MUSIC EXPERIENCE FOR THE DEAF AND HARD OF HEARING

MEIE 4701/4702

Technical Design Report

Music Experience for the Deaf and Hard of Hearing

Final Report

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April 16, 2019

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Abstract

The goal of this project is to enable deaf people to experience music in a way that they currently cannot. A successful device will help deaf users recognize components of a song being played that they could not recognize before. It will achieve this by converting the notes of a song into vibrations that can be felt by a deaf person. The design consists of a modified lacrosse vest with six exciters (speakers with the cone removed) embedded into the fabric that is worn by a deaf person. The exciters vibrate based on a processed music file of a song the user selected. Through the audio processing in software, the music file was condensed into a range of 1-1000 Hz vibrations so that the user could feel the higher pitches in music that would otherwise be missed when feeling vibrations of regular music. There are two enclosures: one for the user to interact with the device and one for driving the signal to the exciters. Both enclosures are battery powered and connected via bluetooth to deliver maximum portability and convenience.

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1 Problem Statement

To design a device that allows deaf and hard of hearing individuals to experience music through local vibrations on the body, and encourages dancing.

2 Need for the Project

During the market research phase of the project, a survey was distributed to deaf volunteers asking about their experiences with music. The responses indicated that the volunteers had minimal exposure to music but they were very interested in a new way to experience it.

Currently, there is a lack of devices that are designed for the deaf community. There are some products on the market; this report will touch on the positives and negatives of these products and what could be improved about them.

3 Deafness and Hearing Loss

3.1 Deafness by the numbers

According to the World Health Organization, about 5% of the world's population is deaf or hard of hearing. This percentage is a bit lower in the US, with 3.6% of the population reporting deafness or hard of hearing according to the 2011 American Community Survey [1]. This means that more than 11 million Americans experience deafness or hearing loss. From this 11 million, 1 million are functionally deaf, meaning they are unable to hear even with the help of hearing aids [2]. This functionally deaf group is the target for this project because it presents the worst case in terms of deafness.

3.2 Conductive deafness

Conductive deafness is when sound cannot reach the inner ear because of a blockage in the outer or middle ear. It can often be fixed with medical treatment because the cause is usually something physical like wax buildup or an object in the ear. This type of hearing loss is less common [3].

3.3 Sensorineural hearing loss

Sensorineural hearing loss occurs in the inner ear. It occurs when the hair cells of the cochlea become damaged. It can also occur when the auditory nerve, which carries sound signals to the brain from the cochlea, becomes damaged. This type of hearing loss is one which can be helped by hearing aids [3].

3.4 Implants

Cochlear implants are targeted towards people who are completely deaf or severely hard of hearing. The implants bypass damaged nerve endings in the cochlea. It uses a microphone located on the outside of the ear and sends signals to the electrodes located in the cochlea. A cochlear implant has 22 electrodes that send signals to the auditory nerve. This creates signals with a much lower bitrate when compared to the signals sent from the 32,000 nerve fibers in a functioning cochlea. The lower bitrate results in fewer details compared to the signals from functioning auditory nerve endings in the cochlea [5].

Cochlear implants require surgery and cost $40,000 in the US. If an individual is born deaf, sounds will not make sense right after cochlear implant surgery, and there is a chance that they never will. It is also difficult for a person with a cochlear implant to distinguish the different frequencies in music because the implant is designed for frequencies that occur during talking. Music heard with the implant often sounds robotic and static, even for people who experience deafness later in life [6].

Many deaf people are against cochlear implants because it threatens their culture - hearing people often think that once a deaf person receives an implant, they can stop using sign language to communicate. Many deaf people also don't feel that being deaf is something that needs to be fixed. [6].

3.5 Hearing aids

Hearing aids are positioned behind a person's ear and amplify incoming sound so that a person with hearing loss can hear better. They are mostly used by people who have lost their hearing due to aging. Only 16% of people who have hearing loss have used hearing aids [7]. With varying aforementioned views and limitations on hearing devices in the deaf community, there is definitely a market for a device that can translate music into vibrations for someone who is deaf or hard of hearing.

4 Body Response to Vibrations

The way a body responds to vibrations is a key part of choosing a design for the device. The research done will help decide which part of the body the vibrations will be localized. In addition, the body responds to different vibrations in different ways. For example, areas on certain body parts have more densely packed nerve endings which lead to higher sensitivity towards vibrations. To maximize the transfer of vibrations to the user, research was done to determine the best locations for the transducers. This section also touches on the topic of the dangers of vibration, ensuring the device does not cause any health issues.

4.1 Sensitivity

The sensitivity to vibrations on the human body depends on the frequency and the age of a person. Older people tend to be less sensitive to vibrations on their skin, however, this can vary. The sensitivity change with varying frequencies can be quantified. An experiment was done to find how the frequency a vibration on human skin affects sensitivity. The test used vibrations ranging from 25 Hz to 250 Hz, and it showed that human skin is more sensitive at higher frequencies as it requires a lower dB level for a person to feel a vibration [8]. As seen in Figure 1, as frequency increases, the dB level needed to feel the vibration decreases. This data is valuable input on optimal dB level and frequency levels needed for an average human to feel vibrations. Additional testing will be required to find the sensitivity of vibrations with frequencies above 250 Hz up to 1000 Hz, which is the range of vibrational frequency the human skin can feel.

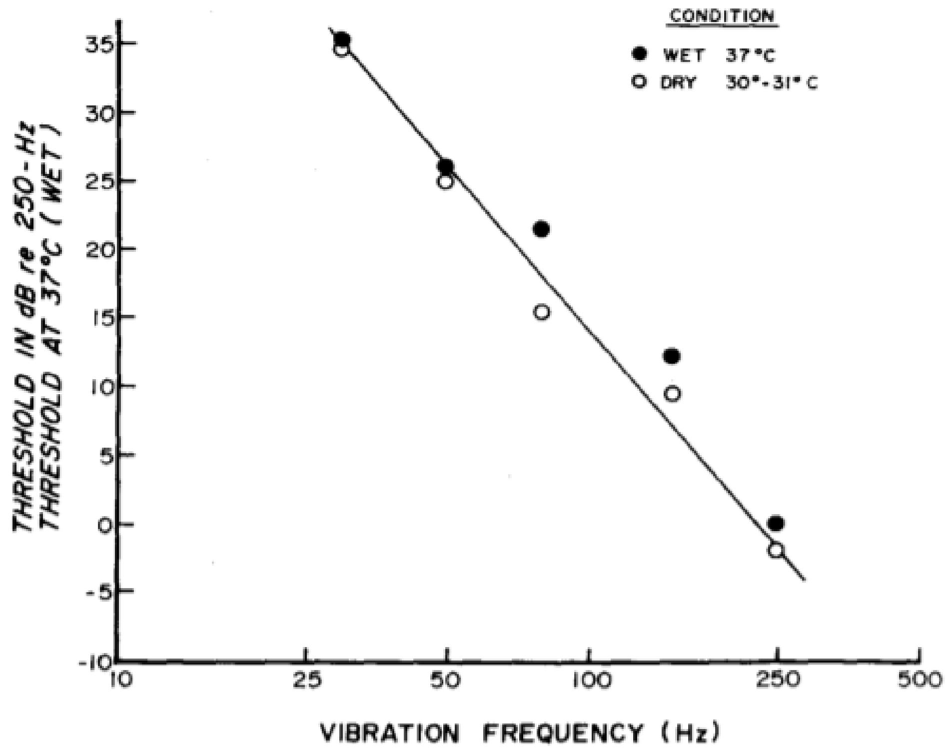

Figure 1 The minimum threshold in dB to feel vibrations at different frequencies [8]

In the same experiment, a test was done to find the relationship between vibrational sensitivity on the human skin and the temperature of the human skin. Figure 2 displays a chart relating the threshold frequency to skin temperature. The chart shows that for maximized sensitivity the skin should be at a temperature of 37℃. Higher body temperatures will decrease the sensitivity of the skin across all vibrational frequencies [8].

