A. JAMES CLARK
SCHOOL OF ENGINEERING

# Automated Medical Percussion Device Materials and Manufacturing Review

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## ENME 472

**Honor Pledge:**
"I pledge on my honor that I have not given or received any unauthorized assistance on this assignment."

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## Executive Summary

Our automatic medical percussion device has not changed in terms of design since our design review report. To create a device that can perform a remote percussion exam, our team came up with a final product design consisting of four distinct subsystems: Movement, Controls, Pneumatic, and Acoustic. Each of these subsystems have their own specific component functions, all of which come together to succeed our total product functions.

Before finalizing the design stage of the product, we have developed a plan to prototype the device to test the efficacy of the pneumatic system, test the efficacy of the microphone chosen, and further evaluate material and shape decisions for the pleximeter. The prototype will consist of only the pneumatic and acoustic subsystems. The pleximeter to be attached will be a combination of one of 9 materials and one of 6 shapes, for a total of 56 different pleximeters to be tested. We have also developed a test plan involving a registered physician, a mock patient, and multiple phases to fully investigate the percussion, microphone, and pleximeter material and shape.

For the material selection, the custom part that we did a material selection for is the pleximeter. The relevant properties we have considered are Young's modulus, density, and the mechanical loss coefficient. We used materials that have worked well as pleximeters to give us a reference as to which property values are ideal. These existing materials are ivory and wood. However, since we are using GRANTA EduPack to complete the material selection, and ivory is not listed in the software, we used a close substitute, cortical bone. After using EduPack to narrow down the materials, we had the following list: fiberboard (extra-hard, hard, and medium density), oak, and bamboo board. Then we took the two best options from that list. The two most viable options for the damping plate material are oak and fiberboard (hard).

For the manufacturing process, we looked into 3 methods of cutting our damping plate. Since the material best suited for the damping plate is either oak or fiberboard wood, the three best methods to create this are waterjet cutting, laser cutting, and CNC cutting. All methods would create a viable piece, however both the waterjet cutting and laser cutting have some disadvantages to consider. With waterjet cutting, it is common that the machine will not have the precision control needed to accurately outline the custom part we require. Since the waterjet medium is liquid, corners tend to be undercut and the cutting fluid commonly wings wide when cutting corners. For laser cutting, the main two issues are that the cost of powering the machine is relatively high compared to the other two methods, and by nature, the laser will create burn marks near the areas in which the wood was cut. From an aesthetic and material property standpoint, this makes laser cutting a secondary option. Due to these disadvantages, the best method of manufacturing our part will be through CNC cutting.

Two quality plans were produced: one for the air tank and one for the motor. The five elements for each of the quality plans were addressed. First, the incoming inspection, where individual components are inspected upon entering the factory. Next, the in-process quality check, where components are inspected during the assembly process. Then, the end-of-assembly-line testing, where we determine if the final product meets all performance specifications. Next, the finished stock audits, where the audit is the last chance to check the finished product before it is shipped. Finally, the conformance testing, where tests abuse the product or accelerate its life expectancy to reveal potential problems with the product that can go undetected when it is new or unstressed. We also developed an assembly procedure, and although it requires more detail before manufacturing, it covers the fundamental process needed for a working final product at a kiosk. Engineering drawings are included in the Appendix.

## Final Design

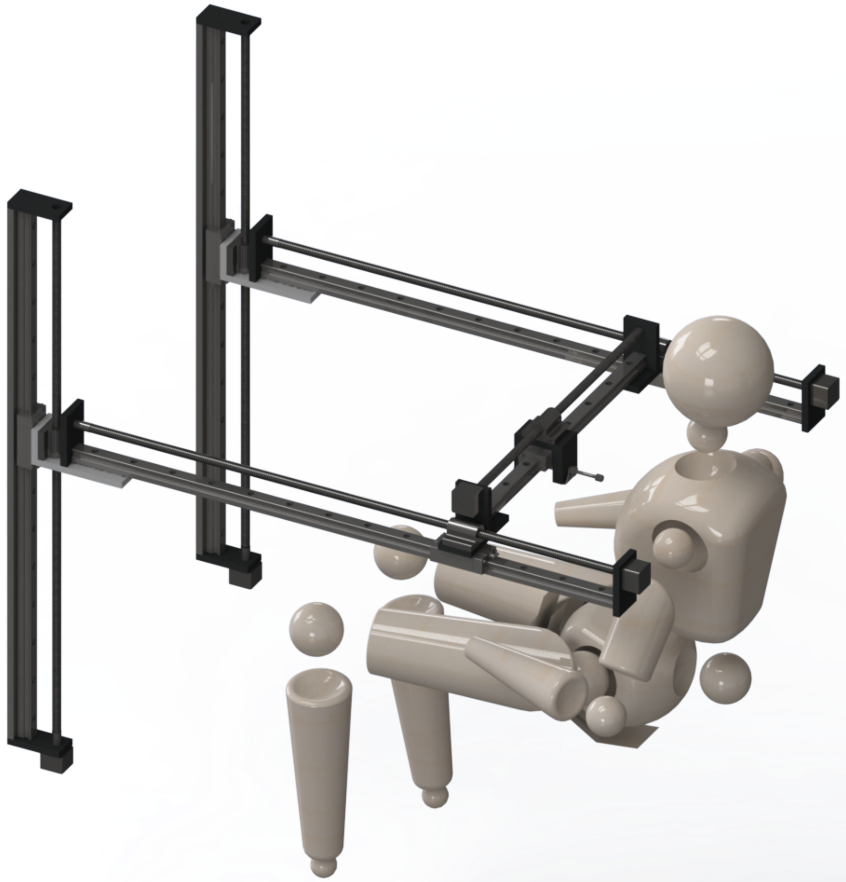

*Figure 1. Final rendering of medical percussion device with human in seated position. While the rendering does not include a kiosk, the two vertical rails have spaced holes for fastening (see technical drawings in the Appendix).*

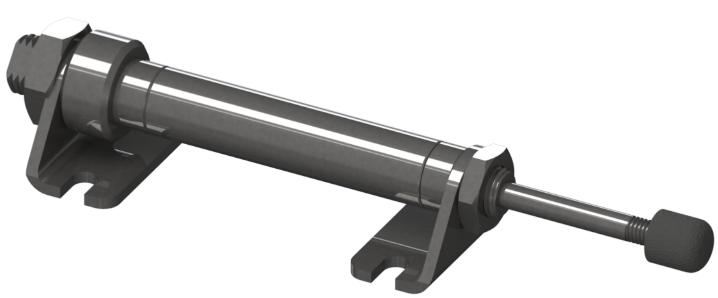

*Figure 2. Close-up rendering of pneumatic cylinder and mounting brackets. Please note that since a final design for a pleximeter (damping plate) was not determined (left for future testing), a rubber damping pad was included at the end of the pneumatic rod. For more detail, please refer to the technical drawings in the Appendix.*

