Device to Improve Diagnostic Yield of Fine Needle Aspiration

Final Design Report
May 9, 2007

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Abstract

The purpose of this project is to improve the current procedure for Fine Needle Aspiration. This procedure is currently manual and requires multiple attempts to yield a viable sample of cells. Our client wants to automate this procedure using a handheld oscillation device. The device must be safe, have an adjustable stroke and frequency, and be ergonomic. In the previous semester, our team built a working prototype of the wheel and motor design. However, this prototype is not reliable for testing, so we propose to build an alternate design, using a pneumatic driving system. With the pneumatic prototype we will begin testing various phantom tissues and eventually human tissue in a clinical setting.

Background

Biopsy

A biopsy is a medical test involving the removal of a sample of tissue from the body for examination by a pathologist. Biopsies are used to diagnose any suspected cancerous lumps. They can be performed on any organs in the body, however, different biopsy procedures are performed for different organs of the body. Six kinds of procedures exist:

1.) **Excisional**: the whole area or organ is removed for diagnosis.
2.) **Endoscopic**: a fiberoptic endoscope is inserted into the gastrointestinal tract, allowing direct visualization of the abnormal area and pinching off small amounts of tissue.
3.) **Colposcopic**: is a gynecological biopsy method to diagnose abnormal pap smears.
4.) **Fine Needle Aspiration**: a small needle is inserted into the lump to withdraw a cell sample for examination.
5.) **Punch**: a sample is taken to test for skin cancer.
6.) **Bone Marrow**: a sample is taken from the bone via a needle inserted into marrow.

Fine Needle Aspiration (FNA)

Fine Needle Aspiration is a biopsy method, which is used to collect tissue samples from the upper region of the body. Procedures are usually performed on neck cysts, breast tissue, thyroid glands, or any place in the upper body where a lump can be felt or visualized by radiographic or sonographic methods. The procedure is currently manual and requires repetitive low yield sampling to collect enough viable cells for testing. If the sampling is inconclusive, the doctor must go back and repeat the procedure.

The procedure for this type of biopsy is not complicated. A doctor first isolates the mass with his or her index and middle finger. Next, a small needle is inserted into the mass in an in and out motion several times. The needles used for this procedure are usually 21 to 25 gauge. On average, about 100 cells should be taken to ensure success of the procedure. After the sample is taken, it is sent to a pathologist to be examined.

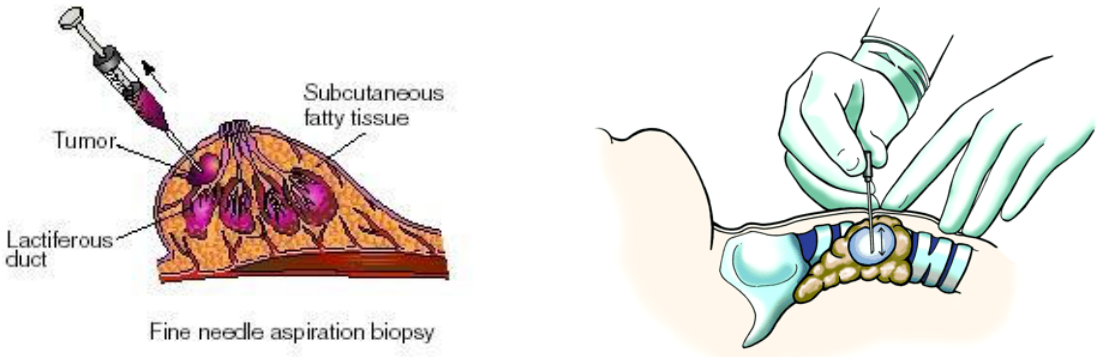

Figure 1: Fine Needle Aspiration procedure in (A) breast tissue and (B) thyroid.

The sample can be categorized in three different ways: malignant, benign, or inconclusive. If the sample is malignant, the mass is growing uncontrollably and possibly spreading to other tissue. If the sample is benign, then the growth is under control and not spreading to other tissue. If the test is inconclusive, the procedure must be repeated. The diagnostic success rate of this procedure is about 70-80%. Currently, this method of biopsy is manual and not very accurate when collecting cell samples the first time. Most of the time it works, but this procedure is time consuming and fails to produce good results in some cases. Furthermore, it is difficult to collect cell samples from harder tissues, as the needle just moves back and forth with the mass and few cells are actually acquired. The latter reasons are why we strive to improve this procedure.

