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Clinical Pipette

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Designing a Digital Automated Pipette
for Clinical Injections

A Major Qualifying Project (MQP)
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Abstract

The rapid rise in the number of Botox procedures, both cosmetic and experimental, has put mounting stress on physicians. The current technique of administration with a syringe and plunger leaves room for user error and imprecision. The project team, in collaboration with University of Massachusetts Medical School, has designed a handheld and automated syringe pump for clinical use in the medical industry. With such a device, injection technique is made more accurate, efficient, and safer for patients. The device was able to dispense an average of 25.5 and 98 microliters when programmed to administer 25 and 100 microliters respectively. Our results confirm that our device falls within the 10 microliter-accuracy minimum, showing its efficacy as an administration tool. The device was also able to inject into skin as exhibited through successful trials into 1% collagen hydrogels. Based on the results gathered, our team has set a series of future electronic and mechanical updates to better suit our design.

Acknowledgements

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Chapter 1-Introduction

From 1997 to 2013 the number of nonsurgical cosmetic procedures has increased by 521% (Cosmetic Surgery National Data Bank, 2013). Rising from 740,751 procedures in 1997 to 9.4 million in 2013, the want and need for nonsurgical cosmetic procedures is at a pinnacle, and will continue to grow in years to come. With the average price of each treatment around $380.00, the Botox industry accumulated total revenue of $1.3 billion in 2012 alone. Although the standard procedure only lasts 20-30 minutes, we see where surgeons can find room for improvement.

In recent years, Botox has been successfully administered for therapeutic uses in addition to its conventional cosmetic applications. Botox injections have now become experimental treatments for various medical conditions including eye muscle problems (strabismus and blepharospasm), severe underarm sweating (hyperplasia), overactive bladder, upper limb spasticity (increased muscle stiffness), chronic migraines, and head and neck pain associated with cervical dystonia (Allergan, 2014). A higher incidence of reported adverse side effects has accompanied the discovery of Botox as a therapeutic treatment as compared to its cosmetic uses (Cote et al., 2005). In 2005, the majority of serious reported cases were attributed to deviation from the FDA's recommendations for "drug dose, dilution, handling, site of injection, and storage" (Cote et al., 2005). As Botox injections become more prevalent in the treatment of medical conditions, these negative side effects, such as temporary paralysis and intravascular damage, need to be minimized. With such a large number of Botox procedures being performed each year, both therapeutic and cosmetic applications of these injections can greatly benefit from a more advanced dispensing device. Improving the ergonomics of the administration

device can reduce human error, and minimalize subsequent side effects for the patient. A syringe-pump device can provide increased efficacy by allowing for better user handling and more precise administration. This enables physicians to ensure the highest degree of safety possible for their patients while also limiting the amount of fluid lost by rudimentary injection techniques. The device can also be adapted for other common types of drug installations such as steroid injections.

When performing a Botox or steroid injection, the surgeon needs to be extremely precise. Any variation in the depth of injection or the volume of fluid dispensed could lead to adverse reactions. In addition to focusing on these two key elements, the surgeon must also carefully monitor the speed at which they are pressing syringe plunger and injecting the fluid. Injecting the liquid too quickly can lead to serious impairments, including blindness when performing facial cosmetic surgeries.

Currently the device for a surgeon to use is a simple plunger syringe and needle. It is entirely up the surgeon to simultaneously control all three parameters: depth of hypodermic needle, flow rate of injection fluid, and volume of liquid dispensed. This can be quite a difficult task because the injection needle needs to be inserted into the proper site and every patient has different features. If a surgeon focuses too much on one aspect of the injection, it can lead a slight neglecting of another aspect.

Our goal is to design a handheld electronic syringe pump that can be used in a clinical setting. By doing so, we hope to enable physicians to perform the procedure with greater ease. The device will have the ability to control the amount of fluid injected and the speed of injection. Also the device will have a display to notify the surgeon how much fluid has been injected. In order for the device to be used in a clinical setting, it

cannot come in contact with the injected fluid or the patients skin. This way only the syringe and needle come in contact with the fluid or patient and can be thrown away after each procedure. A device such as this will enable a surgeon to perform these injections quicker but still maintain accuracy.

Administering injections is a very delicate task and the comfort of both the surgeon and patient must be taken into consideration. Typically this procedure is performed single handedly. During the procedure, the surgeon will rest their fifth digit finger on the patient to improve accuracy. The syringe will rest between the first and second digit web space. For our design to be successful, it must fulfill these ergonomic requirements and be compatible with commercially available syringes. These two objectives will make it easy for the surgeon to use and will keep the cost of use low as well by not needing specialized equipment. For added ease of use the device will be battery operated and rechargeable as well.

To tackle the problem at hand, we will employ a project strategy, in which we first approach the task focused heavily on researching the current landscape of the precision electronic pipette systems, motors and the current protocol for the application of Botox. Through this research, we can establish the need in the market for our product and evaluate existing methods of administering injections. Research will also involve canvasing the current surgeons in the field who are using the current protocol for their application of Botox. This will provide us with an additional perspective of the current problems with basic syringe and plunger administration. Physicians can also provide insight into the desired ergonomics of a new clinical device, and their requests in the design of the final products look, shape and feel.

After in depth research, we will be confident enough to introduce ideas in our brainstorms to address the major problems of nonsurgical Botox procedures. The team will first produce a Gantt chart to establish a timeline to follow regarding deadlines for certain steps on the project development path. The needs that need to be addressed will be obtained from the Objectives, Needs, and Constraints, and the brainstorm will revolve around addressing the objectives and needs by keeping the constraints in mind. The brainstorm will end with the decision to move forward with the top two to three designs chosen. The choice will be made using a variety of techniques, involving a Pairwise Comparison Chart (PCC) to establish a ranking of each criteria being addressed, and the use of a decision making matrix to weight the multitude of solutions proposed versus each other in addressing each criteria. Once the top choices are made, the project will move towards the prototyping phase, in which the actual parts will be purchased/made and produced into a working model. Any multitude of problems that may surface will be analyzed in a fishbone diagram, and subsequently solved on an individual basis. If a problem seems unworkable, and we are thus unable to produce a model of said variation, the second top choice from the PCC will be attempted.

After a proper working prototype of the electronic syringe pump has been made, it will be tested. The testing will also establish specifications, which will be necessary in evaluating the precision and performance of our product. Upon obtaining an acceptable final product, a detailed protocol and manual will be compiled for the use of said device. The market value for the initial prototype, and the cost estimate for the mass manufacture and sale of the product will also be determined. If time permits, and the prototype fully meets its requirements and qualifications, a patent may be pursued.

The overall success of the project will be measured based on the performance of the final prototype, with many criteria yet to be established, including but not limited to the quality, ergonomics, precision and performance in field. The success of the product will also be measured based on its ability to meet all of the objectives, needs and constraints. A final secondary success measurement will be the "sell value" of the product, which will be established by the client/advisor, Dr. Naram. He intends to market the final product to his coworkers and inquire about their perceived value for the product. With the similar yet exclusively laboratory-grade products in market selling for considerably more than what our project is aiming for, this will be a good baseline to establish possible market success.

Chapter 2-Background

2.1 Significance

The cosmetic industry has seen a 521% increase in nonsurgical procedures

between 1997 and 2013 (Cosmetic Surgery National Data Bank, 2013). The growing

popularity and influx of Botox injections have greatly contributed to this increase.

Botulinum toxin (Botox) acts to inhibit acetylcholine release from neuromuscular

junctions of neurons (Lew, 2002). Through intramuscular injections, the toxin can be

used to cause localized, desired muscle paralysis. This neurotoxin comes in two forms for

clinical practice: Type A and Type B. The type A form includes Botox and Dysport, the

European version of the Botox product, whereas type B is manufactured as Myobloc

(Hamdy et al., 2007). In the cosmetic realm, Botox has been characterized the fastest

growing nonsurgical procedure, with roughly 9.5 million procedures in 2013 alone

(Cosmetic Surgery National Data Bank, 2013). These injections are primarily utilized to

reduce glabellar lines of the face of patients typically between the ages of 35 to 64

(Cosmetic Surgery National Data Bank, 2013).

Botox injections are now expanding from their traditional use in cosmetic

procedures into experimental treatments for a variety of medical conditions. Although the

FDA has additionally approved the use of Botox for management of hyperhidrosis,

cervical dystonia, blepharospasm of the eyes, and chronic migraines, research is ongoing

for its further applications (Hamdy et al., 2007). Botox has shown promise in treating

Raynaud's condition, where extremities are more prone to excessive numbness and

cooling as a response to stress and environment temperature. It has also been used in

clinical trials for gait function and partial denervation of ankle and foot muscle in patients

with cerebral palsy (Koman et al., 2000). Research has also examined Botox use for pain alleviation and analgesic effects post-operatively in limb deformity procedures. Repeated Dysport injections have been utilized in treating vaginismus and vulvar vestibular syndrome. Researchers have deemed Dysport to be effective in treating these conditions after one study reported 82% recovery rate in patients selected for experimental treatment (Pacik, 2011). This finding has resulted in the FDA approval of a future pilot clinical trial of 30 patients suffering from vaginismus to receive Dysport injections (Pacik, 2011).

Even though Botox has been successful for its therapeutic uses, more adverse effects have been reported when compared to its cosmetic applications (Cote et al., 2005). The majority of negative reports have been attributed to deviation from the FDA's recommended "dilution, dosage, handling, and site of injection" (Cote et al., 2005). The need exists for a more clinically advanced dispensing device for nonsurgical injections. An ergonomic device would improve user handling during injection procedure, in turn minimizing possible human error. A digital syringe pump would also serve to increase precision of liquid volumes as a way of maximizing patient safety. Such an administration device could be made adaptable to other fluid types such as steroid and filler injections. Steroids are most often used as anti-inflammatory agents to reduce immune system response and activity. On the other hand, fillers are cosmetic injectable utilized to increase fullness in the face.

2.2 Current Procedure

Multiple forms of botulinum toxin exist, including conventional Botox, Disport, Xeomin, and Myobloc. The ideal form is administered based on the condition being treated. Myobloc is generally used on patients with chronic migraine conditions, while

Botox is the norm for cosmetic applications. Even though physicians may administer injections with slight variations based on their own preferred technique, the general procedure remains constant. A physician first preloads a sterilized syringe with the properly stored injection fluid. Depending on the procedure type and frequency of injection sites for that patient, the syringe size varies from 1 cc to 5 cc, or 1 ml to 5 ml. A sterilized hypodermic needle is then inserted into the syringe. Typically Botox liquid requires the use of a 32-gauge needle whereas a more viscous fluid, like a steroid, will need a 27-gauge needle. Chosen injection sites vary depending upon the condition being treated.

For facial cosmetic procedures, the locations of glabellar lines and crow's feet are recognized and marked. Botox sites for chronic migraines generally include three to five glabella, four to six temporal, and three to six forehead areas (Binder et al., 2000). The frequency of sites is dependent on the severity of migraines for each individual patient. Points within intramuscular bundles on the hand are targeted for treating Raynaud's condition. The injections are generally administered along the superficial palmar arch at each digit (Iorio et al., 2012). For cervical dystonia, areas of sternocleidomastoid, splenius capitis, and trapezius are most commonly used as injection sites (Odergren et al., 1998). The hypodermic needle is then inserted into the muscle cavities of the various marked locations. Some physicians aspirate pre-injection to ensure that the needle is not penetrating any blood vessels. If blood is seen in this pre-aspiration, the needle is removed and reinserted to avoid puncturing any vessels. Once proper location is determined, the physician will dispense the liquid intramuscularly by using manual force to push down the plunger system. The flow rate of the liquid is entirely under the

discretion of the physician. Once the desired amount of fluid is successfully administered, the needle is slowly removed and repositioned into each of the remaining injection sites. The procedure usually takes twenty to thirty minutes to complete. Botox treatments are often repeated every four to six months to maintain the beneficial results.

Botox is most often purchased as single-use 50 and 100 unit vials. The liquid must be reconstituted and diluted to 4 units/0.1 ml (Allergan, 2014). The dilutent is then injected back into a vial and mixed generally with 0.9 ml of saline. For a single, traditional procedure, a Botox dosage of 20 units/0.5 ml is used to treat glabellar lines. Hyperhidrosis procedures typically require 100 units of Botox. Dosage size varies between patients, individual physician protocols, and the particular condition being treated. However the FDA recommends that a patient does not exceed 360 units over a three-month period (Allergan, 2014).

