Vibrotactile Device
for Optimizing Skin Response to Vibration

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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. Future work will be conducted to determine optimal materials for the tactor, as well as the required circuitry needed to drive the system.

1 Introduction

1.1 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.

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 [25]. 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 will be displaced [26]. 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 [25]. 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.
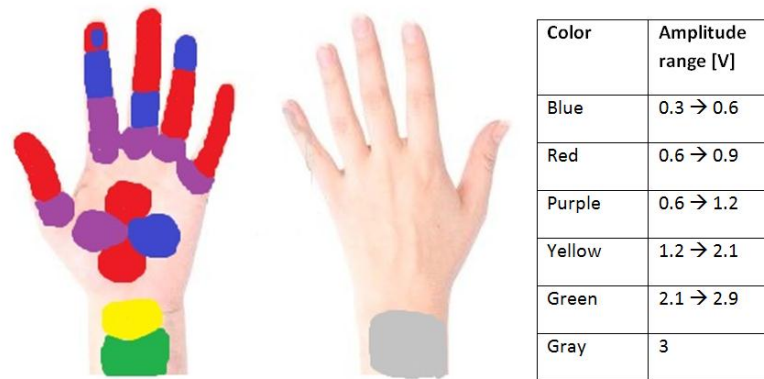
Stochastic resonance (SR) is a phenomenon that occurs when a sub-threshold signal is enhanced by the presence of noise [5]. As shown in Figure 1, SR can assist a sensing system in detecting a signal by adding a predetermined amount of noise. This noise has the same modality as the signal, but does not contain significant information to the system, or is sub-threshold. 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.
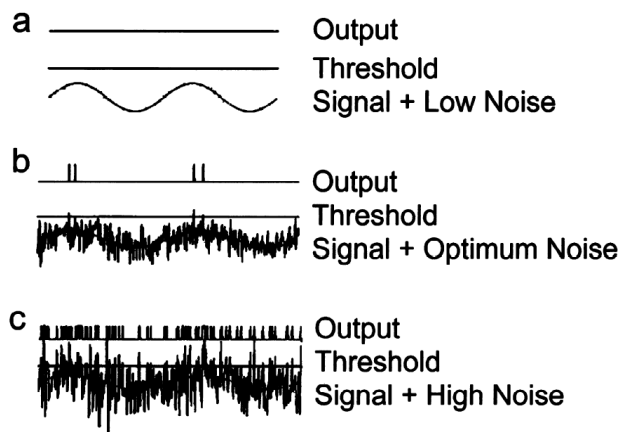
Figure 1. Example of stochastic resonance. (a) When the signal and noise is low and does not exceed the threshold, the system won't produce any output. (b) When optimal amount of noise is added to the signal, the signal and noise cross the threshold whenever the signal reaches its peak. (c) Excess of 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 sub-threshold 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.

The results from experiments performed to determine the most sensitive regions of the hand are showed in Figure 2 [7]. According to Figure 2, 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. Also, the experiments indicated that a frequency range of roughly 30 Hz to 300 Hz is most sensitive to the hand skin receptors. Different stimuli (such as force, temperature etc.) will 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 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 have an adjustable range of frequency from roughly 30 Hz to 300 Hz.

Color	Amplitude range [V]
Blue	0.3 → 0.6
Red	0.6 → 0.9
Purple	0.6 → 1.2
Yellow	1.2 → 2.1
Green	2.1 → 2.9
Gray	3

Figure 2: Map of hand sensitivities based on applied tactor voltage: Notice that there is an increased sensitivity a the tips of the fingers [7].

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 accident at workplace.

3 Design Specification

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 area of interest [8]. As a result, an MR-compatible device must be composed of nonmagnetic and non-conductive 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 1mm in thickness and 1cm in diameter so it may be placed on palmar side of the hand. If it is placed on the dorsal side of the hand, the size may be up to 2mm in thickness and 2cm in diameter. The vibrotactile device has to be able to adjust its frequency output from 30 Hz to 300 Hz and the output vibration should be sub-threshold (meaning the subject won't consciously feel the vibration). Refer to the Appendix for detailed design specifications.

4 Design Options

Based on the above design criteria, three alternative designs were proposed for creating the vibrotactile stimulator. Each design uses a unique method of generating a vibration stimulus. The first design uses a solenoid driver to provide the stimulus to the targeted region. A piezoelectric design option was also conceived; this uses a material that will vibrate due to an applied charge. The final design option is a pneumatic device, which uses changes in air pressure to cause a stimulus. Each individual method was carefully researched in order to understand their advantages and limitations.

