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Vibrotactile Device for Optimizing Skin Response to Vibration

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Table of Contents **Page**

Abstract 3
1 Introduction 3
1.1 Problem Statement 3
1.2 Background 3
2 Motivation 5
3 Original Design Specification 5
4 Vibration Method Chosen 5
5 Fall 2011 Design 6
5.1 The Voltage Source 7
5.2 The Driving Circuit 7
5.2.1 The 555 Timer 8
5.2.2 The 3469 Amplifier 9
5.3 The Piezoelectric Tactor 9
6 Client Discussion and Modifications from Fall 2011 10
6.1 Client Meeting at UW-Milwaukee 10
6.2 General Modification of Specifications from Fall 2011 11
7 Design Modifications 12
7.1 MP3 waveform source 12
7.2 Circuit Modifications 12
7.2.1 LT3469 Option 12
7.2.2 741 Op Amp Option 13
7.2.3 Circuit Comparison 14
8 Final Design 15
8.1 Circuit Design 15
8.2 Piezoelectric Buzzer and Finger Attachment 15
9 Testing 17
9.1 Voltage Output from Different Sources 17
9.2 Circuit Gain Testing 18
9.3 Hand Sensitivity Testing 19
10 Future Work 21
10.1 MRI Compatilbility 21
10.2 Size Reduction 22
10.3 Displacement and MRI Testing 22
11 References 23
Appendix 25
A – Project Design Specifications 25
B – Estimated Cost of Parts 26
C – Work Hours Log 27
D – Anthropometric Data of U.S. Army Personnel 28
E – Hand Sensory Statistics 29

Abstract

It is important to understand stochastic resonance on the hands in order to prove how it effectively enhances vibrosensory perception. To do this, an MR-compatible tactor is needed to provide a vibration stimulus to the hand during an MRI of the brain. The key design requirements of the device are that it must run at a frequency range of 30-300 Hz, and be small enough to fit on the subject's finger while maintaining a 1 mm thickness. In order to achieve these requirements, three design options were evaluated: solenoid, piezoelectric, and pneumatic. Of these three options, the piezoelectric device was determined to be the best-suited design. Using a 741 operational amplifier circuit, a random audio signal was amplified to drive the piezoelectric circuit. Testing of the device consisted of circuit gain and amplitude tests, along with a perception test of the fingers on both left and right hands. The index and thumb fingers were determined to be the most sensitive to vibrations. Future work is to be conducted by Professor Na Jin Seo to test the piezo buzzer's displacement, along with stochastic resonance in an MRI to observe brain function.

1 Introduction

1.1 Problem Statement

Falling from ladders or scaffolds is one of the leading causes of workplace injuries and fatalities. A device must be developed to improve the workers' response time by stimulating their sense of touch through vibrations in their hands. The device must be MR-compatible in order to analyze brain activity during the stimulus to the hand. The overall goal is to prove that a continuous stimulus on the hand can improve the range of sensory frequency perception.

1.2 Background

According to previous studies, the skin sensation of hand is believed to be the first available sensory cue for workers to detect and react to the fall initiation. On average, healthy young people took about 100 ms to arrest and stabilize their bodies when sudden forces were applied to the ladder [4]. Out of the 100 ms period, approximately 40 ms was because of the delay in the brain cortical reflex loop, while the other 60 ms was mainly from the delay of hand skin receptors to detect the change in contact force [4]. If this 60 ms time period could be reduced by decreasing the amount of time skin receptors used for detecting the change in force, then the person's ability to rescue the fall could be greatly enhanced [4].

The Pacinian corpuscle is the main nerve center in the hand for receiving signals from vibrations [15]. The Pacinian corpuscle is a part of the somatic sensory system; it is located in the hypodermis, which is the inner-most layer of the skin. When a vibration occurs, it travels through the skin and to the hypodermis, causing the cell membranes of the Pacinian corpuscle neurons to be displaced [16]. These neurons are mechanoreceptors, meaning that they will convert this mechanical displacement into electrical impulses, or signals. The electrical signals are sent to the central nervous system (spinal cord and brain) via peripheral nerve pathways. Vibration signals sent by the Pacinian corpuscle are rapid pulses, similar to sine waves. Like all nerves in the body, the Pacinian corpuscle has a designed threshold that a vibration stimulus must overcome in order to trigger a signal to the brain [15]. If a vibration is not strong enough to cause the Pacinian corpuscle to reach threshold, the brain will not sense the vibration, and the body will not respond. In the case of falling from ladders or scaffolds, there will be an early vibration on the hands that is too weak to reach the threshold of the Pacinian corpuscle, and the vibration is not sensed by the brain. This precedes a large vibration that can cause the person to lose their grip and fall. If the body were able to sense the early vibrations in the ladder or scaffold, they would be able to respond by gripping the ladder tighter before the large vibration causes them to fall. In order to allow the Pacinian corpuscle to sense these small vibrations, it may be possible to increase the amplitude of small vibrations above threshold by introducing an additional noise signal (in this case the noise is subthreshold vibrations).

Stochastic resonance (SR) is a phenomenon that occurs when a subthreshold signal is enhanced by the presence of added subthreshold signals (noise signals) [5]. As shown in Figure 1, SR can assist a sensing system in detecting a signal by adding a predetermined amount of noise. This noise has the same modality as the signal, but does not contain significant information to the system, or is subthreshold. When adequate noise is added to the signal, it increases the amplitude of the signal, which can bring it above threshold as shown in Figure 1b. In most cases, it is preferred to eliminate noise from a signal; however, in the case of sensing small vibrations, an outside noise is helpful for bringing the signal above threshold and allowing the body to sense the small vibrations.

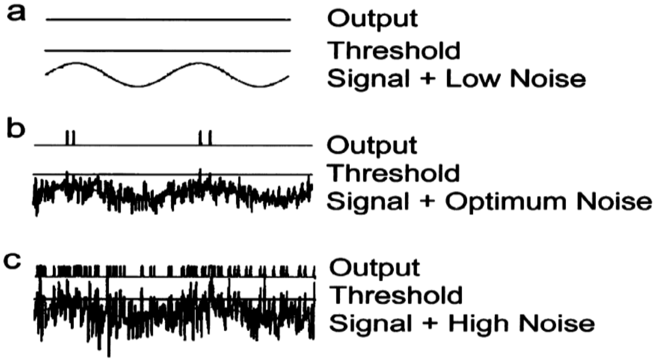

Figure 1. Example of stochastic resonance. (a) When the signal and noise are low and do not exceed the threshold, the system won't produce any output. (b) When optimal amount of noise is added to the signal, the signal and noise cross the threshold whenever the signal reaches its peak. (c) Excess of noise is added to signal; the threshold crossings do not reflect the phase of the signal (because it is greatly affected by noise) [5].

In order to reduce the amount of time for skin receptors to detect the vibrations from a ladder or scaffold, a vibrotactile device can be used to add the additional noise for Stochastic Resonance to occur. This will enhance the response of skin receptors by allowing subthreshold signals to gain amplitude and reach threshold. The vibrotactile device would produce small amounts of vibration at a high frequency (optimum noise) so that the small vibrations generated in a ladder or scaffold prior to fall initiation can be detected by the skin receptors. Such a device has already been shown to enhance skin sensation in young and old healthy people, as well as reduce the walking gait variability in elderly fallers [5, 6]. However, the vibrotactile devices used in these experiments were designed for the foot and would be too bulky to fit between the hand and rung/scaffold.

Experiments conducted by N. Alawieh (UW-Madison BME Department) indicated that a frequency range of roughly 30 Hz to 300 Hz is most sensitive to the hand skin receptors [7]. Different stimuli (such as force, temperature etc.) affect different receptors in the hand. The receptors related to this project are Meissner corpuscles and Pacinian corpuscles, which are both rapid adapting receptors. Meissner corpuscles cover about 40% of the tactile receptors in the hand and they serve as velocity sensors to provide feedback on grip and grasping function. They mainly work at frequency range of 3 to 40 Hz. Conversely, Pacinian corpuscles cover about 13% and are sensitive at 200 Hz to 350 Hz [7]. As a result, a vibrotactile device that is designed for hand stimulation should include a range of frequencies from roughly 30 Hz to 300 Hz.

2 Motivation

The motivation behind this project is the high number of falls from ladders and scaffolds in the workplace. These falls are usually started due to destabilization of the ladder/scaffold, and it is believed that by using the SR phenomenon, the reaction time to these destabilizations can be significantly reduced. A tactile stimulator that can be used in an MRI would allow observation of brain activity during the stimulus, and examination of the effects of SR on the sensory threshold. The brain activity study may help the researchers to verify and obtain direct evidence that vibrotactile stimulation can reduce reaction time and further prevent falling accidents at the workplace.

3 Original Design Specifications

The purpose for designing this vibrotactile device is to reduce the amount of lag time between vibration stimulus and reaction. In order for researchers to study the brain activities during tactile stimulation, the device needs to be MR-compatible. The MRI scanner applies extreme magnetic fields, rapidly changing magnetic field gradients, and radiofrequency pulses to create images for the area of interest [8]. As a result, an MR-compatible device must be composed of nonmagnetic and nonconductive materials, or be heavily shielded, in order to not interfere with the imaging process. The tactor design for this project should aim for dimensions of less than 1 mm in thickness and 2 cm in diameter so it may be placed on the palmar side of the hand. If it is placed on the dorsal side of the hand, the size may be up to 2 mm in thickness and 2 cm in diameter. The vibrotactile device has to operate at a random frequency output, changing in a range of 30 Hz to 300 Hz and the output vibration should be subthreshold (meaning the subject won't consciously feel the vibration). Refer to the Appendix for detailed design specifications.