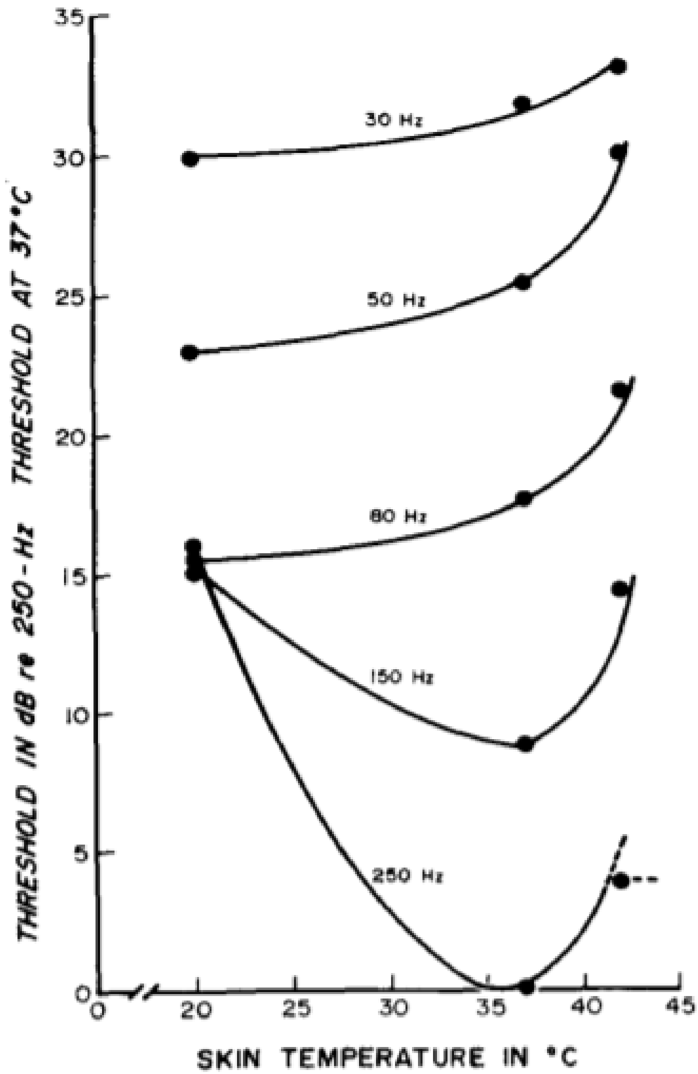

Figure 2 The minimum threshold in dB at varying vibration frequencies and skin temperature [8]

This information on optimal skin temperature and the relationship between dB level and frequency level plays a key part in the design of the prototype.

4.2 Sensitive areas

Another important design consideration is the location of the prototype on the body. It is known that human skin has different sensitivities based on the location of the body targeted. In a study published in *Frontiers in Behavioral Neuroscience,* differences in tactile sensitivity, direction discrimination, and "pleasantness" in different locations on the body were determined. The study found that tactile discrimination and sensitivity does vary across the skin. The areas tested in this study were the forehead, shin, thigh, arm, and palm. It was found that the forehead and palms showed higher tactile discrimination and sensitivity than the other sites [9].

The group met with Daniel Polley, an expert in brain plasticity and body response, to look for suggestions regarding where to place the prototype so its vibrations would be felt the ‘best’. Polley recommended the lips, fingers, palm, and tongue as potential locations for the prototype. These locations have a large number of nerve endings, causing an increased sensitivity in these body parts. These locations will be a high priority on the list of potential areas for the prototype.

4.3 Anatomical landmarks

An anatomical landmark can be defined by a part of the body that has a specific purpose or function and is important to the biomechanics of the body. This includes any joint or external organ. Due to the nature of these anatomical landmarks, they are more sensitive to touch when compared to other parts of the body. When examining the arm and the vibration response of it, it is found that the parts of the arm closest to the wrist, elbow or shoulder are more sensitive than the middle of the forearm or upper arm. An experiment was done which asked subjects to indicate which tactile stimulator was vibrating on their skin along their forearm and upper arm [10]. The study found that the subjects had a higher chance of answering correctly when the stimulators closest to the wrist, elbow, or shoulder were activated, as shown in Figure 3 below.

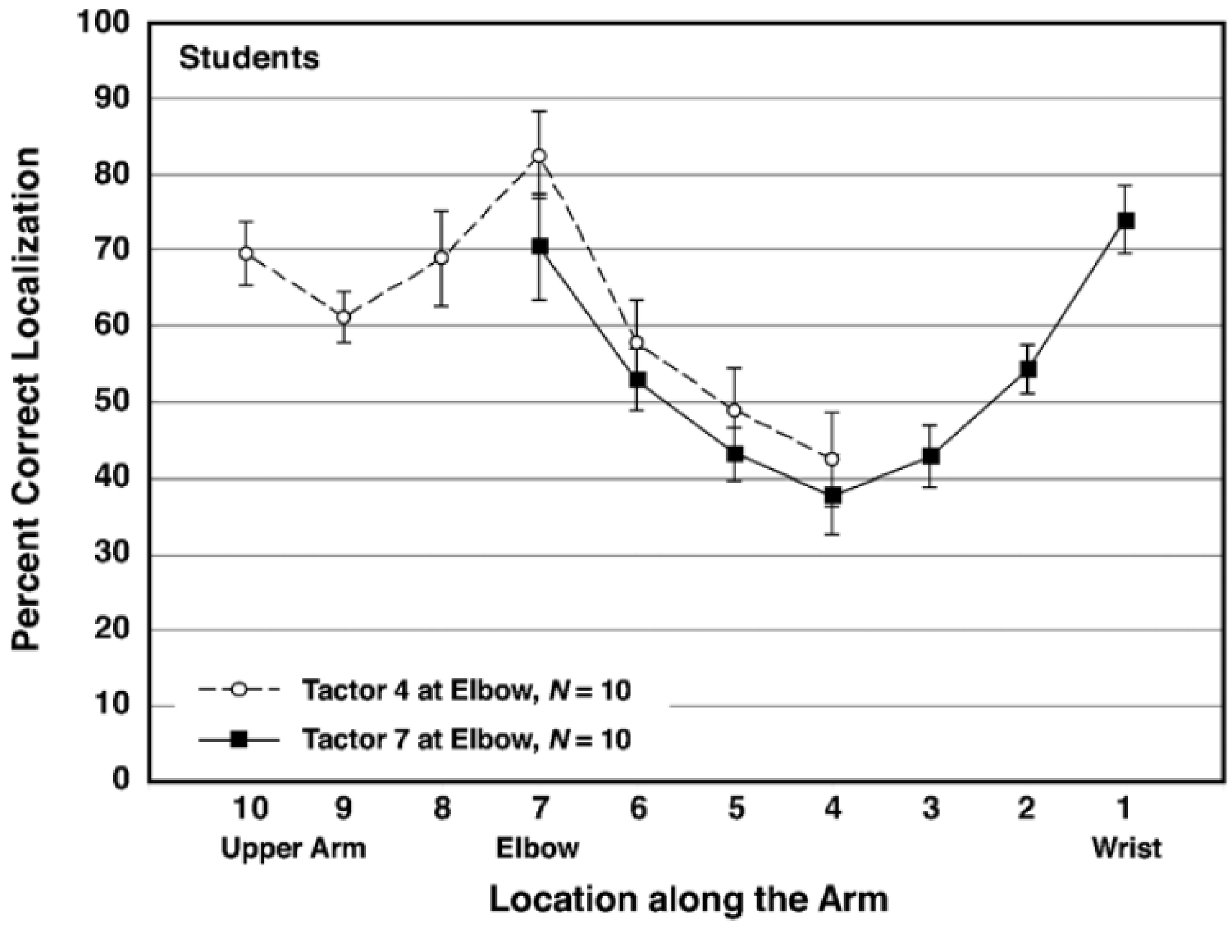

Figure 3: Percent correct localization of vibrations on the arm [10]

In addition to anatomical landmarks, the fingers are one of the most sensitive locations on the body. In a research paper, Wu, Krajnak, Welcome, and Gong modeled the human finger in a computer simulation. They wanted to confirm an experiment done by Harada and Griffin in 1991 [11]. They found that the resonant frequency in their simulated finger was 125 Hz. This increased vibrations by 50%. They had also found that vibrations at 63 to 250 Hz cause excessive dynamic strain in the deep zone of finger tissues. This prevents high-frequency mechanoreceptors from working properly. On the other hand, vibrations below 31 Hz cause excessive dynamic strain in the superficial (surface) layer of finger tissues causing lower-frequency mechanoreceptors from working properly. Mechanoreceptors are cells that respond to mechanical stimuli, such as vibrations. In order to achieve the best response in vibrations, these mechanoreceptors should be targeted in the prototype.