4.1 Design Option 1: Solenoid

The solenoid design takes advantage of the magnetic field produced by running a current though a coil of wire. By placing a magnetic rod in the center of the coil, it is possible to move the rod back and forth by changing the direction of the current flowing though the solenoid, as shown in Figure 3, left. Using an alternation current makes it possible to adjust the frequency of the magnetic rod's movement within the necessary 30 Hz to 300 Hz range.
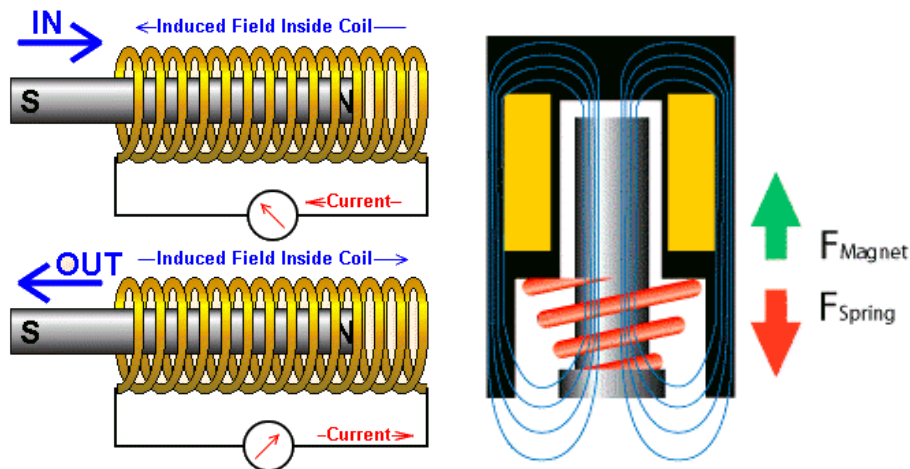
Figure 3. Solenoid theory (left) and Pull type Solenoid (right): These two figures show different methods of using a solenoid to drive a stimulation. The solenoid theory shows how reversing the current through the coil of wire reverse he magnetic field. The pull solenoid uses a spring to reverse the cores direction when the current is turned off, stopping the magnetic field. [9]

One of the problems with using an alternation current as described above is that solenoids can overheat if they are powered too long. This problem can be reduced through the use of heat syncs or cooling devices. Another way to elevate this problem is to use a push or pull solenoid. Push and pull solenoids use a spring in order to move the magnetic rod in one

direction and a magnetic field to move the rod in the opposite direction. For example, in a pull solenoid the force from the magnetic field pulls the core when the field is active, and the spring moves the solenoid back into position after the field is deactivated as shown in Figure 3, right [9]. Since the tactor design requires continuous movement, the use of the spring would make it necessary to only power the solenoid half of the time. This reduction in power usage would help to reduce the amount of heat developed by the solenoid.

Besides overheating, there are some other problematic design considerations for the solenoid. One of these problems comes from the activation and deactivation of the solenoid in the form of a voltage spike [9]. Because of the high inductance a solenoid possess, a large voltage spike will occur when initiating the magnetic field. This can be solved by making sure the circuit is reverse current protected. The overall construction of the solenoid is another issue because for the 30-300 Hz frequency desired for this prototype, extreme precision would be required to meet specifications. At the size desired, it would be very difficult to build a functioning prototype. The tactor design calls for a 1 mm thickness. This means that the core will need to be less than 1 mm long because of the need for some movement and the tactor's casing. Complied with the problem of getting a magnet of that length, it will be difficult to make a solenoid that has enough wire turns to produce the magnetic field required to produce the appropriate force needed for stimulation. Even if the wire wraps are stacked on top of each other, the constraint of a 10 mm diameter will likely be too restrictive.

4.2 Design Option 2: Piezoelectric Vibration Device

When a mechanical force is applied to some solid materials, an electrical charge will form as a result. This is known as piezoelectricity [10]. There are a variety of ceramic and crystalline materials that are piezoelectric. The specific properties of the materials 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 electrical charge to form. This charge is directly related to the amount of force applied, and can be easily measured.
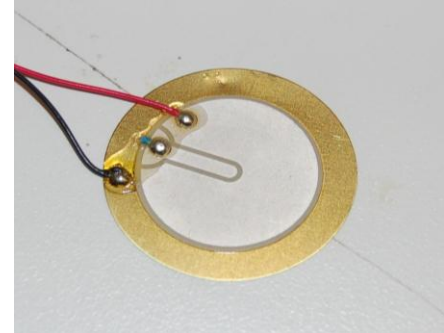

Figure 4: Piezoelectric vibrator [11]

The property of piezoelectricity can be reversed by applying an electrical 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 4. The voltage source is used to apply a charge to the piezoelectric material through the wiring. The frequency of vibration is dependent on the amplitude of the charge, so increasing or decreasing the charge will have the same effect on the vibration frequency, making the system easily adjustable [12].

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 [13]. Another benefit of such a system is that the frequency would be easily adjustable based on the voltage 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 non-ferrous wiring in the system; however, the materials are not the only determining factor in MR-compatibility. Any wires in the system that have a charge running through them will create a changing electrical current that will create an 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 charge for vibration. The wires would require heavy shielding in order to prevent any interaction between the wires and the magnetic field of the MRI.

4.3 Design Option 3: Pneumatic Vibration Device
Pneumatics is an approach in engineering applications using the change in pressure of gas to produce motions, or vibrations. The general pneumatic vibration system is composed of four main components: air compressor, pressure-regulating element (solenoid valves), control unit, and stimulator, as shown in Figure 5.
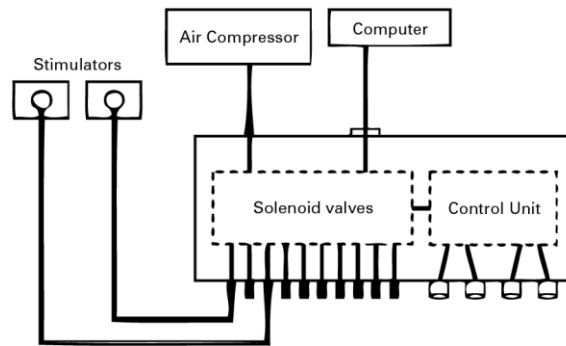