Although generally minor, adverse responses have been reported days to weeks after Botox procedures (Allergan, 2014). Few cases have been reported for the purely cosmetic applications for Botox as well as the FDA approved treatments. More adverse effects have been reported related to unapproved and experimental Botox treatments for various chronic spastic conditions. The movement of botulinum toxin beyond injection sites is the most notable. This can cause a variety of symptoms in patients including asthenia, muscle weakness, diplopia, and ptosis. Individual hypersensitivity to Botox may also cause the same adverse reactions in patients. Few cardiovascular post-procedural responses have been reported as well resulting in arrhythmia and myocardial infarction. However Botox has been shown to be more dangerous for patients with pre-existing

cardiovascular conditions. It is also suspected that younger aged patients are at higher risk of developing negative symptoms from Botox as compared to adults.

Clear issues exist with the rudimentary and entirely manual nature of Botox administration procedures. Because the physician is in total control of the amount of fluid volume dispensed, limited precision and accuracy is achieved. The physician determines each aliquot administered as he observes syringe measurements. This allows for the possibility of human error is the amount of liquid dispensed. It is also important to consider that a physician must take into account three parameters simultaneous when administering injections: volume of Botox dispensed into each injection sight, depth of the hypodermic needle into patient muscle, and flow rate of liquid, or injection speed. The depth of the needle varies from patient to patient, with dependence on the context of the procedure being carried out. The flow rate must also be kept slow enough to avoid causing a vascular response in the patient. It is difficult for a user to monitor each constraint in a single procedure. Not only can this inconvenience lower precision, it can also lead to strained interaction between the physician and patient. While focusing on the three parameters, the physician can only limitedly communicate with the patient. By allowing for least one parameter to be controlled by the injection device, the "bedside manor" can be improved. A final issue with current procedure is post-injection drip. A small amount of fluid can be lost onto the patient's skin after each aliquot is dispensed. With total loss of fluid accumulating over time, wasted cost of unused fluid becomes a economic concern. Physicians, especially in private practice, could benefit from a device that minimizes the costs of injection drip.

2.3 Market Competitors

Currently there are no devices on the market that have the same purpose and goal to the one the team is designing. Although there are devices that are laboratory grade equipment none are certified for the clinical setting. However three devices were found for laboratory use and have certain aspects that should be seen in the final design of the clinical syringe pump.

The first device, the eVol hand-held automated calibrated analytical syringe from LGC Standards is a digitally controlled dispensing system. This laboratory grade device couples a digitally controlled electron drive and an XCHANGE enabled analytical syringe. The key benefits of this device include that it is digitally programmable to perform a variety of liquid handling procedure and is very user independent. This programmable calibration procedure can hold up to ten XCHANGE syringes. The device allows for interchangeable analytical syringes, however can only be used with particular containers manufactured by LGC Standards called CERTAIN. The eVol also can only hold three different capacities of syringes, a 5mL, 50 mL, and 500 mL. Although its high level of 0.2% accuracy, reproducibility, and speed I key to success of this product, it would not work in a cosmetic procedure due to the fact that a typically syringe of botox is 1, 3, or 5 mL. EVol also came out with a NMR addition, which would be more appropriate for a clinical use due to the fact that it facilitate smaller volume manipulation, and has operator independent accuracy, precision, and reliability. Although this allows for a more accurate manipulation, the device cost more money, and comes with custom syringe and needles. Its one handed ergonomic design also closely resembles our vision of the syringe pump however the device is a thicker than we anticipate (Evol, 2014).

The second device is called the Eppendorf Multipette. This device houses the syringe on the outside of the device. Not only does it holds up to nine different sizes of Combitips; specially designed tips for their custom syringes, but it can also hold up to 112 different volumes. This volume dispensed is displayed through the LCD screen, which can be found on the outer portion of the device, which is located by the plunger. Unlike the eVol, the Eppendorf is requires aspiration and titration before dispensal. Aspiration is a key constraint that would be found in the design of the syringe pump as well. Its one button tip ejector and ergonomic design is key for lab use, but would not be helpful in a clinical application. Its positive displacement system and contact-free Combitip attachments are ideal for our objective with no liquid contact, but its less than 3% precision is not desired for the syringe pump (Dispensing with Style, 2014).

The third device that was found was by Hamilton. This GasTight syringe is also housed on the outside of the device. The biggest device of the three, the GasTight syringe is easily the most advanced. It not only has an LCD screen with four modes of display, volume, series, syringe size, and hold volume, display, but it also comes with a button to change the device mode. Equipped with a zero button and a fine thumbwheel adjustment, this battery-powered device is efficient and up to 1% accurate. Although this device is ideal for lab use, it is still not up to clinical grade, due to the fact that liquid would come in contact with the device. This application is used specifically for gas and liquid chromatography (Syringe Catalogue, 2014).

2.4 Clinical Setting Requirements

Since our device is going to be targeted towards clinicians, a thorough understanding of the clinical environment is needed. A visual inspection of the hospital does not prove if

the area is clean or not. Microbes are invisible to the unaided eye and infections can spread throughout the hospital.

Certain areas in hospitals will contain more pathogens than others, especially items that are frequently touched. Some examples of frequently touched items include sheets, lockers, and side or over bed tables. These sorts of items act as pathogen reservoirs and host numerous pathogens. Once a person touches that surface, these microbes will then spread on their hand and can be placed somewhere else (Dancer, 2011).

The spread of bacteria must be taken into account when designing a handheld device. There are a number of cleaning chemicals in clinical environments including bleach and chlorinated products. Each cleaning product also has an application where it is most potent. For example, bleach is essential for containing the spread of norovirus and chlorinated products are great disinfectants but will not destroy biofilms. (Dancer, 2011). In addition to cleaning products, there are also materials that are anti-microbial and prevent the adhesion of bacteria and microbes. Understanding the environment that the device will be used in will enable better selection of materials and an enhanced knowledge of what disinfectant methods may be necessary.

2.5 Movement Mechanisms

2.5.1 Stepper Motor

Stepper motors function by receiving an electrical impulse, which in turn is translated into mechanical motion. Every pulse is causes one step, or increment, and the shaft is magnetically latched at each point (Kuo, 2014). Each increment a stepper motor goes through is a fraction of a rotation. Due to this, these motors are able to provide high

torque at low speeds. Also, since they move in incremental steps, they are able to count

each step and keep track of every motion without the need of an encoder (Sandhu, 2009).

One type of stepper motor is a variable-reluctance motor as shown in *Figure 1*.

Letters A, B, and C represent different wiring phases, while N and S represent

north and south magnetic poles. Only the wiring for phase A is shown in the figure.

When this phase receives impulses, the four rotor teeth will align with the stator teeth.

Next, phase B will be energized while phase A is de-energized. This causes the rotor to

shift position clockwise so that the phase B stator teeth align with the rotor teeth (Kuo,

2014). This type of stepper motor requires a unifilar winding. This means that there is a

single coil on the pole of the motor. Applying a current causes a flux to occur when there

is no magnetic polarity. The flux creates a magnetic polarity at the end of the pole and

causes it to move. When the current is reversed, so is the magnetic polarity (Kuo, 2014).

2.5.2 Servo Motor

While servo motors also function through electrical pulses, these pulses must be more frequent than with stepper motors. In order to accurately maintain their position, servo motors must receive about 60 pulses every second (Sandhu, 2009). This time requirement can lead to lag and possible slippage in some applications. Another difference between stepper motors and servo motors is that servo motors are used in constant speed applications. Inside the motor, the rotor is made of laminated steel and has bars of another conducting material running through it. Just like stepper motors, servo motors also have a stator, made of steel, except these have slots with a number of windings. When the power supply applies a voltage to these windings, a rotating magnetic field is produced. This causes a current in the bars in the rotor and the rotor is accelerated and approaches the synchronous speed. Servo motors operate at speeds below this speed because once synchronous speed is reached, the torque becomes zero (Firoozian, 2009).

2.5.3 Slider-Crank (Piston)

There are many systems in which motors can control. Mechanical systems work through the translation of energy to different components, causing movement. Some of the components that allow the transfer of energy from the motor throughout the system are cranks and rockers. A crank is a link that revolves in relation to the frame and a rocker is any link that does not revolve (Knowledge, 2007).
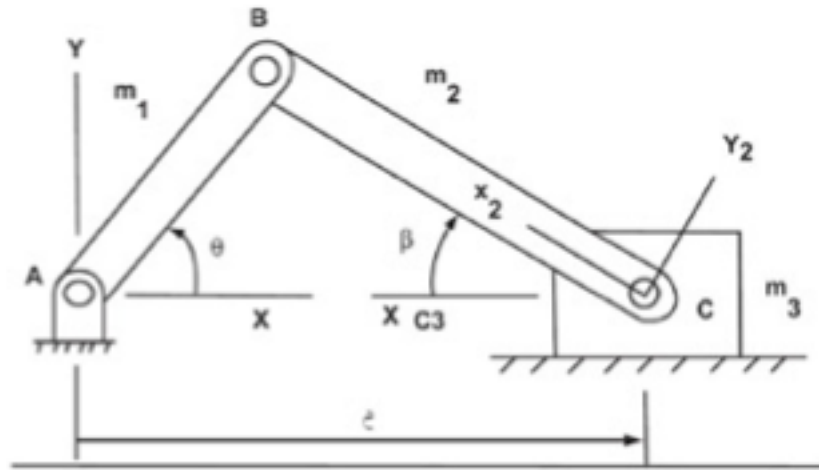
Figure 2: Components of slider-crank mechanism (Knowledge, 2007)

Figure 2 shows the basic components of a slider-crank mechanism. This is a simple

system with two linking components and one rocker, which is the part underneath block

c. Slider-crank systems take the rotational motion of a motor and turn that into a

reciprocating motion. This can be seen in *Figure 3*.
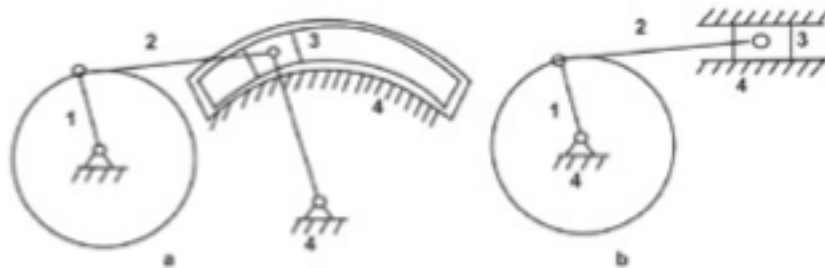
Figure 3: Slider-crank mechanism(Knowledge, 2007)

As seen in the above figure, as the links are moved in the circular motion, the block is

able to move along the rocker. This sort of mechanism can be used in many different

ways depending on which links are kept stationary (Knowledge, 2007).

2.5.4 Air Displacement

This mechanical system uses a piston to aspirate and dispense liquids. It is very commonly seen in laboratory pipetting devices. Pipettes work by adjusting a piston to a certain height within the device. Then the user depresses the button and the piston moves down and displaces air. When the tip is now inserted into a liquid and the button is released, the piston moves back up and pulls the liquid in to replace the missing air (Zinnen, 2004). *Figure 4* is a diagram that illustrates this concept.
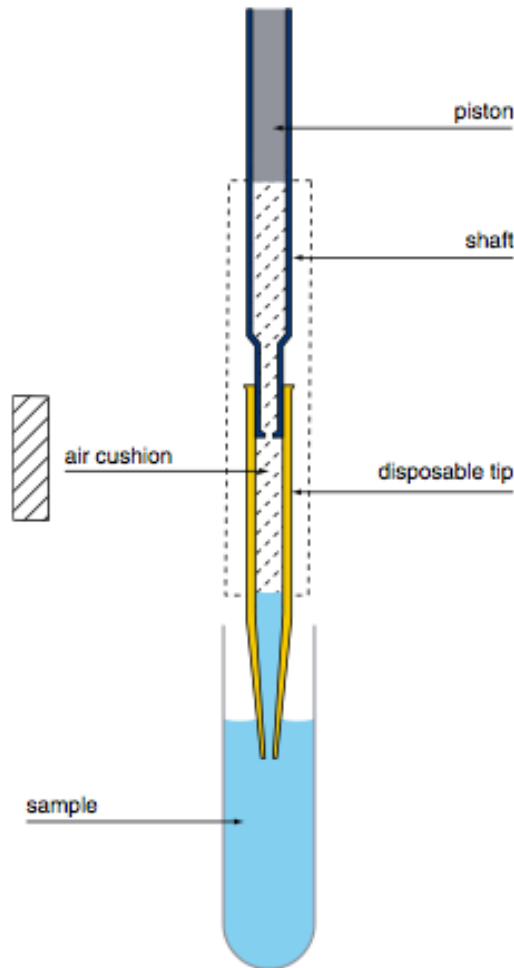
Figure 4: Air-displacement method in a pipette (Gilson Inc, 2005)

2.5.5 Linear Actuator

As the name implies, linear actuators create motion along a single axis, through the use of a lead screw and nut. Most often DC motors control screw/nut components, although stepper motors are known to be used in operations requiring specific positioning with feedback loops (Sclater, N.). Linear actuators are known for their use in heavy load operations, with most commercial linear actuators able to achieve a minimum of 25 lbs ("25 lbs. Linear Actuators") and maximum of 25,000 lbs ("The Eliminator HD"). The linear actuator functions through the activation of an electric motor to move a mounted screw. The lead screw, in turn, rotates in place. A casing tube surrounding the lead screw is encased with a threaded nut matching the thread of the screw. Any motion on the lead screw causes motion on the lead nut and tube.