In addition to considering optimal locations for the prototype, suboptimal locations should be considered. Vibrations can cause errors in movement based on the location of the vibration. Multiple studies have found that vibrations in antagonistic and agonistic muscles cause errors in motion. Antagonistic and agonistic muscles are muscles that work together but in opposite motions. For example, the bicep and triceps are an antagonistic pair - when one contracts, the other retracts. In one experiment, it was found that vibrations on the antagonistic and agonistic muscles caused an overestimation, or underestimation, of 6 - 10 degrees when a subject tried to bend or extend their arms [12]. Another similar experiment found an overestimation of 10 - 13 degrees in movement with the tricep and bicep [13]. In the group's design, these combinations of antagonistic and agonistic muscles will be avoided.

4.4 Behavior of vibrations on the body

Vibrations can be determined by the frequency and amplitude of a wave. Frequency is the number of oscillations a wave undergoes in a second, measured in Hertz (Hz). The most common method to measure the magnitude of vibrations is to calculate the root-mean-square (RMS) value of the acceleration. This is the square root of the arithmetic mean of the square of the acceleration.

As mentioned previously, high-frequency vibrations (above 1000 Hz) are difficult to feel on the body, but easy to transmit in a small speaker because they require a smaller amplitude than low frequencies. This will be a challenge for the group - finding a way to transmit low frequency, high amplitude vibrations to the body without making a device that is too heavy or bulky. A low-frequency transmitting device needs a lot of space to create a large amplitude which is why subwoofers, the type of speakers that deliver low-frequency sounds, are so large. More testing needs to be completed to determine the solution. After speaking with Professor Ratilal, it became clear that the fundamental math describing the intended product's behavior is likely not complicated. Ratilal suggested simply testing speakers or transducers at different distances from the body first, and later explaining the math if necessary.

4.5 Effects of prolonged vibrations

This device has the potential to be used for long periods of time. Prolonged vibrations on the body can cause lower back pain, motion sickness, bone damage, and more. To ensure the consumer's safety, research was done to find the cause and effects of prolonged vibrations on an individual. A study was done at the University of Colorado, called the Effects of Prolonged Vibration on Motor Unit Activity and Motor Performance [14]. This study focused vibrations on muscles because muscle spindles are affected by vibrations. It was found that prolonged vibrations cause a reduced maximum force applied during maximum contractions. During submaximal contractions, the force applied sometimes fluctuated during prolonged vibrations. Other studies also found that prolonged vibrations "reduce muscle force, the tendon jerk response, and the Hoffmann and stretch reflexes". [15]

Damage to the body from exposure to vibration depends on three main aspects: duration of exposure, frequency, and amplitude of the vibrations. Depending on the type of vibrations, ISO standards have designated certain frequencies of vibrations to be monitored for health safety. The standards require an analysis of the vibration's influence on health and have metrics for different frequencies and different locations on the body [16].

As part of our analysis, it was found that perpendicular particle motion velocity follows the wave equation:

$$v = \pi fA\cos(2\pi ft) \quad (1)$$

where v is particle velocity, f is frequency, A is amplitude, and t is time. This means the maximum velocity for a particle is πfA and if this maximum velocity reaches a certain threshold, then vibrations could begin causing physical harm [17]. The group will reference the range of vibrational velocity that is safe and ranges that can cause harm to the human body throughout the project. This information provides good insight into what duration and types of vibrations to avoid.

5 Brain Plasticity in Deaf People

It is often thought that the bodies of people who have lost sensory ability in one or more areas will increase the sensitivities of the remaining senses. A small-scale experiment was done by Levanen to evaluate the validity of this statement. Subjects who were born deaf and also subjects of normal hearing were both used in this study. Experiments were conducted to determine the tactile sensitivity to different vibrations. It was found that the smallest frequency difference in vibrations detectable by deaf subjects was smaller than the hearing subjects. Deaf subjects could feel differences in vibrations of 21 +/- 3 Hz [18]. Hearing subjects could feel differences in vibrations of 28 +/- 4 Hz. However, due to the small number of subjects, the results were found to be non-significant.

Within the same study, it was found that deaf subjects could detect suprathreshold frequency changes significantly better than the hearing subjects. In this experiment, a suprathreshold frequency is when there is a random, sudden change in frequency, while there is a constant vibration. These results support the idea that there is a difference in tactile sensitivity in deaf people and hearing people [18].

The human brain is extremely adaptable. In someone who is deaf, the brain can convert the location normally allocated to processing sounds to help process vibrations [19]. Studies were done where deaf people and people with normal hearing had their brains scanned while receiving intermittent vibrations on their hands. The brain scans, pictured in Figure 4, showed that in both groups, the part that normally processes vibrations was active, but in the deaf group, the auditory cortex, which is usually only active during auditory stimulation for a hearing individual, was also active. In addition to vibrations, when shown visual rhythmic cues, the part of deaf people’s brain that is activated is the same part that is activated in hearing people, as shown in Figure 4 [20].

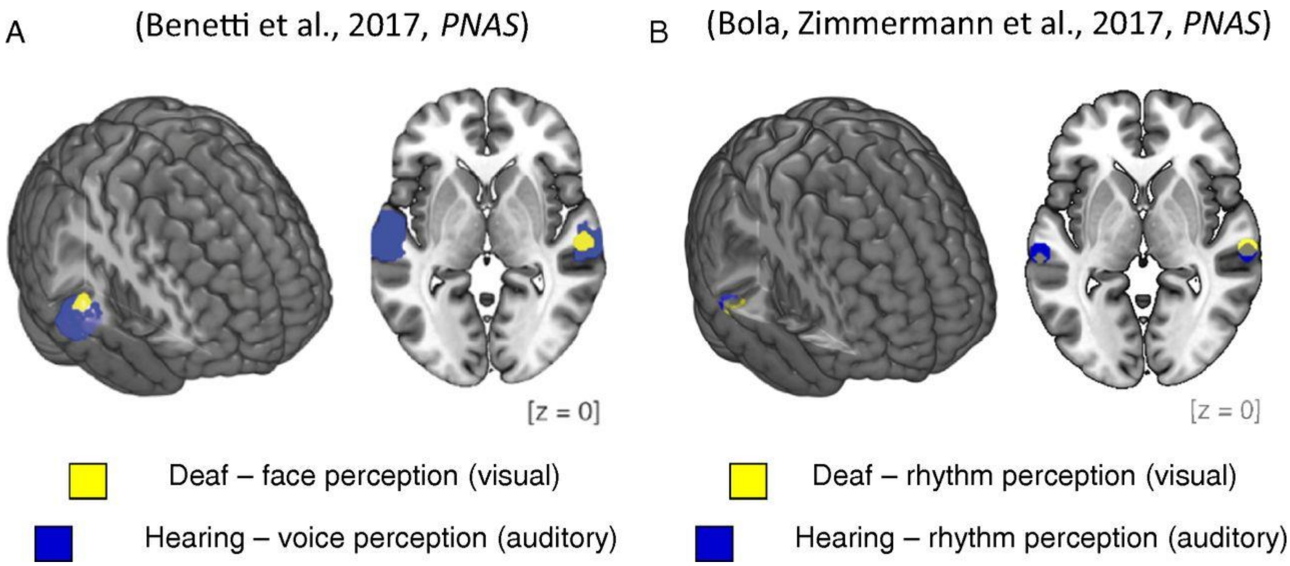

Figure 4: Comparison of the active parts of the brain of a normal hearing person and a deaf person [21]

The human brain is an extremely adaptable organ. There are many cases where the brain reforms due to the loss of a sense. In order to understand more about brain plasticity, the group met with an expert in brain plasticity. Polley, the researcher the group met with from Mass Eye and Ear, also recommended a paper by Stephen G Lomber about brain plasticity in felines. Lomber conducted experiments on the brains of deaf cats. The auditory cortex in cats can adapt to activate when somatic nerves are activated [22]. This further supports the idea that tactile vibrations are a viable approach to conveying musical information to those who are deaf or hard of hearing.

