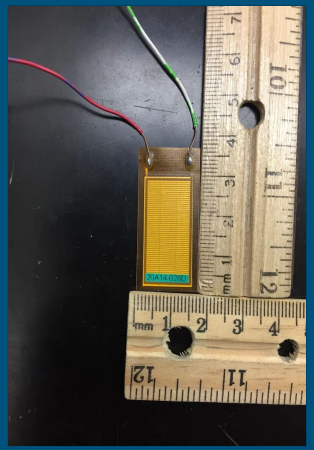
Respiratory Chest Strap

Sphygmomanometer

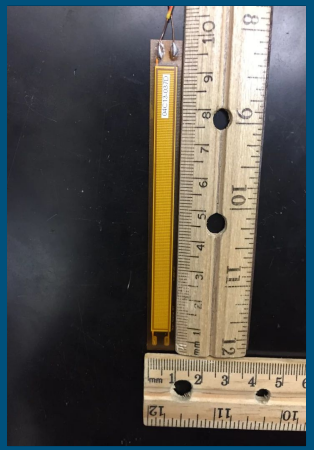
Experiment 1

Piezo Experiment

- Piezo materials of different sizes and shapes are used on both subjects for each vital sign in multiple trials
- For each trial, the Data Acquisition (DAQ) device reads the voltage from the piezo in a 30 second interval
- The piezo material is used in the same manner as the control for each vital sign



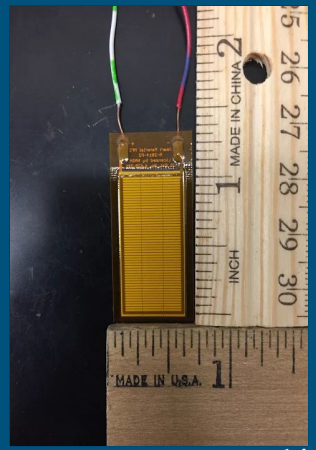
Piezo #1



Piezo #2

Piezo #3

Piezo #4



Piezo #5

Experiment 1: Control Experiment

Finger Sensor

- The subject's right index finger was placed on top of the sensor and wrapped around their finger fittingly

Respiratory Chest Strap

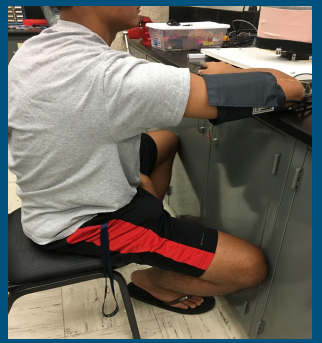
- The strap was wrapped around subject 1’s upper chest and the base of subject 2’s sternum

Sphygmomanometer

- The cuff was wrapped around the subject’s upper arm

Finger Sensor Subject 1

Respiratory Strap Subject 1

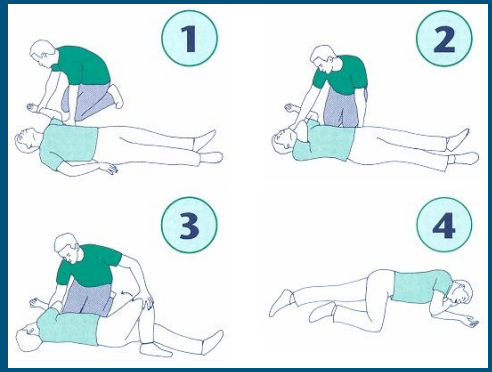


Blood Pressure Cuff Subject 2

Experiment 1: Piezo Experiment

Subject 1

- The subject participated in multiple trials in relation to body position
  - Sitting in an upright position
  - Standing
  - Laying down on her back
  - Recovery position
- The subject only used one piezo material
  - Piezo #5



Recovery Position

Subject 2

- The subject participated in multiple trials with the use of various piezo materials
  - Piezo #1
  - Piezo #2
  - Piezo #3
  - Piezo #4
- The subject sat in an upright position for all trials

Experiment 1: Piezo Experiment

Heart Rate

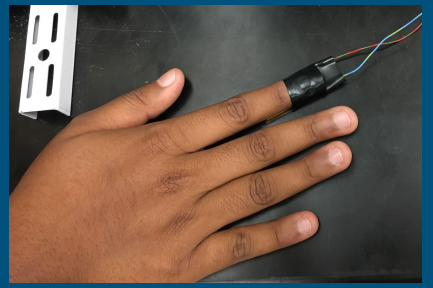
- The piezo was taped around the subject's right index finger

Respiratory Rate

- The piezo was wrapped around subject 1's upper chest and the base of subject 2's sternum

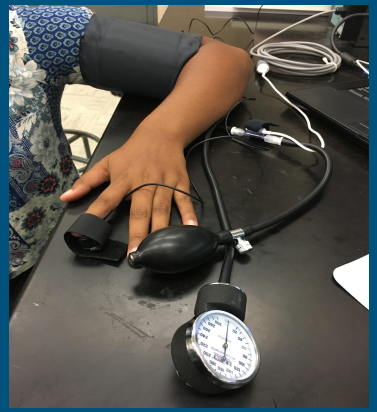
Blood Pressure

- The piezo was in the blood pressure cuff
- The cuff was wrapped around the subject's right upper arm



Piezo
Subject 1

Piezo
Subject 1



Piezo
Subject 1

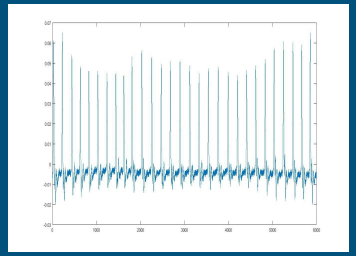
RESULTS: EXPERIMENT 1

Experiment 1

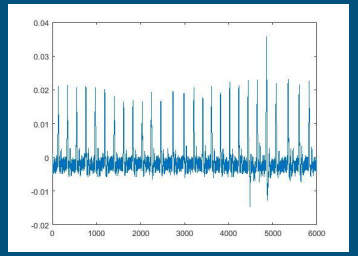
- Using the input analog read by the DAQ, the frequency for each trial was computed by the FFT
- The control and piezo data were graphed by both the DAQ and FFT within a 30 second interval, therefore using 6000 data points.
- For each vital sign, the control graphs are shown, along with the piezo graphs that are most comparable to the control.