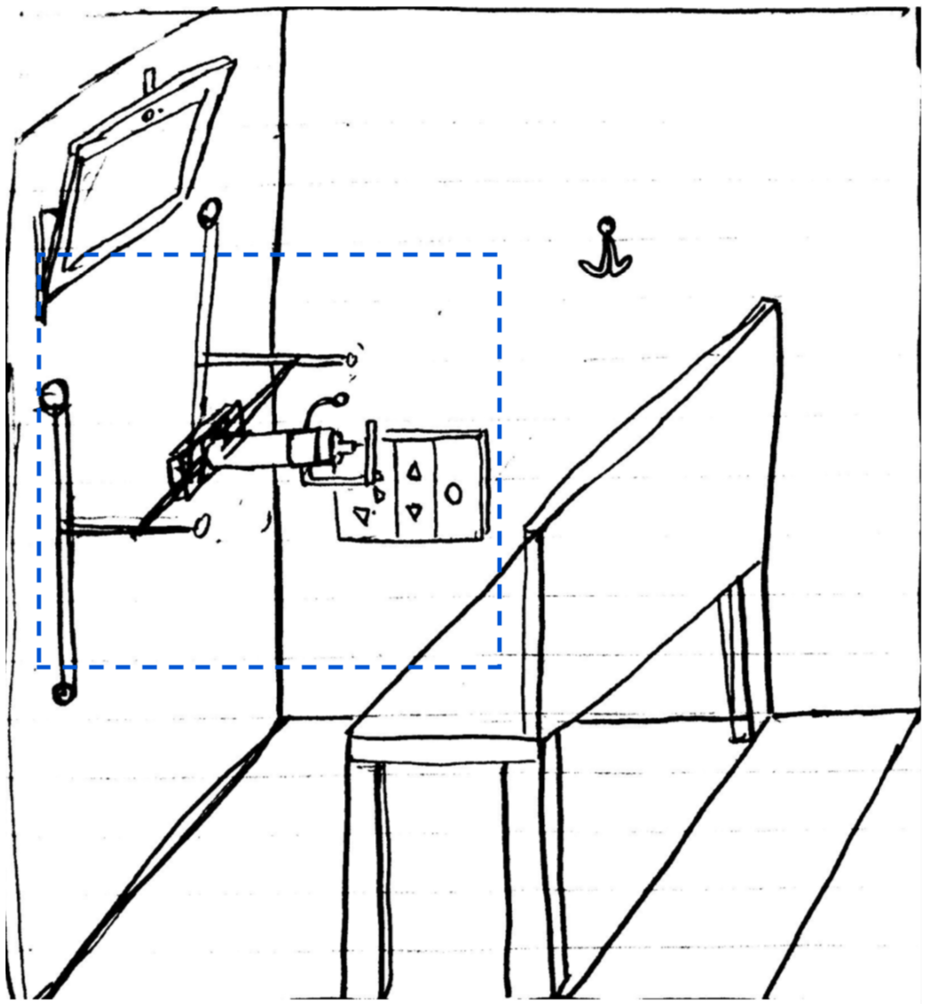

*Figure 3. Isometric view of product in kiosk. (Not to Scale)*

The figure above depicts the product (outlined in dashed blue) as it will sit in and interact with the kiosk we have designed it for. For patient privacy, the kiosk will be closed on all four sides, with a door that can be locked and unlocked from the inside. The patient will sit in the kiosk and be connected virtually to a physician via a video chat so that the patient and physician can see and hear one another. Following the physician's instructions, the patient will control the movement of the device, adjusting the percussor to a specific point on their chest. When instructed, the patient can activate the percussion at the push of a button. As needed, the physician can instruct the patient to adjust the percussion force, all from the control system provided.

In order to achieve the primary functions we defined in our problem definition phase, as listed in the Design Specification Matrix below, and briefly explained above, the product we are designing consists of four distinct subsystems.

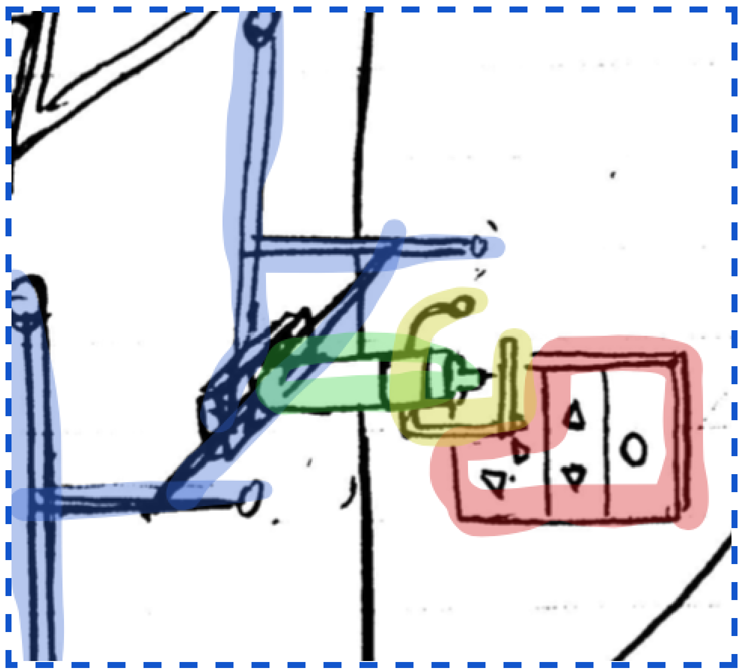

*Figure 4. Zoomed in isometric product view, subsystems colored.*

In the order that each subsystem will appear in this report:

- The **blue** system depicted in Figure 4 is the movement subsystem. The mode of movement we decided on is a lead screw mechanism and will be described further below. This mechanism allows the percussor to translate in 3 directions smoothly and quietly.
- The piece outlined in **red** is the control panel. This is where the patient will control the movement and activation of the device. This system allows the patient the ability to adjust the percussion force as needed.

- The **green** system depicted in Figure 4 is the pneumatic subsystem. This subsystem is responsible for producing the motion and force of the percussion. An air tank not depicted supplies air to the pneumatic cylinder which transforms pressurized air to translational motion. The physics and calculations for this sub-system will be described further in the pneumatic section.
- The **yellow** system seen in Figure 4 is the acoustic subsystem. This subsystem consists of the microphone that reports the resultant sound to the physician and the damping plate. The purpose of these components and design decisions are described in the acoustic section.

Behind the scenes, but included in our design are air hoses for the pneumatic system and electrical wiring and circuitry for the microphone, control system, and any other function that requires electrical energy.

This mounted layout is not the first component layout we considered. In Figure 5 below, you will see our first layout consideration, drafted during our concept selection phase.

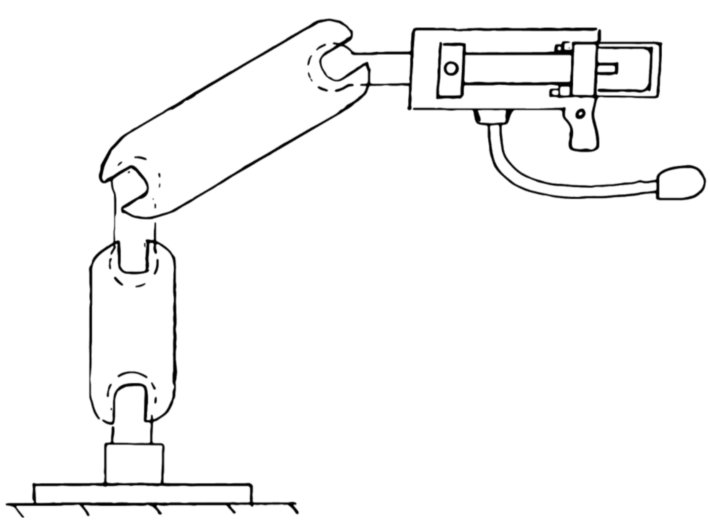

*Figure 5. Initial Product Architecture.*

As seen on the left, all the same subsystems were included (with the exception of controls), but the environment for our product hadn't been considered. After considering movement dimensions, physics of bearings, and human factors, this layout no longer satisfied our design criteria.

## Prototype and Test Plan

### *Prototype*

In our Design Review Report, we evaluated design decisions of our total system, individual subsystems, and small details including fasteners and wiring schematics. However, we were not able to come to any strict conclusions on the design of our custom pleximeter, or "damping plate" as we had previously referred to it. Since there is little to no literature on data regarding percussion test pleximeters, we must start from the beginning with respect to the design of the pleximeter. We have developed a plan to build a prototype to simulate the percussion and pleximeter function. Since the movement subsystem is the most expensive and reliable component of our design, the prototype would consist of only two sub-systems: the pneumatic system and the acoustic subsystem, composed of the microphone and the pleximeter. One goal of the prototyping would be to test the efficacy of the pneumatic system as a percussive method. In an in-person semester, we would have purchased a pneumatic cylinder during the concept generation phase and tested it before choosing it as our final concept. And while we've moved forward with the concept through the design phase and into the prototyping phase, we'd still require testing that the pneumatic cylinder functions in the way we predicted it to. In addition to testing the function of the pneumatic cylinder.

An additional and equally important goal of the prototype phase would be to come to nearly final material and shape conclusions for the pleximeter. The prototype would need to be configured with the microphone and fasteners to attach, detach, and reattach pleximeter prototypes of different shapes and materials.

The materials chosen to create the different prototypes were based on several sources. The different types of wood listed in Table 1 are based on a study [1] that researched the substitution of wood for bone for bio-mechanical purposes. While the study never came to any concrete conclusions about the relation between wood and bone, we decided to include them in our materials list to test them ourselves. The plastics listed in Table 1 were chosen as they represent different types of plastic: hard, inexpensive, brittle, expensive, etc. Ivory was included as it was used previously [2] in old-fashioned pleximeters. This is a highly expensive and non-sustainable material, so in order for us to choose ivory as our final material, it would have to be the only material that worked. Lastly, aluminum is a commercially available, easily recyclable metal that was included to diversify the materials used.