6 Speaker Power Considerations

The amount of power a speaker consumes does not determine how loud the speaker will be. Consumers are directed to purchase speakers based on their SPL (sensitivity) rating, which the group kept in mind when purchasing speakers. A higher SPL value means that the speaker is more efficient [23]. Additionally, most of the energy transferred into a speaker is converted to heat, because normal speakers are only about 0.5% to 2% efficient [24]. This will be an issue for an intended design because it should not become hot and uncomfortable for a user to wear. The amount of power consumed by the prototype will likely be on the same order of magnitude as a normal speaker power output, which is approximately 1 Watt at a normal volume [25]. It is also likely that the prototype will need to be powered from bulky power supplies given the time frame of this project, so power source is not a major concern for the scope of this project. The decision is therefore to likely make this prototype non-portable.

7 Music Experience

In the US, 91% of people listen to music, and on average they spend twenty-four hours listening to music a week. Music is special in that it not only generates activity in the auditory cortex of the brain but also in other seemingly unrelated parts of the brain. Music is known to strongly engage the parts of the brain responsible for remembering and contribute to the way memories are formed. Furthermore, music causes anticipation and predictability which “have tremendous influence on the regulation of nonmusical temporal processes in perception, cognition, and motor control [25]”.

Research by Blood and Zatorre from the Montreal Neurological Institute found that when enjoyable music gives you shivers down the spine, it’s actually activating similar neural systems of reward and emotion as those stimulated by food, sex, and addictive drugs [26]. In a research study with a similar goal of allowing the deaf to experience music, researchers worked with a diverse group of 41 deaf or partially deaf people and found that 32% of them are involved in musical activities [27]. A large majority of the deaf that were involved in musical activities used their other senses to enjoy music, with 32% of them watching visual displays and 27% of them feeling the vibrations created by the music. The same group was also asked whether or not they are unhappy about their inability to enjoy music as much as they would like, and 67% reported that they are unsatisfied with it [27]. This provides good insight for the interest that exists for a device the group is trying to make.

Currently, most deaf people enjoy music by going to venus where loud music is played, like a concert hall or a club, and they feel the music on their body as the sound waves are strong enough to vibrate their body. However, due to the properties of sound waves traveling through air, only the low-frequency waves are strong enough to be felt via vibrations. This means that a large percentage of the music is lost when only felt through vibrations. The team plans to eliminate this information loss when creating the device.

8 Existing Technology

Deaf people have access to several tools which partially achieve the goal of conveying musical information inaudibly. Some of the devices explored are specifically made for deaf people while some are targeted towards the general public.

8.1 Patents

There is only one patent found for a device that allows deaf people to enjoy music. This patent, number NL1036585C, is from the Netherlands. The patented device includes a handheld device which has 20 LED lamps that light up in tandem with the sound to give a visual representation. The device also has vibrating pads that go on the wrist of the user and transmit vibrations as another representation of the sound. This device is connected to an interactive electronic drum kit with drum pads that will give a unique response to represent the sound generated [28].

This device is interesting to the group because it is similar to the group’s final aspirations of conveying music. However, the device is used in tandem with LEDs, which is something the group wanted to get away from. The user needs to look at LEDs which means that more attention is required from the user than with just vibration transducers. It also requires processing music to correspond to lights, which the group decided was too broad for this project.

8.2 Devices made for deaf people

8.2.1 Emoti-Chair

The Emoti-chair, seen in Figure 5, is a project that was completed at Ryerson University with the goal of providing a musical experience to the deaf community. The main goal of the device was to be able to convey emotions from music to the deaf user. The chair had sixteen exciters on the back where the user's back would contact and included a music input to the system. The digital audio signal would then be split into different bands and sent to the designated exciters [29].

To test the device, a study was done that had a group of deaf users experience two sad songs and two happy songs. Different forms of signal processing were used in this study to see which was most effective in conveying emotion to the user. In its most successful test, it was able to achieve 85% accuracy when the user was asked about the emotion of the song he or she had just experienced [30].

The group at Ryerson University chose to use exciters as transducers, as they can directly create vibrations from frequency and amplitude information. The group chose to take advantage of the large surface area on the back to maximize the number of transducers and increase the amount of musical information it could transmit. This device achieved its goal of providing a good musical experience for the deaf with vibrational signals while conveying the emotions of the song. However, the design of the device adds constraints to the user as it can only be used in a chair while the user is sitting down in it.

Figure 5: Picture of the Emoti-chair [29]

8.2.2 Fujitsu Ontenna

Shown in Figure 6 is Fujitsu's product targeted at the deaf and hard of hearing community that attaches to a person's hair and transmits vibrations in real time so that they can feel alerts from something like the ringing of a doorbell or the timer on an oven. While this product is interesting, it is not focused on transmitting musical vibrations - only simple vibrations for live alerts in the user's environment.

Figure 6: Picture of a user wearing the Ontenna [31]

8.2.3 Sound Shirt

The Sound Shirt, shown in Figure 7, is connected to a computer system that analyzes audio signals from a microphone. Then, it converts the signals to vibrations in motors based on the intensity of the music. The Sound Shirt has multiple areas of vibrations, which will vibrate based on the highs and lows of music. The group will take the lightweight design and ergonomics of the Sound Shirt and implement it in the designs of the group's device in another fashion. However, the need of having microphones and transferring that signal to the shirt greatly lowers the resolution of the music. It was also made to be worn at a live music location with microphones set up which limits the location at which this device can be used.

Figure 7: The Sound Shirt [32]

8.3 Devices made for hearing people

8.3.1 SubPac

The device shown in Figure 8 is called the SubPac. It is a device targeted toward music producers and gamers because it translates digital audio signals into vibrational signals so that they can better feel the music. The vibrational signals are transmitted through two exciters with vibrotactile membranes onto the back of the user when the user is wearing this device. The device has a range of 1Hz to 200Hz, so it can only transmit the bass frequencies of a song. From testing the SubPac, it was determined that in most of the songs tested, the drum beat and the bass were split between the two different exciters. This is a concept that should be implemented into the design of this project.

Figure 8: SubPac Mx2 [33]

Testing was conducted on the SubPac after the group ordered it. The members of the group wore the SubPac while wearing noise-canceling headphones playing white noise to ensure the user did not hear anything. One song was randomly chosen to play out of this list:

Beat it - Michael Jackson (happy and fast beat)
San Francisco - the Mowgli's (happy and fast beat)
Mad world - Gary Jules (sad and slow tempo)
Wait - m83 (relaxing and slow tempo)
Don't stop me now - Queen (song with a change in tempo)

The user was then asked to pick out which song was played. The goal of this test was to see if the SubPac could transmit enough musical information to the user.

From conducting this test with 3 different users, it was determined that they were only able to correctly identify one song out of the 5 songs played. All 3 users were only able to identify Beat It by Michael Jackson. This is because Beat It has a very distinct bass line and beat. Since both of these fall into the frequency range of the SubPac, the device was able to transmit this musical information to the user very well.

Upon more testing of the SubPac, users have expressed that they felt discomfort after around 15 minutes. The concept of a well-packaged wearable device is a feature that the group will try to implement in the final design. However, the limiting frequency range of the SubPac sets it back and the group will aim to create a device that can perform over a bigger range.

8.3.2 Woojer Strap

The Woojer strap, shown in Figure 9, is a direct competitor to the SubPac. It is smaller and cheaper than the SubPac and it is noted by this group because it can be worn in different ways. It is similar to the SubPac in that it can only transmit the lower frequencies of a song, specifically 5hz to 500hz with the peak at about 150hz. It uses haptic technology instead of woofers like the SubPac. Many users recommend getting two Woojer straps for a better experience, which makes the device more expensive than the SubPac. The team did not procure a Woojer strap for testing because many reviews pointed at the SubPac being a more immersive experience.

