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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

Based on the data from U.S. Bureau of Labor Statistics, the number one cause of disabling injuries and second leading cause of fatalities at construction workplace are due to falls from ladders or scaffolds [1, 2]. The annual compensation for these types of injuries is roughly $6.2 billion [3]. Some of the falling incidents, however, could be avoided if the person can detect the impending destabilization and then quickly activate the upper limb muscles to stabilize the body on the ladder or scaffold.

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 milliseconds to arrest and stabilize their bodies when sudden forces were applied to the ladder [4]. Out of the 100 milliseconds period, approximately 40 milliseconds was because of the delay in the brain cortical reflex loop, while the other 60 milliseconds was mainly from the delay of hand skin receptors to detect the change in contact force [4]. If this 60 milliseconds time period could be reduce 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].

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 the system to detect the signal by adding optimal amount of noise (has same modality as the signal, but does not contain significant information to the system). When adequate noise is added to the signal, it lowers the threshold for the system to detect the signal (Figure 1b). In order to reduce the amount of time for skin receptors to detect the vibrations from the ladder or scaffold, a vibrotactile device can be used to enhance the response of skin receptors by lowering their detection threshold (the effect of SR). The tactor would produce certain amounts of vibration (optimum noise) so that the small vibration generated during fall initiation (signal) can be detected earlier 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.

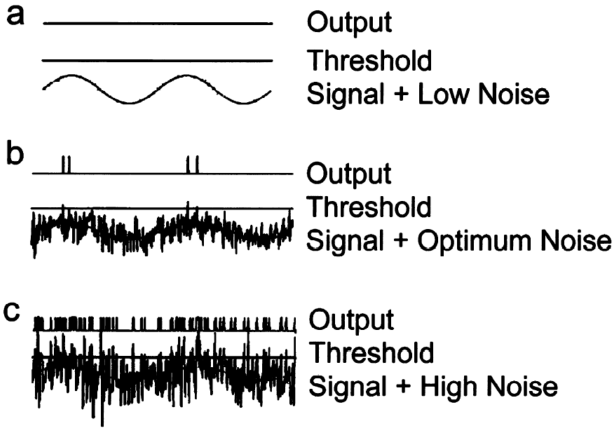

Figure 1. Example of stochastic resonance. (a) When the signal and noise is low and does not exceed the threshold, the system won't produce any output. (b) When optimal amount of noise is added to the signal, the signal and noise cross the threshold whenever the signal is high. (c) Excess of noise is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

During the summer of 2011, a Biomedical engineering student at the University of Wisconsin-Madison conducted an experiment that intended to determine the most sensitive regions on hand. The results 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, this report 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 (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.

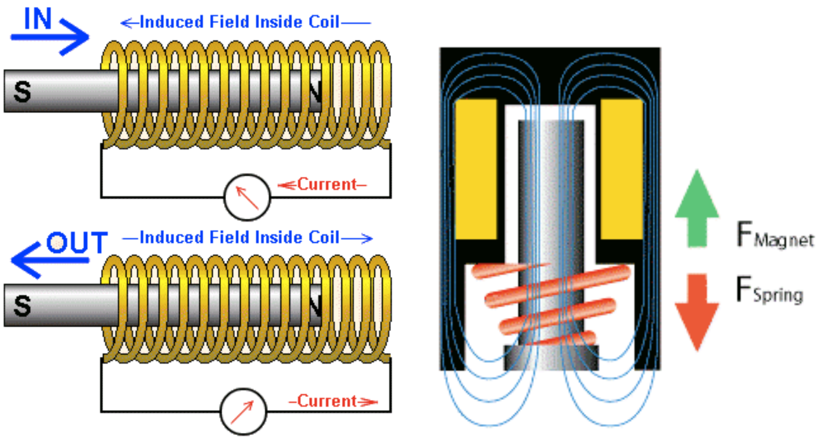

Figure 3. Solenoid theory (left) and Pull type Solenoid (right): These two figures show different methods of using a solenoid to drive a stimulation. The solenoid theory shows how reversing the current through the coil of wire reverse he magnetic field. The pull solenoid uses a spring to reverse the 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 (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. One of the other problems with the solenoid design is in the construction of the actual device. Because of the frequency that we want to move the magnetic rod at, the solenoid will have to be constructed well. What makes the construction an issue is the size that needs to be implemented. 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.