Dimension (inches):

	2	4	6	8	10	12
L3 Stroke Length	2	4	6	8	10	12
L1 Stroke Length	7.47	9.48	11.49	13.49	15.50	17.51
L2 Stroke Length	9.47	13.48	17.49	21.49	25.50	29.51
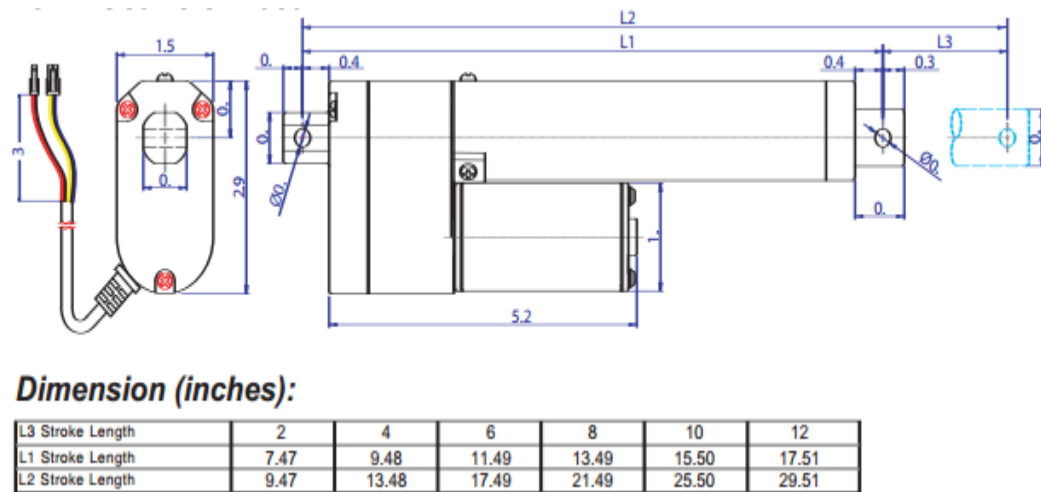
Figure 5: Linear actuator with potentiometer feedback (IMD3-Series Linear Actuators with Potentiometers)

Linear actuators are most often longer in length than other systems being investigated due to the fact that the casing with the lead nut assembly and the lead screw must be the same size to achieve maximum stroke length (length of actual motion). Limit switches can be equipped to the top and bottom of the assembly in order to prevent loosening of the casing and lead nut from threaded length beyond the zero plane. Without

a limit switch the casing and lead nut can go beyond the threaded length and into the motor. Upon contacting the limit switch, the circuit knows the stop operations to prevent any damage to the assembly. Most often, when positional information is desired, linear actuators are equipped with a built-in potentiometer for position sensing. Through the use of a potentiometer, the user can also program the linear actuator to move to a specific stroke length rather than activate and stop based on time calculations for calculations of stroke length. (Sclater, N.) ("4 Inch Stroke 110 LB Linear Actuator with Feedback") In essence, linear actuators provide very specific linear positional movement when equipped with the correct modules. However linear actuators are costly, with unit prices in the $100s. In addition the forces for each the actuators are meant to achieve are unnecessarily high for intended operations.

Stepper motor linear actuators function in a manner mimicking the linear actuators discussed above, but with some slight alterations. As highlighted in the stepper motor section, these motors are known for their accuracy and lack of missed steps. Stepper linear actuators possess internal rotary motion generated by said motor into linear motion created by the shaft (Sclater, N.). These systems come in three major types, captive, non-captive, and external.

A captive system holds the turning rod with an anti-rotation collar. This stepper motor is restricted from moving, and any motion generated on the shaft of the said motor will be generated into rotational force on the stainless steel shaft, which in turn extends the shaft. The captive actuator has a built in anti- rotation mechanism, and is usually designed to enable short strokes. Figure 6 shows the internal schematic for an example

captive stepper motor. Number 27 depicts the axis of motion enabled by the motor

(Adami, H.J., 1983)
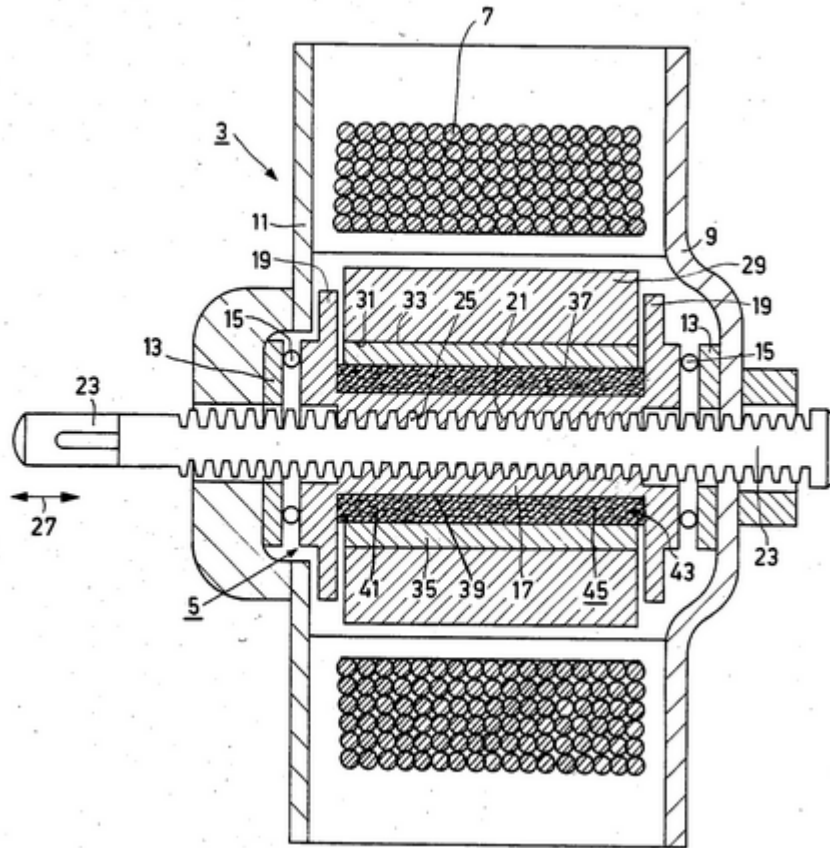
Figure 6: Captive stepper motor housing showing threaded rod control (Adami, H.J., 1983)

Noncaptive actuators have a lead screw that passes through the motor. It has no

stroke limits, and can therefore be attached to an assembly that will not rotate. This

attachment will allow the non-captive actuator to function much like a captive system.

When not captured, the screw will turn in place, not generating any linear movement.

This system is meant for longer length strokes. Figure 7 shows an external schematic of a

non captive stepper actuator. As seen in the figure, the screw extends through the motor

without any captive element.
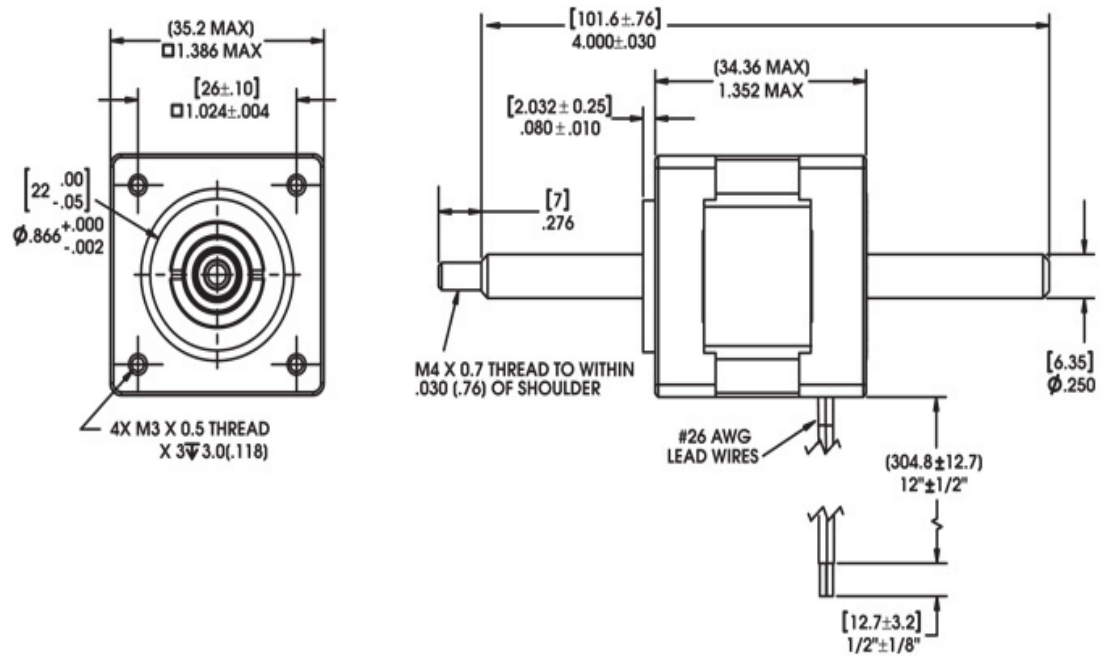
Figure 7: Non-captive stepper actuator (HaydonKerkExpress)

Lastly, external linear actuators use a lead screw and nut combination to extend out of the motor. The lead screw turns in position as the nut travels back and forth. (Sclater, N.) As can be seen in Figure 8, the external linear nut is the source of movement in the assembly, as all the other units either exhibit rotational force, or are stationary during operation.
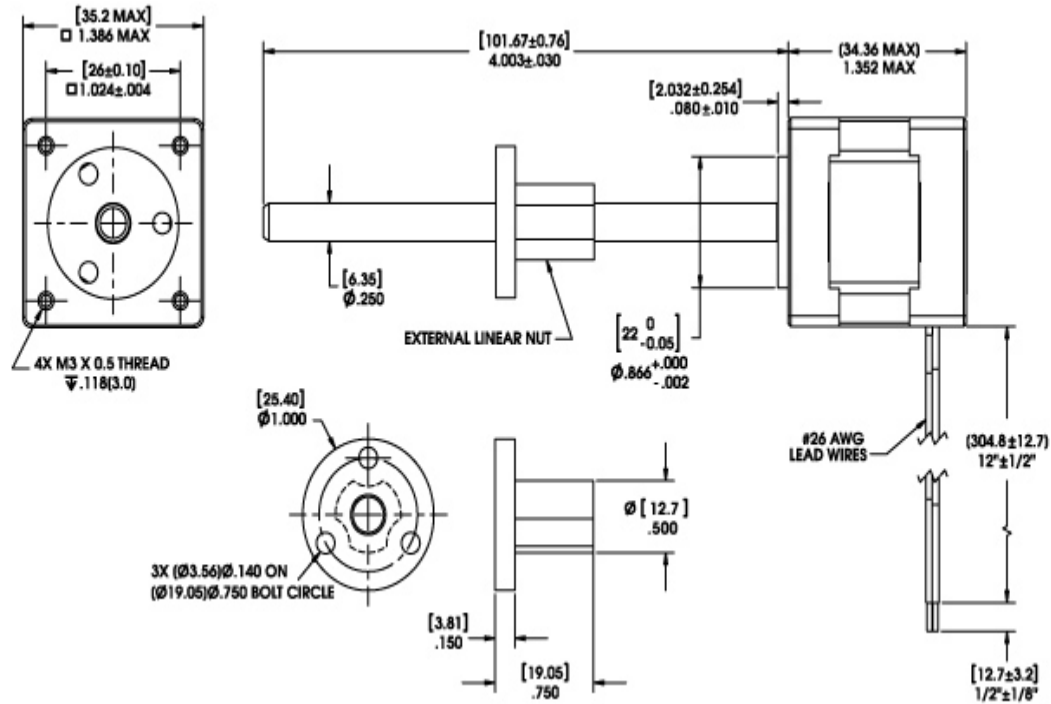
Figure 8: External linear stepper actuator (HaydonKerkExpress)

The stepper linear actuators are used mainly for their excellence in resolution achievement. A major producer of these assemblies, Haydon Kerk, is also a provider of product information for their marketed assemblies. Their observations, seen below, along with extensive datasets, acknowledge that with an increasing force, the velocity of movement will decrease in a linear fashion. However, the slope of decrease is fully dependent on the resolution of the stepper motor A higher resolution (smaller step size much like 0.0030mm, or N) seen below can produce slower speeds, and endure higher forces. On the other hand, low-resolution steppers allow for a higher range of speed control with a lower force tolerance. In essence, a higher resolution provides a better movement accuracy at a higher torque and slower speed, whereas lower resolution steppers provide a larger and higher range of velocities at a lower accuracy and lower force threshold.