Figure 9: Woojer Strap [34]

8.3.3 Dance Studio with vibrating floor

One dance studio called Feel the Beat, located in Colorado, uses a vibrational dance floor so that people can literally feel the beat through their feet while dancing. It is advertised that the dance floor covers frequencies from 5Hz to 17kHz. However, this is only targeted towards dancers and also has a very restrictive environment of usage, and it is unclear how frequencies above 1000 Hz are experienced by a deaf user.

8.3.4 BW App

There is also a smartphone app that analyses the beat of the song, called BW App. The app vibrates the user's phone and flashes a light along with it. The team downloaded the app and tested it, and quickly found that the app is very inconsistent and does not actually follow the beat. Even though this app is very user-friendly and most people with a smartphone have access to it, it does not solve the problem of creating an accurate representation of music.

8.3.5 Bone conduction headphones

Bone conduction headphones transmit vibrations through the mastoid bone to the middle ear. People with conductive hearing loss can benefit from bone conduction headphones, but this type of hearing loss is the rarest, and it still requires a functioning cochlea. It is not a viable solution for most people with hearing loss. Furthermore, this project is not directly targeting this group of people, but instead focusing on people who cannot hear at all.

8.3.6 Live Jacket

The Live Jacket in Figure 10 was created by a group from the University of Tsukuba [35]. The idea of this wearable device is to imitate the feeling of a live concert where you can hear the music and also feel the vibrations from the speakers on your body. The device creates the vibrations while the user either listens to music from headphones or speakers. The idea of creating the experience that a user is at a live concert can be used by the deaf community. However, this device was not meant to be enjoyed by deaf people. Instead, the goal was to create a more complete music experience in the concert setting.

Figure 10: The Live Jacket [35]

The device actually uses the SubPac, mentioned above, but is modified with additional speakers mounted on the rest of the torso and arms. In the report, it is not stated whether the full frequency range of music is covered by the speakers.

To use the device, the user needs to use a digital audio workshop, like Logic Pro or Pro Tools, to split the music into different tracks. This requires the user to have the separate audio files of each instrument played by a member of an orchestra during the recording process. These different tracks are then sent to different speakers on the device via an audio interface and amplifier.

Even though having separate audio tracks on a digital audio workshop and sending it to different speakers is a good way of having different signals go to different speakers, it adds extra difficulty for the user. Not every person would have access to a digital audio workshop, and even fewer would have access to the audio files created by an artist when the song was recorded. Without that, the device is simply like a SubPac but with more speakers. This means that it would create unrecognizable vibrations on the body.

The feedback from the people, all not deaf, who tested the device stated that the device was heavy and uncomfortable, and some of them said that the device created poor sound quality, mostly due to the unrecognizable vibrations [35].

9 Speaker Design

A speaker is basically a giant electromagnet attached to a cone. The cross section of a speaker is shown in Figure 11.

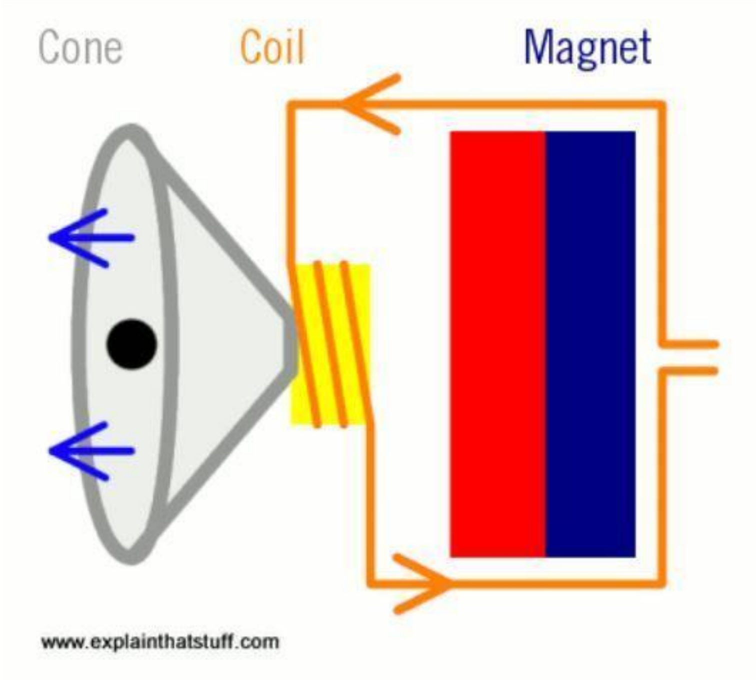

Figure 11: Layout of a speaker [36]

The direction of current changes the direction of the force in the electromagnet. When the current is in the counterclockwise direction as shown in the figure, there is a force that pushes the cone to the left. Then the current reverses, which forces the cone to the right. This force creates a displacement which changes the pressure in the air. This change in air pressure is heard as sound. The alternation of the current drives the frequency and amplitude of the speaker and is controlled by the digital audio signal [36].

This is one way to create vibrations, but cannot directly be used in this project because for the vibrations to be discernible through contact, the speaker would have to be turned up to a significant volume, which would be uncomfortable to people with normal hearing. However, one way to remove this discomfort is by removing the sound aspect of a speaker. This can be done by removing the speaker cone. The leftover device would just be the voice coil of the speaker, and this will be the primary device for generating vibrations in the design. In the rest of the report this will be referred to as an exciter.

9.1 Alternative devices – haptic feedback

Haptic feedback is any form of interaction involving touch as a mean of communication. Haptic feedback is a possible solution for this project to communicate music through vibrations. The three most common haptic feedback devices are an eccentric rotating mass (ERM), a linear resonant actuator (LRA), and a piezoelectric. The function of each device along with their pros and cons are discussed below.

9.1.1 ERM

The eccentric rotating mass actuator shown in Figure 12 is the simplest actuator. It consists of a motor that rotates an unbalanced mass connected to a shaft. Rotating the unbalanced mass causes a vibration due to the net centripetal force caused by the unbalanced mass. The speed the mass is spun can be controlled to vary the intensity and frequency of the vibration by controlling the input voltage. The input to an ERM is a DC voltage between 1 and 10V. As voltage increase, so does the amplitude of vibration. The frequency of the vibration ranges from 1 to 300 Hz, which will change according to the voltage. An ERM has a typical response time of 40-80ms and requires the most power out of the three haptic technologies mentioned. While it is the simplest actuator, it is not the best for power efficiency and precision of vibrations [37].

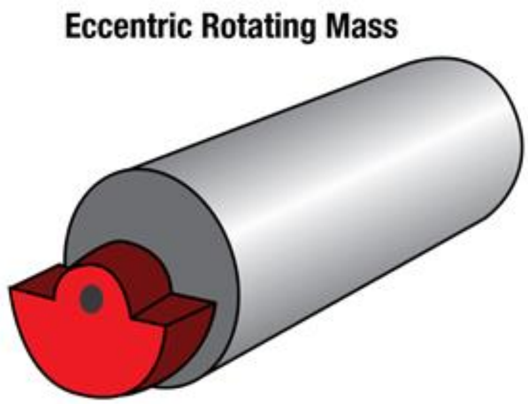

Figure 12: The layout of an ERM motor [37]

9.1.2 LRA

While ERMs work by spinning an unbalanced mass, LRAs work by oscillating a mass, which can be modeled as a spring-mass system. LRAs requires an alternating driving signal that can move the actuator up and down. As shown in Figure 13, the LRA acts as a mass-spring system. The resonance frequency of the mass-spring system will be the best driving frequency of the LRA. Outside of the driving frequency range, efficiency drops off sharply. LRAs have better power consumption than ERMs and slightly better response of 20-30 ms. The faster response time and alternating voltage source allow for more precise vibrations, although the resonant frequency severely limits the range with which the LRA will be useful to the project [38].