4 Vibration Method Chosen

Based on the above design criteria, a piezoelectric system for vibration was chosen to provide adequate noise for stochastic resonance. When a mechanical force is applied to some solid materials, an electrical charge will form as a result. This is known as piezoelectricity [9]. There are a variety of ceramic and crystalline materials that are piezoelectric. The specific properties of the materials

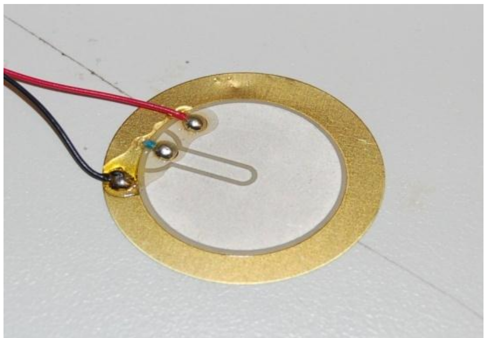

Figure 2: Piezoelectric vibrator; model # PPW-81631 (50mm dia.) [10]

that create the piezoelectric effect are dipolar crystal patterns. When the material is stressed, the dipoles are displaced, which redistributes the ions of the material, causing an electric charge to form. This charge is directly related to the amount of force applied, and can be easily measured.

The property of piezoelectricity can be reversed by applying an electric charge to a piezoelectric material, which causes a mechanical force or vibration directly proportional to the amount of charge applied. The system would require a voltage source, wiring to connect the voltage source to the piezoelectric vibrator, and the piezoelectric material itself as shown in Figure 2. The voltage source is used to apply a charge to the piezoelectric material through the wiring. The amplitude of vibration is dependent on the amplitude of the signal (input voltage), so increasing or decreasing the voltage will have the same effect on the vibration amplitude, making the system easily adjustable [11].

A piezoelectric vibrator system is advantageous because it can be made with non-ferrous materials. Piezoelectric parts are also relatively inexpensive, and the vibrator itself would cost approximately $50 [12]. Another benefit of such a system is that the frequency would be easily adjustable based on the frequency applied. Piezoelectric systems run at a wide range of frequencies, and for the purposes of the tactile stimulator, it could be adjustable from 30-300 Hz.

The main limitation of a piezoelectric system for use in an MRI is the fact that the system would require wiring inside the MRI tube to lead from the vibrator to the voltage source. It would be possible to use nonferrous wiring in the system; however, the materials are not the only determining factor in MR-compatibility. Any wires in the systems that have a current running through them will create a changing electrical current that will create a competing magnetic field, interfering with the MRI. Another limiting factor of the wiring system would be that the strong magnetic field of the MRI would induce its own current to the wires. The system could possibly be designed to compensate for the MRI current, but if the current is too strong it may cripple the system and make it impossible to achieve the correct current for vibration. The wires would require shielding in order to prevent any interaction between the wires and the magnetic field of the MRI. Shielded wires can protect the signals from being disrupted by strong electromagnetic fields through the use of a non-conductive wire placed in between the two wires carrying this signal, as well as a shield that can reflect magnetic waves. This extra wire is grounded, and draws the magnetic energy, then transfers it to the ground, thus effectively eliminating the interference signal [18].

5 Fall 2011 Design

Based on the evaluation of each design and the scoring from the design matrix, the Piezoelectric Tactor was chosen. In order to drive the piezoelectric system, as shown in Figure 3, three components are need: a voltage source, a driving circuit, and the piezoelectric tactor itself.

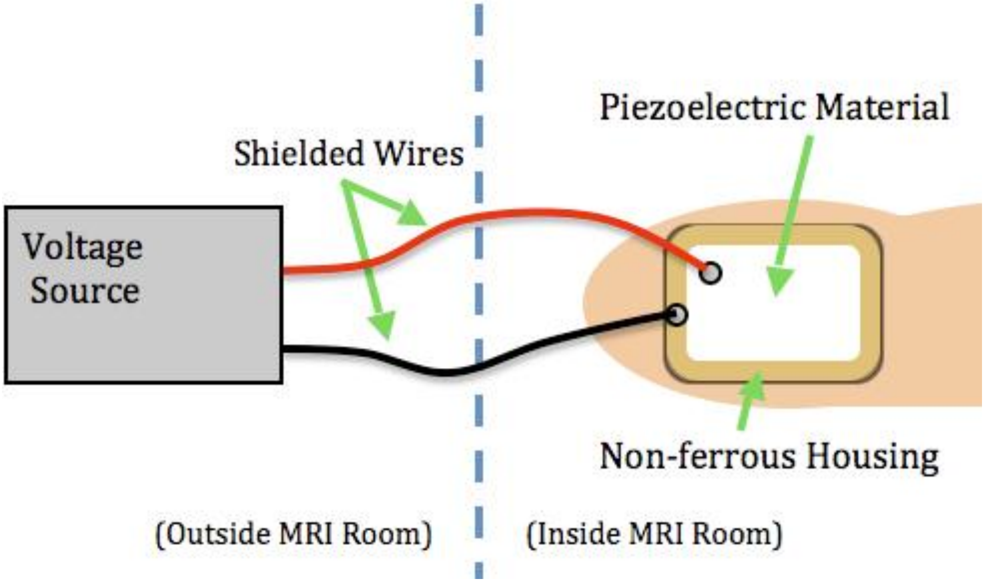

Figure 3. Diagram of the Piezoelectric system: Shows the connection of the outside voltage source to the piezoelectric tactor inside the MRI room.

In order to avoid extra complications due to the MR-compatibility requirement, the system will be set up so that the voltage source and the driving circuit will be located outside of the MRI room, with shielded wires running into the MRI room. The piezoelectric system operates by using a DC voltage source to power the circuit element. The circuit then converts the DC source to AC with the desired frequency. The driving circuit then powers the piezoelectric tactor using frequency and displacement parameters set by the user. Each component is described in detail below.

5.1 The Voltage Source

Since the voltage source will be located outside of the MRI room, a standard ferrous voltage source can be used. Due to the nature of the piezoelectric tactor that was chosen for the system, and the circuitry that was built around it, only a 9 V battery is required. Two of the benefits from reducing the voltage source to a 9 V battery are that the system will be easily transportable, and the overall cost will be greatly reduced. The value of 9 V was chosen mainly because it is the recommended operating value for the 555 chip and because 9 V falls in the voltage range required for the LT3469 chip.

5.2 The Driving Circuit

In order to properly drive the piezoelectric tactor, a circuit is needed that can change the DC input voltage to an AC output at variable frequencies, as well as have the ability to drive a capacitive load. In order to achieve these two requirements, the circuit can be broken down into two subcircuits. The component that changes input DC to an AC output uses a 555 timer, while the component for driving the capacitive load uses a 3469 amplifier.