As for the shapes considered in Table 1, several shapes were included for simplicity, like the rectangles and hemisphere. The rods are also being tested since a human finger most nearly represents a rod when simplified to a geometric shape. Several sizes of each shape will be tested to diversify the shapes used and test the relevance of volume on the efficacy of the percussion. As needed, if testing is inconclusive, more shapes and materials will be considered.

| Materials | Shapes |
|---|---|
| **Wood** | Thin Rectangle |
| Oak | Thick Rectangle |
| Pine | Rounded Rectangle |
| Spruce | Hemisphere |
| Lignum Vitae | Thin Rod |
| **Plastics** | Thick Rod |
| Polypropylene | |
| High Density Polyethylene (HDPE) | |
| Acrylic | |
| **Other** | |
| Ivory | |
| Aluminum | |

*Table 1. Shapes and Materials used for prototype testing.*

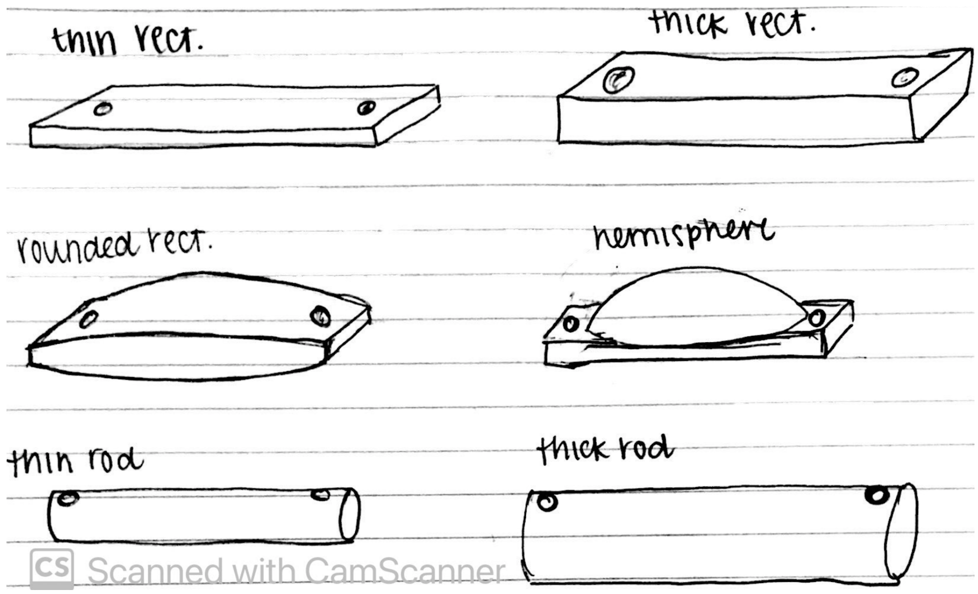



*Figure 6. Different shape materials being prototyped.*

<u>Test Plan</u>

1. The first part of the test plan is to create the prototype "tapper" by attaching a pleximeter of material and shape listed in table 1. With 9 materials and 6 shapes on the list, in order to test every combination, we will create at least 56 pleximeters to test. As shown in Fig. 6, the pleximeters all have two holes that make fastening to the actual device easy.
2. With a licensed physician present, the prototype will be placed on a mock patient's chest, while the physician directs the movement verbally. Once the pleximeter is placed firmly against the patient's chest, the percussion will be activated and the pneumatic cylinder rod will tap the pleximeter once.
3. The microphone attached to the prototype will register the reflective sound in addition to the physician listening to the sound in person. The physician listening will run steps 2 and 3 through several times, adjusting the position and tap force as necessary, taking note of the sound he or she is hearing and how it compares to a typical percussion exam.

4. After carefully evaluating the prototype in person, the doctor will then listen to the recording of the sound as it was picked up by the microphone on the device, taking note of the sound he or she is hearing and how it compares to a typical percussion exam.
5. After fully evaluating both the in-person and microphone-transmitted percussion, the process will then be repeated for all combinations of material and shape.
6. After the testing, we will have data on all the combinations of shapes and materials. We will use this information to find trends in specific material properties, geometric properties, and to find out if our microphone is sufficient. Note: later in this report we will address material selection and manufacturing of the pleximeter using information we already have about acoustic properties of materials. When we finish testing, we would revisit material selection and manufacturing using the data derived from our prototype test in addition to the literature referenced at this time.

*Finalized Human Factors and Testing*

When it comes to human factors as they relate to usability, we haven't changed anything regarding human interaction with our product since our Design Review report. To summarize, the patient's interaction with the product is two-fold. The patient is in charge of not only the movement of the percussor, but also the actuation of the pneumatic cylinder. As it can be seen in Fig. 7, the control panel is simple with only four buttons and three switches which control direction.

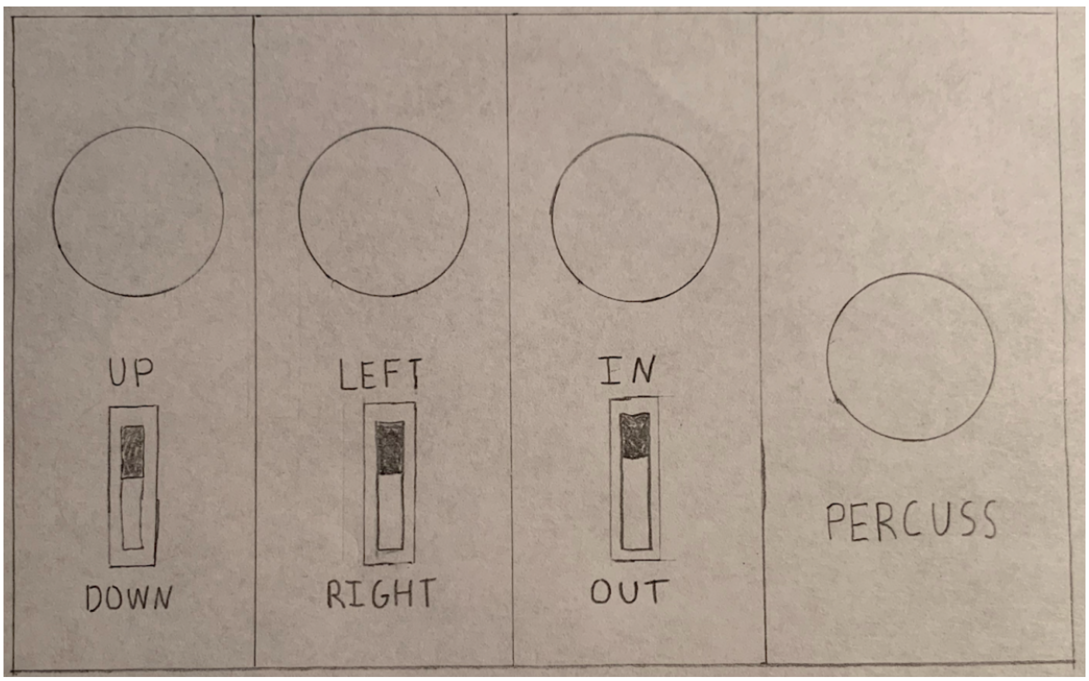


*Figure 7. Drawing of the control panel.*

While our movement subsystem is highly complex utilizing 5 lead screws and motors, the control panel, in addition to a doctor leading the patient verbally, makes the movement of the device easy. The actuation of the pneumatic cylinder is even easier with only one button which causes the rod to tap and then revert back to its original position.

As far as the ease of the verbal instructions, our team conducted a test over a virtual platform to evaluate the effectiveness of directing movement remotely. Using a live video chat, one member of the team acted as the patient while another acted as the physician, with an idea of a specific location on the patient's chest. During the video call, our "physician" directed our "patient's" hand to that desired place on his chest. In under a minute, the "patient" had located the exact spot. While the directions took a few seconds to figure out, once they were, communication was easy and clear. Our conclusion was that if the physician being video-called into the kiosk was familiar with the patient's understanding of their left and right directions, the movement would be feasible for patients to control.

In addition to human usability, we will gather useful human factor data from our test plan detailed in the section above. Specific information we might find useful would be if the percussion was painless, which was one of our main customer requirements and if the temperature of the pleximeter was uncomfortable, another, albeit low-weighted, customer requirement from our problem definition phase.

## Material Selection

The custom part that we will do a material selection for is the damping plate. The acoustic response of the percussion test relies on the function of this part. The damping plate will serve as the pleximeter of the percussion device. After conducting research on materials used for pleximeters, the following pleximeter materials work well: ivory and wood [3].