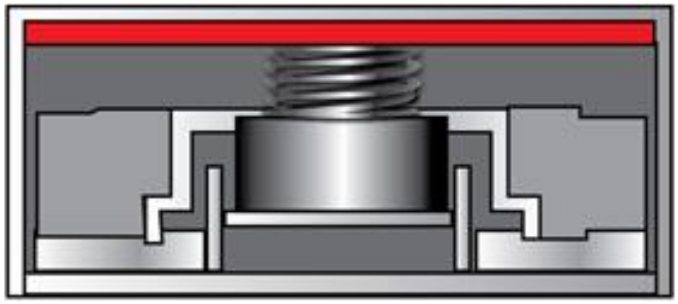

Figure 13: The layout of an LRA motor [38]

9.1.3 Piezoelectric

Piezoelectric materials are materials that can convert between electrical and mechanical energy. For a piezoelectric material to be an actuator, electrical energy will be inputted and then converted to mechanical energy in the form of vibrations. By applying a voltage between the two ends of a piezoelectric strip, the strip will bend. The input voltage is a sine wave, so when the voltage reverses the strip will bend differently. This bending causes very controlled vibrations that allow for control of the amplitude and frequency and can have a very wide frequency range. Also, since there are no moving inertial moving parts of a piezoelectric actuator, the response time is very quick - less than 1ms. Although piezoelectric actuators can create very precise vibrations, they require a high voltage (50-200V) to run, are slightly more expensive, and have higher power consumption than other haptic technologies [39]. Considering the wide range of input frequencies, the necessity of fast response times, and the wide range of output vibrational frequencies in music, the piezoelectric actuator is most suitable for this project.

10 Intermediate Designs

The design went through several iterations. One of the first designs was a stationary device where the user could press as hard as they wanted on an exciter to engage with the music. Some of the challenges with using this solution were the fact that the user had to remain seated and relatively immobile while using the device. As the client had a dancing background, she wanted to have more freedom to move. This feedback was used to create an iteration where the exciters were placed on a vest to stay on while moving. The client commented that this iteration was more conducive to dancing , however her neck and underarm were uncomfortable because the shoulder pads were digging into her skin. The client also commented that the front of the vest was too loose. Using this feedback, a final iteration was created where the shoulder pads were removed and the velcro strips in the front were replaced by belt buckles. Additionally, fabric was added to cover the front of the exciters for a clean look. The iterations of the design can be seen in Figure 14.

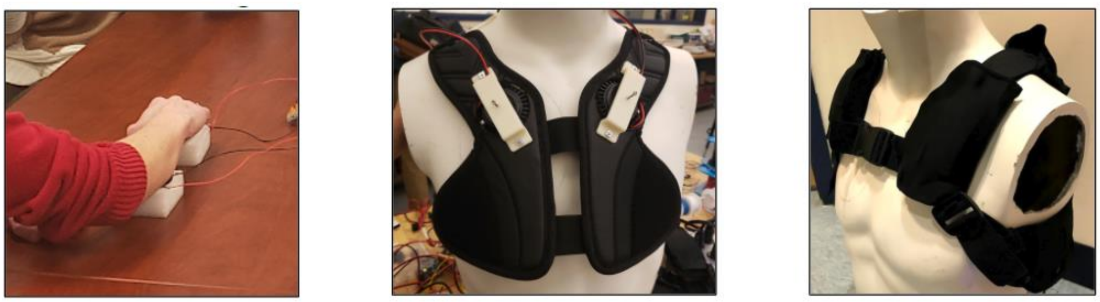

Figure 14: Design Iterations

10 Final Design

10.1 Overview

Figure 15: Final Design

The final design is shown in Figure 15. It consists of a modified lacrosse vest with six exciters held in place by six 3D printed bridges. A nylon fabric covers the wires that connect the exciters to the amplifiers positioned on the back of the vest. A 3D printed enclosure contains all three amplifiers plus three bluetooth receivers and a battery. The bluetooth receivers automatically connect to three bluetooth transmitters located in a separate 3D printed electronics box. The transmitters receive data from a Raspberry Pi running a Python script. A user interface on a touchscreen display allows the user to select a song they loaded onto a USB drive. The song is processed by a separate executable file that the user runs on their computer.

10.2 Vest

10.2.1 Exciter Selection

The six exciters on the vest came from Dayton Audio and have part numbers DAEX32EP-4 and DAEX25VT-4. The former has an optimal frequency of 150 Hz and the latter 400 Hz, so the different bands could be optimized through different exciters. Overall, these exciters work well up to 1000 Hz and weigh less than the alternatives making them strong choices for the final design. An exciter is shown in Figure 16.

Figure 16: Back view of DAEX32EP-4

10.2.2 Exciter Positioning

The location of the exciters was based on body symmetry, exciter separation, and internal anatomy. The left and right sides of the body respond to vibrations similarly and a symmetric arrangement leads to the most balanced weight distribution, a necessity for the force of contact to remain consistent while moving. The distance between exciters needed to be large enough such that different signals would not interfere with each other or the body's ability to perceive them. Lastly, the parts of the body with bones closer to the skin (such as the lats) needed lighter contact forces and lower frequencies for optimal sensitivity. These criteria lead to the decision to place two speakers on the upper torso by the collarbone, two over the lats, and two beside the shoulder blades, as shown in Figure 17.

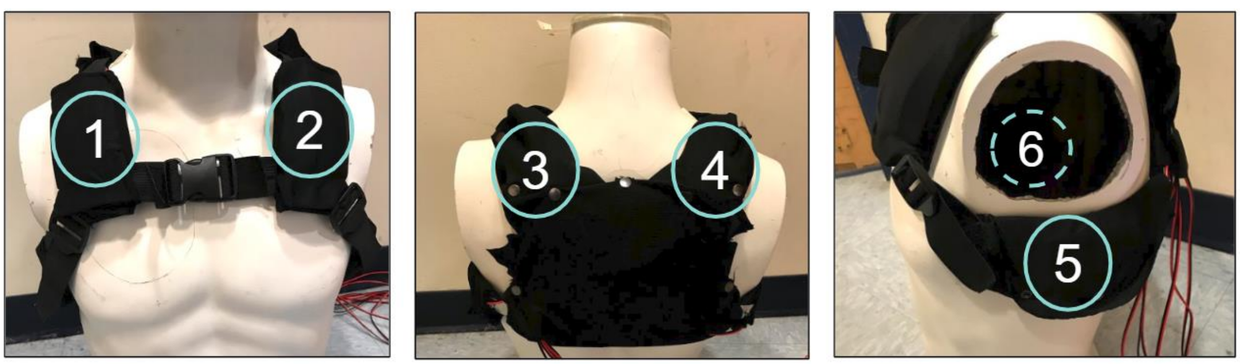

Figure 17: Exciter placements

10.2.3 Fixture for Securing Exciters

The exciters needed to be secured in the vest so a fixture was designed to be 3D printed and embedded into the vest at each location for an exciter. The fixture was built to minimize the movement of the exciter while the user is active while still being secure enough to hold the exciter steady. The ends of the fixture are bolted to the vest while a screw in the middle adjusts the height of the speaker above the body. Grommets were cut out in the side to provide strain relief for the wires coming out of the exciter. Slight variations in dimensions were required between different exciters for a comfortable fit at all six locations. An exploded view of the fixture assembly is shown in Figure 18.

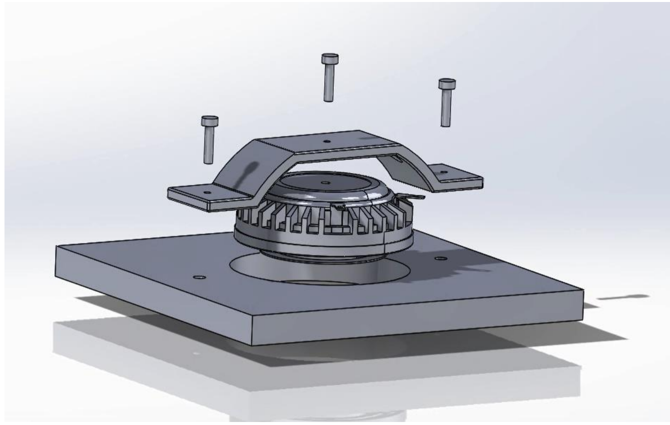

Figure 18: Exploded view of bracket design

10.2.4 Electronics on the Vest

Exciters had to be driven by an auxiliary signal strong enough to both power the exciters and create "audible" vibrations. DROK 30W amplifiers were chosen because they met these requirements best. They featured a knob to make adjusting the intensity possible, and this knob was used as an effective volume control for the vest. The enclosure the knobs were housed in was designed to allow the user to easily access them. The amplifiers were powered by a single 12V rechargeable battery mounted on the back of the vest. The wires were bundled and covered for protection. A power switch and charging port were exposed for easy access and emergency shut-off. Three bluetooth receivers listen for data from their corresponding transceivers inside the user console. An image of the electronics is shown in Figure 19.