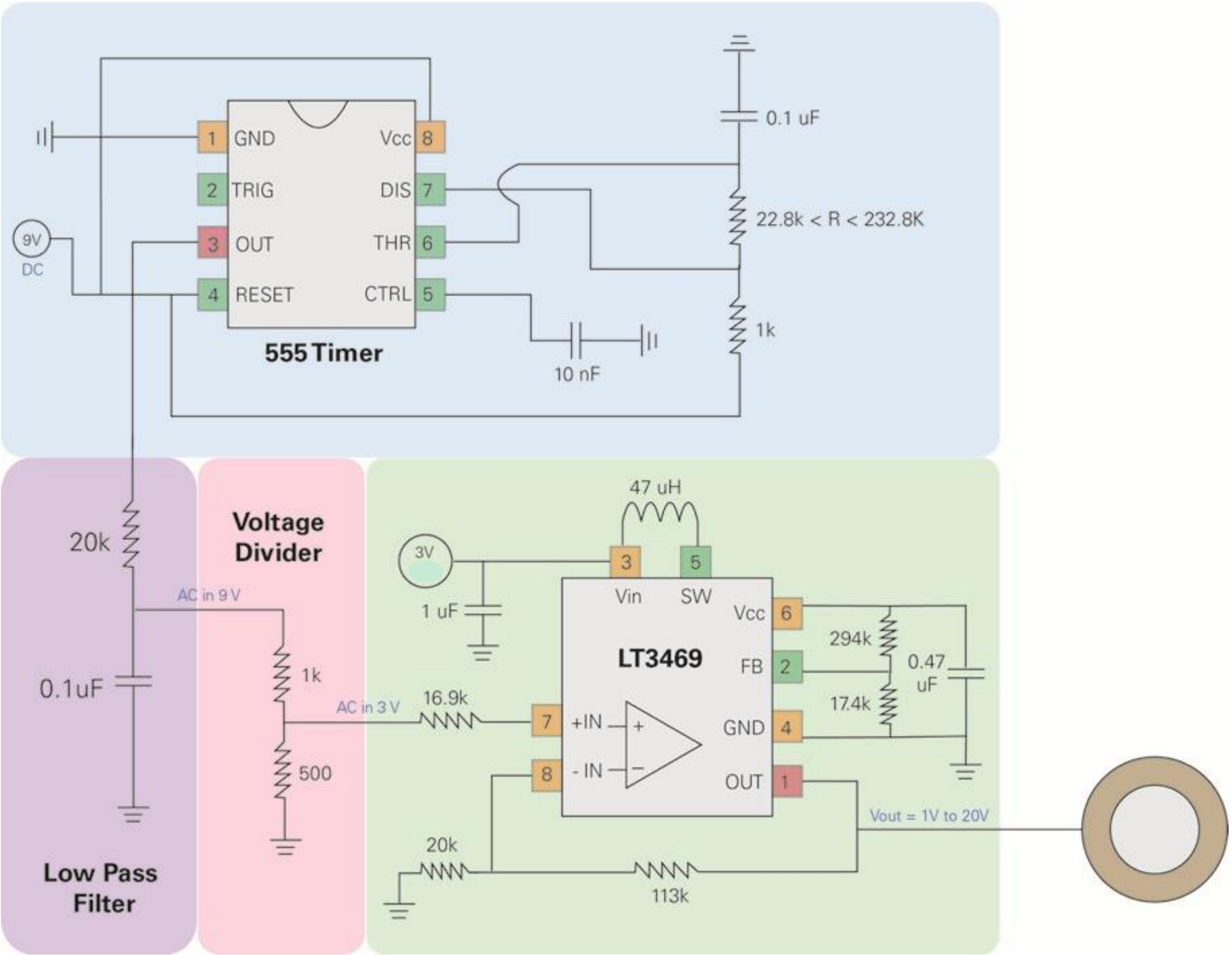

Figure 4: Driving circuit with power source and attached piezoelectric tactor. Shows the: 555 timer (Blue), Low-pass filter (Purple), Voltage divider (Pink), 3496 amplifier (Green).

5.2.1 The 555 Timer

$f = 1 / [\ln(2)*C*(R_1 + 2R_2)]$ $T_m = 0.7*(R_1 + R_2)*C$ $T_s = 0.7*(R_2)*C$ $R_2 = 0.7 / (f*C)$

The circuit diagram for the 555 timer can be seen in Blue section of Figure 4. This circuit is powered by the 9 V DC and outputs a ~9 V_{pp} square wave. Since the output frequency needs to be able to be variable in the range of 30 Hz to 300 Hz, a potentiometer (pot) is used. Using the equations listed above, the necessary capacitor and resistor values were calculated to give a duty cycle close to 50 percent. For simplicity, a value of 0.1 µF was chosen for the capacitor, and an arbitrary resistor value of 1000 Ω was chosen for the first resistor and the pot was used for second resistor. Using the equation for R_2, the range of resistance needed for the 30 Hz to 300 Hz range was calculated as $22.8\ k\Omega \leq R_2 \leq 232.8\ k\Omega$. To meet this frequency range, the circuit uses a 500 kΩ pot (a 250 kΩ pot would have worked, but there was a 500 kΩ pot available).

After some testing it was discovered that because of operating frequency range of the piezoelectric tactor, audible noise is produced when using a square wave input. To remedy this problem, the square wave is passed through a low-pass filter so that the square wave can be converted into a sine-like wave. The low-pass filter uses a 20 kΩ pot so that the cut-off frequency can be modified based in the square wave's frequency. It is possible to avoid using the low-pass filter by modifying the 555 timer to produce a sine wave. By the time this option was discovered, it was only a week before the winter presentation (Dec. 9, 2011) and there was not sufficient time to order the parts necessary.

5.2.2 The LT-3469 Amplifier

The circuit diagram for the LT-3469 amplifier can be seen in the Green section of Figure 4. This circuit takes in the waveform, amplifies the voltage, and improves the current's ability to drive a capacitive load such as the piezoelectric tactor.

Along with allowing for driving a capacitive load, this portion of the circuit is also responsible for varying the voltage output. Because this is the sub-circuit that amplifies the voltage going to the piezoelectric tactor, a pot can be inserted into the circuit (at the location of the 113 kΩ resistor) to control the voltage output. By changing the resistance value of this pot, the gain from the amplifier can be adjusted. Taking advantage of this adjustability, and the LT-3469 chip's ability to give a 1 V to 20 V output range, control over the volt input to the piezoelectric tactor can be achieved. The reason this control is necessary is so that the magnitude of displacement for the piezoelectric tactor can be controlled.

Notice that between the low-pass filter and the LT-3469 amplifier, there is a voltage divider. The reason for this is that the input signal for the amplifier must be between 0 V_{pp} and 3 V_{pp}. As mentioned previously, the 555 timer's output has a magnitude of 9 V_{pp}. In order to require only one voltage source, it is necessary to insert a voltage divider.

5.3 The Piezoelectric Tactor

In choosing the piezoelectric tactor that could meet the frequency and the displacement requirements, the size requirements suffered. Because the resonance frequency of a piezoelectric crystal is dependent on physical size of the crystal, a piezo with a diameter larger than 10 mm or a stack of piezos with thickness of greater than 1 mm is needed. Alone with the frequency constraints, in order to get a displacement in the range of 10 µm to 500 µm would require driving voltage in the kilovolt range if a small piezoelectric element was used. This large voltage brings up the safety concern of using the system in close contact with living subjects. Considering this information, as well as discussing the important aspects of the device, it was determined that size could be sacrificed for frequency and displacement.

With this in mind, a piezoelectric buzzer sold by CUI inc. was found. The piezoelectric buzzer (CEB-44D06) has a resonance frequency of 600 Hz with a maximum input voltage of 20 V_{pp}. The 600 Hz resonance frequency allows the piezoelectric buzz to operate effectively in the 30 Hz to 300 Hz range and the input voltage is low enough that safety is not a concern. Since the maximum operating voltage is only 20 V_{pp}, the piezoelectric buzzer can be safely used around living subjects, and does not require a large voltage source. Another good aspect of this piezoelectric buzzer is that the size was not overly compromised. The piezoelectric element chosen for the Fall 2011 design has a 25 mm diameter, ensuring that it is still small enough that it would match size with a thick finger (see Appendix D). For more details on the piezoelectric buzzer, refer to its data sheet.

Since the piezoelectric buzzer needs to be free to vibrate, it cannot be directly attached to the subject's finger. Therefore, a prototype housing unit was built (Figure 5). The housing unit sandwiches the piezoelectric buzzer's nonferrous outer layer as to not disrupt the vibrations. A semicircular piece of PVC tubing is attached with a strip of elastic to allow for adjustment for a thicker finger. Padding was then inserted into the concave section of the PVC for comfort as well as added adjustability for varying finger thicknesses.

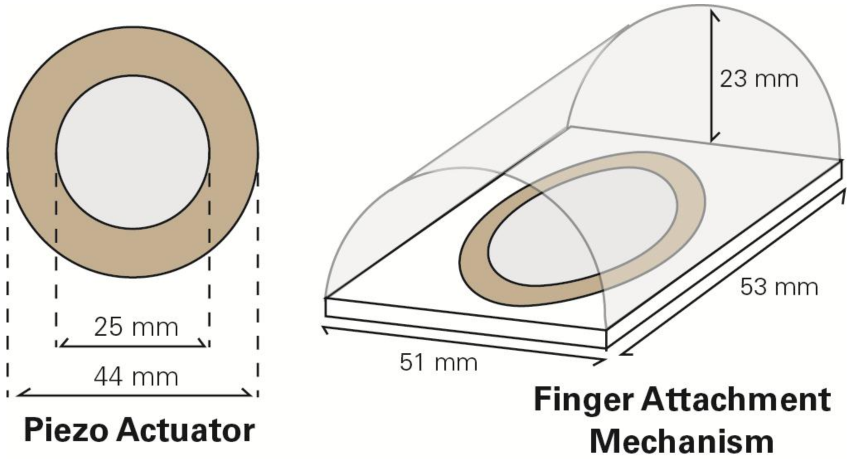

Figure 5: The piezoelectric buzzer's housing unit: The CEB-44D06 piezoelectric buzzer (left) is shown in the housing unit (right).

6 Client Discussion and Modifications from Fall 2011

6.1 Client Meeting at UW-Milwaukee

The team was able to drive to Milwaukee to meet Professor Seo, her associate Pilwon Hur, and the rest of the Hand Rehabilitation Laboratory at UW-Milwaukee. The purpose of the meeting was to learn more about the lab, and give them a presentation of the piezoelectric device from last semester, because they were not able to come to Madison to see it and observe its function during the semester. The team learned about all of the testing done in the lab, with the main concern being the portion of their research that is directly related to stochastic resonance, which was useful for the design of the piezoelectric device. The key testing mechanism used was a hanging bar, which the user would grab. Embedded into the bar was a solenoid device that produced the random vibration for stochastic resonance. The random frequency varies from 30 to 300 Hz, which is a design feature that was previously unknown to us. This changing frequency is generated by an audio file, which drives the solenoid device. The test subject grabs the bar and the bar is quickly pulled away from the subject; tests of reaction time are conducted by recording the subject's ability to maintain their grip on the bar with the actuator powered on and off. Their testing had not been fully completed at the time, but it had been shown that the stochastic resonance from the vibrator improved the subject's reaction time.