Figure 5. General schematic of a pneumatic vibration system (modified from [14])

The first component, the air compressor, is the main source of air. Pressurized air comes from a compressed air tank, a building compressed air supply, or a compressor. The air is then pumped into the connecting tube out of the compressor [14]. The pressure-regulating element is the part of the system controlling the airflow to the designated stimulator. Usually this regulating element is a pneumatic solenoid valve. Depending on the specifications of each design, different numbers of solenoid valves will be used; with one solenoid valve connected to one stimulator. These solenoids are connected to a computer for monitoring and adjustment in order to control the airflow from the compressor to the stimulator. Figure 6 provides some examples of the existing pneumatic solenoid valves.
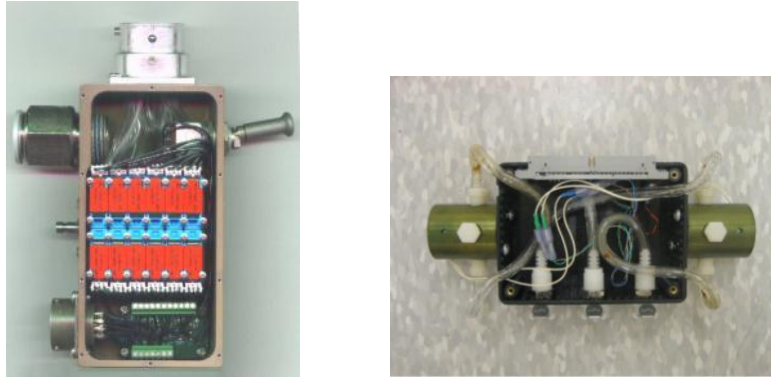
Figure 6. **Existing examples of the design of the pneumatic solenoid valves for regulating airflow into different stimulators:** V24 (left) contains 24 solenoids to handle 24 tactors [15], and the one on the right contains 2 solenoids on each side of the box, which regulates the airflow into one stimulator [16].

A control unit will usually be implemented in order to increase its adjustability. Ideally a control unit should be able to adjust the vibration frequency and intensity for testing purposes. A control unit can be a commercially available microprocessor [17] or RC timing circuit [14]. The last component is the stimulator, which is the part being in contact with the subject's skin and where the stimulation occurs. There are several existing designs for the pneumatic system stimulator of finger application. The first example is the pneumatic tactor, which consists of a distensible latex rubber diaphragm, mounted in a semi-rigid flat plastic holder (Figure 7, left). Since the latex rubber diaphragm is flexible, the air flowing through the plastic tube and entering the tactor can create vibration [14]. A cuff-type stimulator is another possible design in the pneumatic vibration system (Figure 7, middle). The finger cuff consists of an inflatable air bladder surrounding the subject's finger. This concept is similar to the cuff used in blood pressure measurements [17]. The third existing design is a hand-size cylinder. The entire stimulator is built inside a PVC casing which functions as the region of contact with the subject's hands and fingers. There are two air channels for air to enter. The air drives the fans, which is powerful enough to rotate a rod (acting as a turbine). The vibration is then caused by the inclusion of the offset mass (Figure 7, right) [16].
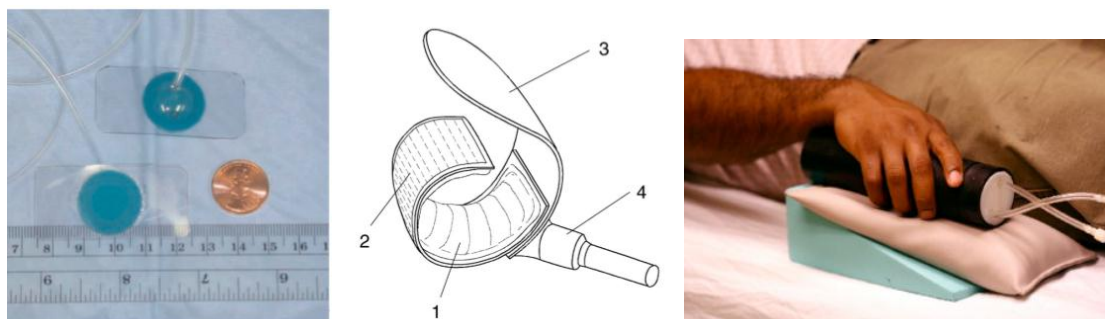
Figure 7. Various designs for the stimulator in pneumatic vibration systems: The left one is the pneumatic tactors (adapted from [14]), and middle one is the cuff-type stimulator (adapted from [17]), and the right one is the cylindrical stimulator (adapted from [16]).

The most advantageous feature of using a pneumatic device is its MR-compatibility. There are several pneumatic stimulation devices developed and used for MRI scanning, meaning that the pneumatic approach is certainly feasible for MR-compatibility. Another advantage of the pneumatic system is the adjustability of the vibration frequency it can accomplish. Both the solenoid valves and the control unit are the main components providing the adjustability of the vibration frequency and intensity via the control of the airflow. However, the maximum frequency the pneumatic system can achieve is far below the design requirements (300Hz).

Some of the other limitations of the pneumatic system include the size of the stimulator and the air compressor. There are several forms of the stimulators, and therefore, the size of the stimulator depends on the overall design and mechanism. The cost could also be a problem due to the relatively high price of components such as the air compressor and control unit.