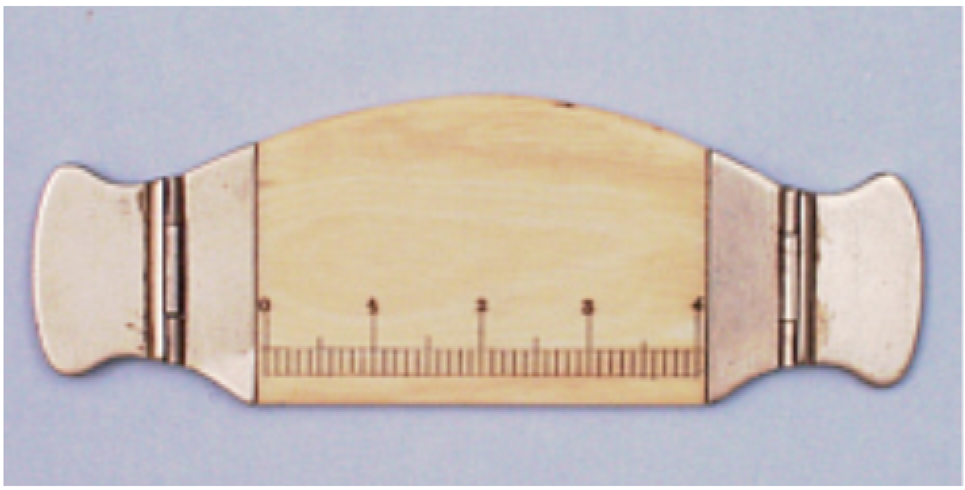

*Figure 8. An example of a pleximeter made of ivory. Reproduced from [4].*

### <u>Relevant Properties</u>

After doing extensive research, we have not found any literature that specifies what material properties are important for pleximeters. However, a report was provided to us that identified a very important acoustical characteristic for selecting materials for sound applications. This important characteristic is the sound radiation coefficient. This coefficient is a measure of how much a material's vibrations get damped due to sound [5]. A material with a large sound radiation coefficient will produce a loud sound when it is struck.

The following equation is the sound radiation coefficient as a function of Young's modulus and density [5]:

$$R = \sqrt{E/\rho^{3}}$$

As shown, the two relevant properties here are Young's modulus and density. We will use these properties to determine which materials will function well as a pleximeter. Since we don't know what ratios of Young's modulus and density are optimal, we will use the existing pleximeter materials to guide us.

Since ivory is a heavily restricted material, it is not on GRANTA EduPack. So, in order to use the software to help us with the material selection, we will use a material that has a similar sound radiation coefficient to ivory. The table below lists potential materials and their sound radiation coefficients.

| Type of Material | Young's modulus (GPa) | Density (kg/m^3) | Sound radiation coefficient |
|---|---|---|---|
| Ivory | 10.7 [6] | 1800 [2] | 1.35 |
| Horn | 8 | 1260 | 2.0 |
| Cortical bone | 11.5 | 1940 | 1.26 |
| Enamel | 76.3 | 2965 | 1.71 |
| Antler | 8.8 | 1825 | 1.20 |

*Table 2. The Young's modulus, density, and sound radiation coefficient for materials similar to ivory (obtained from GRANTA EduPack).*

As shown, the material above with the closest, elastic modulus, density, and sound radiation coefficient to ivory is cortical bone. Therefore, when using GRANTA EduPack, we will be simulating ivory with cortical bone. Since ivory and wood were used to make pleximeters, we will be using cortical bone and oak as references in the software.

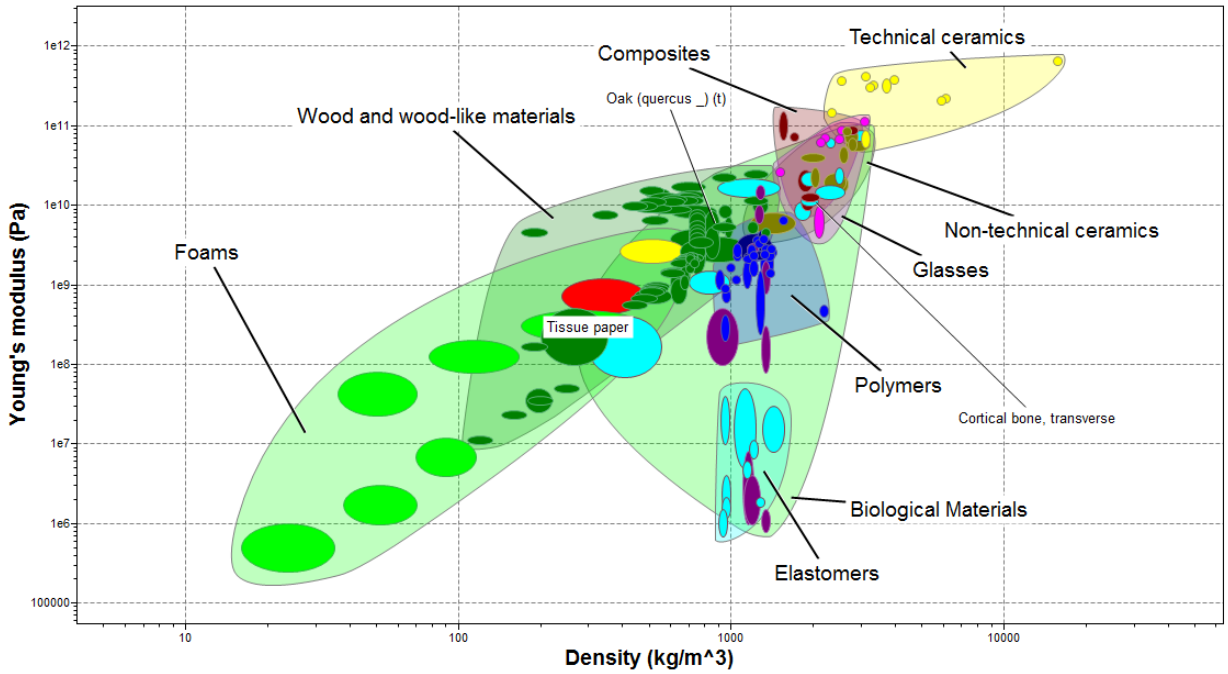


*Figure 9. This chart shows the relationship between Elastic modulus and density for several families of materials. Reproduced from GRANTA EduPack.*

From the above chart, we can see that biological materials, wood, and wood-like materials, glasses, polymers, nontechnical ceramics, and composites all contain materials that are potentially similar to oak and ivory.

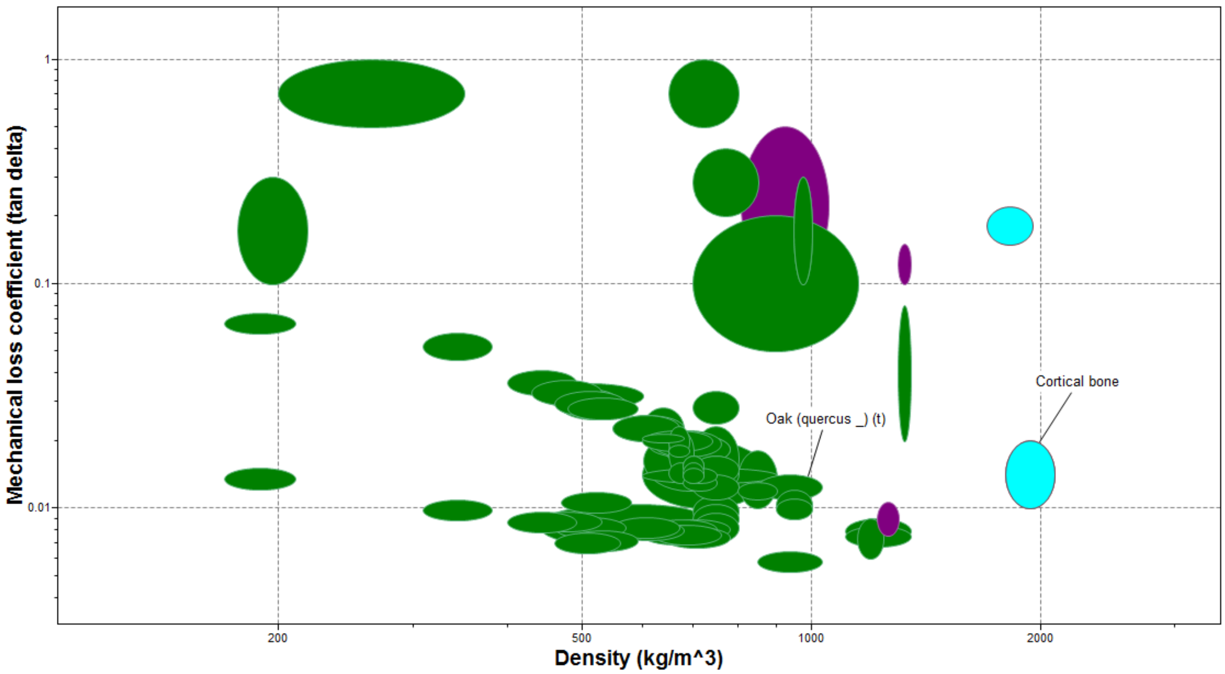


*Figure 10. This chart shows the relationship between the mechanical loss coefficient and density for oak and cortical bone. Reproduced from GRANTA EduPack.*