After observing the Hand Rehabilitation's application of stochastic resonance, we showed them our piezoelectric device. Professor Seo and Pilwon were able to give some recommendations for future work, including the implementation of the random frequency from the audio file used in their lab. They were satisfied with the in-progress prototype and will use the final design in their testing.

6.2 General Modification of Specifications from Fall 2011

There were a number of problems with the design from last semester that required modification in order to produce a workable prototype for the client to test in an MRI. The most significant change to the design was the incorporation of a random, changing frequency for the actuator. This was a design feature that the group was unaware of because of a miscommunication with the client. Professor Seo and her group in Milwaukee use an audio signal with a changing frequency to drive an actuator at randomly changing frequencies. In order for the piezoelectric device to operate at the random frequencies that the client wants, it was determined that the simplest way to drive the piezoelectric actuator is to use the same audio signal from the other device. As a result, the circuit for the piezoelectric device must be modified to run with the input being an audio signal. Modifications were made for the voltage input, because it is assumed that the audio signal will have a different voltage than the 3 to 6 volts from the original power source (described in Section 7.2).

The actual circuit from last semester must also be modified to include the LT3469 driver chip, which was backordered and not received before the end of the semester. We received the chip over winter break, and discovered that it had a SOT23-8 pin package; this will make the chip very hard to incorporate in our circuit because the tiny pins will not fit into a breadboard for testing. There are a number of options for converting the package to fit into the breadboard, but for simplicity it was decided to look for a converter chip that would connect the smaller package to a set of DIP-8 SMT pins that will fit into the breadboard.

Other modifications to the final design will be mainly aesthetic, and have the purpose of making the prototype easier to operate for Professor Seo and her group in Milwaukee. The first modification will be to make a finger attachment mechanism that is not made from scrap parts, and makes it easy for the actuator to be attached to the finger. It may also be possible to look into smaller piezoelectric actuators, because the client originally wanted an actuator that was small enough to fit on a person's fingertip. It has been thought that a smaller piezoelectric device would not work for this application because smaller piezoelectric devices have resonant frequencies that are much higher than the 300 Hz, but testing of the 300-600 Hz piezoelectric buzzer showed that the resonance frequency did not mean that the device could not run at lower frequencies. Therefore, it could be possible to use a smaller piezoelectric device, regardless of its resonant frequency.

7 Design Modifications

After meeting with Professor Seo at her UW-Milwaukee lab, the design team was presented with some new information about stochastic resonance. In order for stochastic resonance to work, the subthreshold wave needs to be constantly changing between 30 Hz and 300 Hz, not just able to be adjusted to provide a constant frequency between 30 Hz and 300 Hz. In order to achieve this randomly changing frequency, it was decided that the best course of action would be to use an MP3 file to feed the waveform into the piezoelectric buzzer. Due to this change, the circuit from the previous final design was modified.

7.1 MP3 waveform source

In order to take the waveform from the computer and use it to drive the piezoelectric buzzer, a 3.5 mm mono male to stripped end, shielded, audio cable was used. The 3.5mm end is the standard end for computer, MP3 players, and smartphone audio ports. The MP3 file that will be used was created by Pilwon Herr (Post-Doc in Professor Seo's lab). Along with producing the randomly changing frequency, the use of an MP3 file allows for easy adjustment of the strength of the waveform (and therefore the input voltage driving the piezoelectric buzzer) simply by changing the volume on the device playing the MP3 file.

7.2 Circuit Modifications

With the addition of the MP3 waveform source, certain parts of the previous circuitry became unnecessary. Along with removing the unneeded components, two different circuits were considered to best drive the piezoelectric buzzer.

7.2.1 LT3469 Option

The first option uses the LT3469 driver circuit that was shown in the previous final design, along with a voltage stepper circuit (Figure 6). The voltage stepper circuit shifts the waveform up by 1.5 V so that all of the wave peaks are positive in value. This is needed because the LT3469 chip requires 0 V to 3 V for an input. This circuit requires one LT3469 chip (\$2.45), 3 capacitors (\$2.49), 7 resistors (\$0.91), 1 inductor (\$1.44), and 1 SOT23-8 to DIP-8 SMT Adapter (\$2.99). This gives a total component cost of \$10.28 for this circuit option (note voltage sources not included).

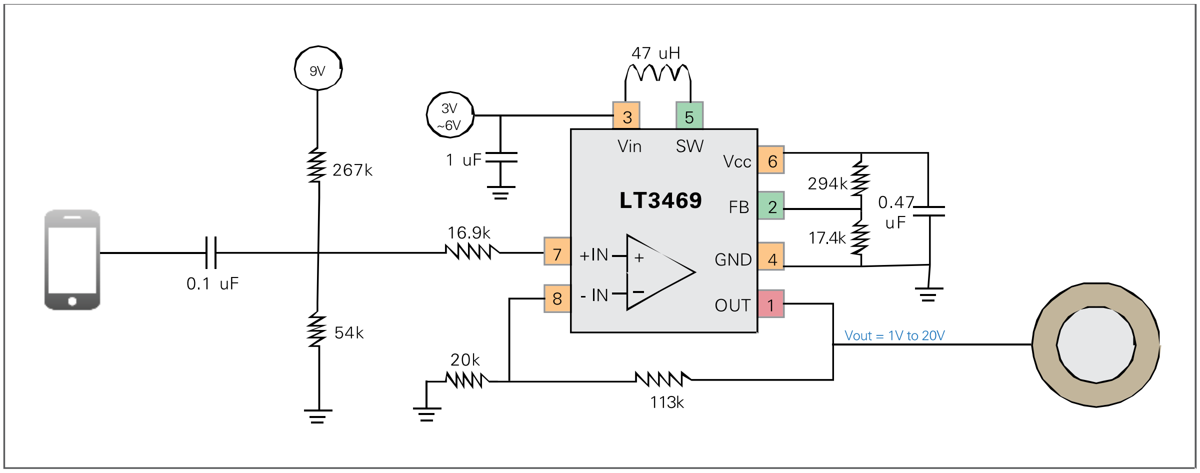

Figure 6: Circuit design for using the LT3469 driver chip to amplify the audio input.

7.2.2 741 Op Amp Option

The second circuit option simply uses a 741 op-amp (Figure 7) to amplify the waveform. The op amp uses two 9 V batteries to power the op amp and give a gain of 11. This circuit requires 2 resistors ($0.26) and 1 741 chip (~$0.75). This gives a total component cost of ~$1.01) for this circuit option (note voltage sources not included).

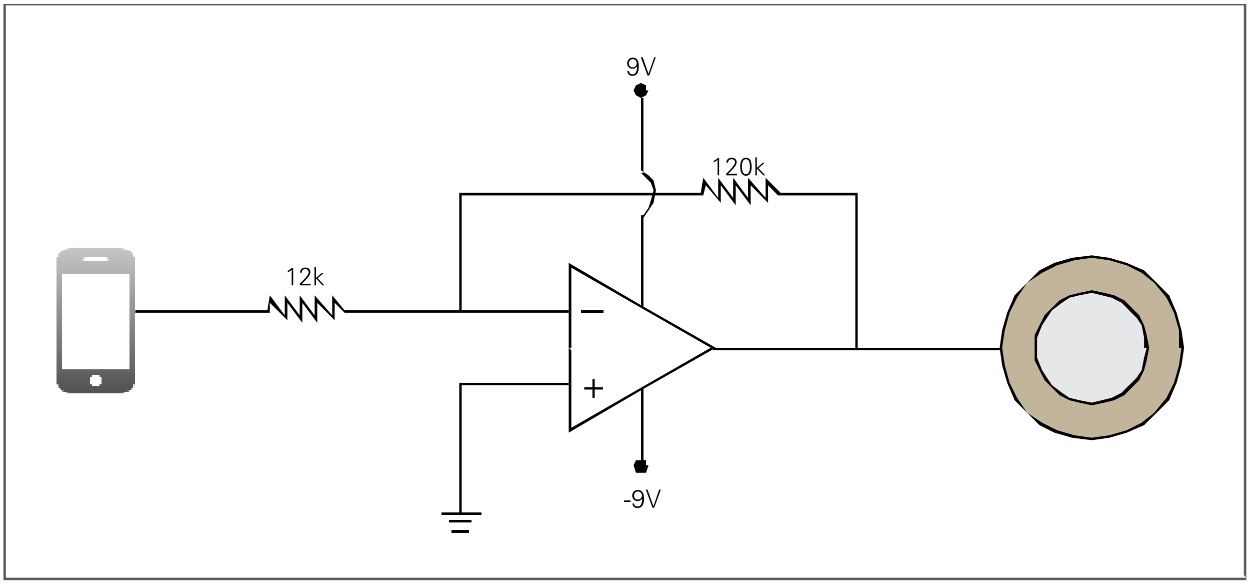

Figure 7a: Circuit design for using the 741 operational amplifier to drive the piezo.