5 Design Evaluation

5.1 Design Matrix

In order to evaluate the possible designs, 7 factors were taken into account and weighted appropriately. The most important feature of the design is its MR-compatibility, meaning device does not interact with the MR field. This was weighted as 25% of the evaluation. The frequency of stimulation is the key factor in achieving sub-threshold stimulation. Each device's ability to operate within a range of 30-300 Hz accounts for 20% of the total score. The tactor size and adjustability each account for 15% of the decision matrix. This is because the tactor must fit on the subject's finger to provide adequate stimulation, and the device must accommodate a range of vibration frequencies. 10% of the total score was attributed to the motor size, which greatly affects the size of the tactor. The device should last approximately one year, and 10% of the points were allotted to each device based on this criteria. Finally, cost will play a factor in the final design, but there has not been an established budget for this project, so it only accounted for 5% of the total points.

Table 1: The Design Matrix: Rates each design based on their ability to meet the requirements

	Solenoid	Piezoelectric	Pneumatic
MR Compatibility (25)	0	20	24
Frequency (20)	15	15	10
Tactor Size (15)	8	12	10
Adjustability (15)	10	11	9
Motor Size (10)	7	8	5
Longevity (10)	6	8	7
Cost (5)	3	3	2
Total (100)	**49**	**77**	**67**

5.2 Design Evaluation for Solenoid

The major contribution factor to the low score was due to MR compatibility in which it scored zero out of 25 points. The reason for this score is that the design uses magnetic fields to drive the stimulator. Without very strong shielding, the magnetic field of the solenoid would not only be overpowered by the magnetic field from the MR device, but the metal required to make the solenoid would not be able to be placed into the MR device. In the frequency category, the solenoid scored a 15 out of 20 points.

While the solenoid should be able to operate at the desired 30Hz to 300Hz range, the ability to achieve this range would depend on the quality of the solenoid's construction. For tactor size, the solenoid scored an 8 out of 15 points. The reason behind this score was based on how the solenoid uses a core moving back and forth to drive the stimulus. Because of this, building the solenoid well, and maintaining the 1mm thickness diameter would be difficult. The solenoid scored a 7 out of 10 points in the driver size category for the same reasons mentioned for the tactor size. The solenoid design should be easily adjustable, therefore scoring a 10 out of 15 points. The reason this score is not higher is because the adjustability would rely on the frequency capabilities. In the longevity category, the solenoid design scored a 6 out of 10 points. Again, this score reflects the solenoid construction. For cost, the solenoid scored a 3 out of 5 points since the parts to build it would be relatively inexpensive. The Solenoid design scored a 49 out of 100 overall points, the lowest out of the three designs.

5.3 Design Evaluation for Piezoelectric

The piezoelectric system received the highest score out of all possible designs because of its overall ability to achieve all of the specifications. The system got a score of 20 out of a potential 25 points for its MRI compatibility because the system can be made from all non-ferrous materials, but it is uncertain as to how the wiring would affect (and be affected by) the magnetic field used to create the MR image. The frequency of the system would be easily adjustable and could theoretically be designed to run at the frequencies required for the tactile stimulator; however, there are no commercial vibrators that run at the specific 30 Hz to 300 Hz range, so this design received 15 out of 20 points.

A piezoelectric vibrator could be made to fit any size requirements, but because of an inverse relationship between tactor size and frequency, the design scored 12 out of 15 points in that category. The driver of a piezoelectric system would only require a voltage source to apply a charge, which led to an 8 out of 10 potential points. The piezoelectric system could be easily adjusted based on the charge applied, which resulted in 11 out of 15 potential points for Adjustability. A piezoelectric system would have a long service life because of its simple design and mechanics, so it got 8 out of 10 for Longevity. The cost of this design would be relatively low, resulting in 3 out of 5 possible points. Overall, the piezoelectric system received high scores in all categories and a total score of 77 out of 100 points, making it the most feasible design option for the tactile stimulator.

5.4 Design Evaluation for Pneumatic

Since a pneumatic vibration device is mainly driven by air rather than electrical wiring system, the materials used are mostly plastic, or non-metal, meaning that the MR-compatibility is promising. Due to the air-driven mechanism and the required materials within the system, MR-compatibility turns out to be the most advantageous feature competing with all other options, which make this option score a 24 out of 25 points for MR-compatibility.

Another crucial specification along with the design is its vibration frequency, which is aiming at a range from 30Hz to 300Hz. However, most of the existing pneumatic vibration systems cannot achieve a frequency exceeding 100Hz. In order to generate a vibration frequency of 300 Hz, a driving motor must be capable of operating at 18,000 rpm (300(1/sec)*60(sec/min)=18000rpm). In this category, the pneumatic option scores a 10 out of 20 points, which is lower than the other two options. It would be fairly easy to adjust the frequencies of a pneumatic device; however, the range of adjustable frequencies is very limited to lower frequencies. It is for this reason that the device had the lowest score (9 out of 15) for Adjustability.

Since the vibration stimulus is to be applied onto certain locations on the fingers, the target tactor size needs to be small enough, ideally 1cm in diameter in order to fit on one finger. In this category, the pneumatic stimulator scores 10 out of 15 points, which is slightly less than the piezoelectric tactor because of the larger surface area that the plastic diaphragm would take compared to a piezoelectric wafer. The pneumatic system might also have a disadvantage because the size of the air compressor needs to be large to carry a large amount of air. Therefore, the pneumatic option obtains the lowest score of 5 out of 10 points in this category.