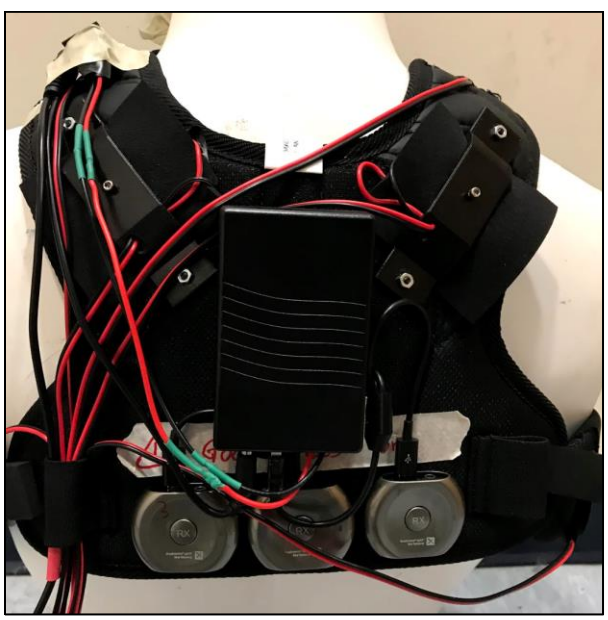

Figure 19: Vest electronics

10.2.5 Component Connections

A variety of fasteners and connectors were incorporated into the vest to ensure a reliably enjoyable user experience. The wires were soldered to the amplifiers and the exciters. Buttons on the fabric snapped together for a strong seal over the internal electronics. Velcro was used on the front pads to ensure a snug fit. Screws held the securing fixtures in place on the vest. OEM cables were used for power, USB to audio converters, and aux cables.

10.2.6 Fabric cover

A removable cover was made for each different part of the vest. One was made for each of the two front portions of the vest hosting the front exciters. One was made for each of the two side portions of the vest hosting the side exciters. Finally, one was made for the entire back portion of the vest which hosts the two back exciters, battery, and the three bluetooth receivers. The cover is made from a 4-way stretch athletic wear fabric made up of polyester with velcro and snaps attachments. This allows the fabric to stretch and fit tightly around the vest. It is also a lightweight and breathable material.

The purpose of the cover is to cover all the components of the vest for aesthetic reasons, as the group’s client had requested the wearable vest to not stand out too much. The cover was made to be removable so that if the cover gets dirty, the user can remove it and wash it without damaging any components.

11.3 User Console

The purpose of the user console is to contain the electronics and computer that control the music. These electronics include a Raspberry Pi (plus touchscreen), bluetooth transmitters, and audio splitters. An enclosure was made using Solidworks, as shown in Figure 20. The enclosure was designed to snap into place.

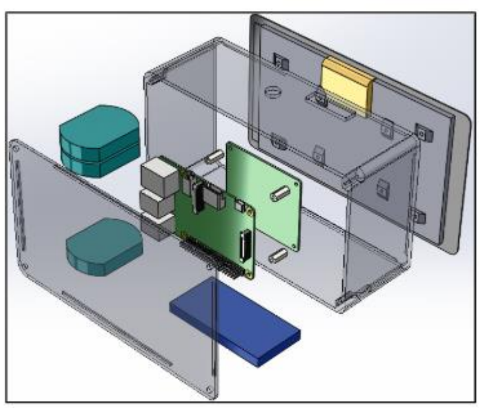

Figure 20: Exploded view of the user console

10.3 Software processing

The goal of the music processing is to extract the essential information in music before translating it to vibrations. Music produced for the general public has a frequency range that is made to match the frequency range of the human auditory system, which is from 20 Hz to 20 kHz. However, human skin can only distinguish vibrations up to 1000 Hz. This means if the music is translated into vibrations on the skin without any preprocessing, only a small fraction of the frequencies of a song are comprehensible and the remaining frequencies distort the music substantially.

To do this, a Python script filters out frequencies not essential to the main information in the music. This reduces the range of frequencies that needs to be further processed to fall in the range of below 1000 Hz. Frequencies higher than 3000 Hz - the generally recognized end of the mid-range in modern music - get filtered out because they are mostly harmonic overtones rather than fundamental frequencies of musical melodies. Then the remaining frequencies get pitch-shifted down into six frequency bands in the range of 1 Hz to 1000 Hz based on the widely accepted Bark scale [40]. General practices in digital signal processing that use Fourier transforms for band-pass filtering and pitch-shifting were followed. The Python program was packaged into an executable file called compGUI.exe that can be downloaded on any Windows computer. This program is separate from the program that actually plays the music on the Raspberry Pi because processing takes a few minutes and only needs to be done once for each song.

10.4 User Interface

In order to provide a better experience for the user, a user interface was designed for the touchscreen. When the device is powered on, the main display has a single icon labeled **ME Capstone 2019**. When clicked on, the graphical user interface (GUI) launches, displaying a minimalistic window asking the user to select a music directory. The chosen music directory must contain the folders created by the separate executable file, **compGUI.exe**. After the directory is chosen and 'Select' is tapped, the list of available songs is displayed. In addition, the user has the option to choose between six different bands of frequencies or three different bands playing on two speakers each. The default is three bands. After selecting the type of signal to send, the user can then choose which song to play. Three buttons are displayed below the songs, 'Play selected', 'Previous', and 'Next'. These buttons can play and pause a song as well skip to the next song or return to the previous song. The GUI is shown in Figure 21 as it would appear on the touchscreen.