Problem Statement

The goal of our project is to improve this process by maximizing the tissue sample size in a single, timely procedure. We propose to develop an automated needle oscillation device which cooperates with an automated vacuum mechanism. The fine needle aspiration device will be tested on phantom tissues and hopefully on human tissue in clinical setting. The design needs to be safe and must reduce the fine needle aspiration time and procedure number. The device must be handheld, reusable, and durable. Furthermore, this device must be able to have variable stroke lengths and frequencies. The needle should be able to penetrate the tissue without breaking or bending. Furthermore, when used for taking samples from harder tissues, the needle must take viable samples, rather than move along with the mass. The device should also be dependable and precise.

Problem Motivation

The device would reduce the time and number of procedures compared to the current method. By incorporating an automatic oscillation method, the amount of tissue collected in one operation would increase. The device can be customized for each procedure by adjusting the depth and frequency of the needle. A locking mechanism would prevent the needle from changing depth during the procedure. Increasing the sample yield would reduce procedure time because only one sample would need to be analyzed by the

pathologist. Reduction in the number of passes by the needle would also decrease the procedure time and increase patient comfort.

Competition

The fine needle aspiration competition is relatively thin, as most procedures are still done manually and require multiple passes. There are primarily two devices, however, that serve as alternatives to the manual method.

Cameco Syringe Pistol

The Cameco Syringe Pistol (or Gun), shown at right, boasts a constant suction during procedure. The suction, however, is trigger-based and – though easier withdraw than a simple syringe – still requires the doctor to manually withdraw the cells. There is also specimen filter within to prevent the cells from making it into the syringe. Yet the device is bulky and expensive, and therefore is not widely used.

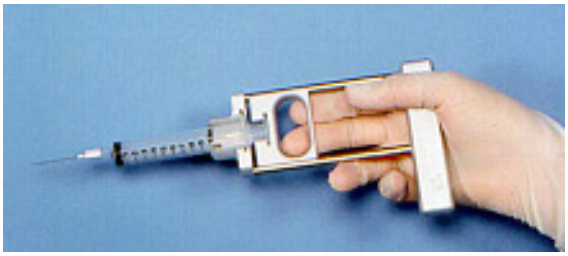

Figure 2: Cameco Syringe Pistol

Tao Aspirator

The Tao Aspirator (also known as the Pencil-Grip Syringe Holder), shown at right, is a more practical alternative to the manual method. It is much smaller than the Cameco Syringe Pistol and offers a close hand-to-needle distance for a more agile approach. One hand can support the mass while the other operates the aspirator. Perhaps the most novel innovation of the Tao Aspirator is its automatic suction. The button on the side can be set to automatically withdraw the plunger to that point. The device also has a preset and precise amount of suction that can be applied. Despite the advantages that both of these devices have, neither one possesses an automated needle drive mechanism, which is what we hope to accomplish along with an automated vacuum mechanism.

Figure 3: Tao Aspirator

Design Constraints

Our design is constrained by a set of criteria. These criteria include frequency and stroke length variability, performance requirements, safety and reliability, accuracy and repeatability, dimensions and weight, ergonomics, and shelf life.

The device must allow adjustment of two primary variables: frequency and needle stroke depth. The frequency of the device must withstand a constant oscillation that can be varied from 0 to 9 Hz. Moreover, depending on the types of tissues being aspirated and their positions in the body, the needle stroke depth must be adjustable from 2.5 mm to 15 mm. The device must also produce a force sufficient to penetrate the skin and mass.

Some tissues such as liver and muscle require more force than epidermal or gland tissues. We would like to test many types of tissue with our device.

The device must satisfy several performance requirements. It must be reusable up to 3 tests in 20 minutes, and endure chemical sterilization methods between procedures. The device should operate efficiently at 23 degrees Celsius, and effectively produce a consistent, adequate sample in each procedure.