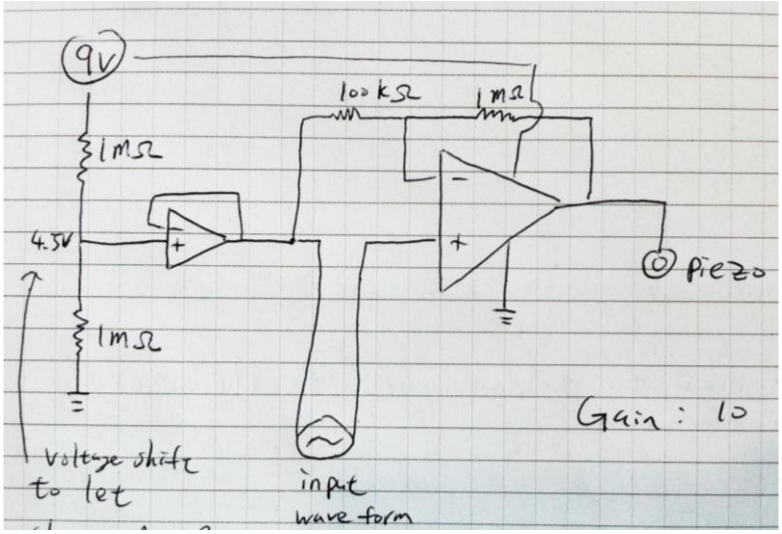

Figure 7b: Circuit diagram for 741 operational amplifier using a single battery source.

7.2.3 Circuit Comparison

Each of the above circuits has benefits and drawbacks as seen in Table 1 below. The 741 op-amp as simple circuit with only 3 components, while the LT3469 driver is more complex and uses 12 components. Because of the extra components, the LT3469 driver circuit is significantly more expensive (although still relatively cheap) than the 741 op-amp. However, the 741 op-amp's simplicity is what causes its drawbacks. The 741 only has the ability to amplify to a certain voltage. After this voltage is reached, the wave saturates, causing the wave to take on square wave properties. This saturation occurs around 16 V for this circuit, which is an acceptable voltage for the CEB-44D06 Piezoelectric Buzzer (15 V_{pp} suggested input), but may not be sufficient for small, high voltage demanding buzzers. In comparison to the 741 op-amp, the LT3469 should not saturate, but should be capable of outputting 20 V for the circuit shown in Figure 7a above. The LT3469 only requires one 9 V source (with the addition of a voltage divider so it can be used to power the chip itself) while the 741 requires two 9 V sources (since it needs both a positive and negative input to power the chip). Figure 7b shows a circuit using a 741 op-amp with only 1 voltage source. However, this circuit only has the capability of producing a 7 V output, which is less than half of what is required to drive the piezo. Having two power sources slightly increases the cost of the 741, but not to the extent of becoming more expensive than the LT3469.

Table 1: LT3469 versus 741

	LT3469	**741 Op-Amp**
Circuit	Complex	Simple
Cost	higher	lower
Voltage Range	Ideal	Acceptable
Voltage Source	Smaller	Larger

8 Final Design

8.1 Circuit Design

After implementing and testing the different modification that were discussed in the previous section, the final design will implement the MP3 waveform sources and will operate using the 741 op-amp. The decision for using the 741 op-amp over the LT3469 driver circuit came after series of unsuccessful tests. For reasons unbeknownst to the design team, as well as Tim Balgemann (MS) and John Webster (PhD) the circuit was not operating properly. While working with Tim, the circuit reduced the voltage of the 2 V_{pp} input to a 1.8 V_{pp} output instead of amplifying the input to ~20 V_{pp}. However, when the voltage source was reduced from 3 VDC to 6 V DC the output would be amplified to ~7 V_{pp}. Amplification would also occur when the input waveform was decreased. After the tests with Tim, we consulted John Webster; however, before consulting John Webster, it appeared that the LT3469 chip had burnt out as a result of previous testing. At this point, the design team decided to used the 741 op-amp as part of the final design for various reasons.

While the LT3496 driver circuit gave a higher amplification and only required one battery, along with being notably more expensive, the circuit had a higher level of complexity as well as requiring an additional circuit component to offset the input waveform so that it only operated in the positive voltage range. Since the cheaper and less complex 741 op-amp would give a sufficient amplification for the driven piezoelectric buzzer to operate properly, the design team decided to follow the engineering principle articulated by Clarence Leonard "Kelly" Johnson, “Keep it simple stupid” [17]. Figure 8 shows a picture of the prototype circuit after it has been placed on perfboard.

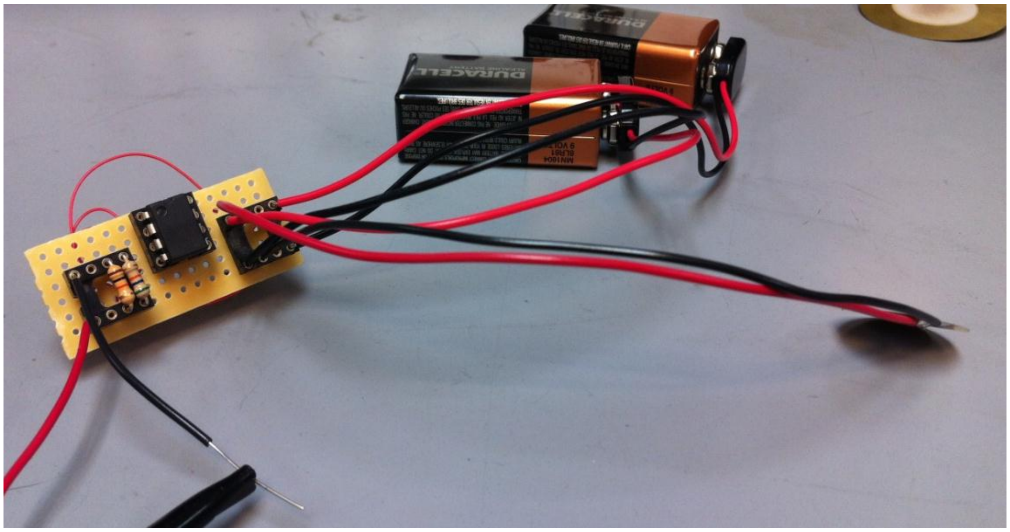

Figure 8: Photograph of the final prototype outside of its housing.

8.2 Piezoelectric Buzzer and Finger Attachment

Along with making modification and choosing the desired circuit, the design team located a piezoelectric buzzer with an outer housing diameter of 20 mm and a piezo diameter of 15 mm and a 1 mm thickness (See appendix for specifics). This piezoelectric buzzer is over half the surface area of the 42 mm piezoelectric buzzer that was used the previous design. Using anthropometric data from the U.S. Army, it was determined that this piezo was small enough to for the fifth percentile female to place on the end of their second distal interphalangal digit. Since the design team implemented a smaller piezo, modification were also make to the finger holder (Figure 9) so that it could properly hold the smaller piezoelectric buzzer. The new figure holder was designed in SolidWorks® to be able to fit the 95th percentile male's second distal interphalangal digit using anthropometric data from the U.S. Army. For calculations involving anthropometric data, see the Appendix D.

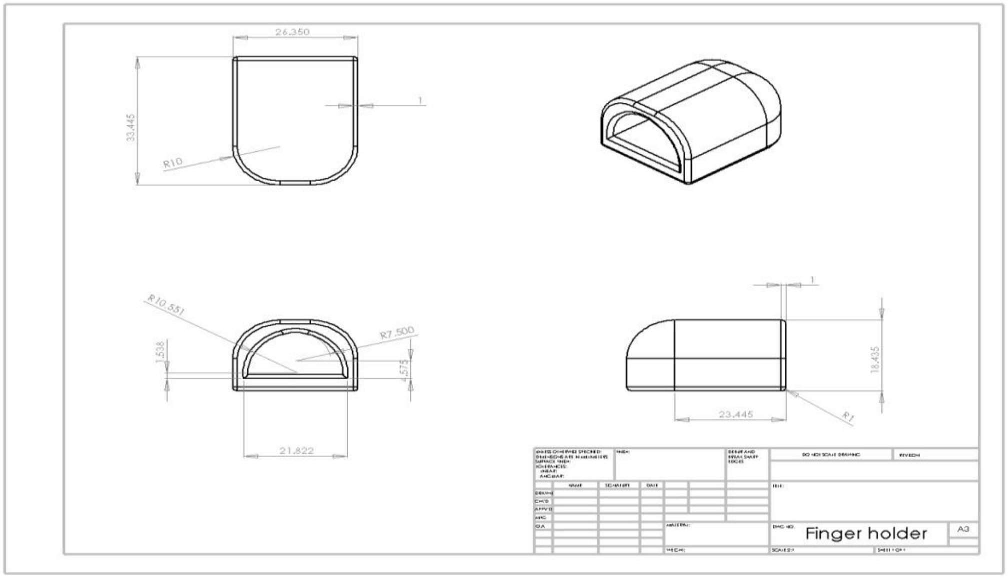

Figure 9: Dimensioned 2D drawing of the 3D SolidWorks® CAD model.

Along with the decision on the circuit design, the change in the piezoelectric buzzer, and the modification to the finger holder, the design team also made a housing for the circuit board and batteries and calculated the length of the shielded audio cable. Using the blueprints of the MRI room and the surrounding areas provided by Professor Seo, the design team determined that a 15.2 m shielded audio cord would be needed in order for the circuitry to remain outside of the MRI room. Figure 10 shows the final prototype with the wire, housing, piezo, and finger holder.