From the chart above, we can see that the cortical bone (ivory substitute) and oak have a very similar mechanical loss coefficient of about 0.015. The mechanical loss coefficient or damping coefficient measures how much a material dissipates vibrational energy by internal friction [5]. As stated in the report, "Wood for sound" [5], materials with low loss coefficients will create clear and loud sounds when vibrated while materials with high loss coefficients will get damped. Therefore, the three important properties we will be considering are mechanical loss coefficient, Young's modulus, and density. We will now look at individual materials that have values for all the important properties in between the values for oak and cortical bone.

| | Young's modulus (GPa) | Density (kg/m^3) | Loss coefficient |
|---|---|---|---|
| Cortical bone | 10-13 | 1800-2080 | 0.01-0.02 |
| Oak | 5-5.8 | 850-1030 | 0.011-0.014 |
| Ranges | 5-13 | 850-2080 | 0.01-0.02 |

*Table 3. The Young's modulus, density, and loss coefficient for cortical bone and oak (obtained from GRANTA EduPack).*

We will use the listed ranges to see other potentially viable materials. To accomplish this we will create a filter on EduPack specifying the noted ranges.

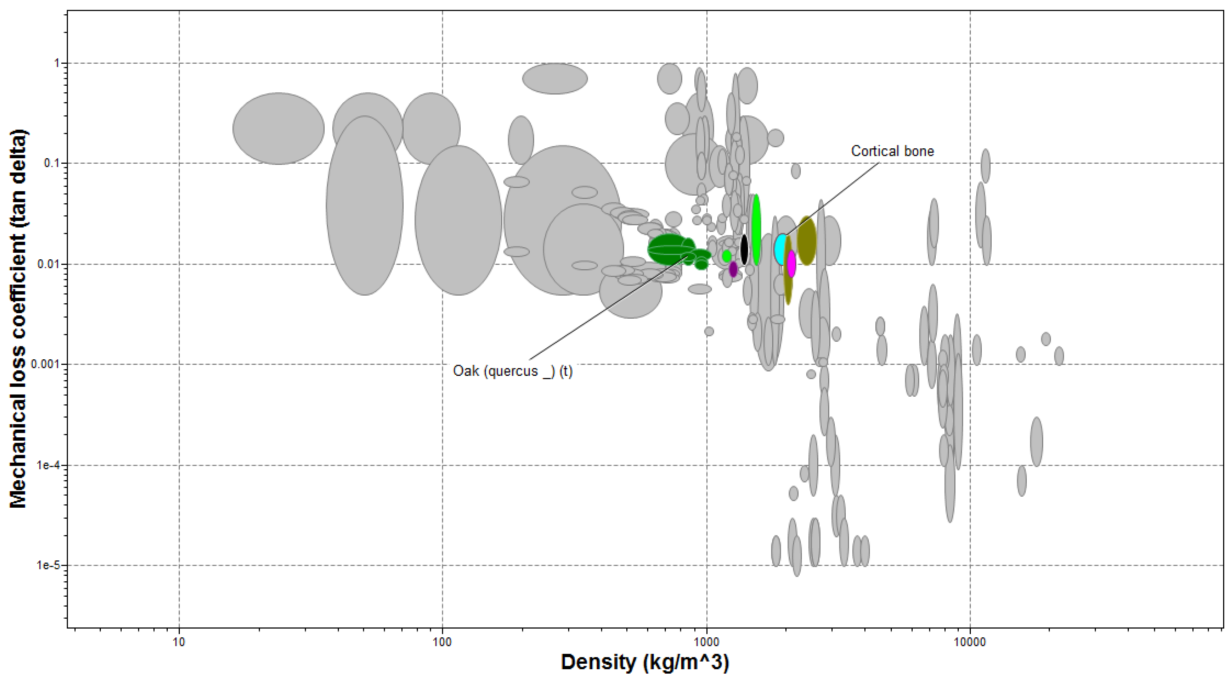


*Figure 11. This chart shows the relationship between the mechanical loss coefficient and density, the highlighted materials have property values within the specified range. Reproduced from GRANTA EduPack.*

The following is a list of the highlighted materials:

- Bamboo board
- Brick
- Coir fiber
- Concrete
- Cortical bone, longitudinal
- Cortical bone, transverse
- Cotton fiber
- Fiberboard, extra hard, parallel to...
- Fiberboard, extra hard, perpendic...
- Fiberboard, hard, parallel to board
- Fiberboard, hard, perpendicular t...
- Glass-ionomer
- Horn
- Medium density fibreboard (MDF)
- Oak (quercus _) (t)
- Polyester fiber (Dacron)

*Figure 12. This is a list of materials that satisfy the ranges noted above. Reproduced from GRANTA EduPack.*

From this list, we can start eliminating materials based on common knowledge. We can rule out the fibers (coir, cotton, and polyester) because they are not able to hold a shape and will therefore not function well as a damping plate. Since the damping plate will be subject to impact forces, we can rule out the following materials that are too brittle: brick, concrete, and glass-ionomer. We can also rule out the following biological materials since they are not common: cortical bone and horn. Therefore, we are left with the following materials: bamboo board, fiberboard (extra hard), fiberboard (hard), fiberboard (medium density), and oak.

| Material | Young’s Modulus (GPa) | Density (kg/m^3) | Loss Coefficient | Sound radiation coefficient |
|---|---|---|---|---|
| Cortical bone | 11.5 | 1940 | 0.015 | 1.26 |
| Oak | 5.4 | 940 | 0.013 | 2.55 |
| Fiberboard (extra-hard) | 5.4 | 950 | .011 | 2.51 |
| Fiberboard (hard) | 3.8 | 850 | 0.014 | 2.48 |
| Fiberboard (medium density) | 4.0 | 750 | 0.014 | 3.08 |
| Bamboo board | 8.6 | 736 | .015 | 4.64 |

*Table 4. The important properties and their values for the remaining materials (obtained from GRANTA EduPack).*

We are going to use the property values of oak and cortical bone as references to determine whether a material should be eliminated. We can neglect the cost because it will be very low compared to the rest of the device. From the table above, we can eliminate bamboo board and fiberboard (medium density) because of their high sound radiation coefficients, and low densities. We can also eliminate fiberboard (extra-hard) due to its low loss coefficient. Therefore, the most two viable options for the damping plate material are oak and fiberboard (hard).

## Manufacturing Process Selection

The two materials selected based on relevant properties of a damping plate were both wood material in nature. Because of this material selection, the methods of manufacturing for both potential materials will be the same. Factoring in the simplicity and small size of this part, there are several ways the damping plate can be manufactured. The general idea is to cut out our part from a solid block of material so with that in mind, there are 3 methods to choose from.

*Alternative Manufacturing Processes*

Waterjet

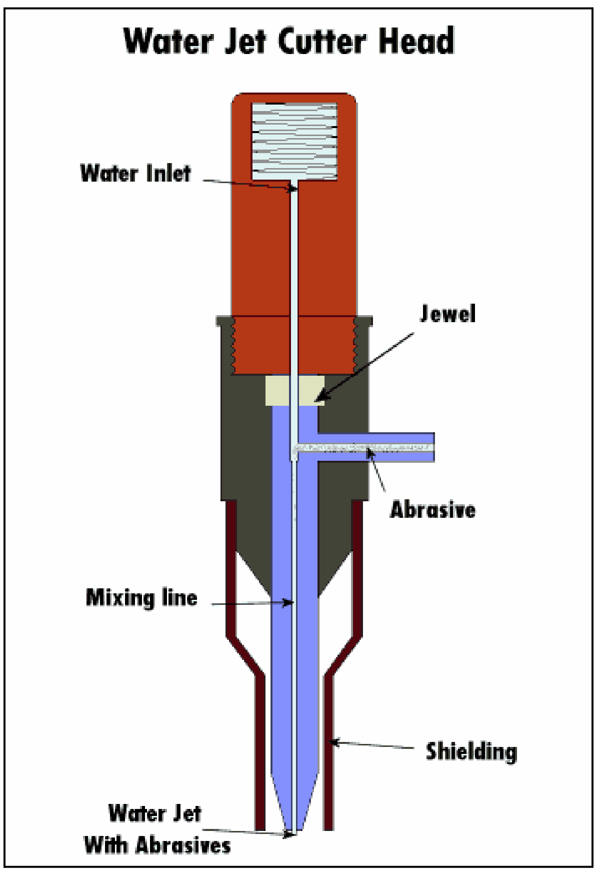


*Figure 13. Waterjet Outlet Head*

In this method of manufacturing, the material is cut into a specific shape using a high powered stream of water. The waterjet uses a to pressurise the water to a high pressure [7]. This high pressurized water is then led into the outlet nozzle. It is here in the nozzle where the previously pressurized water is directed into an extremely small channel with the purpose of increasing the water's velocity. For tougher materials such as metal, in this channel it is also possible to mix in an abrasive element into the water stream for a more powerful cut.