Safety and reliability are also very important. A locking mechanism will ensure the needle does not penetrate beyond desired boundaries and cause unwanted tissue damage. All materials must be non-toxic and non-allergenic. Needle integrity must be preserved as well, with no bending or blunting.

Accuracy and repeatability ensure the success of the procedures. Precise needle insertion depth is mandatory. The penetration depth must be variable from 2.5 mm to 15 mm, and the frequency of the ‘in-and-out’ needle cycle must be variable to 9 Hz. The biopsy sample must be retained within the needle shaft so that the pathologists can easily obtain the culture for examination.

The product should be small and operable by one person. Any cords or wires in the design must not constrain the performance of the device. Furthermore, since fine needle aspiration is operated frequently on the neck when the patient is completely conscious, the noise from this device must be minimal and comfortable for the patients.

The device must be ergonomic. The device should be operable in either the left or right hand and not restrict maneuverability. The maneuver should be possible using only one surgeon and the control of the device must be simple, yet maintain all essential functions. Aesthetics are also considered, and the finished product should not intimidate or concern the patient in appearance.

Previous Achievement

Last semester we were able to build a working prototype using the wheel and motor model.

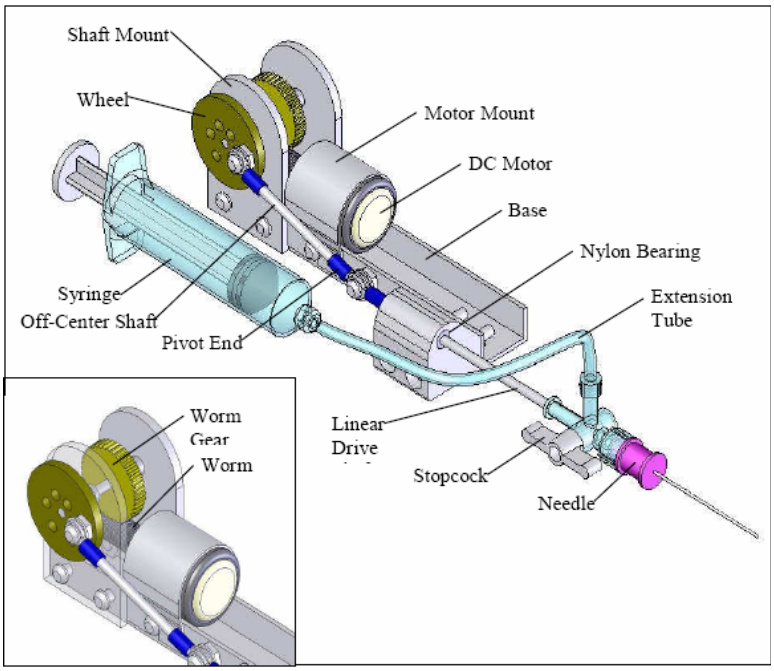

Figure 4: SolidWorks model for the wheel and motor design.

A small 9 to 18 volt DC motor drives a worm gear. The worm gear rotates a matching tooth gear that is mounted on an axle adjacent to a radius-adjustable wheel. The radius of this wheel can be varied from 0.5 – 1.0 cm. The radius adjustment corresponds to a 1.0 – 2.0 cm needle stroke. A steel shaft is attached to the wheel with a #8-3/8 inch screw. The shaft is attached to another linearly constrained member, which is epoxied to a three-way stopcock. A fine needle can be screwed to the stopcock, while a tube and syringe are connected to the stopcock as well to apply a vacuum. The vacuum is created manually by a second physician, independent of the device operator. The frequency of the needle can be changed by adjusting the input voltage to the motor. Based on experimental results, the frequency can increase up to about 7 Hz. There is a linear relationship between the input voltage and the needle oscillation frequency as shown in *Figure 5*. This test was conducted when the device was set to have 1cm needle stroke depth and no load.