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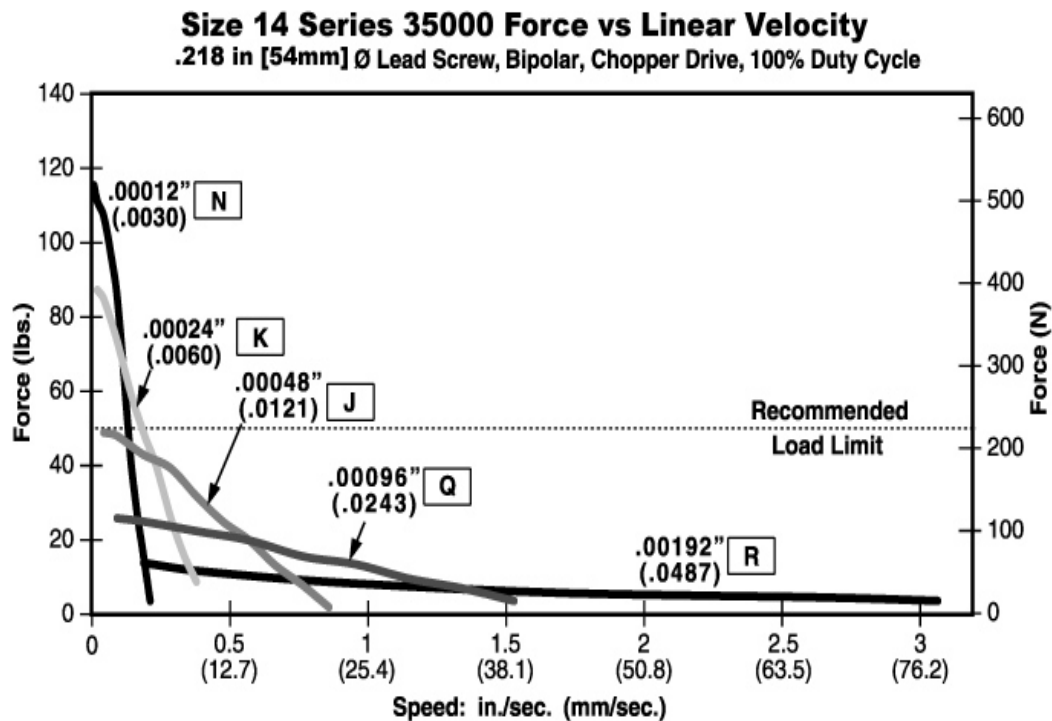
Figure 9: Force vs. Velocity graph for varying resolution stepper (HaydonKerkExpress)

2.5.6 Rack and Pinion

The rack and pinion is a form of a linear actuation system that uses a pinion gear to move a set of linear teeth set called the rack. The rotational force from a motor turns the pinion, which in turn causes linear motion of the rack. In other iterations, the rack may be constrained, resulting in free movement of the pinion. The rack and pinion systems are known for their long-term, backlash free operation. Some advantages include its possible unlimited travel length (dependent on size of rack), lower cost than other systems, and variations in size for specific precision and power. On the other hand, the rack and pinion must be kept consistently lubricated and clean. The system can also

undergo possible backlash as the gear settles into the gear teeth. So for instance, if we desired an aliquot of 10uL and the gear had not set in place, there could be extra movement on the rack system, thus causing a higher or lower dispensal than was desired. Another problem to consider would be that the motor engages the rack only on one side, and thus, with regards to our applications, the rack cannot be freely suspended for travel. It would be constricted on the axis of travel so that the rack travels in the direction desired. (Sclater, N.) (Wittenstein)

Figure 10: Rack and pinion mechanism (Knowledge, 2007)

2.6 Electrical Components

The information display, volumetric dispensal controls and the movement mechanisms of the device will all electrically controlled. In order to properly control these electrical components, microcontrollers will be required. Although stepper

controllers, ADC converters, and encoders will be described hereon, their use will be fully dependent on the mechanisms through which we aim to achieve our objectives.

2.6.1 Arduino Microcontroller

The microcontroller currently being used for research and idea development purposes is the Arduino Uno. In principle the size of the Arduino does not affect the overall performance or behavior of the controls, Thus although rough prototyping will be completed on the Arduino Uno, the final programming is to be completed on an Arduino mini for the benefit of saved space. It will be assumed in the paper herein that Arduino implies to the general working principle of the Arduino microcontroller, and not the variation in size.

A microcontroller (uC) is in essence a small computer serving a specialized singular purpose. It has all the working components of a computer, with a processing core, memory, and input/output peripherals. However the sizes and method of achieving said components are different from normal personal computers one might find in desktop and laptops. Microcontrollers are meant for use in embedded systems, serving to automatically control mechanisms of a device. One product known for its ease of use, first time user friendliness, and flexibility is the Arduino line of microcontrollers. Based on an ATMega328 microcontroller, the Arduino provides 14 digital input/output pins, with 6 Pulse Width Modulation outputs, 8 analog inputs, and lastly a 16 MHz crystal oscillator (Arduino).
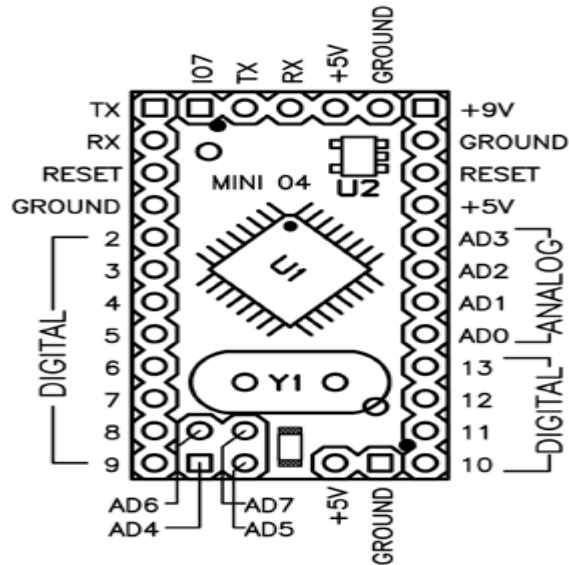
Figure 11: Arduino Mini 04 pin schematic (Arduino)

The ease of use of an Arduino originates from its AVR code in the Integrated

Development Environment (IDE) which is an application written in Java. A more

straightforward form of C language simplifies the programming process for unfamiliar

users with the software and programming technicalities. (Arduino Introduction) In

addition, the Arduino provides a free library populated by user-generated code for a

variety of common applications. With this resource of vast codes, any user can

manipulate a pre-existing code for their personal application. The Arduino is also cross-

platform, allowing for programming on any OS, and relatively cheap in comparison to

other microcontrollers.

The ability to program Arduino systems does not directly translate to general

microcontrollers. Learning Arduino programming does not require knowledge of bigger

concepts of IDE functionalities. Because of this, users may be able to properly program

an Arduino but not other varieties of microcontrollers. Frequent Arduino users often

highlight this as a major consideration and possible drawback of the use of Arduino for

device development. Although it was highlighted in the advantages section that the Arduino is cheap, that is to be taken with respect to other easily programmable microcontrollers. If our group had experience in the field, a microcontroller without IDE would cost only a few dollars, and use much less memory in achieving required task by bypassing the IDE. (Cheng, Z) (H.S.)

2.6.2 Stepper Controller

Stepper controller's power and control stepper motors in designated stepping styles. One such controller is the Microstepping driver with translator made by Allegro microsystems, 3967. It is designed for bipolar stepper motors, with the ability to control the motor in a full, half, quarter and eighth step modes. In essence, a stepper controller acts as a mid-connection between the micro controller and stepper motor to mediate movement generation. As described in the previous stepper motor section, the stepper motor is controlled by PWM signals. The resolution of the stepper motor can be controlled by activating the magnets at different combinations for different degrees of steps. The stepper controllers' major role is to set a reset input that turns off all outputs and ignores all inputs until "home state" is achieved. Step input sequences are used to advance the motor by one step at a time. Microstep select terminals set the step format and desired resolution. Direction inputs set the state of rotation for the stepper. The Shutdown functions disable all inputs in the event of a fault in operation (Sparkfun).

2.6.3 Analog to Digital Converters (ADC)

Sensors are often required for positional input or force input during product operation. ADC is required for this data collection. ADC's are used to convert analog

signal, the data obtained by sensors, into digital signals so that the microprocessors can

read, understand and act according to the sensors output. Two main parameters control

the quality of the ADC: sampling rate and sampling precision.

If we assume that:
- $fs = 1000$ samples per second
- $N = 10$ (dividing the y-axis to 10 intervals)
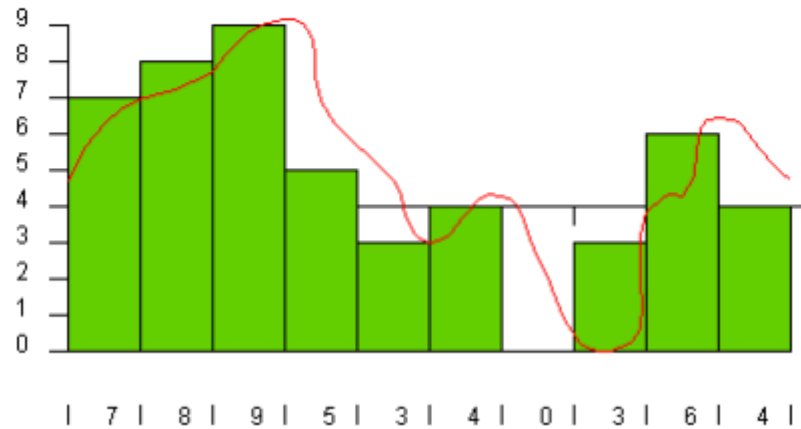
Figure 12: Analog sample translated to a digital output (green bars) (Kazerooni, H)

Sampling rate refers to the number of samples that is taken in a second. Sampling

precision is the quantization level, or how precise the digital value output will be, for the

sampling process. As one might assume, a higher sampling rate as well as a higher

sampling precision both yield a more accurate representation of the actual sample value.

However the price and power needed for such a precise ADC is not necessary in many

operations (Kazerooni, H).

2.6.4 Incremental Encoder

An encoder is used to convert the angular position of the stepper motor. Although the

types and means of obtaining rotary information vary, the general functionality is the

same with all encoders. The obtained motion is interpreted as digital code to determine

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the position and movement. In our application, the encoder will be used, if necessary, to serve as a feedback system for the stepper motor to check for missed steps when dispensing the aliquots. A missed step may occur if the motor faces a high resistance. The feedback loop will check the actual steps the stepper motor achieved versus the programmed and desired steps, and correct in the case of a mismatch. Encoders mainly work by offsetting two high and low signals by 90 degrees. This offset is changed after every pulse, and the resolution of the encoder is defined by Pulse Per Revolution (PPR,), which is the total number of pulses in 360-degree motion.
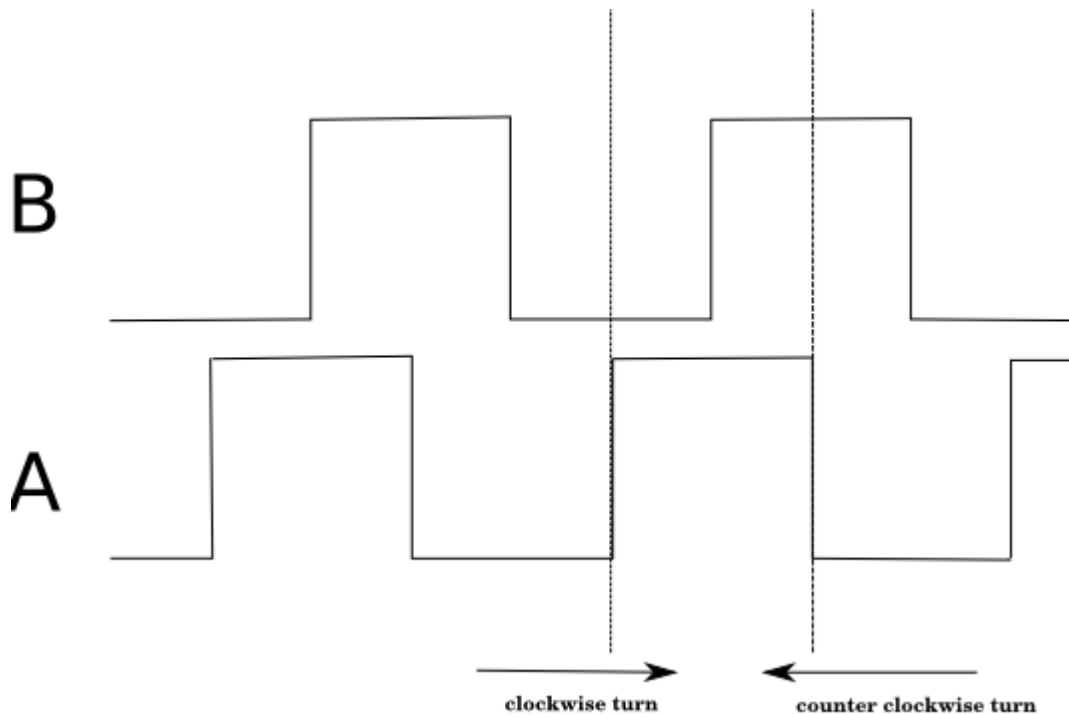
Figure 13: Incremental encoder quadrature waves (Sclater, N.)