Experiment 1: Heart Rate

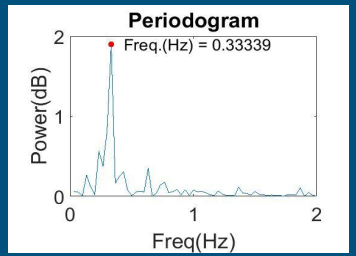
Subject 1



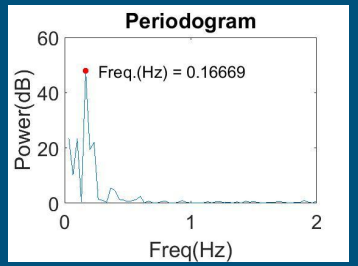
Finger Sensor
Condensed Graph



Piezo #5
Condensed Graph

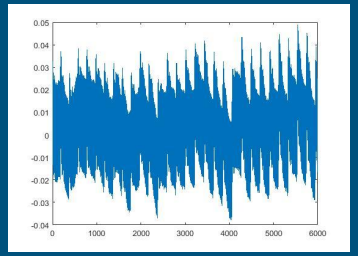


Finger Sensor
FFT Graph

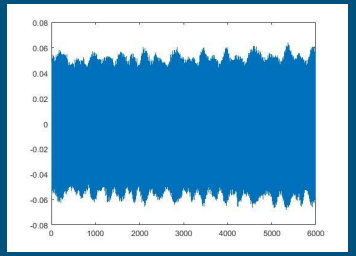


Piezo #5
FFT Graph

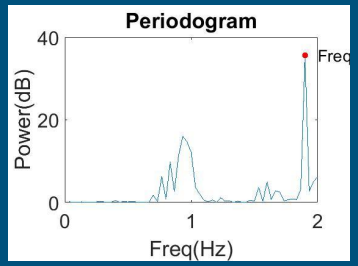
Subject 2



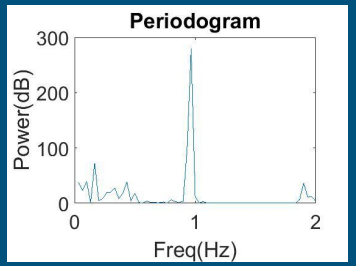
Finger Sensor
Condensed Graph



Piezo #3
Condensed Graph



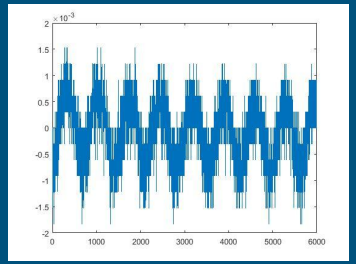
Finger Sensor
FFT Graph



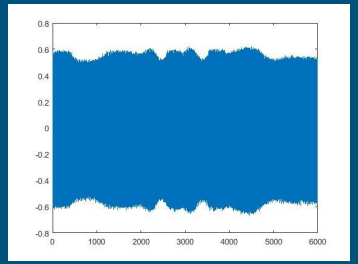
Piezo #3
FFT Graph

Experiment 1: Respiratory Rate

Subject 1

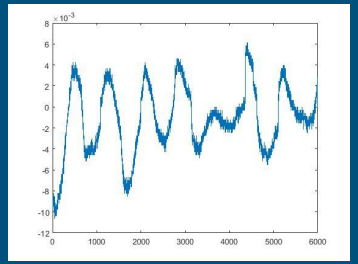


Respiratory Strap
Condensed Graph

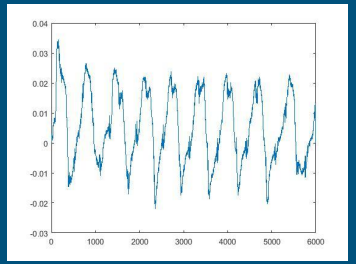


Piezo #5
Condensed Graph

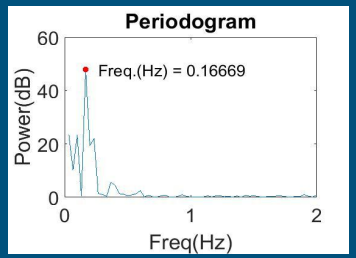
Subject 2



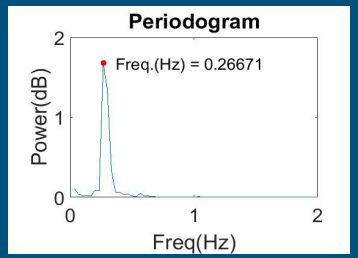
Respiratory Strap
Condensed Graph



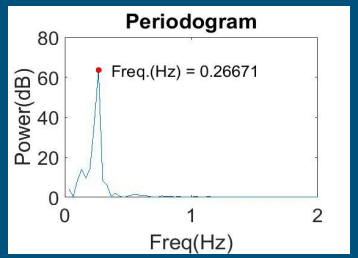
Piezo #3
Condensed Graph



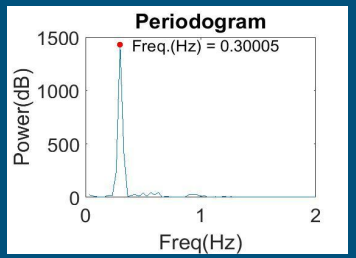
Respiratory Strap
FFT Graph



Piezo #5
FFT Graph



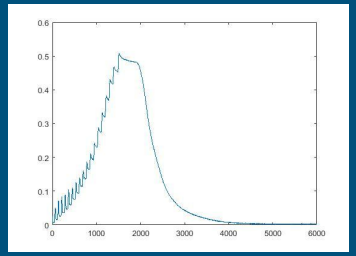
Respiratory Strap
FFT Graph



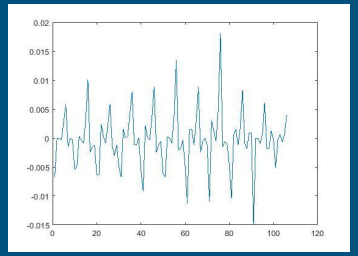
Piezo #3
FFT Graph

Experiment 1: Blood Pressure

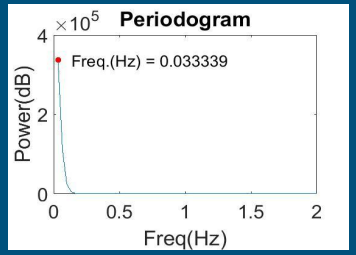
Subject 1



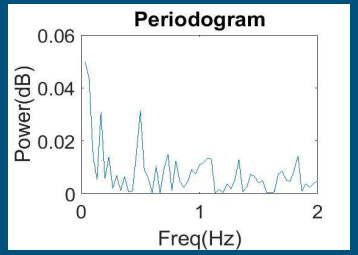
Blood Pressure Cuff
Condensed Graph



Piezo #5
Condensed Graph

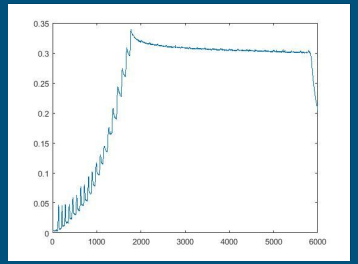


Blood Pressure Cuff
FFT Graph

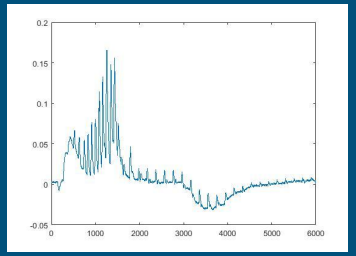


Piezo #5
FFT Graph

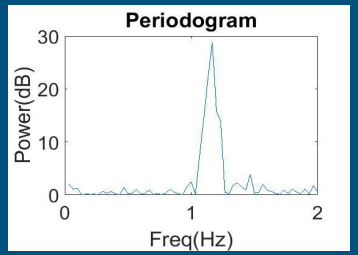
Subject 2



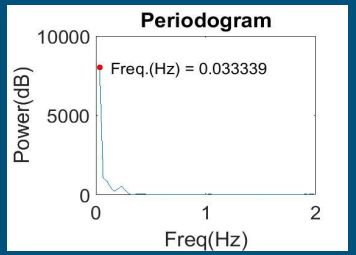
Blood Pressure Cuff
Condensed Graph



Piezo #3
Condensed Graph



Blood Pressure Cuff
FFT Graph



Piezo #3
FFT Graph

PIEZOELECTRICITY: EXPERIMENT 2

Experiment 2

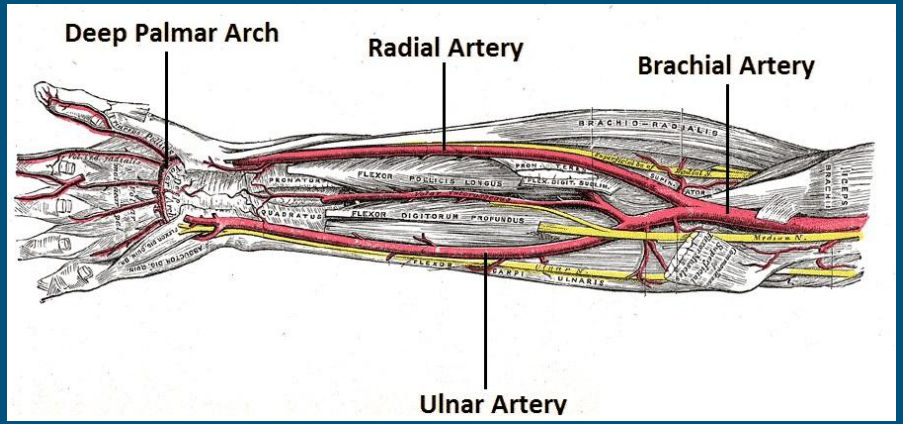
Pulse Wave Velocity

- Pulse wave velocity (PWV) is the velocity at which the arterial pulse propagates through the circulatory system.
- Pulse transit time (PTT) is the time it takes the pulse pressure wave to propagate through a length of the arterial tree.
- Pulse wave velocity and pulse transit time respectively, were shown to have a correlation with systolic blood pressure (SBP).
- Pulse wave velocity may be measured in various segments of the arterial circulation. The time delay and distance between two pressure waves can be recorded and measured at two different sites of the vascular tree.

Mathematical Relationships:

$$Pulse\ Wave\ Velocity = \frac{Distance}{Pulse\ Transit\ Time}$$

$$Pulse\ Transit\ Time = \frac{Point\ Difference}{200}$$



Experiment 2

Pulse Wave Velocity

- Two piezo materials of different sizes are used on both subjects in multiple trials to measure the pulse wave velocity.
- For each trial, the Data Acquisition (DAQ) device reads the voltage from each piezo in a 30 second interval
- The distance between Piezo #1 and Piezo #2 on each subject are recorded for each trial
- Both subjects are sitting in an upright position in the various trials
- Elastic bandages are used to wrap each piezo on both subjects

Piezo	Size
1	10.5mm x 3.1mm
2	10.2mm x 3.2mm

Piezo #1

Piezo #2

Experiment 2: Pulse Wave Velocity

Trial #1

- Piezo #1 was placed on top of the subject's heart and wrapped around their chest
- Piezo #2 was placed on top of the subject's brachial artery and wrapped around their left elbow

Trial #2

- Piezo #2 was placed on top of the subject's heart and wrapped around their chest
- Piezo #1 was placed on top of the subject's brachial artery and wrapped around their left elbow