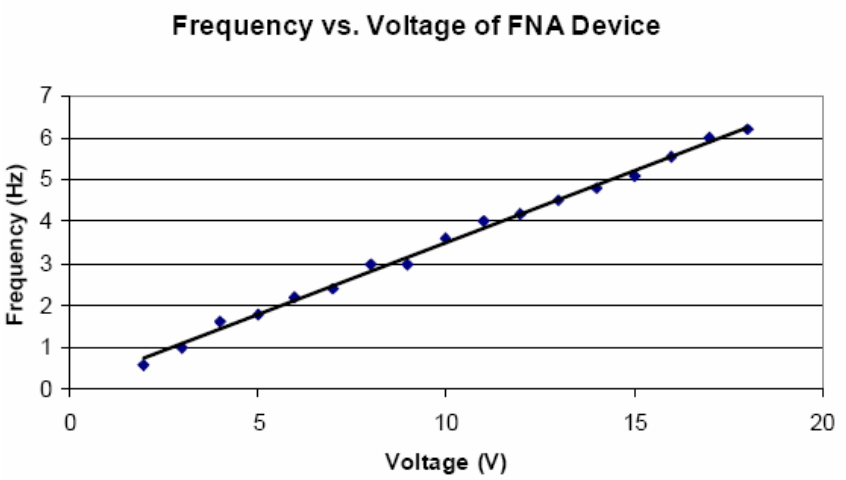

Figure 5: Linear relationship between input voltage and frequency.

The prototype was able to operate at the maximum frequency of 7Hz and yield a sample size approximately 0.63 mm^3 when performed on egg yolk phantom tissue.
This previous prototype has some characteristics that make it unreliable for testing. The worm and rotational gear do not align well and cause grinding accompanied by undesired noise. This is also responsible for the poor efficiency of the device. The prototype has poor repeatability and does not yield a consistent sample size in each procedure. Moreover, in order to adjust the needle stroke in each maneuver, a set pin must be adjusted. This adjustment is time consuming. The prototype also exhibits strong inertial vibration. This is an inconvenience to the operator.

Alternate Designs

Improvement to Current Device

Improving the previous device would entail enhancing the wheel and motor drive. The wheel and motor drive utilizes a beam member mounted to a rotational wheel by a rotational joint. The beam is offset from the center of the wheel (variable radius) and connected via a hinge joint. The assembly uses the rotation of the wheel to produce linear motion through the members. The drive mechanism is similar to that of a piston. The wheel is driven by a 9-18 volt DC motor. The improved device would use the aforementioned assembly to drive the needle. The components would be housed in an ABS plastic encasement. ABS plastic is light and durable, and not susceptible to humidity fluctuations. This is important so that the meshing and alignment of gears and dynamic components is maintained. The encasement would mount all parts in a similar location to the image. However, the gray housing would be entirely replaced with a single machined stock of ABS plastic. Additionally, all current nylon bearings would be replaced with Delrin plastic. Delrin is also resistant to humidity. The bearings would not constrict about the axle members and cause unwanted friction. Delrin plastic is also very strong. The advantages to improving the prototype are significant. The new components would allow our prototype to run fluidly. The device would not grind and misalignment would be nearly eliminated. The device would also be smaller, lighter and more ergonomic. The ABS plastic housing is a very light alternative to aluminum. The new

prototype would be easily handheld. Additionally, the motor and gear placement would only have to be set one time, and necessary adjustments would be minimal. The motor would also be mounted to the prototype, and eliminate any slipping. Delrin plastic bearings would facilitate a smooth motion for all dynamic axles. The components are also found locally, and the idea is novel. The disadvantages of this idea are also apparent. There is a drop in needle force relative to the prototype as the frequency is lowered. This would present a problem as consistency would be lost. Additionally, the motion is still not entirely linear. The wheel produces angular motion while linear motion is preferred. Inertial vibrations may still exist as well.

Conceptual Design

Other than the wheel and motor design and the pneumatic, we researched other potential power sources as well. Although several options were considered, the two most intriguing alternatives were sonic scalers and vibration motors. These innovations are included as a reminder that, although they are not currently part of our prototype design, they nonetheless may later enhance and improve the device.