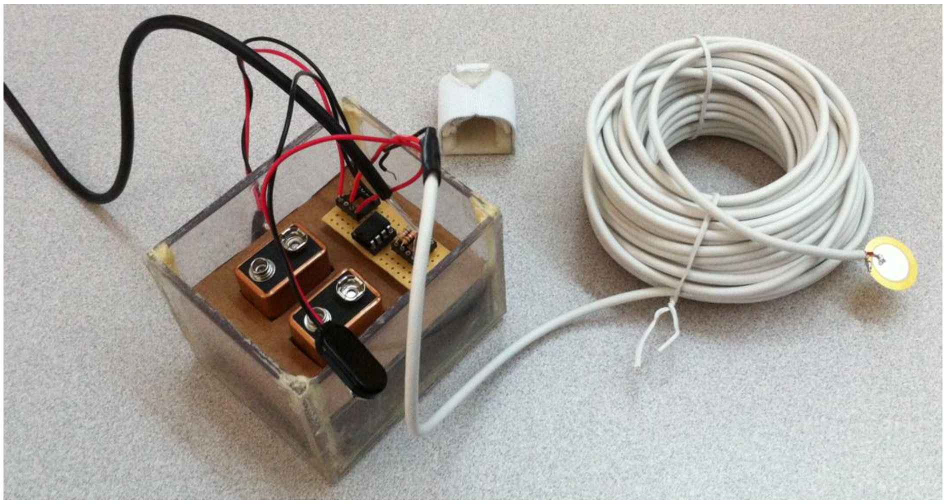

Figure 10: Completed assembly of the final prototype.

9 Testing

9.1 Voltage Output from Different Sources

Due to the fact that our design uses waveform generated from the audio file provided by the client, it is important to determine the output voltage of the device that is playing the audio file. Since the client might use different devices to run the audio file, the output voltage could vary between each device. Regardless of the circuit design (op-amp or LT3469 circuit) eventually used in the final design, the voltage feeds into the circuit should be carefully regulated to ensure our design works properly. As a result, the team surveyed several devices including Dell Optiplex 980 desktop, Apple's MacBook Pro, iPhone 4, and iPod Touch 4th generation about the voltage output from their audio jacks.

To test the voltage output from various devices, the team used a tuning audio file posted on YouTube [14], which plays constant frequency (523.25 Hz) at maximum volume, and measured the output voltage of each device's audio jack. Fifteen samples were taken for each device to see the consistency of output voltage, and the data is shown in Figure 11. The averages and standard deviations of the maximum voltage outputs were calculated and plotted in Figure 12. From Figure 12, it clearly indicated that different devices had different output voltages even when playing the same audio file. This means that the current circuit design might need some further fine-tuning in order to accommodate the wide range of output voltage from different audio-playing devices.

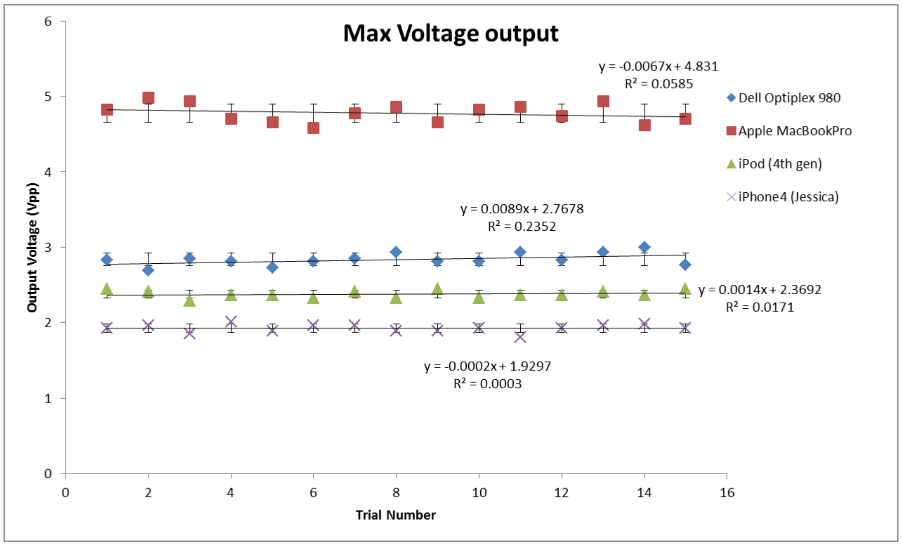

Figure 11: Graph of maximum V_{pp} throughout 15 tests using the random-frequency signal from different audio sources (DC offset voltage = 0).

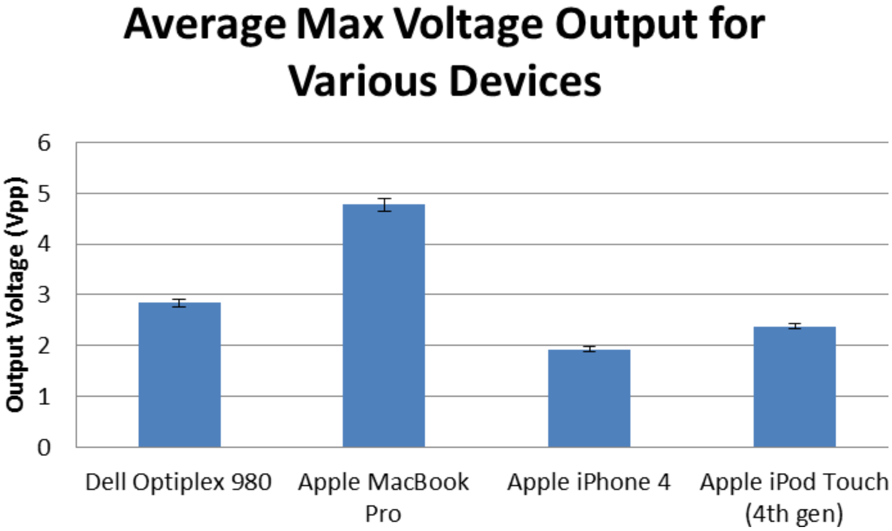

Figure 12: Average values for maximum output V_{pp} for each of the tested audio sources.

9.2 Circuit Gain Testing

By using the audio file provided by Prof. Seo’s research group, the peak-to-peak voltages from a computer (Apple’s MacBook Pro was used) were measured and served as the input voltages for the 741 op-amp circuit. The volume of the computer was slowly increased in order to increase the voltages from the computer, and that increasing input voltages were matched with the corresponding output voltages generated by op-amp circuit to produce Figure 13. The output voltages were used to power the piezoelectric vibrator. From data in Figure 13, the equation for the linear relationship between input and output voltages was calculated and displayed in Figure 13. We were able to obtain roughly a gain of 4.5 from our op-amp circuit according to the equation. This experimental gain was a little lower than our expected gain (5.6) probably because there was an offset of voltage (0.90 V when the input voltage is supposed to be 0 V) from the measurement. There seemed to be a plateau when higher input voltages were supplied. This could be due to that our 741 op-amp chip was only powered by +9 V and -9 V DC but not at its optimal range (+15 V and -15 V DC). This is not a significant concern for this project because the input voltage that Prof. Seo would be using should normally lie within the range that the team tested here.

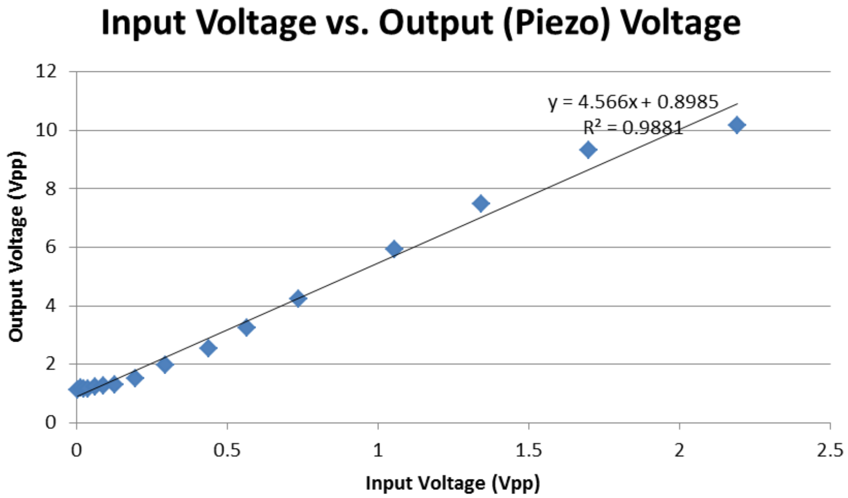

Figure 13: Correlation of input voltage from audio source to voltage at piezo.

9.3 Hand Sensitivity Testing

The results from previous experiments performed by N. Alawieh to determine the most sensitive regions of the hand are showed in Figure 14 [7]. According to Figure 14, the most sensitive regions of hand are fingertips and the middle of palm because the amount of voltage required (for the vibrotactile device to vibrate) is the smallest. This means that the ideal spots to place the vibrotactile device are at fingertips and palm.