The longevity of the pneumatic system might not be the most ideal since the materials used in the system are mostly plastics, meaning that it would most likely wear out faster than the piezoelectric and solenoid systems. Therefore, the pneumatic system scores a 7 out of 10 possible points. Lastly, the cost of the pneumatic system might be another limitation. Although the stimulator and the tubing might be cheaper comparing to other options, the air compressor and the control unit would cost more than the electrical drivers required in the two other options. The pneumatic option therefore scored 67 out of 100 total points, making it less feasible than the piezoelectric option.

6 Final 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 8, three components are need: a voltage source, a driving circuit, and the piezoelectric tactor itself.
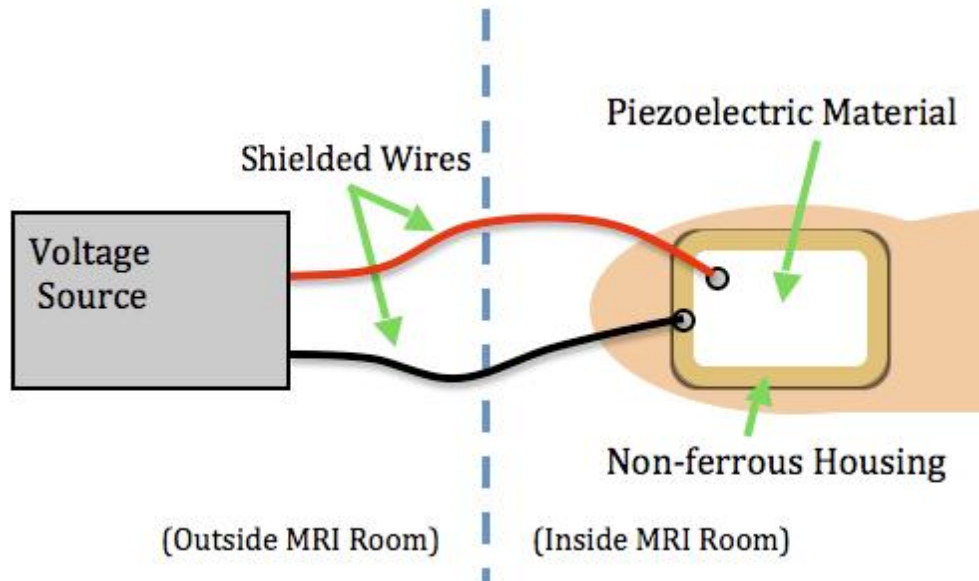
Figure 8. Diagram of the Piezoelectric system: Shows the connection of the outside voltage source to the piezoelectric tactor inside the MRI room.

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 shield 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.

6.1 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 build around it, only a 9-volt battery is required. Two of the benefits from reducing the voltage source to a 9-volt 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.

6.2 The Driving Circuit

In order to properly drive the piezoelectric tactor, a circuit is needed that can change the DC input volt 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 sub-circuits. 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.
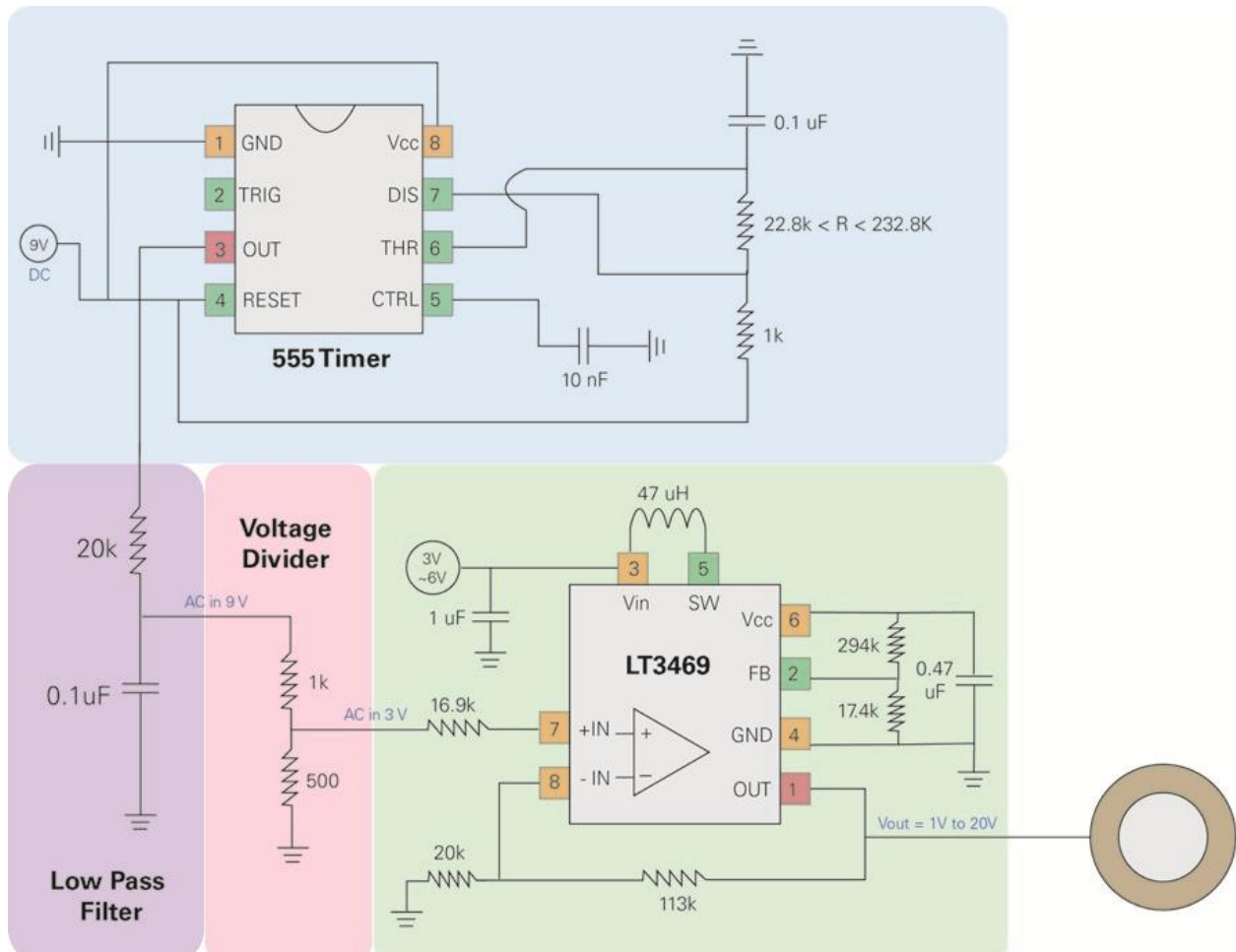
Figure 9: Driving circuit with power source and attached piezoelectric tactor. Shows the: 555 timer (Blue), Low-pass filter (Purple), Voltage divider (Pink), 3496 amplifier (Green).