Sonic Scalers

Sonic scalers, along with ultrasonic scalers, are currently applied in the dental industry in treating periodontal disease. The technique requires extensive cleaning under and between the gum and teeth, and these apparatuses do so by oscillating and vibrating a very small hooked metal appendage. In addition, the scalers used by dentists release small amounts of water to ease access under the gums. This is similar to the necessary application of our FNA device, given the hooked appendage is replaced with a needle. Ultrasonic scalers, which make use of a magnetostrictive motor that converts magnetic energy into motion, were immediately disregarded as overly powerful. They are small, but create a frequency output of up to 15 kHz (15,000 Hz), which is vastly beyond the 10 Hz max we require. Sonic scalers, on the other hand, make use of an air-turbine unit and are much less powerful at a maximum of 6,000 Hz. However, this is still much more than needed and sonic scalers are quite heavy at 15.5 pounds. They are also expensive at around $200. For these reasons, sonic scalers at this time do not seem practical for our design.

Vibration Motor

An interesting alternative, or perhaps addition, to our design is the utilization of a vibration motor. They are incredibly small, having a length shorter than 20 mm, a diameter of less than 6 mm, and weighing less than a gram. This is extremely advantageous in terms of ergonomic capabilities; the smaller the device, the more easily it can be maneuvered for the procedure. Unfortunately, the only ones found were too weak to move the needle with enough force to penetrate the skin (all under one Newton). Though disheartening, this realization proposes another option – perhaps these tiny motors could be used to vibrate the needle such as to potentially increase sample yield. This is a definite consideration as our client, Dr. Frederick Kelcz, initially suggested in his problem statement to design a device that will “hold the needle, vibrate it at a rate with controllable frequency, stroke and suction in a manner that is more efficient than the

manual method currently performed." Therefore, adding a vibration motor to the design may very well improve our device.

Design Matrix

In order to choose one design over the other, we used a design matrix, where we weighted both designs on eight different categories based on how important they were to our client (safety was all-or-nothing). The matrix is shown below, totaled out of a possible 100 points. Given the results, we have chosen to change directions and pursue the pneumatic device.

Feature (possible points)	***Improved Motor and Wheel***	***Pneumatic***
Safety (essential)	*Yes*	*Yes*
Ergonomics (10)	*2*	*7*
Durability (10)	*5*	*7*
Repeatability (22)	*14*	*17*
Frequency Adjustability (22)	*16*	*20*
Stroke Adjustability (22)	*10*	*15*
Patient Comfort (10)	*5*	*6*
Cost (4)	*4*	*4*
Total (100)	*56*	*76*

Figure 6: Design Matrix

Materials

-1 length 1/2" diameter CPVC pipe (~6 inches): Housing device
-1 small LEGO brand ABS plastic actuator: For oscillatory drive
-1 length 3/8" diameter PVC pipe (~3/4"): For stroke adjustment
-2 quantity 3/32" set screws: For stroke adjustment
-20' of 1/8" rubber tubing: Remote pressure transport
-3 Pneutronic inductive flow valves: Actuator control and bleed valve operation
-1 Small piston pump: Vacuum generation
-3 Omron G5V-1 relays: Signal amplification
-3' Wiring: Signal control circuits
-1 Aluminum box: Housing control components
-1 Function generator / oscilloscope: Signal generation and display
-1 Power supply: To power elements
-1 Gas pressure supply: To power actuator
-1 Gas pressure regulator (3 stage component) and affiliated hosing: To regulate desired pressure