Chest to Elbow
Subject 1

Chest to Elbow
Subject 2

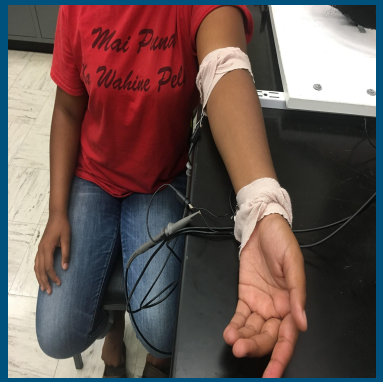
Experiment 2: Pulse Wave Velocity

Trial #3

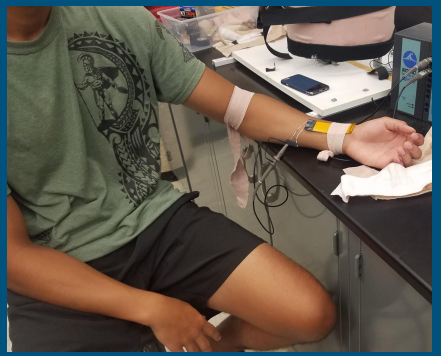
- Piezo #1 was placed on top of the subject's brachial artery and wrapped around their left elbow
- Piezo #2 was placed on top of the subject's radial/ulnar artery and wrapped around their left wrist

Trial #4

- Piezo #2 was placed on top of the subject's brachial artery and wrapped around their left elbow
- Piezo #1 was placed in top of the subject's radial/ulnar artery and wrapped around their left wrist



Elbow to Wrist
Subject 1



Elbow to Wrist
Subject 2

Experiment 2: Pulse Wave Velocity

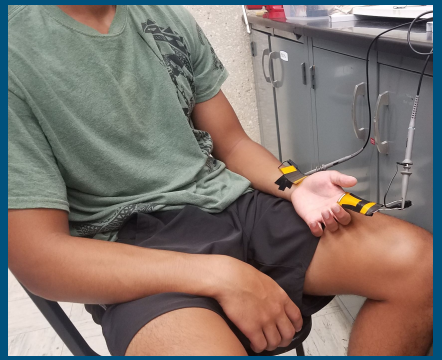
Trial #5

- Piezo #1 was on top of the subject's radial/ulnar artery and wrapped around their left wrist
- Piezo #2 was on top of the subject's digital artery and wrapped around their left index finger

Trial #6

- Piezo #2 was on top of the subject's radial/ulnar artery and wrapped around their left wrist
- Piezo #1 was on top of the subject's digital artery and wrapped around their left index finger

Wrist to Finger
Subject 1



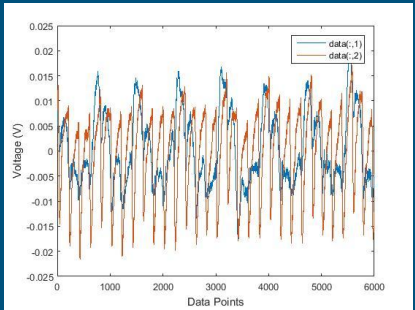
Wrist to Finger
Subject 2

RESULTS: EXPERIMENT 2

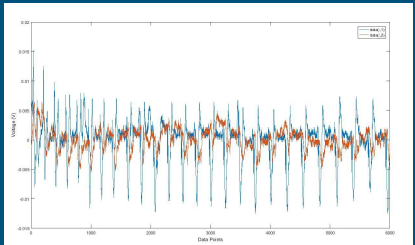
Experiment 2

- The distance between each piezo was measured and recorded for both subjects in each trial.
- Using the input analog read by the Data Acquisition (DAQ) device, the voltage peaks of both piezos for each subject was recorded and plotted in a graph for each trial.
- The data for each trial was graphed by Matlab within a 30 second interval, therefore using 200 data points per second.
- The peaks from the graphs were used to find the average point difference of each piezo within the various trials.
- Due to the graphs having 200 data points per second, the average point difference is divided by 200 to find the pulse transit time, therefore calculating the pulse wave velocity.

Experiment 2: PWV Trial #1



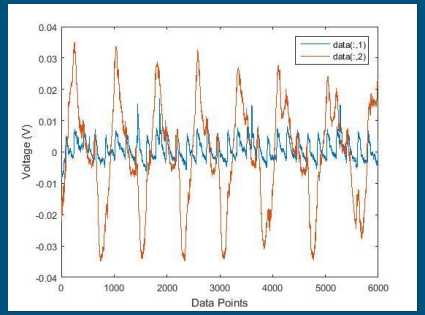
Subject 1



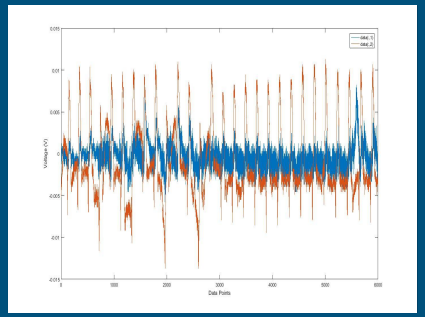
Subject 2

Placement of Piezo #1	Placement of Piezo #2	Subject 1			Subject 2		
		Piezo #1 Peaks	Piezo #2 Peaks	Point Difference	Piezo #1 Peaks	Piezo #2 Peaks	Point Difference
Heart	Brachial Artery	1158	1198	40	35	49	14
		1380	1404	24	99	108	9
		2184	2208	24	388	391	3
Chest	Elbow	2759	2798	39	389	405	16
		4583	4609	26	1153	1161	8
		4746	4809	63	1219	1235	16
		Average		42	Average		11

Experiment 2: PWV Trial #2



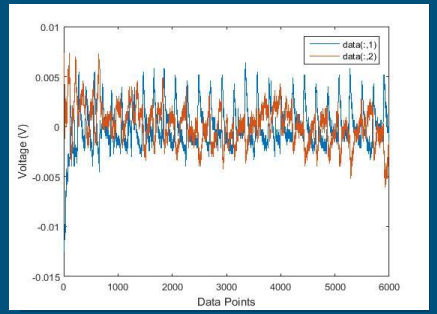
Subject 1



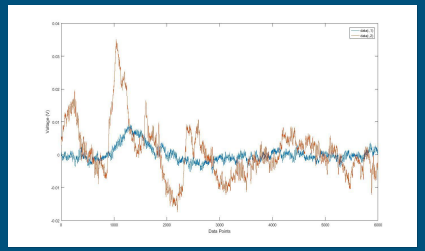
Subject 2

Placement of Piezo #1	Placement of Piezo #2	Subject 1			Subject 2		
		Piezo #1 Peaks	Piezo #2 Peaks	Point Difference	Piezo #1 Peaks	Piezo #2 Peaks	Point Difference
Brachial Artery	Heart	249	253	4	150	167	17
		1623	1639	16	344	364	20
		1849	1863	14	954	975	21
Elbow	Chest	3333	3340	7	1158	1175	17
		3500	3523	23	2212	2225	13
		4256	4276	20	2419	2438	19
		Average		14	Average		17.83

Experiment 2: PWV Trial #3



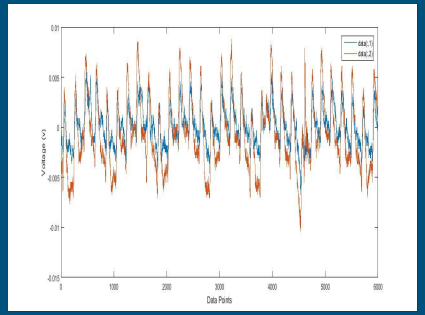
Subject 1



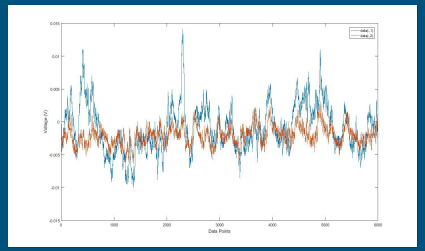
Subject 2

Placement of Piezo #1	Placement of Piezo #2	Subject 1			Subject 2		
		Piezo #1 Peaks	Piezo #2 Peaks	Point Difference	Piezo #1 Peaks	Piezo #2 Peaks	Point Difference
Brachial Artery	Radial/Ulnar Artery	394	409	15	64	72	8
		541	567	26	340	351	11
		862	881	19	445	448	3
Elbow	Wrist	1632	1665	33	602	603	1
		1830	1849	19	904	912	8
		2260	2280	20	1048	1235	187
		Average		22	Average		36.33

Experiment 2: PWV Trial #4



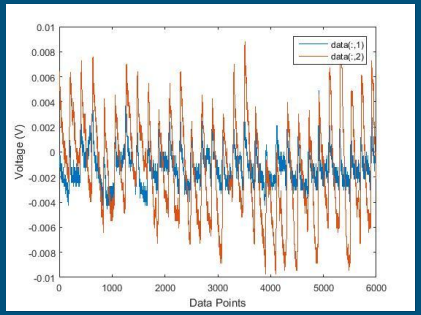
Subject 1



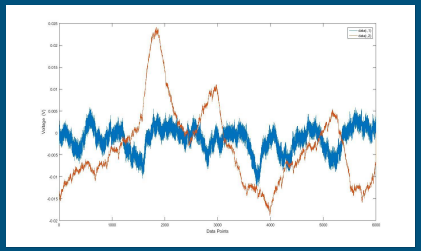
Subject 2

Placement of Piezo #1	Placement of Piezo #2	Subject 1			Subject 2		
		Piezo #1 Peaks	Piezo #2 Peaks	Point Difference	Piezo #1 Peaks	Piezo #2 Peaks	Point Difference
Radial/Ulnar Artery	Brachial Artery	62	80	18	125	138	13
		458	473	15	185	188	3
		869	883	14	282	291	9
Wrist	Elbow	1062	1077	15	335	347	12
		1252	1271	19	365	370	5
		1446	1455	9	408	418	10
		Average		17.5	Average		8.67