6.2.1 The 555 Timer

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

The circuit diagram for the 555 timer can be seen in Blue section of Figure 9. This circuit is powered by the 9-volt 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 below, the necessary capacitor and resistor values were calculated to

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give a duty cycle close to 50 percent. For simplicity, a value of 0.1μF 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 kΩ ≤ R_2 ≤ 232.8 kΩ. To meet this frequency range, the circuit uses a 500 kΩ pot was used (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. The reason that we did not do is was primarily because it requires a transducers which was unavailable due to time constrictions that did not allow for ordering more parts.

6.2.2 The 3469 Amplifier
The circuit diagram for the 3469 amplifier can be seen in the Green section of Figure 9. 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 LT3469 chips 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 3469 amplifier, there is a voltage divider. The reason for this is because 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.
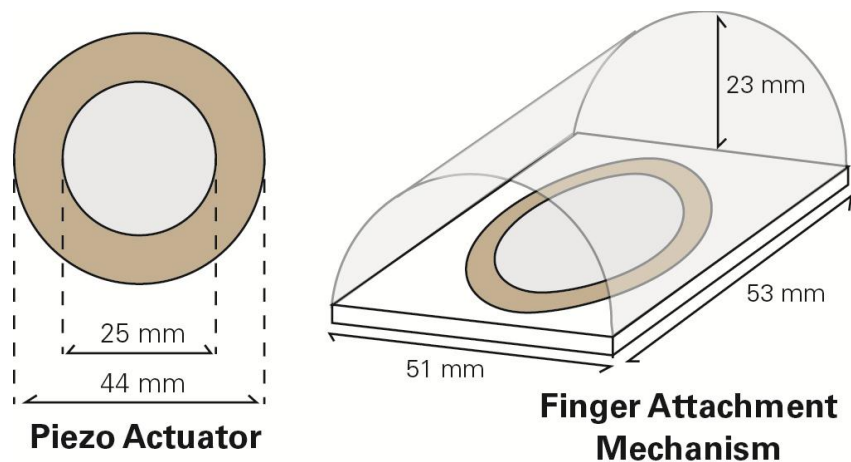
6.3 The Piezoelectric Tactor
In choosing the piezoelectric tactor that could meet the frequency and the displacement requirements, the size requirements suffered. Because the resonance frequency of piezoelectric crystal is dependent on physical size of the crystal, a piezo with a diameter larger than 10 mm is or a stack of piezos with thickness of greater than 1 mm is needed. Alone with the frequency constrains, in order to get a displacement in the range of 10 μm to 500 μm would require and driving voltage in the kilovolts 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 for 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 max operating voltage is only 20 V_{pp}, the piezoelectric buzzer can be used safely around living subjects, and does not require a large voltage source. Another good aspect of this piezoelectric buzz is that the size was not overly compromised. Since the piezoelectric element has a 25 mm diameter, it is still small enough that it would match size with a thick finger. 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 housing unit was build (Figure 10). The prototype housing unit sandwiches the piezoelectric buzzer's non-ferrous outer layer as to not disrupt the vibrations. A semi-circular 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 10: The piezoelectric buzzer's housing unit: The Piezo Actuator (left) is shown in the housing unit (right).