Final Design

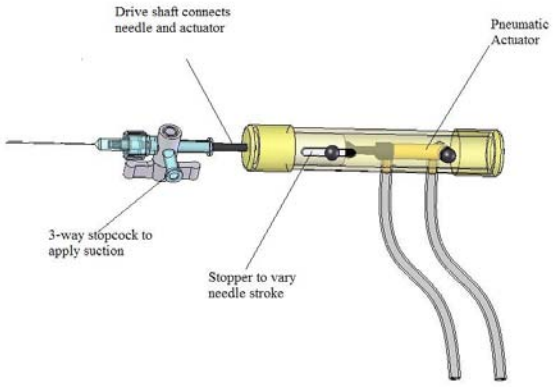

Figure 7. Final Prototype design

The final design utilizes an ABS plastic pneumatic actuator to facilitate linear oscillatory needle motion. The said actuator is mounted within a CPVC cylinder such that its pressure ports extend outside the cylinder to mate with external tubes carrying pressure. The actuator is fixed within the tube through a rear eyelet. The actuator's path is constrained by a cylindrical stopper adjustable by set screws. These set screws clamp the stopper in against an adjustable slide. The stopper can vary the stroke length of the actuator from 0 to 15 mm, approximately the total travel of the actuator. A straight aluminum drive shaft is mounted to the armature of the actuator and threads through the stopper. The drive is constrained in a linear fashion by a cap at the top of the housing cylinder. This cap funcions as a bearing to maintain linear motion. At the end of the drive shaft a stopcock is mounted. This stopcock provides the means to apply a negative pressure through the needle to aid in extraction of tissue. The airway between the needle and a remote vacuum is maintained open by the stopcock.

The actuator control and vacuum system are located remotely from the handheld device. Flow valves are used to control actuator motion. Two 272 ohm Pneutronic flow valves (inductive elements) simultaneously throw upon initiaton by an amplified square wave signal. Pressure is connected to one valve via a normally open port, while on the other to a normally closed port. When both valves are off, the normally open port pressurizes one side of the actuator while the other valve exhausts. When both valves are open, the opposite occurs. By controlling the frequency of the amplified signal, the frequency of the actuator can be controlled. The amplified signal is generated by a function/waveform generator and amplified by a relay and power source. The vacuum system is a normally open circuit. The circuit contains a piston pump to create a vacuum, a bleed valve to relieve excess negative pressure through the circuit when the vacuum is deactivated, and a length of tubing connected to the needle. When the piston pump is activated, the bleed

valve closes and negative pressure is maintained within the needle. When the pump is deactivated, the bleed valve opens and negative pressure throught the system is relieved.

The advantages of this design are numerous. The ergonomics of this option are strong. The actuator is light and small. All motion is linear, and there is only one true mechanical component within the device and drive. The force applied via the actuator to the needle is consistent, regardless of frequency. The force is defined at the armature with respect to the pneumatic cylinder, and thus the needle with respect to the housing. This force is adjusted by regulation of the input pressure. The needle stroke is also easier to adjust, and fine adjustments are possible. The frequency can be set exactly by use of the software. The software will also integrate a function to run single needle iterations. This will allow the user to place the needle properly. The device is quiet as well, as it will be placed in close proximity of the ear. This is important to patient comfort. Additionally, the actuator runs very fluidly and efficiently with minimal mechanical complication.

Some of the disadvantages of this device are the pressure tubes that would connect the device to the pressure source. These tubes potentially become hazardous. Also, an actuator's motion is absolute. The device would have to be fully extended or occluded. Thus only a square wave drive is allowable. If a sine wave is desirable, analog flow valves must be incorporated.

Testing and Results

Our initial proposed test for the prototype consisted of six phantom tumors made of either olives or egg yolks suspended in three different consistencies of agar gel to simulate tissue. A seventh phantom contained a chicken breast to test the strength, rather than the sample yield, of the device. The prototype was able to penetrate the breast tissue easily. Initially, we proposed using the prototype versus the manual method on each of the six phantoms with imitation tumors and comparing the sample yield of each against each other at different frequencies and stroke lengths. This was soon found to be unfeasible, however, as there was no adequate way to accurately measure the amount of cells contained in each sample. Furthermore, Dr. Kelcz notified us in our last meeting with him that it was not necessary to perfect the sample size until using actual human tissue; proving that the device worked and would collect a sample would be sufficient.

We thus formed a new experiment that would test the maximum operating frequency of the device, because at high frequencies the actuator would fail. The test was then run at pressures varying from 40-60 PSI and a stroke varying from 2.5 mm to 15 mm in 2.5 mm increments. At each successive stroke length, the frequency was slowly increased until the actuator failed, then decreased to find the maximum frequency. This was done in two different settings for each PSI, one in air (no load) and one in the firmest olive phantom (load). The results at 50 PSI are graphed and displayed below.