While this is a viable way to manufacture our damping plate, it is not the best method because of the quality in which it cuts wood. The average waterjet machine will not have the precision control needed to accurately outline the custom part we require. Because the waterjet medium is liquid, it tends to undercut corners and swing wide when cutting a curved section [7].

Laser Cutting

This is an additional process we could use to manufacture our part which involves cutting the wood with a laser. The laser cutting system uses a very high intensity beam of light in the form of a single wavelength [8]. The beam of light is then directed through a curved mirror of a reflective lens. After the light is reflected, compressed gas such as $CO2$ is added to the laser steam for an increase in temperature and a more effective cutting process [8].

While this would be an effective process, there are two reasons as to not use this method of manufacturing. First, laser cutters consume a lot of energy, so this would make the process of creating many damping plates relatively expensive to other manufacturing methods [9]. The second reason is that laser cutting by nature burns the wood in order to remove the material [9]. Through this process, our custom product would be marked and scarred with burn marks around the edges of the piece. This would change the properties of the wood at the burnt sections and would not be aesthetically pleasing to the customer.

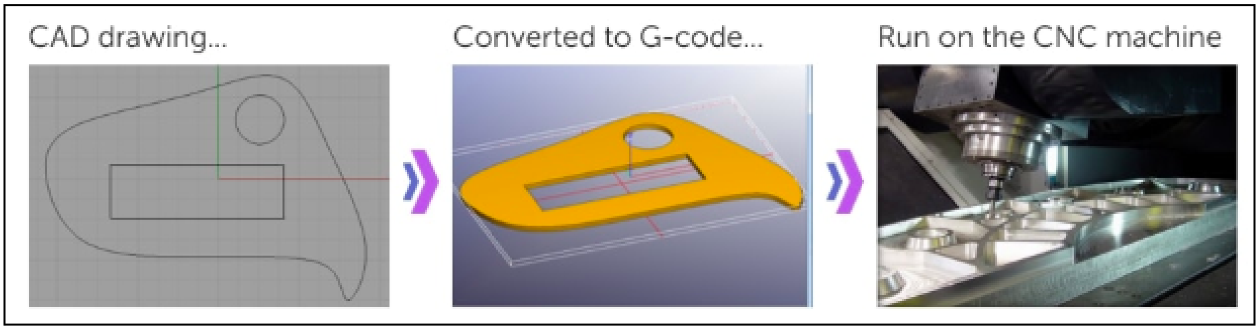


*Figure 14. Steps of CNC Renderings*

*CNC Machining Steps*

1. We must make sure that the CNC machine is properly prepped for any type of carving. The first thing to do would be to choose the size and length of the drill bit being used and make sure to calibrate it so the machine knows how high from the baseplate the drill bit is. This will give the CNC machine a reference of how high it is from the zero point in the Y-axis and also the radius of the cut it will make on the material. .
2. Next we would instal the material. In this case our material will either be Oak wood or Fiberboard. The material would need to be stuck in place so as to not move during the operation. There are a variety of methods for attaching the workpiece, but the fastest and most cost effective one would be to use clamps. Other options include using an adhesive of screws to keep the workpiece from moving.
3. One the material is put into place, the CNC machine must be zeroed in on all 3 axes. The CNC machine will have buttons to press when you manually move the drill bit to the zeroed location. This way the CNC drill will start at the origin on the 3 axes and can properly cut into the workpiece at the right locations.
4. Create a CAD model of the custom part you want to create.

5. This CAD file must be converted into the code that the CNC machine understands which is called G-Code.
6. Once the G-Code is created, then transfer it to the CNC machine to begin the cutting process. For examples of what steps 4-6 may look like, refer to figure 14.

*<u>Guidelines</u>*

For a CNC cutting machine, the main guidelines to follow is how fast the drill bit should be spinning and engaging with the material. Both of these guidelines are based on the material being cut into so in our case that is either oak or fiberboard. In order to find the proper RPM to use for our material, we must first find the required surface feet per minute or how fast the drill bit travels across the material. For wood in general this speed has a range of 300 - 350 SFM [10]. With oak and fiberboard being harder in nature than most wood, we will assume that the required speed for this is 350 SFM. While using a 5/8ths drill bit, the proper RPM for cutting oak of fiberboard with the calculated SFM is 2150 RPMS [10].

**Assembly Procedure**

*Overview*

The assembly process does not require any special equipment or machinery. It is worth noting that more work is needed here to determine exact modes of joining components: specific fasteners for the rails, carriages and brackets, and specific couplings for attaching the motors to the lead screws. With that said, all standard components here use common threads, hole sizes, and mounting bracket sizes; therefore, while this section will use the phrases “connected with fasteners” or “attached to couplings” loosely, we do understand that more detail would be needed to proceed with manufacturing and assembly.

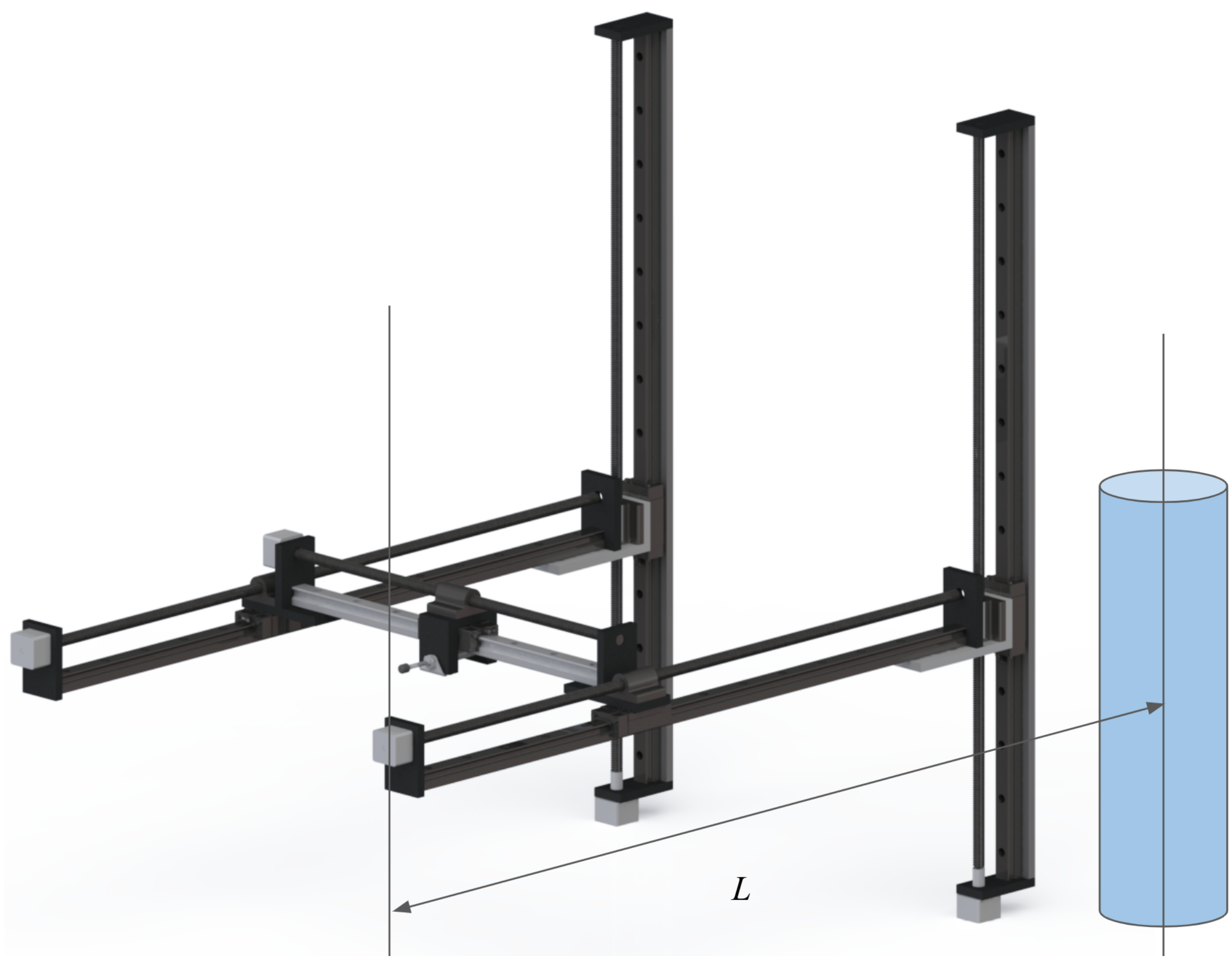


*Figure 15. Additional view of the final rendering for the device. Dimension L shows the minimum distance needed for air hose tubing in order to account for necessary longitudinal range of motion.*