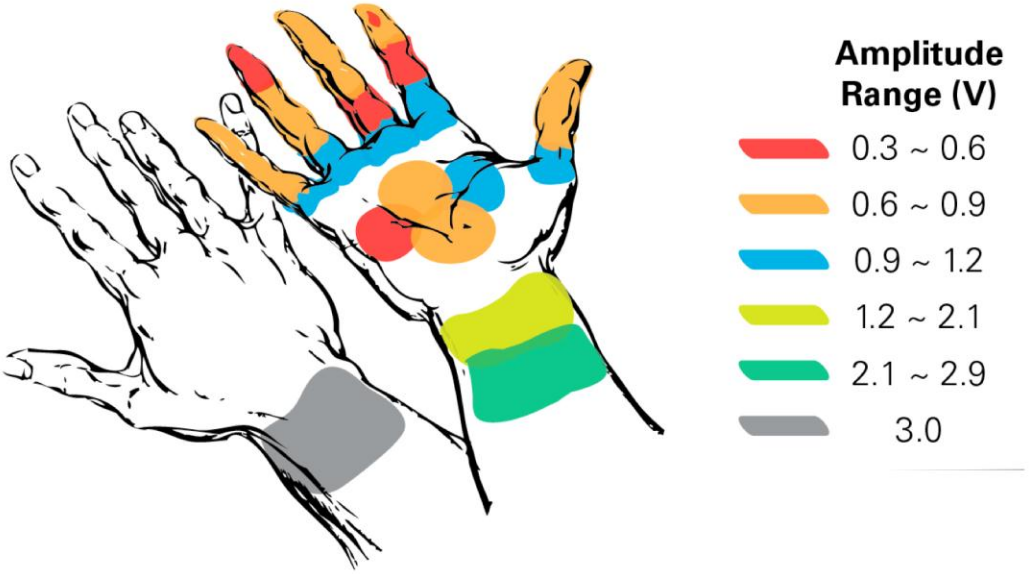

Figure 14: Map of hand sensitivities based on applied tactor voltage: Notice that there is an increased sensitivity a the tips of the fingers [Adapted from 7].

The team also did a sensory mapping of hand and obtained very similar results to the experiment done previously (as mentioned in the introduction section). Please refer to Figure 14 for the results from the previous experiment, as the results from those tests showed significant similarities to the testing conducted by the Tactile Stimulator team. The perception levels of each finger tips were measured and recorded as shown in Figure 15 (left hand) and 16 (right hand).

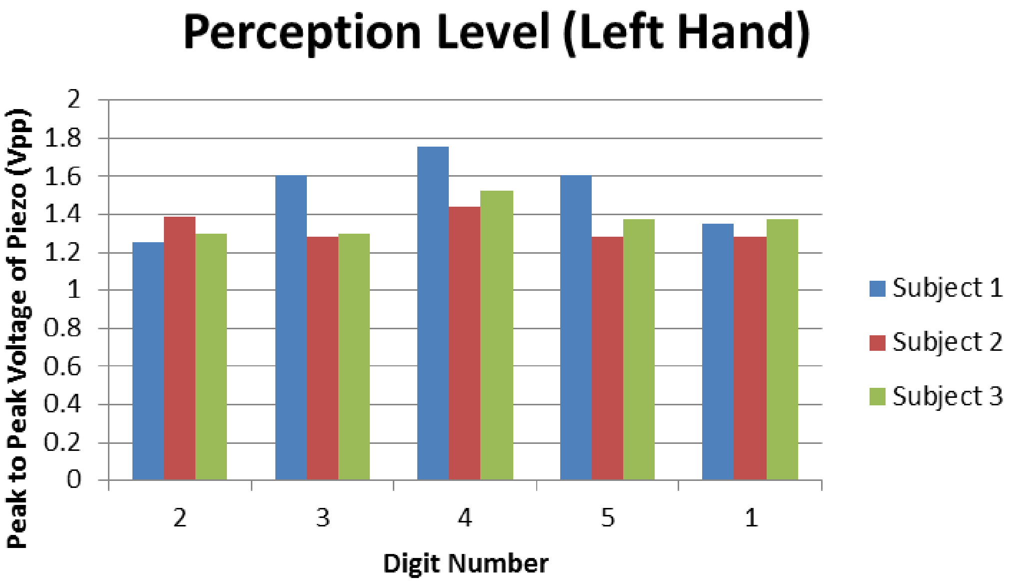

Figure 15: Perception voltages for the Left hand of test subjects. (See Appendix E for statistics).

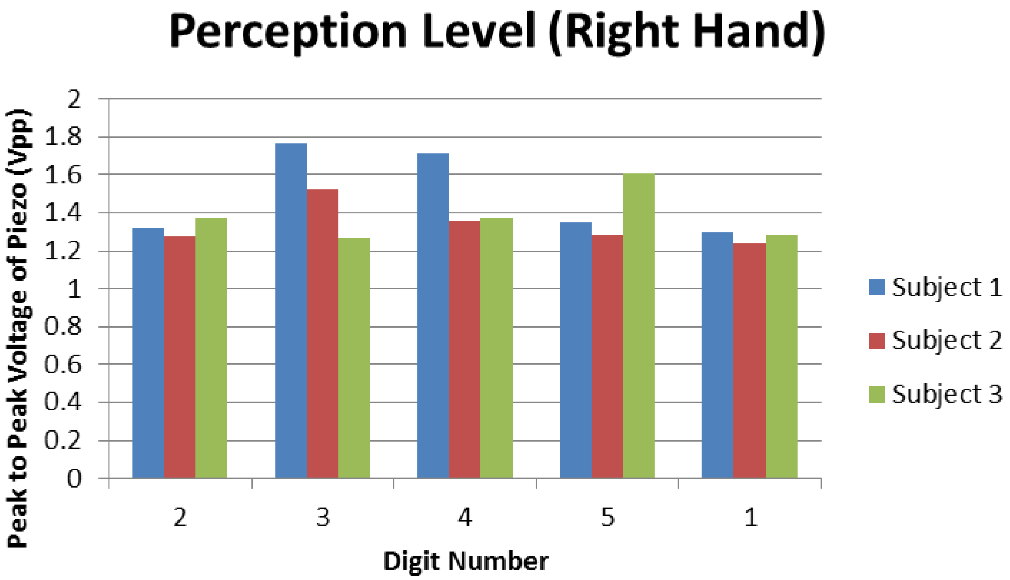

Figure 16: Perception voltages for the Right hand of test subjects (see Appendix E for statistics).

Three human subjects were tested by applying the vibrational simulation of our device to their fingertips. As the volume of the computer slowly increases (this increases the input voltage to the op-amp circuit), the volume levels were recorded when the subject started to sense the vibration. The volume levels were then converted to input voltages going into the op-amp circuit, and the voltages of piezoelectric actuator (output voltage) were determined by using the relationship in Figure 13. Each fingertip of a subject was tested 3 times and the average was plotted in Figure 15 and 16. These figures suggest that different subjects and different hands/fingertips have different sensory levels, so it is important that the device can precisely adjust the level of actuation to accommodate various perception levels. The average perception rankings for the piezoelectric sensitivity testing are shown in Table 2, and indicate very similar results to the previously determined sensitivities from N. Alawieh.

Table 2: Average Perception Rankings for Digits on Left and Right Hand (lower voltage level indicates a higher perception for the digit). Errors in this testing may have resulted from variances in output due to the randomly changing input signal.

Digit	Left Hand	Right Hand
2 (Index)	1.31 V (1)	1.32 V (2)
1 (Thumb)	1.33 V (2)	1.28 V (1)
5 (Pinky)	1.42 V (4)	1.42 V (3)
3 (Middle)	1.40 V (3)	1.52 V (5)
4 (Ring)	1.57 V (5)	1.48 V (4)

Errors in these tests could have resulted from variances in the audio file, which was constantly changing. There were peaks and valleys in the output amplitude of the signal, and perception could have been skewed due to these amplitude variances.

10 Future Work

10.1 MRI Compatibility

The team originally planned to perform MR-compatibility tests on our device by the end of this semester, but this was not completed yet due to the lack of access to MRI room here and a legal procedure for human subject testing in the MRI. Although our client has access to an MRI room in Milwaukee, the team were not able to reach her in the middle of semester, and thus the device could not be delivered to her on time in order for her to start testing by the end of this semester. As a result, the MR-compatibility and possible human subject testing are one of the major future goals for this project. The team also wants to improve the finger holder so that it can have multiple-finger compatibility to enhance research efficiency. By adding the flexibility of fitting multiple fingers or designing different finger holders for each finger, our client would be able to add complexity to her study and have broader applications in the future. And finally, if our client observed positive results from the MR-compatibility testing, meaning the fact that vibration stimulation applied by our device can enhance reaction time is confirmed, then this project can move on to develop some practical applications such as glove fabrication for industrial settings or a treatment device for stroke patients. These applications are aim to help and enhance worker’s or stroke patient’s hand sensations to vibration stimuli.