7 Testing

7.1 Frequency

Even with known input frequency from signal generator, the actual vibration frequency of the piezoelectric actuator still needs to be determined by using two piezoelectric buzzers. While using one as the vibrotactile device with known input frequency, the other piezoelectric buzzer was used for sensing the vibration. Piezoelectric materials have the property to deform in shape (vibrate) when electric charges are applied. Due to the fact that piezoelectric effect is reversible, the piezoelectric sensor was able to sense the vibrational force from the piezoelectric actuator when putting the two piezoelectric buzzer top to top. The piezoelectric sensor would convert the mechanic force into electric signal and sent it to the oscilloscope, which could show the frequency that the piezoelectric actuator was vibrating at. The actual output frequencies measured by the oscilloscope were recorded every 10 Hz starting from 30 Hz to 300 Hz. The testing results were plotted against the input frequencies (from signal generator) and showed in Figure 11. Based on the plot (R^2 = 1), we concluded that the input and output frequencies have 1:1 correlation, meaning the piezoelectric actuator did not mutate the input frequencies.
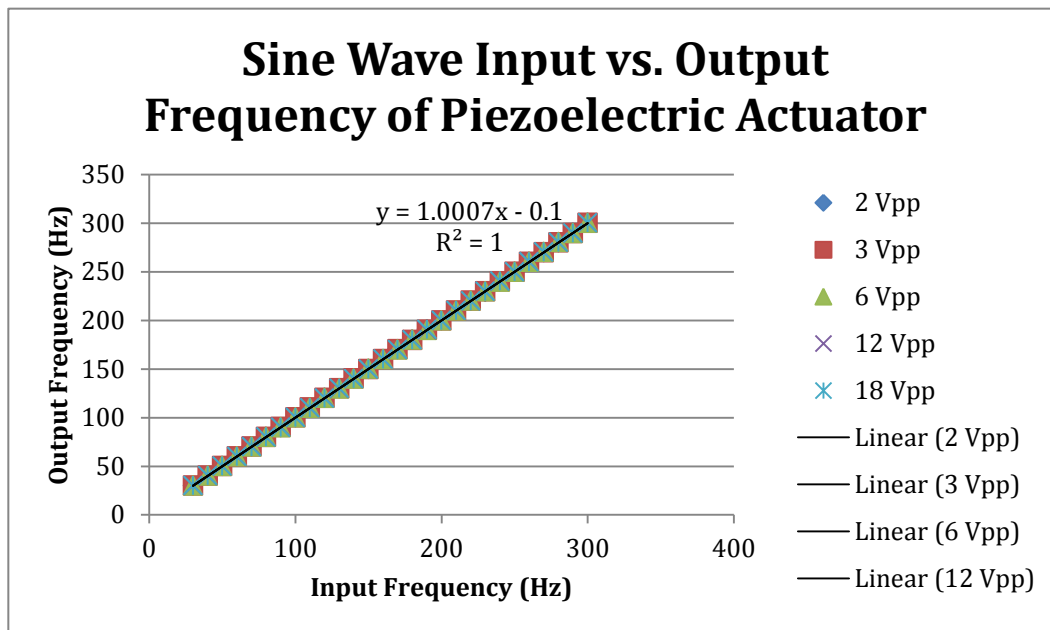
Figure 11: Input-Output frequency correlation for piezoelectric actuator. Notice the 1:1 R^2 ratio for the relationship.

The team then constructed the 555 timer astable circuit, which was designed to convert DC voltages into square wave signals. A simple power source, such as a regular 9V battery, can now power the piezoelectric actuator via the 555 timer circuit. The signal frequency that the 555 timer circuit generates depends on the adjustable resistor placed in the circuit. Also, there was a passive low pass filter inserted in the circuit to change the square wave signal into sine wave-like signal. This was important for reducing the audio noise produced by the actuator. There was also an adjustable resistor used in the low pass filter so that the cut off frequency could be adjustable according to the desired output frequency of the 555 timer circuit. The

team examined frequencies at 30 Hz, 50 Hz, and then every 50 Hz until 300 Hz. At each frequency, the team looked at the output waveform and adjusted the resistor in the filter so that the wave became sine wave-like. The resistances were recorded in order to calculate the cut off frequencies. The cut off frequencies were then plotted against the corresponding output frequencies. The plot is showed in Figure 12. R^2 value was 0.9672, indicating the cut off frequencies chosen by the team were consistent (although could be bias). The equation obtained from the plot allowed the team to adjust the filter when switching the frequencies of the timer circuit.
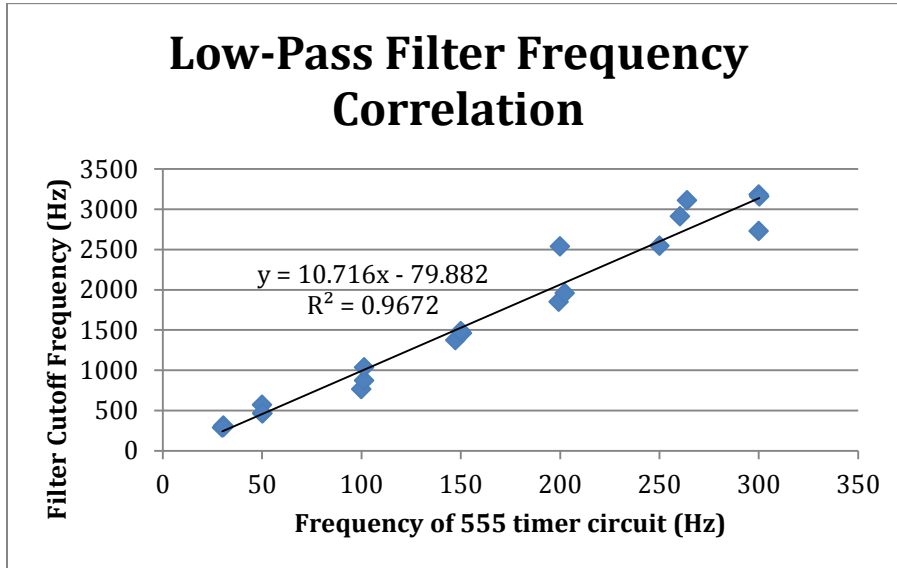

Figure 12: Low-Pass filter cutoff frequency correlation to 555 timer frequency.