Experiment 2: PWV Trial #5



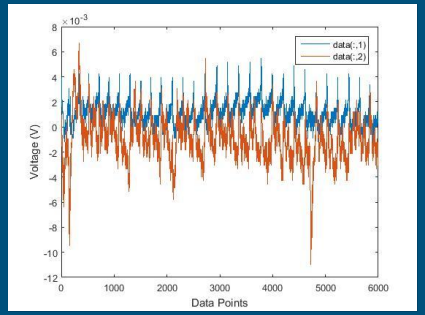
Subject 1



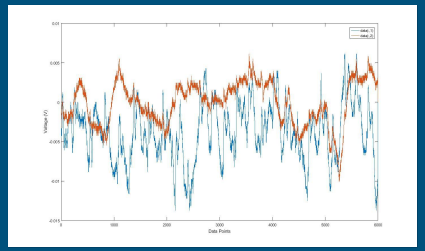
Subject 2

Placement of Piezo #1	Placement of Piezo #2	Subject 1			Subject 2		
		Piezo #1 Peaks	Piezo #2 Peaks	Point Difference	Piezo #1 Peaks	Piezo #2 Peaks	Point Difference
Radial/Ulnar Artery	Digital Artery	199	208	9	99	101	2
		414	417	3	220	231	11
		630	636	6	337	341	4
Wrist	Finger	551	556	5	1167	1171	4
		1060	1062	2	1197	1205	8
		1264	1272	8	1384	1680	296
		Average		5.5	Average		54.17

Experiment 2: PWV Trial #6



Subject 1



Subject 2

Placement of Piezo #1	Placement of Piezo #2	Subject 1			Subject 2		
		Piezo #1 Peaks	Piezo #2 Peaks	Point Difference	Piezo #1 Peaks	Piezo #2 Peaks	Point Difference
Digital Artery	Radial/Ulnar Artery	332	336	4	549	550	1
		1096	1101	5	823	827	4
		1507	1508	1	1096	1108	12
Finger	Wrist	1697	1700	3	1645	1655	10
		1892	1901	9	1922	1927	5
		2101	2103	2	2618	2633	15
		Average		4	Average		7.83

Experiment 2: Pulse Wave Velocity

Trial	Point Difference Average	Pulse Transit Time (sec)	Distance (m)	Pulse Wave Velocity (m/s)
1	42	0.21	0.45	2.14286
2	14	0.07	0.45	6.42857
3	22	0.11	0.26	2.36364
4	17.5	0.088	0.26	2.95455
5	5.5	0.028	0.19	6.78571
6	4	0.02	0.19	9.5000

Pulse Wave Velocity
Subject 1

Trial	Point Difference Average	Pulse Transit Time (sec)	Distance (m)	Pulse Wave Velocity (m/s)
1	11	0.055	0.64	11.6364
2	17.83	0.089	0.582	6.53933
3	36.33	0.182	0.275	1.51099
4	8.67	0.043	0.275	6.39535
5	54.17	0.271	0.231	0.852399
6	7.83	0.039	0.231	5.92308

Pulse Wave Velocity
Subject 2

PIEZOELECTRICITY: EXPERIMENT 3

Experiment 3

The Association Between Pulse Wave Velocity and Blood Pressure

- Blood pressure (BP) is a measurement of the force on the walls of your arteries as your heart pumps blood through your body.
  - Blood pressure readings are usually given as two numbers, your systolic blood pressure over your diastolic blood pressure.
- Pulse wave velocity (PWV) is the velocity at which the arterial pulse propagates through the circulatory system.
  - Pulse wave velocity may be measured in various segments of the arterial circulation. The time delay and distance between two pressure waves can be recorded and measured at two different sites of the vascular tree.
- Pulse wave velocity is closely related to cuff-derived blood pressure.
- Mathematical Relationships:

$$Pulse\ Wave\ Velocity = \frac{Distance}{Pulse\ Transit\ Time}$$

$$Pulse\ Pressure = Systolic\ Pressure - Diastolic\ Pressure$$

$$Blood\ Pressure\ Constant = \frac{Pulse\ Wave\ Velocity}{(\sqrt{Pulse\ Pressure})}$$

$$Pulse\ Transit\ Time = \frac{Point\ Difference}{200}$$

Experiment 3

Pulse Wave Velocity In Relation to Blood Pressure, Heart Rate and Respiratory Rate

- Continuation of the pulse wave velocity experiment, but focusing on the brachial artery to radial/ulnar artery method
- Each subject will participate in a retrial based on the analysis of the data from the previous pulse wave velocity trials

Control Measurement of Respiratory Rate In Relation to Pulse Wave Velocity

- Respiratory chest strap
  - The respiratory rate for each subject is measured as a control while using the pulse wave velocity setup

Reference/Control Measurement of Pulse Pressure, Heart Rate and Blood Pressure

- Wrist blood pressure monitor
  - The pulse pressure for each subject is measured as a reference to calculate the blood pressure constant
  - The blood pressure for each subject is measured as a control
  - The pulse rate for each subject is measured as a control

Experiment 3: Pulse Wave Velocity

Pulse Wave Velocity In Relation To Blood Pressure, Heart Rate and Respiratory Rate

- Two piezo materials of different sizes were used on both subjects in multiple trials to measure the pulse wave velocity.
- For each trial, the Data Acquisition (DAQ) device read the voltage from each piezo in a 30 second interval
- The distance between Piezo #1 and Piezo #2 on each subject were recorded for each trial
- Both subjects sat in an upright position in the various trials
- Elastic bandages were used to wrap each piezo on both subjects

Piezo	Size
1	10.5mm x 3.1mm
2	10.2mm x 3.2mm

Piezo #1

Piezo #2

Experiment 3: Pulse Wave Velocity

Trial #7

- Piezo #1 was placed on top of the subject's brachial artery and wrapped around their left upper arm
- Piezo #2 was placed on top of the subject's radial/ulnar artery and wrapped around their left wrist

Trial #8

- Piezo #2 was placed on top of the subject's brachial artery and wrapped around their left upper arm
- Piezo #1 was placed on top of the subject's radial/ulnar artery and wrapped around their left wrist

Upper Arm to Wrist
Subject 1

Upper Arm to Wrist
Subject 2

Experiment 3: Pulse Wave Velocity

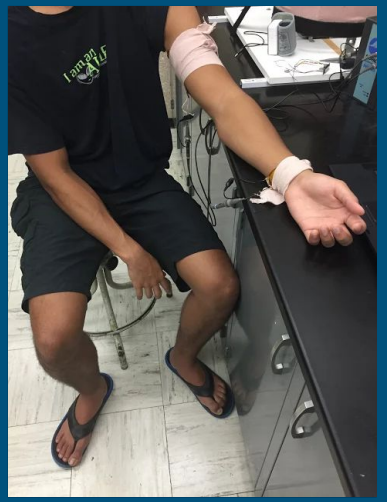
Trial #9: Subject 1

- Piezo #1 was placed on top of the subject's brachial artery and wrapped around their left elbow
- Piezo #2 was placed on top of the subject's radial/ulnar artery and wrapped around their left wrist

Trial #9: Subject 2

- Piezo #2 was placed on top of the subject's brachial artery and wrapped around their left upper arm
- Piezo #1 was placed on top of the subject's radial/ulnar artery and wrapped around their left wrist

Elbow to Wrist
Subject 1



Upper Arm to Wrist
Subject 2

Experiment 3: Control Measurement of Respiratory Rate

Trial #10: Subject 1

- Piezo #1 was placed on top of the subject's brachial artery and wrapped around their left elbow
- Piezo #2 was placed on top of the subject's radial/ulnar artery and wrapped around their left wrist
- Respiratory chest strap was wrapped around the subject's upper chest

Trial #10: Subject 2

- Piezo #2 was placed on top of the subject's brachial artery and wrapped around their left upper arm
- Piezo #1 was placed on top of the subject's radial/ulnar artery and wrapped around their left wrist
- Respiratory chest strap was wrapped around the end of the subject's sternum

Elbow to Wrist
Subject 1

Upper Arm to Wrist
Subject 2

Experiment 3: Reference/Control Measurement

- The wrist blood pressure monitor was wrapped around the subject's left wrist
- Both subjects sat in an upright position
- The systolic pressure, diastolic pressure, and pulse rate read by the monitor are recorded

Wrist Blood Pressure Monitor

Wrist Blood Pressure Monitor Subject 2

Wrist Blood Pressure Monitor Subject 1

RESULTS: EXPERIMENT 3

Experiment 3

Pulse Wave Velocity

- The distance between each piezo was measured and recorded for both subjects.
- Using the input analog read by the DAQ, the voltage peaks of both piezos for each subject was recorded and plotted in a graph.
- The data was graphed by Matlab within a 30 second interval, therefore using 200 data points per second.
- The multiple peaks were used to find the point differences of each piezo within the subject's trial.
- Due to the graphs having 200 data points per second, the point difference for each peak variation is divided by 200 to find the pulse transit time, therefore calculating the pulse wave velocity.