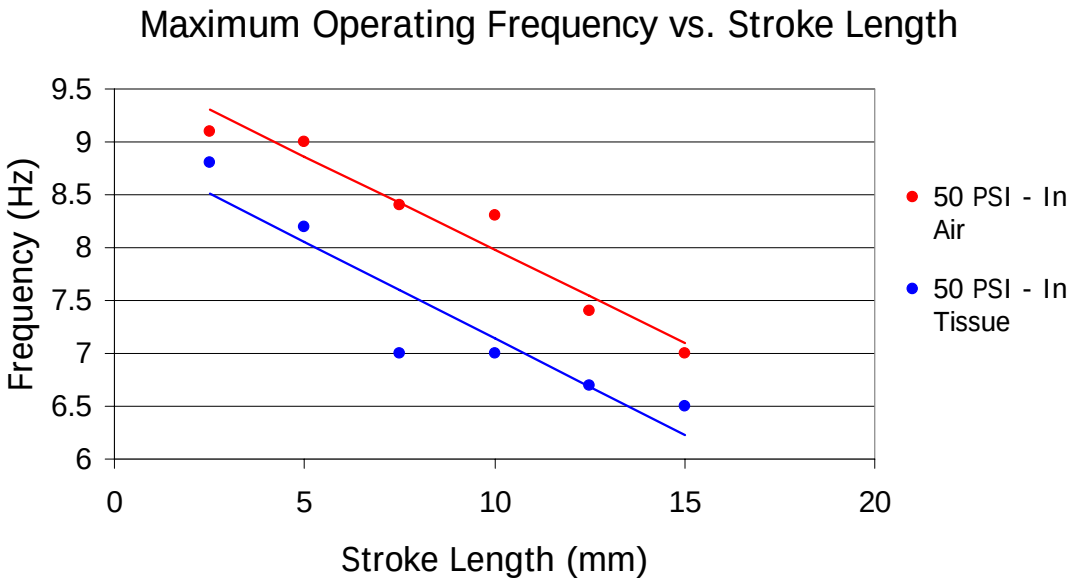

Figure 8. Test Results

As shown above, there is a general linear trend for each run, with an average trend line slope of -0.177. And the linear regression value R^2 is .9464, indicating a strong linear fit. At the very least, there is a direct correlation between increasing stroke length and decreasing maximum operating frequency.

Our preliminary result indicates that oscillating frequencies and penetrating forces our prototype can achieve depend on a specific type of suspected tumor where it is performed on. Therefore, in order to determine the optimal operational frequency at a certain needle stroke, more tests on various types of masses should by conducted.

Conclusion and Future Work

In the future, testing our device's efficiency is our main concern. Currently, even though we are able to obtain a noticeable sample yield, we are not able to evaluate its quality. As a result, our client suggests we test our prototype on various real non-human tissues and have a pathologist count exactly the number of cells and evaluate their qualities in each trial of aspiration. Using these results will help us to statistically compare our device's efficacy to the current manual procedure, as well as to our two competitors- the Tao Aspirator and the Cameco Syringe Pistol.

Simultaneously, we would like to re-modify several parts of our prototype. At the present, we are using a waveform generator to create the square wave that drives the pneumatic system. This machine is very expensive (1500 USD). Therefore, we will replace it with a 5-5-5 generator to lower the cost of the whole system. Moreover, our device is designed to have a stopcock attached to the drive shaft by epoxy glue and the stopcock cannot be replaced after each use. Due to hospital sterilization standards, we have to redesign the

holder that allows the physician to change the stopcock for every fine needle aspiration procedure.

In addition, our team speculates that besides an oscillating motion in-and-out of the needle, a self-vibrating needle will help to increase the diagnostic yield of the sample. It is noticed from our observation and the actual testing that when aspirating, the needle is slightly moved around the point of interest in order to get a better yield. For that reason, we will incorporate a small vibration motor to the needle right after its attachment to the drive shaft. However, this connection cannot affect the vacuum system and add more vibration of the whole prototype.

Finally, we would like to move on testing on human tissue in a clinical setting. Based on our client's requirement, the prototype must be reliable, precise and repeatable. Furthermore, as stated above, for a specific type of tumor, we need to test for the optimal frequency and needle stroke that gives us the maximum efficiency. Hopefully, we will be able to conclude that our device in fact increases the diagnostic yield of the fine needle aspiration procedure.

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