In terms of the assembly process for the pneumatic subsystem, the air tank (arrives empty) will need to be filled by a compressor or other air filling station with air pressurized to 2000 psi. Once the air tank is filled with compressed air, the two-stage regulator is attached by a threaded coupling connection to the air tank. The regulator has a gauge with a knob that allows for the adjustability of compressed air pressure. An air hose is connected with a threaded coupling to the output of the regulator, and must be connected to the one-way valve downstream. Since the valve needs to be accessible by the patient, the air hose tubing from the regulator needs to at least be 40” long, which is represented as dimension *L* in Figure 15. This dimension considers the 32” range of motion in the longitudinal direction, as well as some additional slack to reach the control panel adjacent to the patient. From the valve, another threaded coupling will be used to connect the last section of air hose tubing to the pneumatic cylinder, the length of which will also need to be at least 32” to cover the full longitudinal range of motion. This air hose tubing can be run along the bottoms of the longitudinal rails, as the rails have holes that can allow for fastening of the tubes using 1-hole straps.

In terms of the assembly process of the acoustic subsystem, the damping plate will be fastened with bolts to the C bracket holding the pneumatic cylinder. The damping plate needs to be fixed at the pneumatic cylinder stroke distance (2” - see Appendix) in front of the end of the pneumatic rod. The microphone used to capture the acoustic response will also be secured onto the front of the pneumatic cylinder housing with a C bracket.

For the assembly of the movement subsystem, the shafts of the motors must be connected to the ends of the lead screws with couplings and bearings. Platform nuts are threaded onto the lead screws that translate linearly with the motors rotate the lead screws. Rails and carriages, fastened with bolts to the platform nuts, prevent rotational motion of the nuts and also secure them. In between the platform nuts and rail carriages are L and C brackets, which connect the translation of separate axes.

*Steps for Assembly Procedure (at Medical Kiosk)*

A. Movement

1. Fasten the vertical rails with bolts to the medical kiosk wall. The rails should be offset from the ground.
2. Slide rail carriages onto vertical rails.
3. Attach end plates to vertical rails with bolts.
4. Fasten the L brackets and longitudinal rails to the vertical rail carriages with bolts.
5. Thread the lead screws through the vertical end plates. Fix at the top with bearings and at the bottom with couplings that attach to the motor.
6. Attach the longitudinal rail carriages and end plates to the longitudinal rails.
7. Repeat step 5 for the longitudinal lead screws.
8. Repeat steps 4-6 for lateral movement components.

B. Pneumatics

1. Fill the air tank with compressed air at 2000 psi.
2. Connect the regulator to the air tank with threaded coupling.
3. Connect air hose between regulator and valve with threaded coupling.
4. Connect another air hose between the valve and pneumatic cylinder with threaded coupling.
5. Fasten pneumatic cylinder to later C bracket on lateral rail using foot brackets (Appendix).

C. Acoustics

1. Position the damping plate the distance of a pneumatic cylinder stroke in front of the end of the pneumatic rod.
2. Fasten the damping plate to the C bracket supporting the pneumatic cylinder using bolts.
3. Secure the microphone to the front of the pneumatic cylinder housing with a C bracket.

**Product Cost**

The cost goal of this product was to stay competitive with similar machines on the market such as precision 3-axis CNC machines and blood pressure kiosks. As seen in the bill of materials ("Engineering Documentation" section), the total parts cost of the device comes out to be roughly $3,650 if purchased as individual parts. Although an exact estimate would be difficult at this stage, this cost would likely go down if parts are purchased wholesale for factory manufacturing.

As far as manufacturing cost, there would need to be considerations made for shaping of parts, assembly of the device, labor, and tooling. There is only one custom part needed in the design of this product, the damping plate. As stated in the manufacturing process section, the plate material will be either oak wood or fiberboard, and milled using a CNC machine. The cost of a piece of wood this small should be negligible, and the cost of running the CNC machine will be $35 an hour for the laborer and $75 per hour for the machining [11]. We would expect that it will take less than an hour for a part of this size to be machined, but for cost considerations we will use the full hourly price. Assuming that a factory labor source priced at $12/hour could be used to construct one machine per day, with two laborers each working on assembling a set of two parts, the manufacturing cost per machine will be roughly another $720. (Assumptions made using data from [12].)

Adding on these additional costs, the total amount needed for the construction of one Automatic Percussion Device is $3642.13 + $110 + $720 = $4472.13. This cost will likely be reduced by purchasing materials in bulk and by having a dedicated factory for labor, but even as it is now, the cost fits the team's goal of remaining competitive with similar products.

## Quality Plan

*Air Tank*

For the incoming inspection, we will visually inspect the tank upon arrival to ensure there are no prominent dents or holes. The expected result will be no dents or holes in the air tank and this will be checked by the employee receiving the shipment of air tanks during unloading. If dents or holes are found during inspection, the damaged tank will be returned to the seller and we will request a replacement.

The in-process quality check will occur while the empty air tanks are being filled with pressurized air. The employee filling the tanks will listen for any leaks during and after the filling of the air tanks. In addition to auditory inspection, the employee will check the air pressure in ten tanks per shift with a pressure gauge before bringing them back from the filling station. The expected result from this check will be no audible leaks and the pressure gauge will read 2000 psi. If there is a leak or the tank is not maintaining a pressure of 2000 psi +/- 100 psi, the faulty air tank will be returned to the seller and a new tank will be requested.

For the end-of-assembly-line testing, the pressurized air tanks will be checked with a pressure gauge. The tanks will have been filled and set aside for a while, so to ensure the final product meets performance specifications, an assembly employee will use a pressure gauge on ten tanks per shift to make sure the air pressure inside is still around 2000 psi. If the air tank pressure does not fall between 1900 psi and 2100 psi, the tank will be set aside and inspected for any leaks. If the air tank has only lost a little more than the 100 psi buffer and the gauge reads between 1800 psi and 1900 psi, say due to temperature change and unavoidable factors, and no leaks are detected, it will be refilled to 2000 psi and cleared for finalization.

Prior to product shipment, a finished stock audit will be conducted. Before packaging the device and shipping it, a quality insurance inspector will use a pressure gauge to check the air pressure of the tank. The expected reading is 2000 psi. If the air pressure reading of the tank is more than +/- 100 psi from 2000 psi, the tank will be further inspected for leaks. If leaks or damage is found in the tank, then it will be removed from the assembly and replaced with an acceptable air tank.

For the conformance testing of the air tanks, the life expectancy will be checked. A testing engineer will see how many percussive taps we can perform before the air tank reaches 150 psi, the pressure at which we must refill the tank. This test will be performed on one air tank per shift. The results should match the data collected from design qualification testing. If the air tank reaches 150 psi before an acceptable number of percussive taps are performed, then the tank will be inspected for leaks or other discrepancies that could cause this failure.

*Motor*

For the incoming inspection, a quality assurance inspector will check five motors per received shipment box. The inspector will use a multimeter to check the motor. The multimeter will be set to the "Ohms" setting and the inspector will touch the multimeter leads to the power input terminals on the motor [13]. The inspector will slowly rotate the motor in either direction and take note of the multimeter readings. The expected readings should fall between 10 and 100 ohms and they should vary as the motor is rotated -- this ensures the carbon brushes are in contact with the rotor [13]. If the readings are 0 or infinity, there is something wrong with the motor. The faulty motor will be returned to the seller and a replacement will be requested.

The in-process quality check will occur right before the motors are wired to the assembly. An automated test console will check the no-load torque output of all the motors. The test console will expect test results of at least 0.20 in*lb. If the motor does not produce at least 0.20 in*lb, the motor will be sent back to the seller and a replacement will be requested. If the motor produces more than 0.25 in*lb, it is producing too much torque. The motor will be returned and a replacement will be requested.