Reference/Control Measurement

- The systolic pressure, diastolic pressure and pulse rate read by the wrist blood pressure monitor was recorded for both subjects.
- The data was used to calculate pulse pressure as a reference to then calculate the blood pressure constant of each subject.

Experiment 3

Control Measurement of Respiratory Rate

- Using the input analog read by the DAQ, the voltage input of the respiratory chest strap for each subject was recorded and plotted in a graph.
- The data was graphed by Matlab within a 30 second interval, therefore using 200 data points per second.
- The frequencies of each piezo and the respiratory chest strap was computed by the FFT and graphed within a 30 second interval, therefore using 6000 data points.

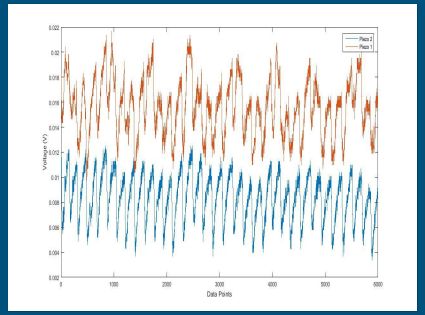
Blood Pressure Constant

- The blood pressure constant of each subject for the various trials were calculated using the data and reference measurements recorded

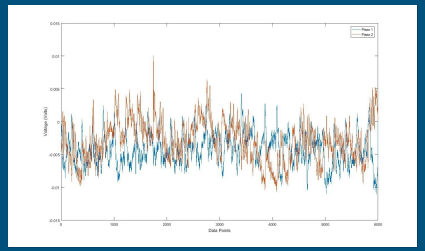
Correlation Between Heart Rate and Respiratory Rate

- The FFT graphs of each piezo and the respiratory chest strap

Experiment 3: PWV Trial #7



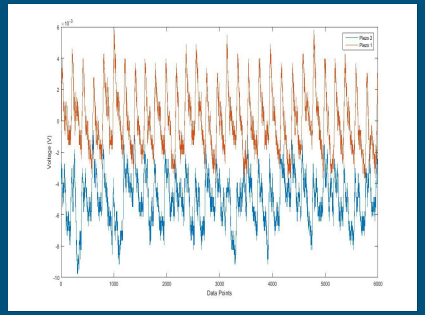
Subject 1



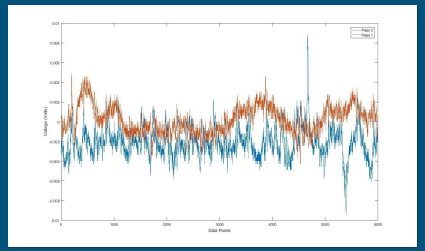
Subject 2

Placement of Piezo #1	Placement of Piezo #2	Subject 1			Subject 2		
		Piezo #1 Peaks	Piezo #2 Peaks	Point Difference	Piezo #1 Peaks	Piezo #2 Peaks	Point Difference
Brachial Artery	Radial/Ulnar Artery	148	152	6	13	34	21
		293	304	11	198	217	19
		660	665	5	595	613	18
Upper Arm	Wrist	855	860	5	800	823	23
		1032	1036	4	1639	1659	20
		1195	1205	10	1857	1876	19

Experiment 3: PWV Trial #8



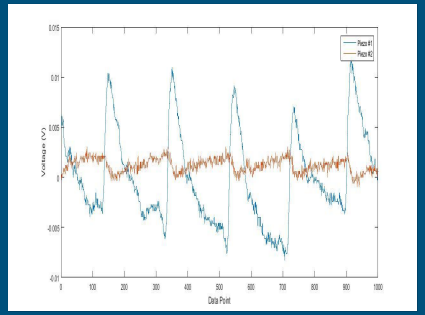
Subject 1



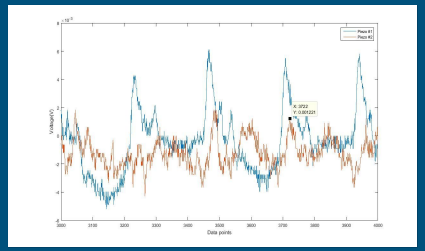
Subject 2

Placement of Piezo #1	Placement of Piezo #2	Subject 1			Subject 2		
		Piezo #1 Peaks	Piezo #2 Peaks	Point Difference	Piezo #1 Peaks	Piezo #2 Peaks	Point Difference
Brachial Artery	Radial/Ulnar Artery	403	418	15	145	132	13
		794	813	19	2047	2035	12
		991	1002	11	2392	2372	20
Upper Arm	Wrist	1188	1211	23	3094	3082	12
		1390	1404	14	3339	3327	12
		1770	1788	18	3897	3884	13

Experiment 3: PWV Trial #9



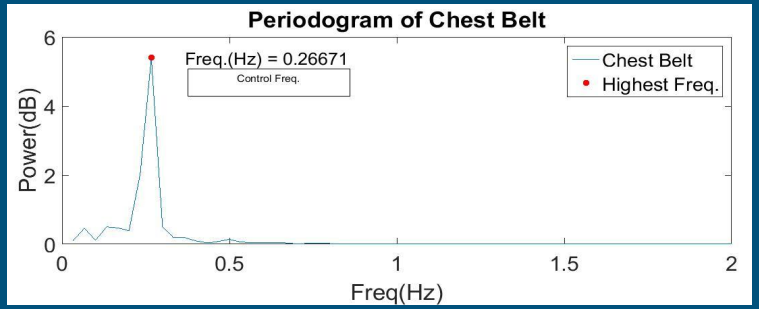
Subject 1



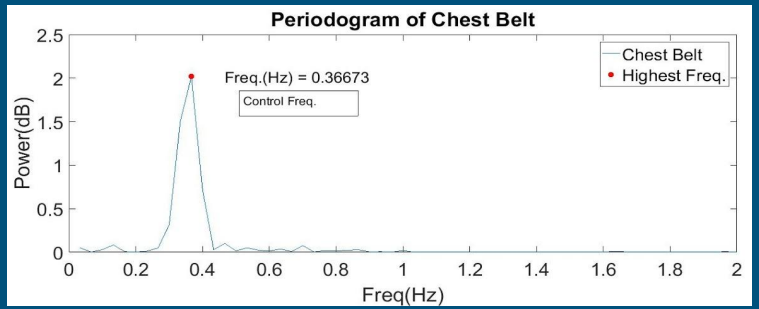
Subject 2

Placement of Piezo #1	Placement of Piezo #2	Subject 1			Subject 2		
		Piezo #1 Peaks	Piezo #2 Peaks	Point Difference	Piezo #1 Peaks	Piezo #2 Peaks	Point Difference
Brachial Artery	Radial/Ulnar Artery	138	151	13	545	16	16
		720	735	15	758	772	14
Subject 1		903	917	14	1187	1202	15
Elbow	Wrist	1500	1510	10	2046	2058	12
Subject 2		2281	2293	12	3465	3482	17
Upper Arm	Wrist	3715	3726	11	3708	3722	14

Experiment 3: RR Control Trial #10



Subject 1



Subject 2

Subject	Frequency (Hz)	Respiratory Rate (breath/min)
1	0.26671	16
2	0.36673	22

Experiment 3: Reference/Control Measurement

Subject	Trial	Wrist Blood Pressure Monitor					Respiratory Chest Strap
		Systolic Pressure (mmHg)	Diastolic Pressure (mmHg)	Pulse Rate (pulse/min)	Pulse Pressure (mmHg)	Blood Pressure (mmHg)	Respiratory Rate (breath/min)
1	7, 8	87	58	59	29	87/58	---------
	9	87	57	61	20	87/57	16
2	7, 8	117	79	57	38	117/79	---------
	9	116	73	52	43	116/73	22

Experiment 3: Blood Pressure Constant

Trial #3							
Subject 1				Subject 2			
Distance (m)	Pulse Transit Time (sec)	Pulse Wave Velocity (m/s)	Blood Pressure Constant (mmHg)	Distance (m)	Pulse Transit Time (sec)	Pulse Wave Velocity (m/s)	Blood Pressure Constant (mmHg)
0.26	0.075	3.46667	0.643744	0.275	0.04	6.875	1.11527
	0.13	2	0.371391		0.055	5	0.811107
	0.095	2.73684	0.508219		0.015	18.333	2.97406
	0.165	1.57576	0.292611		0.005	55	8.92218
	0.095	2.73684	0.508219		0.04	6.875	1.11527
	0.1	2.6	0.482808		0.025	11	1.78