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 (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].

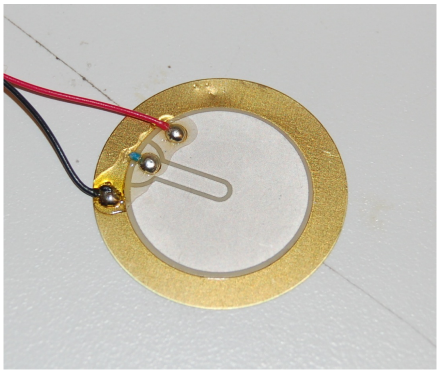

Figure 4: Piezoelectric vibrator [11]

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 [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 (Figure 5).

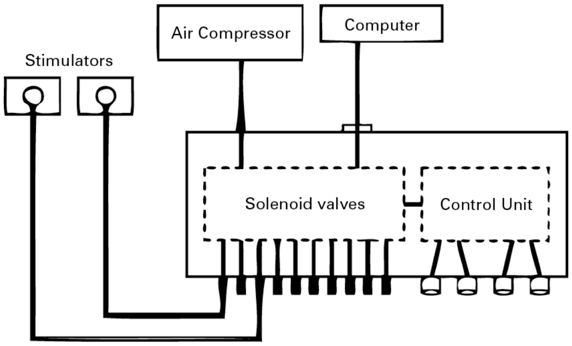

Figure 5. General schematic of a pneumatic vibration system (modified from [14])

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.

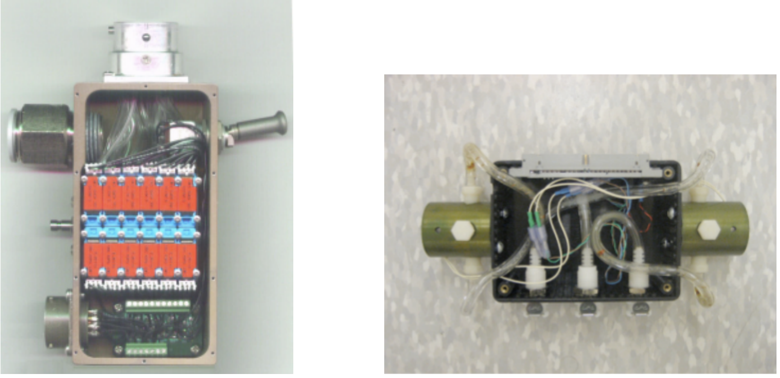

Figure 6. **Existing examples of the design of the pneumatic solenoid valves for regulating airflow into different stimulators:** V24 (left) contains 24 solenoids to handle 24 tactors [15], and the one on the right contains 2 solenoids on each side of the box, which regulates the airflow into one stimulator [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].

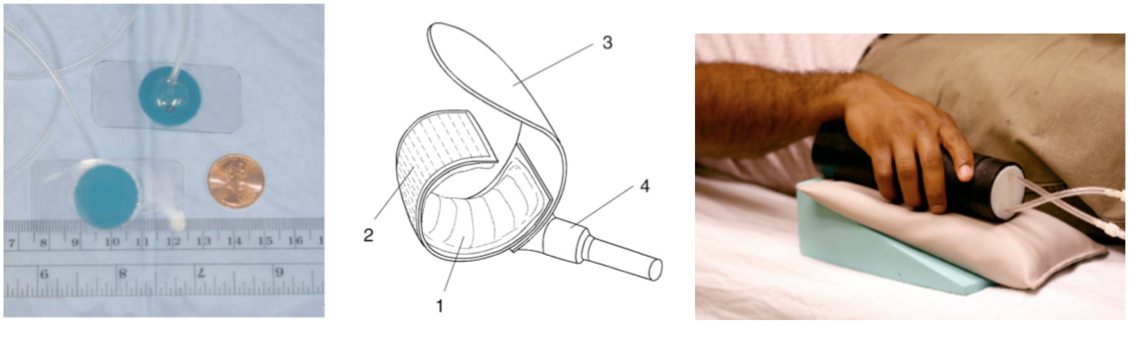

Figure 7. Various designs for the stimulator in pneumatic vibration systems: The left one is the pneumatic tactors (adapted from [14]), and middle one is the cuff-type stimulator (adapted from [17]), and the right one is the cylindrical stimulator (adapted from [16]).