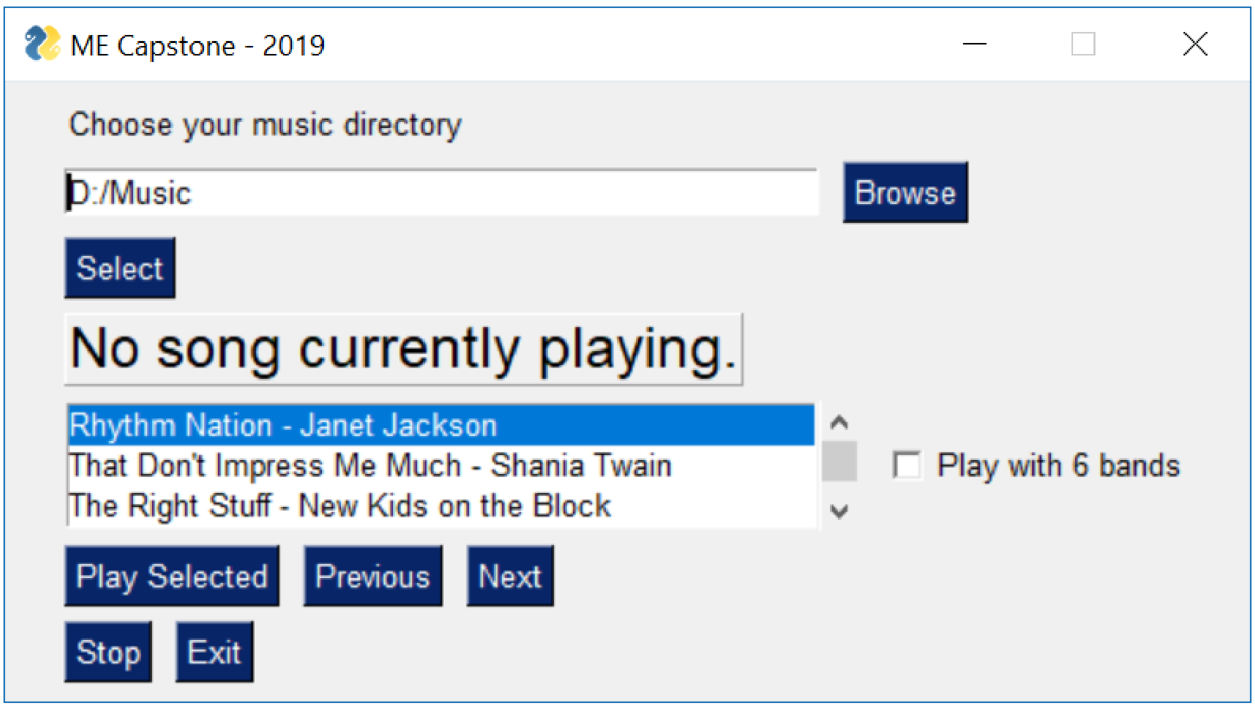

Figure 21: User interface on the console

11 Experimental Testing

Testing has been done on the range of exciters and piezo-actuators that the group has ordered with the goal of trying to find how each one feels on the skin during vibration. Simple prototypes have also been made as a proof of concept. The group did the testing on Northeastern University ASL faculty Laurie Achin, who is deaf, as well as the team members of the group. When the test was done on the group members who are not deaf, white noise was played via noise-canceling headphones worn by the test subject to prevent sound from the transducers making it to the ears.

11.1 Testing Results

In the testing the group has done, the client selected several songs which were then processed by the software. Then these processed songs were played to the client via the vest and user feedback was noted.

11.1.1 <u>Contact force testing</u>

The group wanted to investigate correlations between body locations tightness on the body and frequency. It is common knowledge that barely touching a speaker to skin evokes no response while pressing too hard dampens the vibrations. The group wanted to find the sweet spot on all three locations that that vest targeted. Force sensor from TexScan called Flexiforce ELF B201 sensor was used to measure the contact force at different frequencies at each location. Then these results were compared with the force induced by the vest pressing on the body during normal operation of the device. The results are shown in the graph in Figure 22.

Figure 22: Comparison of vest forces and optimal speaker forces

The red lines in the graph show the regions where the contact force felt most appropriate as compared to a control. The green lines highlight the regions of tightness attainable by tightening the vest. The data indicated that there is a range of force appropriate for each location and fortunately those forces ranges overlap with the forces one can expect to experience during casual use of the vest.

11.1.2 Music recognition

Another test the group completed was testing for song recognition. Using the processed song file, the vest was used on the client to determine if she was able to recognize the name of the song based on the vibrations. The client was able to recognize three out of the four songs that were played to her through the vest. The songs were also repeated also forward or backward without the client's knowledge. The client recognized a difference between the forward and backward songs, but incorrectly did not recognize the song didn't change when it was played back to her in the forward direction. This was attributed to the songs having unusually long introduction that confused the client when she was comparing them to the middle of the same song.

11.2.3 Heat Testing

The group completed a test heating of the amplifier box. This was done by running the device for 10 minutes and recording the temperature of the interior of the box. Because the heats fins on the amplifiers were reduced in size to fit inside the enclosure. Therefore, a fan was added to turn on when a thermal switch measured an operating temperature of 40 degrees Celsius.

11.2.4 Noise level Testing

While testing the device, the group noticed certain parts of the song could be heard from the vest while it was in use. The group wanted to quantify how much noise there was and then minimize it as much as possible so as to not disturb people nearby. The group used foam as a noise dampener and conducted a test to compare the results of the noise levels emanating from the vest both with and without the foam.

A sound level meter was placed 10 inches away from the vest, and 3 different songs were played from the vest at the same volume with pieces of foam covering the exciters. The average sound levels were recorded. Then the same 3 songs were placed with the foam pieces removed, and the average sound levels were compared.

The ambient room sound level was measured to be 57dB. The results are shown in Table 1.

Table 1: Sound level comparison

	Vest without foam (dB)	Vest with foam (dB)
Song 1	63	61
Song 2	65	64
Song 3	74	72

The data indicates that the vest adds about 10 decibels to the ambient noise level and using the foam yielded an overall reduction of 1-2 decibels, which was deemed significant enough to be worth including.

As a result, a layer of foam was added to cover each exciter as it showed that it could lower noise levels coming from the vest. Another advantage the foam has is that it makes the outside of the vest softer by removing all the hard surfaces under the fabric cover of the vest.

Future Work

Though the primary goals of making the device non-invasive, fully comprehensive, and convenient to use were achieved, there was a lot of aspects that could be improved in future iterations. The enclosures for electrical equipment were larger than they needed to be because the amplifiers, wires, and adapters were all commercial off-the-shelf parts that were not meant to fit together in a confined space. Designing a printed circuit board with all necessary electronics built in would drastically reduce the footprint of the electronics boxes as well as strengthen the electrical connections between components. In addition, the contact force between the exciter and the user affects how well the vibrations transmit but it cannot be easily adjusted in the prototype. Future iterations will enable the user to independently control how tightly each exciter presses on their body. Another aspect of the device that could be optimized is processing the music faster because when the song is long, the amount of time it takes to process can be on the order of minutes rather than seconds. The software could also be updated to reduce lag that gets introduced after a long time of using the device. Additional features on the user interface were also considered, such as letting the user control which frequency bands are created in the music processing, enabling the user to choose where in the song to begin playing from, and accepting songs with sampling rates other than the standard 44.1kHz.

12 Intellectual Property

12.1 Description of Problem

Deaf people currently do not have the means to experience music in ways that are non-invasive, fully comprehensive, and convenient to use. Relevant technologies include cochlear implants which are invasive and ineffective for music, the Subpac which only encompasses low-frequency notes, and large venues playing loud music which are inconvenient.

12.2 Proof of Concept

The goal was to design a device that allows deaf people to experience music in a non-invasive, fully-comprehensive, and convenient manner. The design consists of a modified lacrosse vest with six exciters embedded into the fabric that is worn by a deaf person. The exciters vibrate based on a processed music file of a song the user selected. Through the audio processing in software, the music file was condensed into a range of 1-1000 Hz vibrations so that the user could feel the higher pitches in music that would otherwise be missed when feeling vibrations of regular music. This is how the entire spectrum of music was captured in the device. Lastly, the design is packaged in a way that allows for comfortable listening because one enclosure contains the user interface while a separate enclosure holds the amplifiers on the vest. The two enclosures are both battery powered and connected via bluetooth to deliver maximum portability and convenience.

12.3 Progress to Date

Laurie Achin, a deaf faculty member at Northeastern, volunteered to become the team's client for whom the device was going to be built. The first functioning prototype of the device was completed and featured six exciters (two next to the collarbone, two below the armpit, and two beside the shoulder blade) plus two enclosures for electronics. One enclosure was fitted to the back of the vest and wired up to the exciters while the other displayed the user interface that allowed the user to control the device. The enclosures communicated via bluetooth and included long lasting batteries. The user interface allowed the user to plug in a USB drive containing processed music files and choose which song on the USB drive to play. It gave the user control over whether to have the six exciters play different bands of frequencies or to have the exciters that are symmetrically located on the body play the same bands. The user could also adjust the intensity of the vibrations going to each of the three body locations using three knobs on the amplifier enclosure. A separate executable file was created to process any song on any Windows computer. The final vest featured a thin layer of fabric to cover the exciters and exposed wires.

12.4 Individual Contributions

Brian Lin worked on the computer aided design, concept design, documentation, rapid prototyping, and programming. David Shoyket worked on the concept design, programming, and experimental testing. Jeremy Chow came up with the idea for the project originally and worked on the concept design and hardware prototyping. He also directed the music processing procedure and user interface layout. Wai Kit Ho worked on the concept design, computer aided design, and rapid prototyping. Lucas Barton worked on the concept design, hardware prototyping, and mechanical connections.

12.5 Future Work

The device could be improved by decreasing the size of the electronics enclosures, strengthening electrical connections, creating an adjustable speaker height, processing music faster, reducing lag in playback, adding features to the user interface, and giving the user more control over how the music is processed.

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