Experiment 3: Blood Pressure Constant

Trial #4							
Subject 1				Subject 2			
Distance (m)	Pulse Transit Time (sec)	Pulse Wave Velocity (m/s)	Blood Pressure Constant (mmHg)	Distance (m)	Pulse Transit Time (sec)	Pulse Wave Velocity (m/s)	Blood Pressure Constant (mmHg)
0.26	0.09	2.88	0.536453	0.275	0.065	4.23077	0.686321
	0.075	3.46667	0.643744		0.035	7.85714	1.2746
	0.07	3.71429	0.689726		0.045	6.11111	0.991353
	0.075	3.46667	0.643744		0.06	4.58333	0.743515
	0.095	2.73684	0.508219		0.025	11	1.78444
	0.045	5.77778	1.07291		0.05	5.5	0.892218

Experiment 3: Blood Pressure Constant

Trial #7							
Subject 1				Subject 2			
Distance (m)	Pulse Transit Time (sec)	Pulse Wave Velocity (m/s)	Blood Pressure Constant (mmHg)	Distance (m)	Pulse Transit Time (sec)	Pulse Wave Velocity (m/s)	Blood Pressure Constant (mmHg)
0.33	0.03	11	2.04265	0.47	0.105	4.47619	0.726134
	0.055	6	1.11417		0.095	4.94737	0.802569
	0.025	13.2	2.45118		0.09	5.22222	0.847156
	0.025	13.2	2.45118		0.115	4.08696	0.662992
	0.02	16.5	3.06397		0.1	4.7	0.762441
	0.05	6.6	1.22559		0.095	4.94737	0.802569

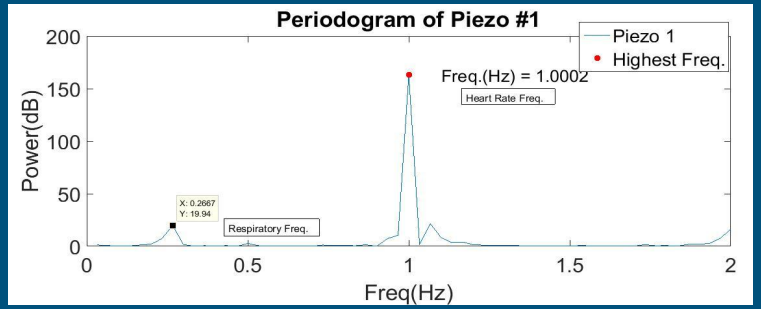
Experiment 3: Blood Pressure Constant

Trial #8							
Subject 1				Subject 2			
Distance (m)	Pulse Transit Time (sec)	Pulse Wave Velocity (m/s)	Blood Pressure Constant (mmHg)	Distance (m)	Pulse Transit Time (sec)	Pulse Wave Velocity (m/s)	Blood Pressure Constant (mmHg)
0.33	0.075	4.4	0.817059	0.47	0.065	7.23077	1.17299
	0.095	3.47368	0.645047		0.06	7.83333	1.27073
	0.055	6	1.11417		0.1	4.7	0.762441
	0.115	2.86957	0.532865		0.06	7.83333	1.27073
	0.07	4.71429	0.875421		0.06	7.83333	1.27073
	0.09	3.66667	0.680883		0.065	7.23077	1.17299

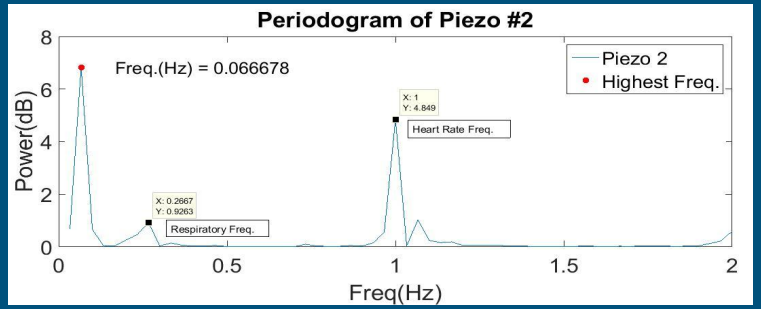
Experiment 3: Blood Pressure Constant

Trial #9							
Subject 1				Subject 2			
Distance (m)	Pulse Transit Time (sec)	Pulse Wave Velocity (m/s)	Blood Pressure Constant (mmHg)	Distance (m)	Pulse Transit Time (sec)	Pulse Wave Velocity (m/s)	Blood Pressure Constant (mmHg)
0.245	0.065	3.76923	0.688164	0.475	0.08	5.93750	0.905460
	0.075	3.26667	0.596409		0.07	6.78571	1.034812
	0.07	3.50000	0.639010		0.075	6.33333	0.0965824
	0.05	4.90000	0.894614		0.06	7.91667	1.207280
	0.06	4.08333	0.745511		0.085	5.58824	0.852198
	0.055	4.45455	0.813285		0.07	6.78571	1.034812

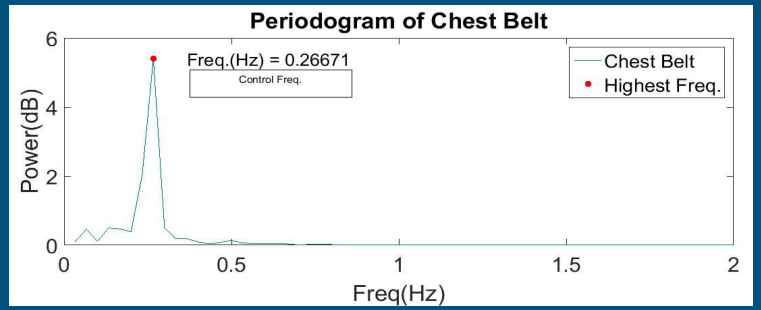
Experiment 3: Correlation Between Heart Rate and Respiratory Rate Using Piezoelectricity



Piezo #1 FFT Graph
Subject 1

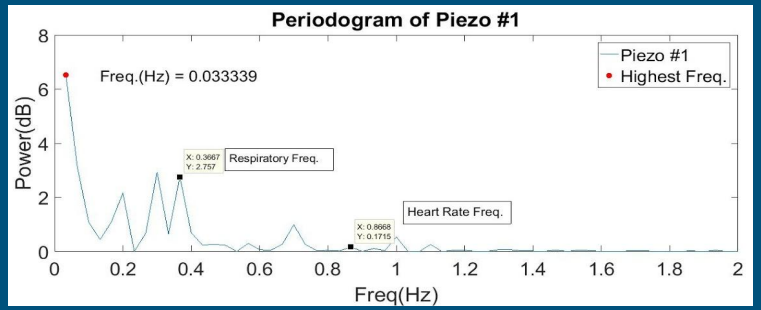


Piezo #2 FFT Graph
Subject 1

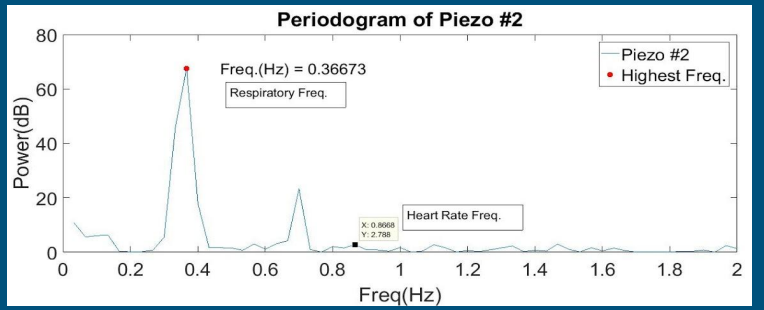


Respiratory Chest Strap FFT Graph
Subject 1

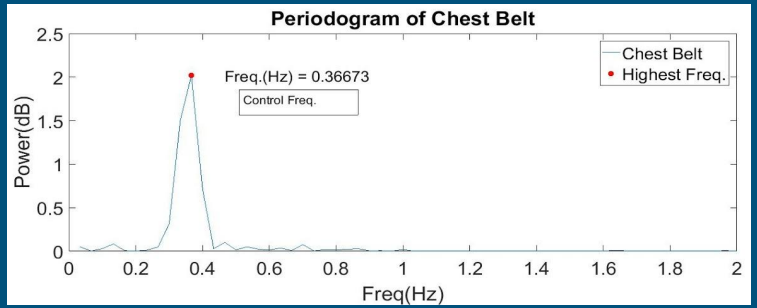
Experiment 3: Correlation Between Heart Rate and Respiratory Rate Using Piezoelectricity



Piezo #1 FFT Graph
Subject 2



Piezo #2 FFT Graph
Subject 2



Respiratory Chest Strap FFT Graph
Subject 2

Experiment 3: Heart Rate and Respiratory Rate

Subject	Trial	Vital Sign	Control	Piezo	
1	9	Heart Rate (beat/min)	Wrist Blood Pressure Monitor	#1	#2
			61	60.012	60
		Respiratory Rate (breath/min)	Respiratory Chest Belt	#1	#2
			0.26671	0.2667	0.2667
2		Heart Rate (beat/min)	Wrist Blood Pressure Monitor	#1	#2
			52	52.008	52.008
		Respiratory Rate (breath/min)	Respiratory Chest Belt	#1	#2
			0.36673	0.3667	0.3667

Percent Error					
Subject	Trial	Heart Rate		Respiratory Rate	
		Piezo #1	Piezo #2	Piezo #1	Piezo #2
1	9	0.016 %	1.7%	0.0037 %	0.0037 %
2		0.015 %	0.015 %	0.0082 %	0%

ARDUINO

Arduino

The goal of this project is to create simpler alternatives to biosensors, such as electrocardiograms(EKG/ECG), thermometers, sphygmomanometers, etc., and data acquisition systems (DAQ) analysis.