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 of the design matrix, the Piezoelectric Tactor design was chosen for this project. In order to create a system to implement a piezoelectric vibrator for finger stimulation, the device would require three main elements: a voltage source, wiring, and the piezoelectric tactor (Figure 8). The charge generated in the voltage source (located outside of the MRI room) will travel through the wires into the MRI room. The wires will be attached to the piezoelectric material that is secured to the test subject’s finger. The charge from the wires will cause the vibration stimulus in the piezoelectric material.

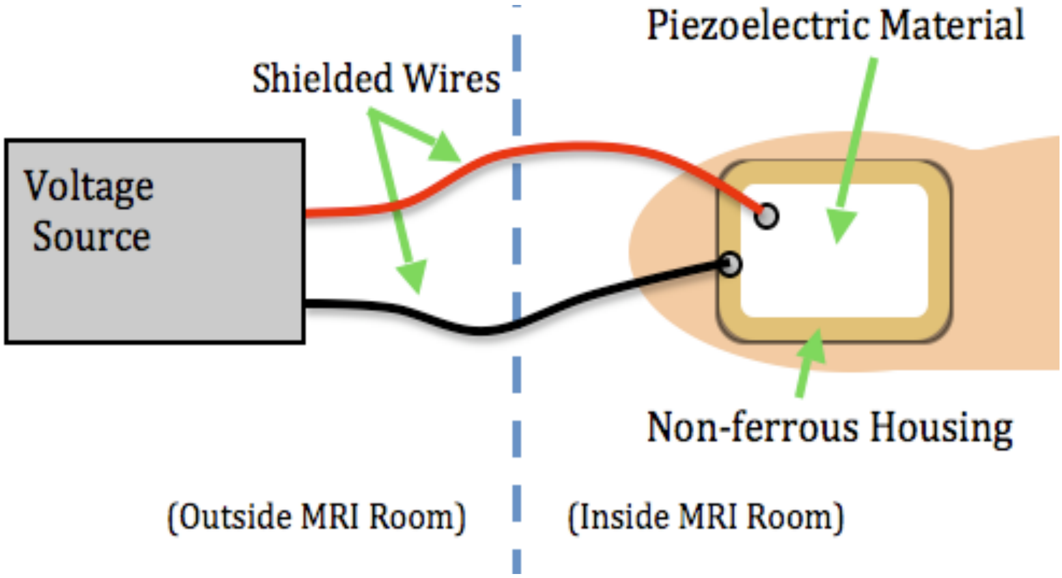

Figure 8. Diagram of the Piezoelectric system: Shows the connection of the outside voltage source to the piezoelectric tactor inside the MRI room.

This system is designed for MRI testing, so the voltage source used must either be non-ferrous, or be located outside of the MRI room. Research indicated that a commercial non-ferrous voltage are expensive and rarely used, so the most practical way of generating a charge for the vibrator would be to have the voltage source outside of the MRI room. Having the system outside of the MRI room will allow flexibility for the voltage source because there will not be size or materials constraints. There are a variety of commercial voltage sources that could be used; however, the voltage requirements will depend heavily on the type of piezoelectric material used. Current commercial piezoelectric devices require a 30 V_{pp} charge for vibration, but Professor Pilwon Hur at UW-Milwaukee has indicated that some piezoelectric vibrators could require up to 200-300 V. Obviously the voltage necessary would depend on the piezoelectric vibrator used, so it is difficult to say what voltage the system would require.