7.2 Displacement

The LT3469 piezoelectric actuator driving circuit is incorporated so that the vibrational displacement of the actuator can be adjusted. The displacement of the actuator depends on the voltage provided, and the LT3469 circuit can vary the voltage input from 1 V to 20 V. Because the piezoelectric buzzer obtained from CUI Inc. did not provide the information on voltage to displacement, thus the relation need to be determined via displacement testing. To measure the displacement of the actuator, a laser vibrometer setup at the Mechanical Engineering department (University of Wisconsin – Madison) can be used. The vibrometer uses the principle of light scattering to detect the micrometer displacement of piezoelectric actuator. The team planned to find out the relationship between voltage and displacement so that our client will be able to change the displacement of actuator simply by adjusting the input voltage. However, due to the lack of availability of LT3469 chip and vibrometer, the team was not able to construct the driving circuit or perform the displacement testing until next semester.

8 Future Work

8.1 Stand-alone power source

The current prototype can be driven by the signal generator, and ideally by the circuitry designed (see Final Design); however, due to the missing of the LT3469 amplifier, a stand-alone power source has not yet been built. This can be achieved once the LT3469 chip arrives, or if the LT3469 is not available, a substituting amplifier with similar specifications should be found and implemented into the circuits instead. Calculations for values of each circuit component may need to be modified at this point.

8.2 MR-Compatibility

One of the major design requirements is to make the device MR-compatible in order to serve as a research tool to monitor brain activity. Although ideally the designed power source should be separated from the MRI room when performing the test, the extended regular wires connected to the piezo actuator will be an issue to induce the undesired current and interfere the MRI system. As a result, shielding of the wires or finding MR-compatible cables is required in order to be used in the MRI system. Coaxial cables might be an option but further modification of the cables is needed since the coaxial cables are too thick. Research on other possible MR-compatible conductive wire will be one of the future tasks for the team.

8.3 Improved design

There are several improvements can be might. First of all, the reading of the frequency generated by the 555 Timer is still relied on the help of oscilloscope, which is not practical when applying the device into the real-time testing. One of the solutions is to purchase a portable oscilloscope so that the operator can measure and determine the frequency using the calculations established previously to maintain the adjustability of the frequency. However, this might not be efficient. Another possible approach to solve this problem is to adjust the potentiometers used in the 555 timer and the low-pass filter. If a correlation between the two potentiometers can be identified, it would be possible to adjust them at the same time by placing them closely together and linking them using an adjusting knob. If this approach fails, a substituting component will be needed in order to provide this adjustability of the range of frequencies. The main reason why a low-pass filter is added into the circuit is because the square-wave signal generated by the 555 timer will produce an audible noise from the piezo actuator. This substituting component will need to have the characteristics of converting the DC input to AC output, adjustability of the frequency, and more importantly, generation of sine-wave signal. If such component can be found, it would be the better solution to improve the circuitry design.

To make the device more user-friendly, a display of the operating frequency can be incorporated into the device so that the user would clearly read out the frequency for testing purposes. In addition, although our client has compromised with a larger stimulator operating at the correct frequency range, a smaller stimulator is still desired for future application in the industry.

8.4 Testing

Up to this point the testing on the relationship between the input voltage and the vibration displacement is not completed yet. As stated in the Testing section, a vibrometer would be used to measure the small displacement of the piezo actuator when energized by the power source. Our target of the displacement is between 10 to 500 microns, which can be modulated by the output voltage from the LT3469 driving circuit. A correlation needs to be identified so that the displacement can be adjustable for different individuals with different sensitivities.

After completing the constructions and the improvement for the design, the device should be tested inside the MRI system. 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
<div align="center">

Product Design Specifications
Tactile Stimulator
John McGuire, Wan-Ting Kou, Alan Meyer, Albert Wang
October 26, 2011
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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 adjustable, and operate between 30-300 Hz

Design Requirements

1. Physical and Operational Characteristics
   a. *Stimulation:* The device must stimulate the Pacinian corpuscle, with an adjustable frequency of 30-300 Hz.
   b. *Size:* Stimulators on the palmar side of the hand cannot exceed 1 mm in thickness and 1 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.
   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

Estimated Cost of Parts

Elements in Prototype	Quantity	Price (USD)
CEB-44D06 Piezoelectric Actuator	1	2.21
LT3469 Transconducance Amplifier	1	2.45
555 Timer Chip	1	.49
Resistors	8	.13
Capacitors	5	.83
Inductor	1	1.44
Finger Attachment Mechanism	1	0
Total Price		**$11.78**

Complete Parts Summary	Quantity	Price (USD)
CEB-44D06 Piezoelectric Actuator	5	2.21
LT3469 Transconducance Amplifier	4	2.45
Resistors	20	.13
Capacitors	8	.83
Inductors	4	1.44
555 Timer Chip	1	FREE (BME Lab)
Finger Attachment Mechanism	1	FREE (COE Shop Scraps)
Shipping	2*	~10.53
Total Amount Spent		**$46.38**

*We will not be able to order all the parts from one company

Appendix C

Work time spent on project:

Team Member	Hours Spent on Project
John	44
Alan	43.75
Jessica	43.5
Albert	41.5
Total group meeting time	40.75
Total combined hours spent	335.75