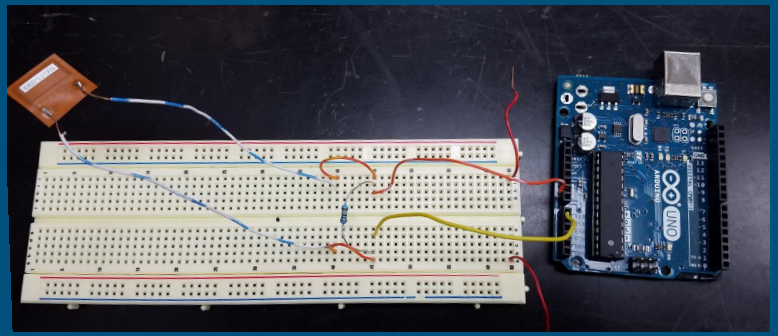
Project Goals

- Sense a basic vital sign (heart rate, blood pressure, respiratory rate) with a piezoelectric sensor
- Analyze piezoelectric inputs using an Arduino
- Avoid complex setup involving Operational Amplifiers (op amps)
- Applying core concepts of peak detection to analyze data
- Easily archive and access data

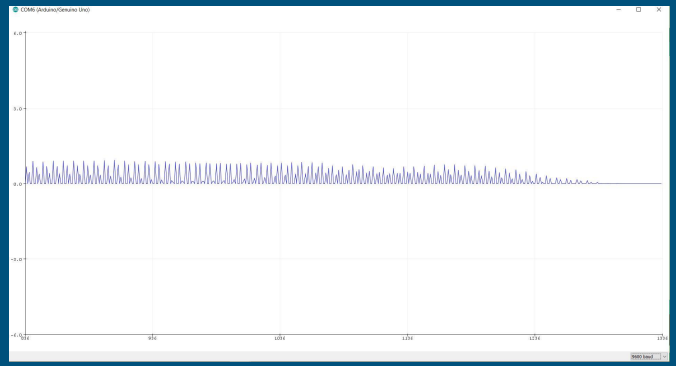
Phase 1: Preliminary Testing

Preliminary testing with Arduino

- Sinusoidal wave plotting was observed, but inaccurate
- Initial voltage readings were very small and difficult to distinguish
    - Voltage readings between 0v and 0.3v



Preliminary circuit with Arduino

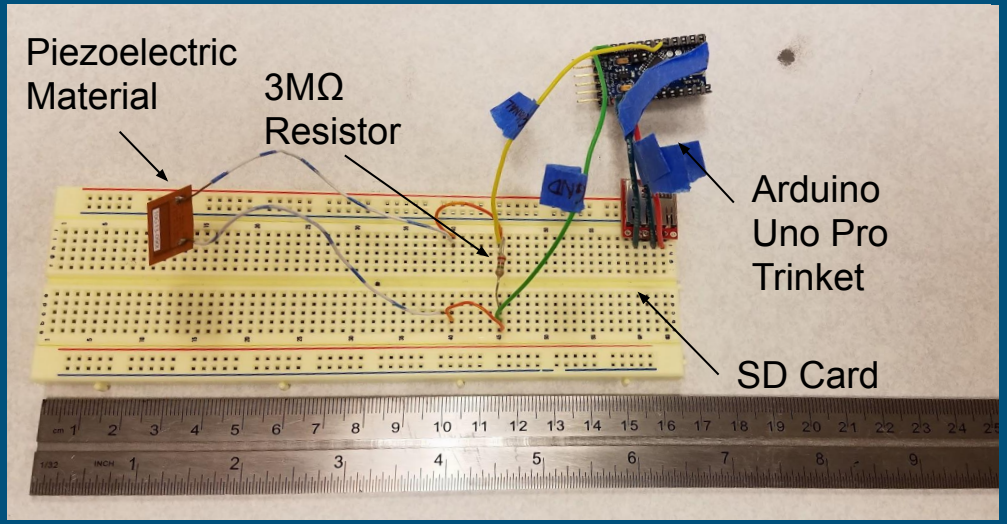


Preliminary graphing from Arduino IDE

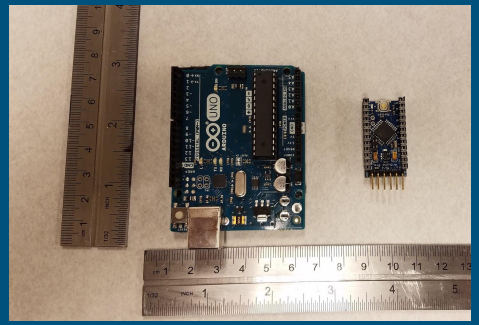
Phase 2: Narrowing down a setup

Narrowing down a setup

- The Arduino Uno R3 was replaced with the Arduino Pro Mini
- Replaced 1MΩ with a 3MΩ resistor
  - Increased voltage output
- Capable of storage via SD card
- Determined that op amps should be avoided to keep it simple



New circuit setup



(Left) Size difference between Arduino Uno R3 and Pro Mini

Phase 3: Developing the theory

Methodology to Calculating values

- DC Voltage (Volts)
- Average voltage (Volts)
- Maximum voltage (Volts)
- Peaks
- Peaking Frequency (Peaks/second)

$$ADC\ Reading = \frac{Analog\ Voltage\ Measured}{1023 * 5}$$

$$Average\ Voltage = \frac{total\ piezoelectric\ voltage}{total\ piezoelectric\ count}$$

$$Maximum\ Voltage = \text{compare voltages and take the higher value}$$

$$Peaks = look\ for\ critical\ points\ in\ graph/values$$

$$Peak\ Frequency = \frac{total\ peaks}{program\ running\ time * 0.001}$$

Equations to calculate values

Phase 3: Developing the theory

Sampling Rate: 125 kHz

Monitor, Calculate, Plot:

- Time (milliseconds)
- DC Voltage (Volts)
- Average voltage (Volts)
- Maximum voltage (Volts)
- Total Peaks
- Peaking Frequency (Peaks/second)

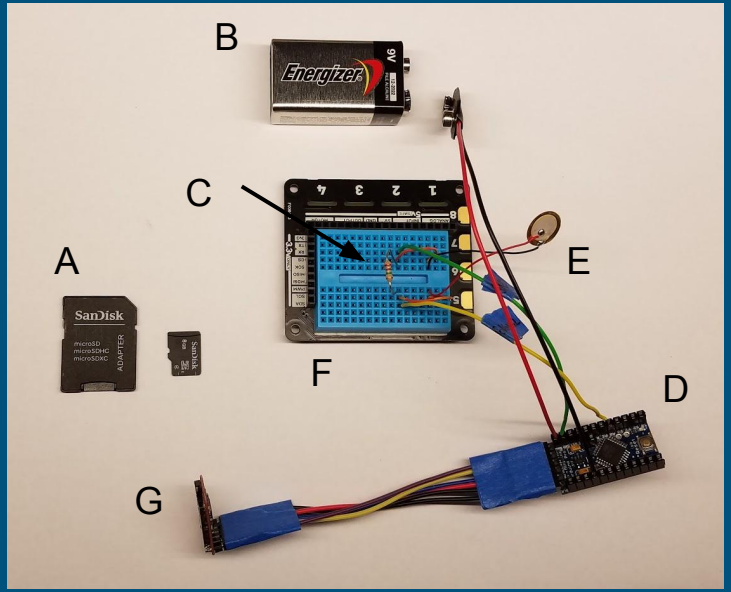
```
void loop() {
//Conversion
int piezoADC = analogRead(PIEZO_PIN);//Read Piezo ADC Value in from port
float piezoV = piezoADC / 1023.0 * 5.0;//Convert analog signal into DC Voltage
//float piezoVm = piezoV + 5; //Add a constant value to shift piezo voltage

//Counting
if(piezoV >0){//if the piezoelectric voltage is greater than zero
  countavg++;//increase the count average
  totalpv += piezoV;//add the total piezoelectric voltage to the piezoelectric voltage
}
//Average Piezo Voltage
avgv = totalpv / countavg;

//Maximum Voltage
maxv = max(maxv, piezoV);//check value of variables and take the higher value as the new maximum voltage

//THRESHOLD
if(piezoV < prevp){//Check if the previous number is higher than the current number
  if(peak == false){//if the peak is false, the peak count should increase
    peakcount++;//increase the peak count by one
  }
  peak = true;//if the peak is true, the counter will not increase
}
if (piezoV > prevp){//Check if the previous number is lower than the current number
  peak = false;//peak is false
}
prevp = piezoV;//Store piezoelectric voltage as previous peizoelectric voltage to compare values for next loop

//Frequency
peakFreqms = peakcount/( millis()*0.001) ;//Get the frequency of the peaks