By reading the pulses and the values for the offset high and low signals, the encoder can detect the direction and distance traveled. Although other ways exist that can detect the position, the incremental method used by encoders would best suit our purpose due to

it's wide application capability, industrial duty with resistance to shake, vibration and shock (Dynapar).

2.6.5 Force Sensor

The method currently being pursued to positionally determine housing volume requires the use of force sensors. Force sensors (Tekscan) are essentially variable resistors with very high resistances (~1MOhm) when not being subjected to a force. However, when the surface of the variable resistor comes into contact with a force, which is determined on a case-by-case basis depending on the force sensor, the resistance changes. This change in resistance can tell the user through a microcontroller how much force this sensor is being subjected to (Dee, Jordan).
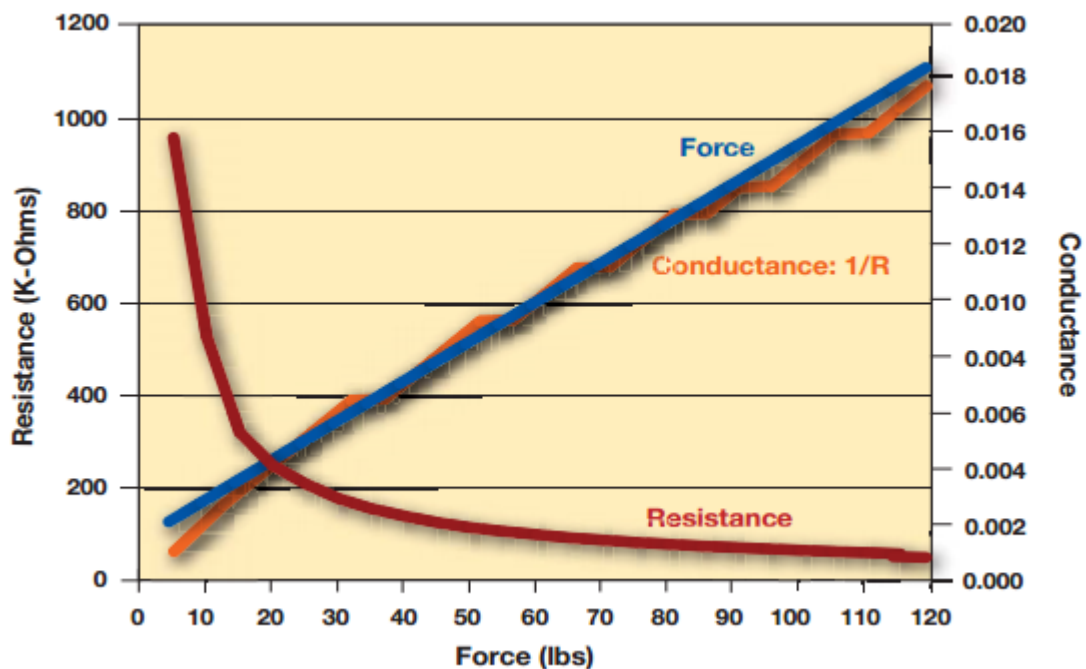
Figure 14: Flexiforce sensor resistor Force response under Load (Tekscan C.)

Another sensor being used as a stopping mechanism for our product is a limit switch. (Evans, W.B.) A limit switch is most often utilized when the moving part is nearing the end of the defined area of operation. Limit switches operate by a shaft that extends through the enclosure. When the switch shaft is pressed down, the limit switch activates, and through the programmed microcontroller, causes a response in the motor to stop movement in the direction it was traveling.

2.7 Exchangeable Syringes

To make the device more commercially available, a universal syringe system must be implemented. As was shown previously, many products on the market currently require special company dependent syringes and parts. This causes the price of the device to increase as well as makes it more difficult to use since the typical syringes surgeons use cannot be used in those systems.

There are various ways that can be implemented to secure universal syringes. One such method is known as a luer lock mechanism as shown in Figure 15.
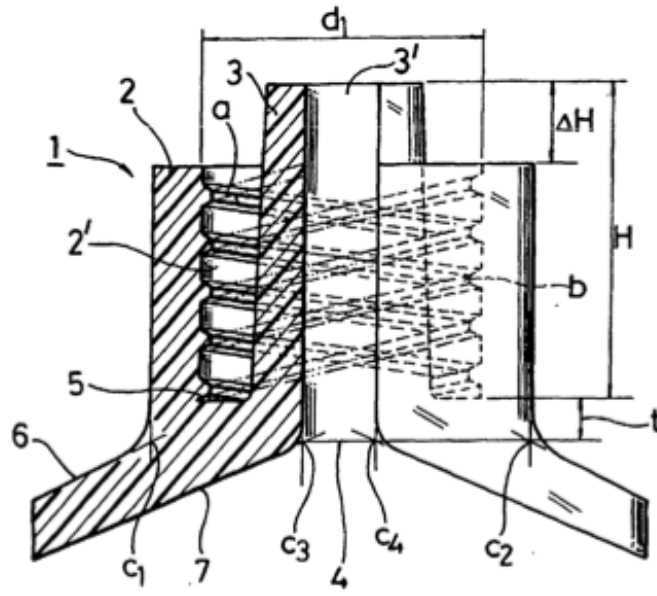
Typically this mechanism is used to secure the needle to the syringe, which makes every needle universal for each syringe. However, a mechanism such as this could be used to help secure the syringe plunger, and thus the syringe itself, to the device.

2.8 Information Display

The desired liquid volume needs to be programmable on a display for the user to see. An LCD display, and a dial system are viable options for delivering this information. At the client's request, the device needs to be equipped with a notification system to signal procedure completion.

2.8.1 LCD Display

Liquid Crystal Displays come in a variety of sizes, 8x1, 8x2, 10x2, 16x2, up to to 40x2 The first number indicates the number of characters in a line, while the second represents the number the rows. All LCDs work with either a 14 pin or 16 pin set up, with 8 data pins carrying data and commands from the local microcontroller. There are a variety of library sets for programming LCD displays on an Arduino, allowing for easy integration to our project (Arduino).

An LCD can be easily programmed to display the information obtained from the microcontroller. The drawback to be wary of is the number of pins the LCD assembly takes up on the microcontroller. The Arduino comes with a limited set of pins for input/output, and thus, if the number of pins needed start becoming scarce, alternative methods would need to be pursued. Also, if the power consumption of the LCD starts becoming a significant draw on total supply available, alternatives may be more desirable. Problems will be addressed if any are to arise as the project progresses (Microcontroller-Project).

2.8.2 Dial System

The dial system would vary the aliquot volume through use of a potentiometer to mark notches indicative of position. The size of the dial system housing and the sensitivity of the potentiometer can all be varied to change the resolution desired. In general, larger dial systems are more accuracy. The advantage of this mechanism would be decreased power consumption relative to a LCD. However the sensitivity that is achievable with a LCD display may not be reached with a dial. It is difficult for a human user to reach high levels of accuracy when turning a dial close to the marked notches.

2.8.3 Notification System

Notifications must alert the user of a completed procedure, and in the event of a failed procedure, also indicate system failure. The notification system can be an LED light, a buzzer, vibration, or change in lighting of the LCD screen. The client desires a slight vibration or clicking noise to mark completion, as that is the main way in which most clinical products notify the user. These requirements can be easily achieved by programming the Arduino with vibration motors and/or buzzers activated by PWM (Microdrives). Some possible drawbacks of vibration notification include patient discomfort if too strong. On the opposing spectrum, if the motor is too weak, the user may never be notified of action completion. An overly loud buzzing mechanism may also be a nuisance to a patient.

2.9 Ergonomics

Considering ergonomics in design is a crucial factor. It is the designer's job to understand what the client wants and adapt the product to their needs. This is especially the case with medical equipment. Technology is constantly advancing and devices in doctor's offices and hospitals are becoming more complicated. Ergonomics is extremely important in creating a device in which device performance and human well-being do not compromise one another.

Devices used in operating rooms especially need to be both comfortable for the operator and optimize efficiency. Surgeons are taught how to do things in certain ways and they adapt to various procedures and devices. After some time, these processes become habits and surgeons become comfortable doing procedures in certain ways. Creating a completely new device that surgeons will need to learn to use would

negatively affect efficiency. This is why the developed product needs to be designed to fit into the surgeon's current environment (Brinkerhoff & Ebrary Academic, 2009).

In order to design products to fit into an already existing environment, the different domains of ergonomics need to be understood. These domains are sensorial, cognitive, and physical. The sensorial domain refers to factors that influence human senses; cognitive ergonomics deals with the amount and storage of information; and physical ergonomics deals wit the interaction of the human body with the device (Brinkerhoff & Ebrary Academic, 2009).

In order to develop a device that will be comfortable to use, all three of these domains must be addressed. The sensorial domain can be addressed by implementing a clip to hold the syringe in the device. When people use various devices, hearing a snap sound yields a sense of assurance that the product will work in some applications. Many medical devices have this feature so it would add a sense of familiarity to the device. The cognitive domain can be addressed through the look of the device. Since our device is going to house a syringe and depress the plunger, creating a housing for the syringe that resembles an actual syringe would create another level of familiarity between the device and user.

Addressing the physical is a little more difficult. Due to the way in which the human body is designed, some motions are naturally more comfortable than others. However, surgeons are also taught how to hold syringes single handedly for injections and they get comfortable doing it a certain way, which links back to the sensorial domain. This means that our device needs to be designed in such a way so that there is no need to learn a new way to perform injections, enable single-handed injections, and be

comfortable enough to avoid fatigue. Factors that will impact comfort of the device include the overall size (length, width, shape) and the weight of the device.

Another way to make the device more ergonomic and familiar would be to eliminate any external cables. Having external cables not only makes the device look less like a syringe, but also could tangled and interrupt the user. To get rid of power cable, rechargeable batteries need to be implemented. The background research section enables a thorough understanding of the design space of this project. Once there is an understanding of the design space, the client statement can begin to be fully understood. The next section is the *Project Strategy* where the client statement is presented, as well as the various objectives, functions, and constraints of the project.

Chapter 3-Project Strategy

Based on the detailed project description provided by the client, Dr. Aparajit

Naram, the team compiled the following initial client statement:

> Develop a ***clinical pipette*** that can be used by a surgeon to house a commercially
> available syringe. The device must be able to control the ***flow rate*** and the amount
> of ***volume*** dispensed by the syringe. The mechanism must also detect the ***size of
> the syringe*** housed along with the ***volume inside.*** This device should be able to
> adapt to a ***variety of hypodermic needles*** depending on the type of liquid. The
> pipette must be suitable for ***hospital or laboratory setting*** and be ergonomic
> enough to be used with ***one hand*** during administration. The information
> specified will be displayed and controlled on a ***digital screen***.

To better gage the scope of the project and client's desired outcome, various

meetings were arranged with Dr. Naram. The team was able to come up with a more

descriptive client statement after discussing the priorities of the project were. With Dr.