For the end-of-assembly-line testing, a quality assurance inspector will check 10 motors per shift. The motors will be tested to make sure they rotate smoothly while experiencing the load applied by the assembly. The power inputs on the motors will be temporarily attached to an 18V power source for 5 seconds to check if the motor rotates. If the motor does not rotate the lead screws, the motor will be sent back to the seller and a replacement will be requested.

Prior to product shipment, a quality assurance inspector will check 10 assemblies per shift. The inspector will visually check that all the electrical wires are enclosed within the assembly and that no wires are accessible from the outside. If loose wires are found, the assembly will be returned to the production line and corrective measures will be taken to secure the electrical wires inside the assembly.

For conformance testing, a test engineer will check the performance of the motor by verifying the device can reach its upper and lower limits of its range of movement even when under more load than expected. The test engineer will check one device per shift. For each trial, the test engineer will direct the motors to turn the lead screws to their distance limits in the x, y, and z directions. Weight will be added to the device following each successful trial and the distance limit process will begin again. Once the motor is experiencing too much load and cannot rotate the lead screws any more, the test will end. As of now, there are no expected results other than the device can reach its range of movement limits with just the load of the percussor and no additional weight.

## Engineering Documentation

*Parts List and Bill of Materials*

| Part Name | Part Number | Quantity | Cost Per Part | Total Cost |
|---|---|---|---|---|
| 1018 Carbon Steel Precision Acme Lead Screw | 99030A326 | 5 | $15.56 | $77.80 |
| Precision Acme Platform Nut | 1710K9 | 5 | $151.27 | $756.35 |
| Roller Bearing Carriage | 9215T62 | 5 | $194.76 | $973.80 |
| 20 mm Wide Guide Rail for Roller Bearing Carriage | 9215T42 | 5 | $163.20 | $816.00 |
| Round Body Air Cylinder | 6498K514 | 1 | $24.78 | $24.78 |
| Foot Bracket Bore Sensor-Ready Round Body Air Cylinder | 4952K126 | 2 | $5.53 | $11.06 |
| Air Directional Control Valve | 2700K14 | 1 | $107.69 | $107.69 |
| Regulator and Size 3, 14 ft^3 High Pressure Pneumatic Cylinder | Q1-209C | 1 | $873.88 | $873.88 |
| CMA-4544PF-W Electret Condenser Microphone from CUI Devices | CMA-4544PF-W | 1 | $0.77 | $0.77 |
| 19.1 V Compact DC Gearmotor | 2709K11 | 5 | $119.24 | $596.20 |
| | | | | $3,642.13 |

*Table 5. Bill of materials for standard parts used for our medical percussion device. Product information and prices reproduced from [14-24].*

<u>Please note:</u> technical drawings (for the same component sequence as seen in Table 5) can be found in the Appendix.

## Conclusions and Reflections

*Project Overview and Results*

In our product definition phase, we developed a list of customer requirements after conducting an interview [25] with two physicians who were able to let us know what they as doctors would need in order to see value in the product. In addition, we as a group of 19-23 year olds who are within the target population of our patient population were able to provide what we as patients would require in order to see value in the product. This final list of customer requirements and associated engineering characteristics can be seen in Table 6. From our interview [25] with the physicians, we were also able to compile a list of essential product functions: Move, percuss, measure and reproduce sound data, and adjust force as needed. In Table 6, these product functions are listed next to each associated customer requirement.

| Customer Requirements | Product Functions | Engineering Characteristics |
|---|---|---|
| Percussion is Harmless | Percuss on Patient's Body | Percussive Force |
| Percussive sound response is clear and mimics that of a manual test | Adjust force Magnitude | Percussive Impulse |
| Fit Different body shapes | Move Apparatus | Force required to move device |
| Fit Different body weights | Move Apparatus | Range of Movement |
| Minimal Interfering Sound output | Measure and reproduce sound data | Sound Output of device |
| Move with minimal effort | Move Apparatus | Operating Power Supply |
| Percussive Instrument is at a comfortable temperature | | Temperature of percussor |

*Table 6. List of related CRs, PFs, and ECs.*

In order to satisfy our customer requirements and product functions, we developed a remote kiosk device that mimics a medical percussive test. The directional movement of our percussive device and the percussive force is fully controlled by the patient through a control panel. The patient will be directed by a physician who will be video conferenced in. A microphone is installed within this design to listen to the reflecting sounds of the percussion and this data will be transmitted to a physician. As far as the temperature of the device, we addressed this in our design review report as a design implementation that we would consider in a future update or edition of our product as it was the lowest- weighted requirement. Additionally, once we conduct our prototype testing, we can gather feedback from the mock patient receiving the test regarding the comfort or discomfort of the temperature of each pleximeter material.

Our product is highly unique and one reason why is that there is no product like it on the market. In our problem definition phase, we determined that the problem with how percussion exams are currently done is that they can only be conducted in an in person doctor's appointment. After market research, we found that while there are many solutions to provide patients with a virtual health check-up, there is nothing on the market that can conduct a remote percussion exam, making our product the only solution on the market.

One analysis that shaped our design was an in-depth human factor analysis for each subsystem. In our design review report, we found that doing a human factors analysis within each subsystem would result in a better-designed and customer-friendly device. We considered not only the physical abilities of humans to design our product but also cognitive ability. For instance, our movement subsystem was designed with a large focus on the physical dimensions and strength of the people who would use our product. Our control system was designed with physical human factors in mind, but with a large focus on the cognitive ability of the patients.

Because this is the root of the human usability of our device, we designed the control panel to be easy to use with consideration of material, shape, color, and more.

*PDP Reflection*

In reflecting on our experiences, I think that there were certain pivotal moments and decisions that steered the project in different directions. While the process was certainly not linear (we were warned of this), it did feel at times that we were either moving forward or backward.

We believe that the product development process (PDP) was an effective model, and while it was helpful at certain stages of the project, it was also somewhat counter-productive at other stages. I believe that we followed the PDP most effectively when we researched medical percussion to understand the problem and developed our functional requirements. Before this point, it seemed that as a team, we were trying to "solve the problem" before understanding the problem at a high enough level to even begin considering potential solutions. We were of course advised not to veer into this line of thought, however I think it was really unintuitive for us not to jump to solutions. Regardless, about two weeks in, we "restarted" the project so-to-speak, beginning with watching some instructional YouTube videos depicting manual percussion, as well as reading some scientific literature on automating chest and abdominal percussion. In hindsight, this step backward was truly more of a step in the forward direction, as it allowed us to simplify the project into smaller, manageable tasks. As such, we thought about our project from multiple perspectives, eventually developing separate subsystems for the product design. This made the project feel less one-dimensional, as we each were able to follow separate specialized aspects of our solution. We placed a considerable amount of effort into the designs of our movement system, our pneumatic system and our acoustic system, some of which required research, while others required extensive calculations. Overall, we certainly spent the most amount of time in the design stage of the PDP.

Based on our experiences, it seemed that a more "useful" approach (perhaps would have been more efficient in getting to an end product) would have been beginning with functional requirements, and placing more emphasis on understanding the physics of the task before customer requirements. I think we understood how customer requirements and engineering characteristics can drive the design of a new product, though when applied to the context of creating a solution, it was somewhat arduous to consider customer requirements and engineering characteristics before fully understanding our functional requirements. In short, I think consideration of functional requirements helped advance our project more than any other stage of the PDP.

*Future Work*

The next step in perfecting our product will be running the test plan. Building and prototyping are some of the aspects which our team was most excited for coming into our capstone class, but were unable to do due to complications from COVID-19. That said, if we are to go forward with this design, prototyping will be a necessary next step. The test plan is laid out in the above section, and based on the results of that test, certain design considerations will be made. Once all of our design considerations are made, a patent should be secured to protect our intellectual property. This should not be an issue, as our design is original and we have already performed patent research to ensure there are no similar products on the market. From there, the team will have to contact businesses which we think will likely be interested in purchasing such a product. In our case, we would likely reach out to local pharmaceutical businesses such as CVS and Walgreens. We know that they already have interest in similar products as we have seen blood pressure kiosks in their facilities. Once a business has expressed significant interest in our product, we will have to reach out and find a manufacturer that will construct our device. Once a contract is signed and a price is agreed upon, parts will be ordered for the construction of the device, and a final prototype will be made for the approval of the team, and subsequently the business interested in purchasing the device. The team will then come up with a profitable price tag for the device, and the device will obviously sell like hot cakes. Finally, once we have all made our millions and retired to neighboring tropical island paradises, we will donate excess capital back to the University of Maryland Clark School of Engineering, and will of course mention our mentor Professor Smela in the acceptance speech of our respective Nobel prizes.

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