```

Main loop of code

Phase 4: Piecing together the final product

Final Components and Layout

A. 8GB Sandisk MicroSD Card and Adapter
B. 9V Battery
C. 3MΩ resistor
D. Arduino Pro Mini Trinket (5V, 16MHz)
E. Piezoelectric Sensor
F. Raspberry Pi breadboard
G. Sparkfun OpenLog Data Logger
H. Wires



Final components and Layout

Phase 4: Piecing together the final product

Capabilities

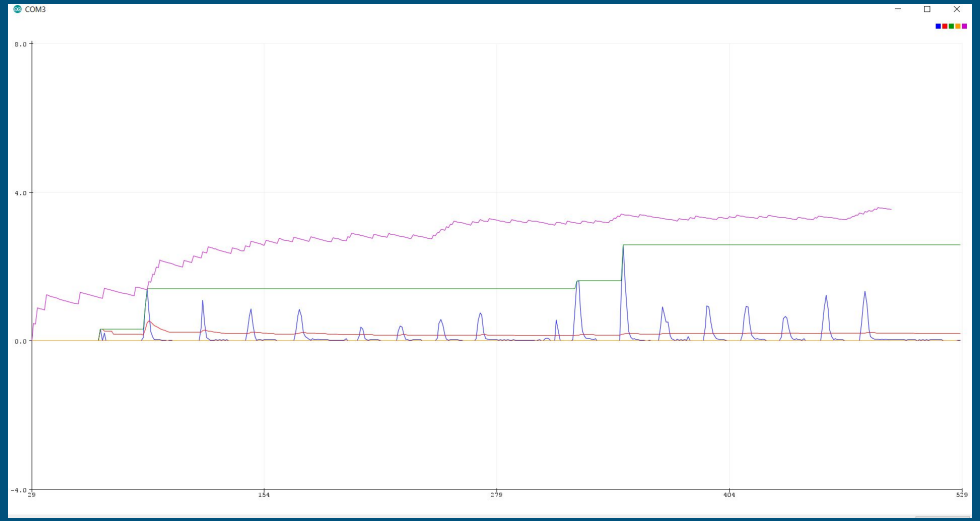
- Read from Analog Input into text file
- Real time plotting in Arduino IDE
- Capable of file conversion to csv
  - Able to access on Matlab

```
Time , Voltage , Average Voltage , Maximum Voltage , Peaking Count , Peaking Frequency
1011 , 0.33235583 , 0.33235583 , 0.33235583 , 0 , 0.00000000
1043 , 0.00000000 , 0.33235583 , 0.33235583 , 1 , 0.95877265
1076 , 0.00000000 , 0.33235583 , 0.33235583 , 1 , 0.92936792
1107 , 0.00000000 , 0.33235583 , 0.33235583 , 1 , 0.90334234
```

Sample of Analog pin data logging into text file

	A	B	C	D	E	F
1	Time	Voltage	Average Voltage	Maximum Voltage	Peaking Count	Peaking Frequency
2	1011	0.332356	0.33235583	0.33235583	0	0
3	1043	0	0.33235583	0.33235583	1	0.95877265
4	1076	0	0.33235583	0.33235583	1	0.92936792
5	1107	0	0.33235583	0.33235583	1	0.90334234
6	1140	0	0.33235583	0.33235583	1	0.87719287
7	1172	0	0.33235583	0.33235583	1	0.8532423
8	1205	0	0.33235583	0.33235583	1	0.82987546
9	1236	0	0.33235583	0.33235583	1	0.80906143
10	1269	0	0.33235583	0.33235583	1	0.78802204
11	1301	0	0.33235583	0.33235583	1	0.76863946
12	1334	0	0.33235583	0.33235583	1	0.74962515
13	1366	0	0.33235583	0.33235583	1	0.73206434
14	1398	0.112414	0.22238514	0.33235583	1	0.71530752
15	1430	0	0.22238514	0.33235583	2	1.39860129
16	1463	0	0.22238514	0.33235583	2	1.36705398

Sample of CSV file



Sample of data logging capability via Arduino IDE

CONCLUSION

Piezoelectricity: Experiment 1

Comparison of measurements between piezoelectric materials and control devices for each vital sign

- Heart Rate
  - A much more noisier graph due to exposure of the piezos
- Respiratory rate
  - Smoother graphs because the piezo is more pressure and movement sensitive
  - Movement of the graphs/line
- Blood Pressure
  - Two graphs were used, one graph read heart rate on the finger sensor and the other graph read from the piezo
  - Finger sensor was placed on right index finger and piezo was placed within the sphygmomanometer nearest to brachial artery.

Piezoelectricity: Experiment 1

Comparison of measurements between piezoelectric materials and control devices for each vital sign

- Piezo 3 and 5 are optimal for heart and respiratory rate
- More precautions in experimentation to limit effects of errors
  - Relaxed pose before running DAQ w/o talking or interruption
  - Secondary subject use equipment while other subject is testing to
  - One person wraps piezos for consistent tightness
  - polarity, scaling, etc. (DAQ prep)
- An alternative method for blood pressure needed
  - Pulse wave velocity (PWV) was to be studied
- Variables
  - Polarity of piezo, vibrations and movement, tightness of wrap, placement, size of piezo, strength of breath, timing and pressure of stability.

Piezoelectricity: Experiment 2

Pulse wave velocity in relation to blood pressure

- Each graph showed how various placement of each piezo reacted differently to each body part.
- Subject 2 allowed the use of electrical tape to allow a better reading.
- Pulse wave velocity seems promising, but things need to be worked out
  - Find better position of piezos to pick up clearer pulse for each subject (inner bicep)
  - Peaks need to be chosen w/ more accuracy (graphs needed to be interpreted better)
  - Finding the correlation between blood pressure and pulse wave velocity
- Variables
  - Polarity, outside influences, position of the subject arm, placement of piezo (vertical v.s horizontal)
- The chest to Elbow method produced the best data due to the voltage peaks being alignment.

Piezoelectricity: Experiment 3

Pulse wave velocity in relation to heart rate, respiratory rate and blood pressure

- Pulse Wave velocity
  - Found the correlation with blood pressure
  - Used an equation to determine each subject constant
  - Measured peaks with a method to produce a more consistent and real data
  - Redid trials to find that the Brachial and wrist placement produced the best data
- Finding all 3 vital signs
  - Used the chest strap for respiratory constant and blood pressure cuff for heart rate constant.
  - Blood pressure cuff also used to find constant(Systolic and Diastolic)
  - Both piezos and constant's data were FFT to see the correlation
  - The piezos were able to display the same frequency as the constants.
- Variables
  - Placement of the piezos, polarity, picking points/peaks, movements (arm or vibrations), FFT showed different peaks that could have been outliers.

Arduino

- Arduino is capable of reading, calculating, and storing data from a piezoelectric sensor.
- Impedance of circuit directly correlates to sensitivity of piezoelectric sensor:
  - A large enough resistor acts similarly to an op amp without using an inverting or noninverting setup by allowing for the greatest load voltage possible
- Piezoelectric sensor was successful in extracting heart rate from finger

Arduino

Analysis of Heart Rate based on Frequencies

Sample Line Number	Peaking Frequency (Hz)	Estimated Heart Rate (bpm)	Estimated Average Heart Rate (bpm)
3	0.9588	57.5	76.4
7	0.8532	51.2	
11	0.7686	46.1	
15	1.3986	83.9	
20	1.8844	113.1	
23	1.7778	106.7	

	Time	Voltage	Average Voltage	Maximum Voltage	Peaking Count	Peaking Frequency
2	1011	0.3323556	0.33235583	0.33235583	0	0
3	1043	0	0.33235583	0.33235583	1	0.95877265
4	1076	0	0.33235583	0.33235583	1	0.92936792
5	1107	0	0.33235583	0.33235583	1	0.90334234
6	1140	0	0.33235583	0.33235583	1	0.87719287
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13	1366	0	0.33235583	0.33235583	1	0.73206434
14	1398	0.1124144	0.22238514	0.33235583	1	0.71530752
15	1430	0	0.22238514	0.33235583	2	1.39860129
16	1463	0	0.22238514	0.33235583	2	1.36705398
17	1495	0.0048875	0.14988596	0.33235583	2	1.33779251
18	1527	0.0048875	0.11363637	0.33235583	2	1.30975759
19	1559	0.0146621	0.09384164	0.33235583	2	1.28287363
20	1592	0.0048875	0.07901597	0.33235583	3	1.88442192
21	1624	0	0.07901597	0.33235583	3	1.84729051
22	1656	0	0.07901597	0.33235583	3	1.811594
23	1688	0.0048875	0.0684262	0.33235583	3	1.77725114
24	1721	0	0.0684262	0.33235583	4	2.32422995

Serial monitor data in Excel

Future Work

Piezoelectricity

- Figure out how to find BP from measurements strictly by piezos
- Find a way to superimpose FFTs of piezo 1 and 2 to find respiratory and heart rate, since both correlate
- Build prototype

Arduino

- Create a portable prototype that is wireless.
- Incorporate different sensors to read and store other vital signs.