Naram the team asking probing questions to narrow down the project goal. After review

of the client statement, an improved revised client statement was developed to further

encompass project goals:

> Develop an ***electrical clinical dispensing device*** that surgeons can use with
> commercially available syringes. The device must be able to ***control and vary the
> amount of volume*** dispensed by the syringe. The device must notify the user when
> each aliquot is fully dispensed. Equipment must compensate for a ***variety of syringe
> sizes***. Pipette system must be suitable for ***hospital or laboratory setting*** and be
> ***ergonomic*** enough to be used with ***one hand and one click*** to administer. The
> information specified will be displayed and controlled on a ***digital screen.*** Device
> must be battery operated and rechargeable.

After finalizing a client statement, a list of objectives was then established. The

main objectives are listed below with detailed descriptions and sub-objectives.

3.1 Safety

Not only did the client want the device to be safe for the patient but also for the

user. The device will be equipped with counter failure measures and an emergency stop

button to ensure the safety of the client while the syringe pump is in use. The pump will also have no direct liquid contact with the device or patient. This design aspect is to ensure that the device will remain sterile during use, and no pre-injection liquid leakage outside of the desired area. Lastly the device will have a mechanism that requires the device to aspirate before injection. Aspiration is required by Dr. Naram to confirm that the liquid is being injected into the appropriate muscle instead of the vein. Although some doctors do not feel comfortable performing aspiration before injection themselves, it is an effective measure to ensure no intravascular response. Lastly, a numbing agent will be used pre injection. This will improve the experience of the patient, minimizing any pain resulting from the insertion of the needle in injection sites. Although this will be taken into consideration, Dr. Naram discussed the addition of a numbing agent as a secondary safety objective.

3.2 User Friendly

This objective includes many of the physical aspects of the design of the syringe pump. The device will be able to be used with one hand, comfortably fitting into the user's first web space between the thumb and index finger. The device also needs to be heavy enough to require less applied pressure so the doctor can avoid fatigue. If the device does not weigh enough, it would take the doctor more effort and strength to hold the device. Dr. Naram, also requested for the device to provide a notification once the liquid finished dispensing an aliquot. A sound, flashing light, or both, will indicate that the pump has finished dispensing the desired amount and is ready to be transferred to the next area of injection. Lastly, the device size was another key component of this main objective. At the client's request, the device will be cylindrical and pencil-like for ease of

use. Dr. Naram explained that physicians would be more likely to use a new device with a familiarity to the conventional devices they have already grown accustomed to. By having our device resemble an enlarged syringe, our client expects that doctors will be less hesitant to use it. This design concept helped shape our first 3D model of the pump, which will be discussed further in the paper.

3.3 Accuracy & Precision

The precision objective emphasizes the desired amount of liquid in each aliquot. Not only should the device be able to distribute the same amount of liquid at each site, but it should also be able to repeatedly do so when the user triggers the dispensing of the liquid.

3.4 Cost

The cost of the design was the fourth objective that needs to be considered. The cost of materials, manufacturing, and labor for the device all factor into this objective. The team will also need to take into account the product's marketability. The future success of the product depends on costs reaching a breakeven point so that profit can be made from the device.

3.5 Reliability

In order to be applicable for clinical settings, the syringe pump must be highly reliable. Dr. Naram stressed the importance of the users having confidence in the functionality of the device. He said that when doctors go through medical school they are taught very specific ways to hold and use certain instruments. Students become so use to these techniques and functionality of the medical devices that when they are introduced

to something new that isn't similar to what they have used for so long, they are automatically caught off guard and are intimidated of the device. By having doctors test out this device in their practice, the team will be able to prove to other doctors that it will make their jobs easier and more time and cost effective. Stowing confidence for user is a priority for our design.

3.6 Aesthetics

The final main objective is aesthetics and appearance of the device. It should appear state of the art; yet function properly for its intended use. If aesthetically pleasing, the syringe pump is more likely to be sought after by physicians looking to draw in clients with new technology. Not only will the syringe pump have a cylindrical appearance, much like the current syringes they use, but it will also have an LCD screen, flashing LED lights, and a notification beeping sound that notify the doctor when the aliquot has finished dispensing. The power activation of the device will prompt the LCD screen display. The user will then input the dimensions of the syringe, along with the desired aliquot size. A clear visual representation of objectives can be seen in the objective tree below in Figure 16.
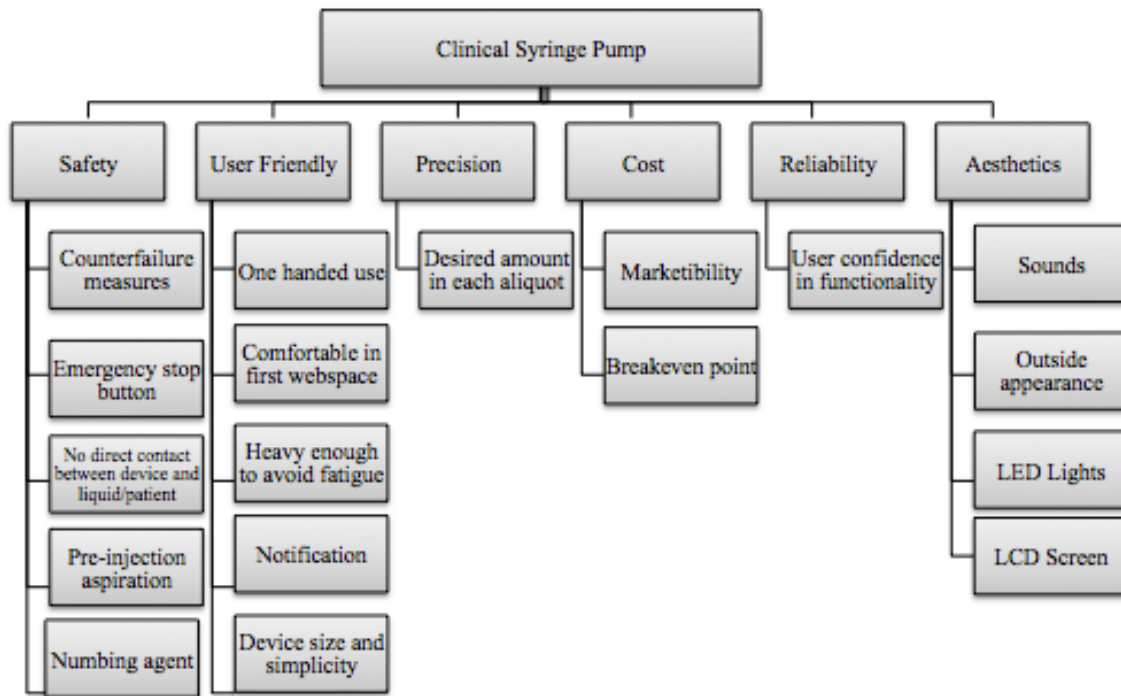
Figure 16: Objective tree

The team then generated a pairwise comparison chart (PCC), to organize and
ultimately rank the project objectives previously discussed. With this technique, Dr.
Naram classified each objective by importance. An objective, in direct comparison with
another, was ranked 0 if it was less important, 1 if it was more important, or ½ if equally
important. To help Dr. Naram fully understand the realm of the objective, each one was
separately described with examples. The safety objective was described as the device
being safe for both user and patient, with possible counter failure measures and
emergency stop button. The user-friendly objective encompassed one-handed use,
comfort in first web space, device size, ergonomics, and a notification system. Precision
was based off of the device's ability to dispense the same desired amount of fluid for

each aliquot. Self-explanatory pricing and marketability were key points of the cost objective. Reliability described the confidence of the device's consistent functionality and simplicity. Finally the aesthetic objective encompassed the device's appearance and attractiveness. The fully completed PCC is displayed below in Table 1.

Table 1: Pairwise comparison chart

	Safety	User Friendly	Precision	Cost	Reliability	Aesthetics
Safety	X	½	0	0	½	0
User Friendly	½	X	0	0	½	0
Precision	1	1	X	½	1	½
Cost	1	1	½	X	1	1
Reliability	½	½	0	0	X	0
Aesthetics	1	½	0	½	1	X
TOTAL	4	3.5	0.5	1	4	1.5

The final ranking of objectives from most important to least important goes as follows: safety & reliability (equal ranking), user-friendly, aesthetics, cost, and precision. Although precision received the lowest rank, it is still key for maintaining the credibility of the syringe-pump device. The device needs precisely dispense the same amount of liquid for each aliquot. Problems may arise if one muscular injection site receives a

different volume of fluid compared to the others. For instance, if unequal Botox volumes are administered into the injection sites of a patient's facial lines, the treatment may prove futile in diminishing the appearance of such lines. Various constraints must be considered in the design of this device. It must be able to house an assortment of commercially available syringes of varying sizes (1 cc- 5cc). The device also needs to be able to dispense liquid within 0.01 cc accuracy. This accuracy value describes the how close to the desired volume that the device must capable of administering, independent of precision. The size and weight of the device must be kept small enough for single-handed use but heavy enough to avoid fatigue in the user as well. The device must meet current medical safety standards for the patient and user. Although it will not require sterilization between procedures, it must be easily cleaned with ethyl alcohol. The syringe-pump must be fully automated, battery-powered, and rechargeable through a docking station.

Chapter 4-Alternative Designs

4.1 Needs Analysis

After speaking with Dr. Naram there were specific requirements that the device needed to have. First, the device needed to be clinical grade. This meant that the device itself could not come in contact with patients and any parts that did (syringe and needle) needed to be disposable. Next, the device needed to be accurate within ten microliters with a constant flow rate and programmable volume dispensing so the user can set the volume they would like to dispense. This meant there needed to be an LCD screen to display this information. The device also needed to be compatible with a commercially available syringe. Finally the device needed to be operated comfortably with one hand. To make the device comfortable in one hand it also needed to have an ergonomic design to limit fatigue on the user.

There were also other requirements that were not as essential as the previously listed ones. One less essential requirement is that the device is compatible with a variety of syringes, such as 1, 3, and 5 mL syringes. This was deemed less important because the 1 mL syringe is the most commonly used for Botox injections and would be sufficient for this application. In addition to this the team wanted a depth gage to control the depth that the syringe is inserted. While this is important, it is not as important as being accurate and having a proper flow rate. The depth gage is less important because both volume and speed will be controlled, leaving the surgeon to focus more intently on the proper depth. In addition to this, the team wanted the device to have rechargeable batteries. This would lead to an added convenience for the user but having replaceable batters would serve the same purpose.

4.2 Functions and Specifications

The device functions to dispense Botox in volumes ranging from 25 microliters to 1000 microliters within 10 microliters of the desired aliquot. It detects and displays the volume inside the contained syringe at all times on the LCD screen for the user. It is equipped with a depth gauge so that the attached hypodermic needle maintains a constant depth inside the patient's skin. The clinical nature of the device makes it so that the shell does not come into contact with the Botox at any point.

4.3 Conceptual Designs

Based on our initial client statement, we first created a CAD conceptual model. As our team gained a better understanding of the scope of the project and user need, we altered our 3D design accordingly.

4.3.1 Initial Model

The original model of the syringe pump was conceptualized after our first discussion with Dr. Naram. Our focus for the first design was simplicity and functionality. As seen below in Figure 17, this design was very elementary and bulky, with little aesthetic consideration.
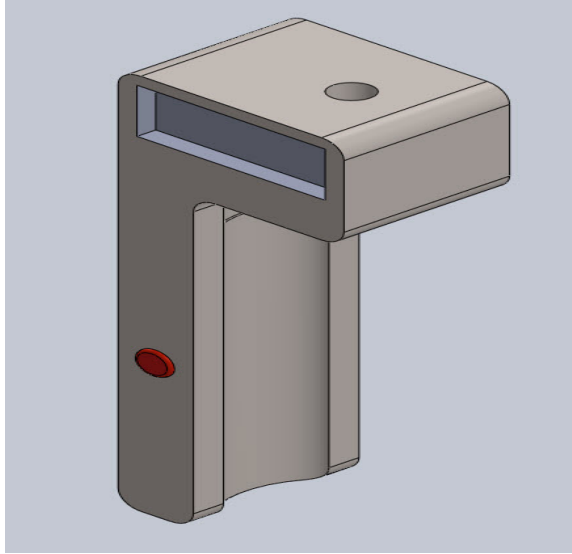
The top rectangular boxed portion measuring 30 mm in length, 22 mm in width, and 20mm in height was designed to hold a motor, and a mechanical system (small circular cutout 5 mm in diameter) that would push and pull the plunger in the Y direction. The upper part of the device would also be responsible for housing the electrical components of the LCD screen. A button was place on the lower left quadrant of the device for the user to easily administer injections. The large ellipse cut out 35.2 mm in length seen in the middle of the device would be the holding dock of the 1mL, 3mL, and 5mL syringes. The circle cut out for the plunger placement measures 15 mm in diameter can be seen from the bottom of the design. Overall the design had a total height of 85 mm and weight of 98.69 grams.