Research has been conducted in order to prepare for each potential range of voltages needed to drive the piezoelectric system. For a system that requires very precise voltage input, a digital multimeter could be used to supply variable DC power (Figure 9). These systems are very accurate, and exact voltage is displayed on a digital readout. The drawback is that digital multimeters are relatively expensive, costing a minimum of $150 for voltages up to $30V_{pp}$, and at least $350 for systems supplying up to 300V [19]. For the testing of the piezoelectric vibrator, it could also be possible to rent a multimeter from the BME department at UW-Madison, which would significantly reduce or eliminate the cost of the power supply.

Figure 9. Digital Multimeter [18]

The charge supplied by the voltage source would travel through wires underneath the door of the MRI room and into the tube of the scanner, reaching the vibrator itself. In order for the wires to function properly, they will need to accommodate the voltage and current supplied.

The key limitation of the wiring will be the MRI compatibility, and the resistance to interference from the strong magnetic field of the MRI. In order to prevent interference, the wires will require heavy shielding, which can be achieved in a number of ways. The most common method of shielding is to wrap a conductive layer around the wire, which can be either a braided layer of wires or a solid foil wrapping [20]. For the piezoelectric vibrator wires, a dual shield using both braided wires and a foil layer will be used to ensure that the wires are completely shielded (Figure 10).

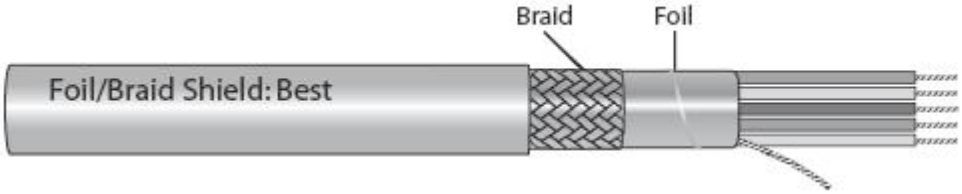

Figure 10. Shielding method using both braided and foil layers [20]

One concern regarding the wiring of the system is the length required to travel from the voltage source to the vibrator; however, research has indicated that shielded wires of up to 50 feet have been successfully used inside an MRI in commercial systems such as the *Kenall Medmaster MRI External Power Supply* [21].

The wiring will lead to the piezoelectric material, which will be housed in a non-ferrous metallic ring (Figure 11). The ring serves two purposes, the first is simply to hold the piezoelectric material and make the tactor more physically stable. The ring will also provide an even distribution of charge across the material, allowing more precise vibration. The piezoelectric material is yet to be determined, but it will most likely be a ceramic material with the crystalline dipoles that best suit the 30 Hz to 300 Hz vibration frequency range. Materials such as bismuth titanates and potassium niobates ceramics have piezoelectric tendencies [23]. Another option would be polyvinylidene fluoride (PVDF), which has strong piezoelectricity due to long, dipolar polymer chains [24]. In order to determine the best material for the frequency and size specifications, piezoelectric vibrator companies and experts on piezoelectricity will be consulted.

Figure 11. Piezoceramic disc with metallic housing [22]

7 Future Work

For the remainder of the semester, the project will be focused on construction and testing. For construction, the housing for the piezoelectric unit must be built, the tactors must be networked, and the circuit that regulates the tactors must be assembled. The testing will primarily consist of making sure that the piezoelectric elements are able to vibrate at frequencies from 30 Hz to 300 Hz. In order to reach the desired frequency range while maintaining the small surface area, different vibration modulations need to be tested in order to determine which is most effective. The two most promising methods for this are using destructive interference and using pulsing. The deconstructive interference would use two piezoelectric vibrators of high frequency and small surface area, offsetting their vibrations. By choosing the correct phase angle for the vibration waves, the desired frequency can be reached. The pulsing method would only require one piezoelectric vibrator. It would act similar to how a Tesla coil plays music; turning a high frequency vibrator off and on at the desired frequency. This would cause the stimulus frequency to fall into the 30 Hz to 300 Hz range even though the frequency of the piezoelectric vibrator itself is not in this range.

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Appendix

Product Design Specifications

Tactile Stimulator
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October 26, 2011

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.