10.2 Size Reduction

While the current piezoelectric buzzer, 20 mm diameter and 1 mm thichness, fulfills the desired dimensions, it may be worth looking into an even smaller piezoelectric buzzer to achieve a more point force like stimulation. Several complications are involved with using increasingly small piezoelectric buzzers. Theoretically, the size of the piezo is inversely proportional to its running frequency, meaning that the smaller the piezo is, the higher the operating frequency. Testing is needed if those smaller piezoelectric buzzers can still vibrate properly at a lower frequency range, 30 to 300 Hz. The piezos with smaller resonance frequencies also require a higher input voltage. Depending on the size of the piezo, this problem could be easily solved through changing the resistors in the circuit to give it extra gain, and thus a higher output voltage to the piezo. However, if the piezo is sufficiently small, the 741 op-amp will not provide sufficient gain due to saturation effects. This would require using a different circuit that is capable of providing a higher gain. If a smaller piezo can be incorporated into the final design, the finger attachment mechanism will also need to be remodeled to fit a smaller piezo. A new attachment mechanism can also be designed for better contact between subject's finger and the piezo. The finger should not apply additional compression force to the piezo during stimulation to prevent inaccuracy.

10.3 Displacement and MRI Testing

Once the fabrication of the prototype is completed, two major tests should be performed. First, the measurement of vibration displacement should be collected in order to obtain the relationship with the voltage input. Professor Seo desires to have data correlating sensitivity to the displacement of vibration. Since the audio signal and driving circuit are incorporated in the design, the vibrational displacement of the buzzer can be adjusted. The displacement of the buzzer depends on the voltage provided. Because the piezoelectric buzzer obtained from CUI Inc. did not provide the information on voltage to displacement, the relation needs to be determined via displacement testing. To measure the displacement of the actuator, a laser vibrometer setup can be used. The vibrometer uses light scattering to detect the displacement of piezoelectric actuator, and the target displacement is between 10 to 500 um. The team suggests that Professor Seo conduct displacement testing to directly correlate displacement to input voltage.

After completing the constructions and the improvement for the design, the device should be tested inside the MRI system. The device should be first tested and proven that it is MR-compatible before entering the MRI room. Once the MR-compatibility is confirmed, the concept of stochastic resonance can be studied and the brain activity can be monitored using the device in the MRI system.

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Appendix A

Product Design Specifications

Tactile Stimulator
John McGuire, Wan-Ting Kou, Alan Meyer, Albert Wang
May 9, 2012

Problem Statement

Falling from ladders or scaffolds is of the leading causes of workplace injuries and fatalities. A device must be developed to improve the workers' response time by stimulating their sense of touch through vibrations in their hands. The device must be MR-compatible in order to analyze brain activity during the stimulus to the hand. The overall goal is to prove that a continuous stimulus on the hand can improve the range of sensory frequency perception.

Client Requirements

- The device must reduce the 60 ms lag time between stimulus and reaction
- Does not obstruct the user's grip while holding onto a ladder or scaffold
- Small enough to fit on the palmar side of the user's fingers
- MR-compatibility for testing purposes
- The frequency must be randomly changing, and operate between 30-300 Hz

Design Requirements

1. Physical and Operational Characteristics
   - a. *Stimulation:* The device must stimulate the Pacinian corpuscle, with a randomly changing frequency of 30-300 Hz.
   - b. *Size:* Stimulators on the palmar side of the hand cannot exceed 1 mm in thickness and 2 cm diameter; stimulators on the dorsal side of the hand should not exceed 2 mm thickness and 2 cm diameter.
   - c. *Operating environment:* The device must function in a Magnetic Resonance Imager in order to analyze brain activity during stimulus.
   - d. *Versatility:* Must accommodate a range of hand sizes. Also should be easily sterilized for repeated use.
   - e. *Sensitivity:* The patient must not consciously feel the vibrations, and the device must accommodate a range of nerve sensitivities in patients. The displacement is desired to be 10-500 um to encompass all ranges of sensitivity (as specified by Professor Seo).
   - f. *Life in Service:* The device should remain fully functional for a minimum of one year under normal work conditions.

2. Production Characteristics
   - a. *Quantity:* One working prototype (for a single hand) must be fabricated for MRI testing purposes.
   - b. *Target Production Cost:* (Will establish with client after creating list of parts needed.)

3. Miscellaneous
   - a. *Customer:* Researchers observing the effects of vibration stimuli to the hand.
   - b. *Competition:* None.

Appendix B

Cost of Parts

Elements in Prototype	Quantity	Price (USD)
668-1004-ND Piezo Buzzer	1	1.02
741 Operational Amplifier	1	.50
Perf Board	1	1.00
S3G-MF-50 15.2 m PCH Cable	1	9.35
Resistors	2	1.66
Finger Holder	1	11.02
9V Battery	2	14.00
Battery Holder	2	7.50
Total Price		**$46.05**

Complete Parts Summary	Quantity	Price (USD)
CEB-44D06 Piezoelectric Actuator	5	2.21
668-1017-ND Piezo Buzzer	1	1.68
668-1004-ND Piezo Buzzer	4	1.02
LT3469 Transconducance Amplifier	4	2.45
9V Battery	2	7.00
Battery Holder	2	3.75
S3G-MF-50 15.2 m PCH Cable	1	9.35
Perf Board	1	1.00
741 Operational Amplifier	3	.5
Resistors	20	.13
Capacitors	8	.83
Inductors	4	1.44
555 Timer Chip	1	.50
Finger Attachment Mechanism	1	11.02
Shipping (Total)	-	18.53
Full Year Expenditures		**$105.01**

Appendix C

Work time spent on project:

Team Member	**Hours Spent on Project**
John	30.0
Alan	40.0
Jessica	40.0
Albert	30.75
Total group meeting time	29.5

Appendix D: Anthropometric Data of U.S. Army Personnel [19].

- Digit 2, Distal Interphalangal Joint breath
    - Male = 2.01 +/- 0.15 cm
    - Female = 1.73 +/- 0.13 cm
- Digit 2, Distal Interphalangal Joint circumference
    - Male = 5.74 +/- 0.15 cm
    - Female = 5.08 +/- 0.18 cm
- Digit 2, Distal Phalax link length
    - Male = 2.84 +/- 0.23 cm
    - Female = 2.54 +/- 0.20 cm
- Use: average + K*(std dev) = size for (x percentile)
    - K = 1.65 (x=95), -1.65 (x=5)
- For 95th percentile Male (largest finger)
    - Breath = 2.26 cm
    - Circumference = 5.99 cm
    - Length = 3.22
    - Height* = 1.11 cm
- For 5th percentile Female (for piezo size requirements)
    - Breath = 1.52
    - Shows that at 15 mm diameter piezo is small enough

*Height = 0.5(circumference – 2*height) +/- 0.15 cm (std dev breath = std dev circumference)

Appendix E – Hand Sensory Statistics

Subject 1	Index	Middle	Ring	Pinky	Thumb
R1	1.52712	2.5452	2.5452	1.52712	1.31502
R2	1.21604	1.52712	1.2726	1.31502	1.2726
R3	1.21604	1.21604	1.31502	1.21604	1.31502
L1	1.2726	1.9796	1.9796	1.52712	1.52712
L2	1.21604	1.31502	1.31502	1.9796	1.21604
L3	1.2726	1.52712	1.9796	1.31502	1.31502

Subject 2	Index	Middle	Ring	Pinky	Thumb
R1	1.2726	1.52712	1.52712	1.31502	1.21604
R2	1.2726	1.52712	1.2726	1.2726	1.21604
R3	1.2726	1.52712	1.2726	1.2726	1.2726
L1	1.31502	1.31502	1.2726	1.31502	1.2726
L2	1.31502	1.2726	1.52712	1.2726	1.2726
L3	1.52712	1.2726	1.52712	1.2726	1.31502

Subject 3	Index	Middle	Ring	Pinky	Thumb
R1	1.2726	1.2726	1.2726	1.9796	1.21604
R2	1.31502	1.21604	1.31502	1.52712	1.31502
R3	1.52712	1.31502	1.52712	1.31502	1.31502
L1	1.31502	1.31502	1.9796	1.31502	1.31502
L2	1.2726	1.2726	1.2726	1.2726	1.2726
L3	1.31502	1.31502	1.31502	1.52712	1.52712

Subject 1	Index	Middle	Ring	Pinky	Thumb
Avg (Right)	1.319733	1.762787	1.71094	1.352727	1.30088
Std (Right)	0.179602	0.695213	0.722802	0.158931	0.024491
Avg (Left)	1.253747	1.607247	1.758073	1.607247	1.352727
Std (Left)	0.032655	0.339458	0.383695	0.339458	0.158931
Subject 2	Index	Middle	Ring	Pinky	Thumb
Avg (Right)	1.2726	1.52712	1.35744	1.28674	1.234893
Std (Right)	0	2.11E-08	0.146947	0.024491	0.032655
Avg (Left)	1.38572	1.28674	1.44228	1.28674	1.28674
Std (Left)	0.122456	0.024491	0.146947	0.024491	0.024491
Subject 3	Index	Middle	Ring	Pinky	Thumb
Avg (Right)	1.37158	1.267887	1.37158	1.607247	1.282027
Std (Right)	0.136361	0.049658	0.136361	0.339458	0.057146
Avg (Left)	1.30088	1.30088	1.522407	1.37158	1.37158
Std (Left)	0.024491	0.024491	0.396509	0.136361	0.136361