4.3.2 Second Iteration of Design

Following a second meeting with Dr. Naram, the project team decided that the second design needed to be more ergonomic with a smooth outer contour. The initial

rectangular shape of the device was not well adapted for physician use. The modified

model is displayed in Figure 18 below.
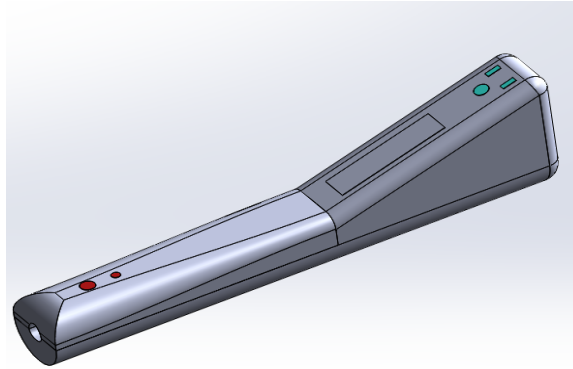
Figure 18: Second CAD model

The triangular top portion was designed to hold the electrical and mechanical

components whereas the bottom area would ideally contain the syringe. The top

triangular area weighed 38.09 grams, while the cylindrical area weighed 50.63 grams**.**

The overall length, width, and height of the design were 31.75 mm, 57.78 mm, and 228.6

mm, respectively. As seen above our team placed the LCD display screen (50.8 mm x

12.7 mm) on the triangular top**.** The bottom portion of this conceptual design was strictly

to house the syringe. Two buttons were inserted for the user to administer and aspirate

fluid. From the bottom of the device the buttons are 7.62 mm away from each other and

9.53 mm from the bottom of the device. They sit on the outer diameter of the device,

which is 31 mm. The inner diameter of the syringe holder was 12.95 mm**,** which also has

an extruded cut. The total weight and overall surface area of this device were 88.72

grams and 70962.67 mm^2, respectively.

4.3.3 Third Iteration of Design

The team aimed to improve the overall appearance of the device in its third iteration. Our goal was to round out the device, making it essentially symmetrical. Therefore the device could be held comfortably in the 5th web space of a clinician's hand. In order to avoid the problem of user fatigue, we also evenly distributed the weight of the device. These modifications can be observed in Figure 19.
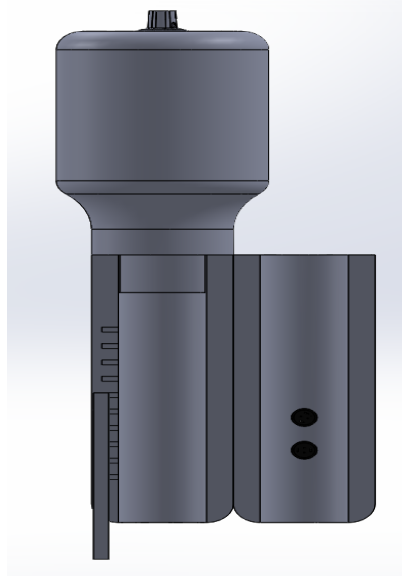
Figure 19: Third CAD model

Although the outside of the device drastically changed, the mechanical and electrical components of the device remained on top, while the bottom portion remained a holding place for the syringe. The top cylindrical portion or the device had a diameter of 90 mm and an area of 37685.34 mm^2. The bottom cylindrical portion of the device had a diameter of 60 mm and area of 34333.18 mm^2. We placed a dial on the top of the device to manage the LCD screen. The cutout on the bottom cylinder for the syringe was 37.32 mm in diameter and cut all the way to the back of the device. This was the last design that only incorporated two parts. On the other hand, this was the first iteration that integrated a depth gauge into the device, with a height of 101.6 mm and width of 6.35 mm. The

overall weight of this device was 450.59 grams with a surface area of 159297.28 mm^2.
This model was purposely designed based on the maximum dimensions that the client
defined.

4.3.4 Fourth Iteration of Design

In the last iteration before our final design, the device was split into four parts.
The motor holder had a 50/50 split while the syringe holder had a 75/25 split. The total
length of this device was 208.19 mm with a total surface area of 43973.51 mm^2. With
all the parts mated together, including the depth gauge, the fourth design had a total
weight of 33.86 grams. The motor holder was responsible for the majority of the weight
at 21.69 grams. Both parts of the motor holder had a length of 139.52 mm, and the inner
circle had a length of 50 mm. The outer circle at the bottom of the motor holder measured
to be 73.83 mm in length; this was where the syringe holder was attached. Since the
syringe was split unevenly, there were a few differences in dimensions. The larger
syringe bottom weighed 5.32 grams, while the top of the holder weighed only 2.81
grams. While they both had a height of 68.88 mm, and a length of 21.04 mm, they
differed in widths due to the 75/25 split. The larger width measured to be 19.86 mm and
the top portion measured to be 6.52 mm. The radius for the cut out of the syringe was
also the same coming in at 11.75 mm. Lastly the depth gauge had a height of 70 mm,
length of 13.935 mm, and a width of 1.5 mm. The outer circle at the end of the depth
gauge had a circle length of 6.250 mm. These alterations are displayed in Figure 20.
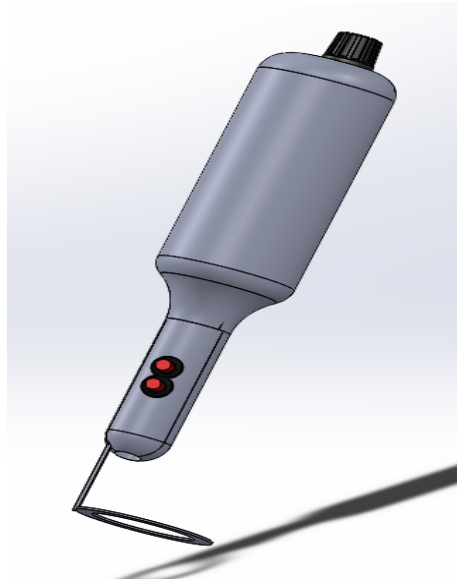
4.4 Feasibility Studies/Design Calculation

The team performed proof of concept testing to evaluate our design. These included resolution tests to determine accuracy capabilities, weight and size tests to assess ergonomics of the design, force tests, and volumetric flow rate tests.

4.4.1 Resolution Measurements

Our team first measured dimensions for a 1 cc, 3 cc, and 5 cc syringes using calipers. From these measurements, we calculated the proper resolution required for the device to mechanically operate at the desired level of precision. The following equations were used to find the resolution for each syringe size:

$$V = \pi r^2 h$$

Where V=volume set to 10 μl= 0.01 ml=0.01 cm^3

r=radius=internal diameter/2

h=resolution needed by motor to achieve successful dispensal

The calculated values for theoretical resolution are displayed below in Table 2.

Table 2: Resolution Measurements

Syringe Size	Radius (cm)	Resolution (cm)
1 cc	.34	0.028
3 cc	.50	0.013
5 cc	.68	0.007

4.4.2 Weight and Size Testing

Trial and error testing was performed with Dr. Naram in order to gauge the rough overall size of the device that would allow for ergonomic use. Dr. Naram was presented with four different wooden rods with variable diameters. By placing each one individually within his first web space, he was able to test whether or not that rough size would prove to be ergonomic enough for the user. The maximum diameter reached before the rod became uncomfortable was roughly 1 inch. The team also attached weights at the lateral ends of the rods to determine the maximum additional weight that would be ergonomic for the user. The preferred attached weight, as desired by Dr. Naram, was in a 1:1 ratio with the original device weight.

4.4.3 Force Testing

A compression test was performed through the INSTRON to measure the force acting upon the plunger of a syringe during a typical injection. To mimic physiological conditions, chicken feet were used as the injection site during the tests. This way, we could observe and measure any resistance that the plunger may experience when injecting through skin. Saline, because of its similar viscosity to Botox, was chosen as the injection fluid. The chicken foot setup is shown in Figure 21. Each syringe size (1 cc and 3 cc)

underwent two trials. The graphical results and calculated values outputed from the INSTRON are displayed below in Figure 22.

Figure 21: Force testing setup
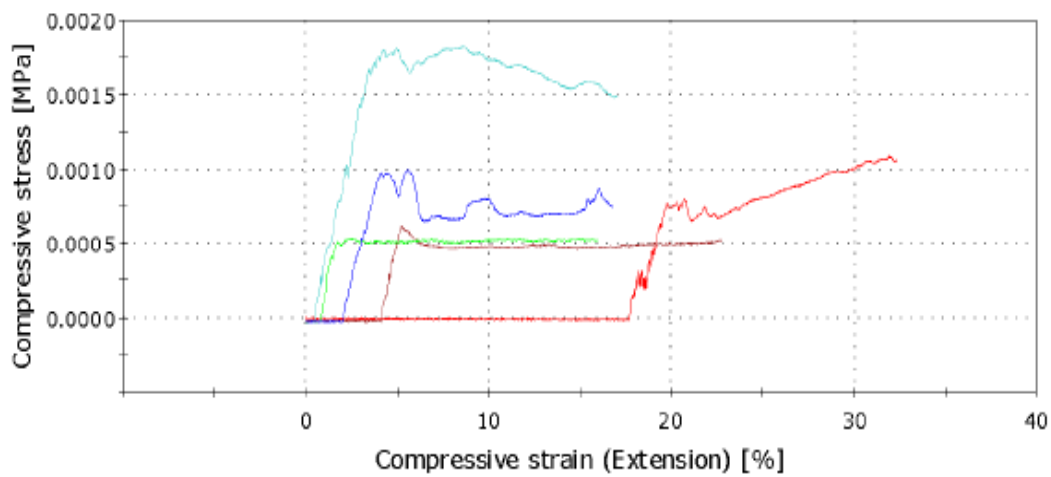
Figure 22: Plunger stress v. strain over injection time

The first trial performed, shown in dark red, was an outlier due to a mistake in setup. The table below shows the numerical values obtained from the INSTRON.

Table 3: INSTRON force values

	Specimen label	Maximum Load [kgf]
1	test	0.28
2	test 2	0.16
3	test 3 sample 2	0.14
4	test 4 sample 2	0.47
5	test 5 sample 2	0.25
Mean		0.26
Standard deviation		0.12998
Minimum		0.14
Maximum		0.47
Range		0.33

4.4.4 Volumetric Flow Rate Testing

In order for the syringe pump device to keep the injection flow rate constant, a basis for the flow rate was calculated based off of a possible user. The chosen user, Dr. Naram, represents the standard client base that will use the device. The subject was instructed to dispense 0.9 ml of saline at the regular rate he would inject into a patient during a usual Botox procedure. This protocol was repeated for 6 trials. The team calculated the average flow rate based upon the trials.

4.5 Decisions & Optimization

From our first design to our last, the team has gone through a very selective process for choosing a set of specifications that would best fit our client's needs as well as keeping the functionality and integrity of our device. One of our main focuses for optimization was the size of our device. We wanted to focus primary on the user and how

we could make the device comfortable and easy to use. The one complication of selecting

our dimensions was that we needed to make sure that our device would be able to fit in

all different sizes of hands. After surveying doctors at UMASS and some of our

colleagues we noticed that women have smaller fingers and web spaces then men. It was

crucial that we take these attributes into consideration when finalizing the location of our

buttons for the final design. To test the comfort of the device in the web space, we did a

series of test with weights and dowels. With this test we were able to determine the best

compromise for weight, length, and width in order to have user versatility and avoid

fatigue. On top of the user, we also needed to make sure that all of the mechanisms and

electrical components fit within the device. This was also taken into consideration for the

final dimensions of the design.

Unlike the dimensions there was no discussion for what type of material we were

going to use for our device. Since one of our design specifications states that our design

needs to be able to be used in a hospital clinical setting, the material that we choose was a

medical grade plastic that would be easy to clean and can withstand the wear and tear of

being constantly used throughout the day.

Chapter 5-Design Verification

A number of tests were performed to ensure proper functioning of the device. Before the device could be built some experiments were performed to determine the flow rate, weight and size, and forces involved in the procedure. In addition to these tests, further tests were performed with a prototype of the device. These experiments were performed to determine the accuracy of the device, to observe the flow distribution after injection, and to determine the maximum amount of force the motor can experience and still work properly.

5.1 Flow Rate Testing

Testing to determine proper flow rate was performed with the 1mL and 3mL syringe because these are the most commonly used for injections. The syringe was equipped with a 32-gage needle to simulate an actual Botox injection. For this experiment, Dr. Naram was asked to fill the syringe and record the exact volume of saline solution in the syringe. To determine the flow rate, Dr. Naram was asked to dispense the liquid in the same manner as he would a typical Botox injection until the syringe was empty. Each injection trial was performed multiple times with two different people timing the injection to limit the error in calculations. Also, the average for each set of times was used in calculations to further reduce error effects. In addition to this, the volume in the syringe was set to the same point for each trial. The experiment performed with the 3mL syringe was a constant flow experiment while the experiment with the 1mL syringe was performed with consecutive 0.2cc, or 200μL, injections. Each injection was timed separately for the consecutive injections. The results from the 3mL experiment are displayed in the table below.

Trial 3mL	Time 1 (Seconds)	Time 2 (Seconds)
1	38.83	38.7
2	54.56	52.95
3	50.46	49.7
4	50.45	49.9
5	53.01	53.6
6	39.5	39
Average	47.8	47.3
Total Average	47.55	

While a full 3mL syringe was used in the previous trials, the 0.2cc experiment used two full 1mL syringes. The results for the 1mL syringe experiment are displayed in the table below.

Table 5: Flow Rate Data (1 mL syringe)

Trial 1mL (0.2 cc each)	Time 1 (Seconds)	Time 2 (Seconds)
1	2.23	N/A
2	3.18	3.0
3	2.95	2.7
4	2.83	2.7
5	2.5	2.4
6	2.71	2.4
7	2.18	2.2
8	2.78	2.6
9	2.66	2.5
10	2.1	1.88
Average	2.612	2.487
Total Average	2.55	

The next step was to calculate the average flow rate using the following equation.

$$Q = \frac{C}{t}$$

Where Q is flow rate, C is the capacity of stored fluid, and t is the time it takes to dispense the fluid. For the 3mL tests, the capacity of stored fluid is 3mL and for the 1mL tests the capacity of stored fluid was taken as 0.2cc. These calculations are shown below.

$$Q_3 = \frac{3000 \ \mu L}{47.55 \ sec}$$

$$Q_3 = 63 \frac{\mu L}{sec}$$

$$Q_1 = \frac{200 \ \mu L}{2.55 \ sec}$$

$$Q_1 = 78 \ \mu L/sec$$

For our design a flow rate between these two values will be sufficient. This will ensure that the fluid is not being injected too quickly and that it is not taking an excessive amount of time for the surgeon to complete the procedure.

5.2 Weight and Size Experiment

In addition to determining the optimal flow rate, it was necessary to determine the appropriate weight and size of the device. Using the appropriate weight will ensure the operator is experiencing as little fatigue as possible while using the device. First, the maximum size of the device was determined. Dr. Naram was given a series of wooden dowels of varying lengths and diameters. The diameters ranged from half of an inch to two inches and the lengths ranged from eight to ten inches. Also, an additional square shaped rod was given to him to determine which shape would be most comfortable. After holding each of the dowels, Dr. Naram determined a diameter of one inch and length of nine inches to be the optimal device size.

After the appropriate size was determined, two screws were inserted into each end of the wooden dowel. Two sets of hanging weights were used to vary the weight experienced on each end of the device. The hanging weight had a base of 50 grams and had other five and ten gram weights that could be added. It was determined that only the

weight of the 50 gram hanger was too heavy on the back end and weight needed to be added to the front to balance the device. Weight was then added to the front and back, each side having a different weight. It was determined that having a one to one weight ratio from front to back was the optimal weight distribution. This weight distribution will increase the comfort of the device and limit user fatigue.

5.3 Plunger Force Testing

Once the proper dimensions were determined, it was necessary to determine the amount of force required to push the plunger. An Instron with clamp inserts was used in a compression test to determine the force required to move the plunger. The Instron was programmed to move at a rate of 10mm/min so accurate forces could be determined. After the Instron was set up and programed properly, a dry run was conducted with a 1mL syringe and 32-gage needled to ensure the apparatus was working properly. The 1mL syringe was clamped with the bottom clamp, while the top clamp was shut completely to push the plunger down. When consistent results were obtained with the dry run, additional experiments were conducted with saline solution and chicken feet.

New materials were used for each run of the experiment. First the syringe was loaded with saline solution and a 32-gage needle. The apparatus was set up as before and the needle was inserted into a chicken foot. Injecting fluid into the chicken foot simulated the forces present when injecting into tissue. This experiment was conducted a total of five times and in different sections of the chicken foot to ensure accurate results. Once the needle was inserted into the chicken foot, the foot was also secured so unwanted movement didn't disrupt the results. The compression program was run and the results were recorded in a table as seen below.

Test	Maximum Force (Newton)
1	2.75
2	1.55
3	1.37
4	4.61
5	2.45
Mean	2.55
Maximum	4.61
Minimum	1.37

This was an important test because this shows that on average the device will need to overcome forces of 2.55 N, but will also need to overcome forces of 4.61 N when resistance is encountered. Having these numbers enables better selection for the proper motor to drive the plunger.

In addition to identifying the maximum force that needs to be overcome, this experiment also set specifications needed for a force sensor. Knowing the minimum force enables a way to detect the top of the plunger without dispensing any fluid. This way the force sensor can be set to a threshold force less than that of the minimum required for dispensing. Once the force sensor experiences this force, it will trigger the motor to stop the mechanism so the plunger can be secured. This can also be used to derive an algorithm to convert revolution of the motor to volume present in the syringe.

5.4 Accuracy and Precision Testing

After the device specifications were known, an experimental model was developed in order to perform tests. According to Dr. Naram, the device needed to have a ten-microliter accuracy. To test the accuracy and precision of the device, a specified volume of deionized water was dispensed into a weigh boat and the volume was weighed on a precision scale in a lab. Using deionized water means that the weight of the fluid

should be the same as the volume dispensed. For the purposes of this project, both a very low volume (25 µL) and a larger more realistic volume (100 µL) were dispensed to find what range the device was accurate in. The results of the accuracy tests are shown below.

Table 7: Accuracy and Precision Testing

Specified Volume	25 µL	100 µL
Average	25.5 µL	98 µL
Standard deviation	1.4 µL	2.8 µL

Each of these experiments consisted of 20 trials and these results were averaged together. As shown by the table above, the device is very accurate and is well within the ten-microliter accuracy specification requested.

5.5 Collagen Hydrogel Test

After determining the accuracy of the device, it was also necessary to determine whether or not it could function properly in tissue. Therefore, a one percent hydrogel was used to simulate human skin and injections were performed with the device. In order to see the flow distribution a green dye was used in deionized water. The figure below shows the results of this experiment.
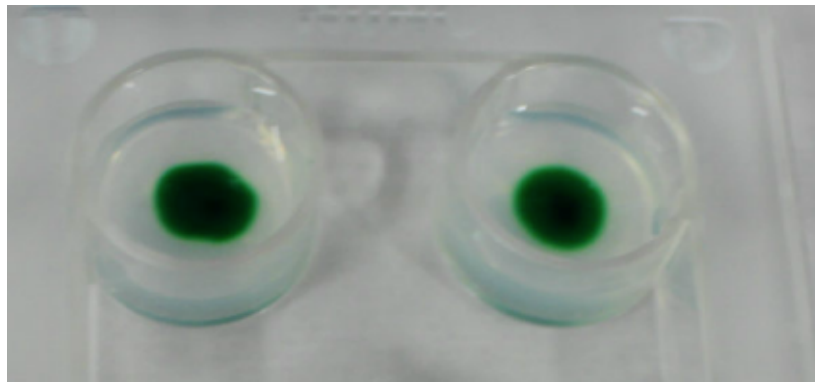
Figure 22: Injection into Collagen Hydrogel

During the injection a sphere of fluid formed initially. Then over time the fluid began to diffuse out into the surrounding gel. This diffusion can be seen as the lighter green circles around the darker green injection sites. In addition to this, there was no backflow of the fluid during the injections. If backflow had occurred it could have meant that the flow rate was too fast, which would be detrimental for Botox injections. After performing this experiment it is clear that the device is properly calibrated and is capable of performing properly on real tissue.

Chapter 6-Discussion of Results

Our CAD design is both ergonomic for the user as well as functional. The final dimensions and specifications are based off multiple meetings and modifications from the client. The curvature between the upper and lower portions of the device allow for it to be held comfortably in the user's first webspace. The accuracy and precision results show an acceptable range of error for the device. A difference of 4 microliters between set and actual volume is very appropriate based on the user's request of a 10-microliter-accuracy threshold. The standard deviation of 4 microliters also serves to show that each individual aliquot is precise in regards to the others. Because collagen is a major component of skin, collagen hydrogels were chosen based on their ability to mimic injection conditions of skin. The success of the injections into collagen hydrogels proves the functionality of our device. Our device can safely overcome the resistance forces of the skin during the course of an injection.

6.2 Progress of Design Aims

Our initial objectives were met through the final device design. Our device is of clinical grade use because it does not come into contact with injection fluid throughout a procedure. It accurately is able to dispense volumes between 25 and 1000 microliters in desirable range. No specific syringes are required for the device to operate; therefore it can properly accommodate a variety of commercially available syringes. The device can detect and display the volume present within the syringe at all times during a procedure. Lastly, it has an ergonomic design ideal for daily clinician use.

6.3 Comparison of Device Against Current Technique

Our design provides benefits for the users that address issues of the conventional technique with syringe and plunger. With the current standard of Botox injections, the clinician must control three parameters at once: speed, volume, and depth of needle. Our syringe pump can be programmed with desired inputs so that the user does not need to eyeball the volume dispensed at each injection site. The speed is also kept constant with the device, so there is no chance that the user may accidently inject too quickly. These improvements allow for injections that are more precise, accurate, and efficient.

In order to properly administer Botox injections, physicians must be trained to use the traditional syringe with plunger. On the other hand, our device is very easy to use and intuitive, requiring little to no previous training. Our syringe pump is also designed to be ergonomic and comfortable for the user unlike the current technique. The syringe plunger method often causes fatigue for the user because it is built for function instead of comfort.

Lastly, our device has multiple settings to ensure patient safety whereas safety with the traditional technique is entirely user-dependent. Our syringe pump is equipped with a depth gauge and pre-aspiration setting.

6.4 Result Limitations

Further work needs to be completed regarding the way in which the device will be powered. Due to time constraints, the team was not able to perform battery testing. Therefore we did not assess how long the device would be usable until needing a battery recharge or replacement.

6.5 Potential Impacts of Design

In evaluating our design, it was key to foresee the possible impacts that the device may have over a variety of realms.

6.5.1 Economics

The design stakeholders of our device include competitive manufacturers and medical professionals and possible patients. Because the device is most likely to be purchased by physicians than individuals, elevated cost of the device are less of a concern. The total functional prototype budget will be approximately $340. After mass production, the total price will be cut in half at approximately $140 per unit. If the device was sold a lower price closer to the true cost, the medical industry may assume it is flimsy and cheap. Therefore our client has advised us to market the device at $1,000 per unit, a high margin.

The device eliminates the issue of post injection drip, saving roughly $50 of wasted Botox per procedure. Over time, these savings accounts for the cost of the device itself, making the purchase price even more manageable for clinicians. The syringe pump also cuts back the time required for each procedure, ultimately allowing for a higher frequency of procedures to be carried out within a certain range of time. This could increase profits on a daily basis.

Even though the product is somewhat costly, it is the only automated device that would fill the gap in the market. Although laboratory grade syringe pumps do exist, none meet this standard for clinical use. In addition previous lab syringe pumps such as the Hamilton and Evol Analytical syringe require expensive and specialized syringes specific to the product. Therefore the market for clinical dispensing devices remains generally

untapped, with large potential. Essentially our device will be the first clinical syringe pump for continuous procedures.

6.5.2 Environmental Impact

Not only is toxic waste expensive to dispose of, but also it can become dangerous to the environment. Therefore it becomes highly beneficial when the amount of lost injection fluid that must be discarded is minimized. That way, our device can limit the amount of toxic waste and positively impact the environment. By choosing to later use rechargeable batteries over disposable ones, our design also reduces the amount of toxic waste. In addition, the recyclability of the plastic chosen for the outer shell of the device poses no threat to the environment.

6.5.3 Societal Impact

By taking some parameters out of the user's control, physicians can have enhanced "bedside manor." This means that the user will be able to gear focus towards interacting/comforting the patient if need be. Patients also will reap benefits of a shorter, less painful procedure. With a better experience, more patients will be likely to return for continuous procedures.

6.5.4 Political Ramifications

The device will have a positive influence on the global medical device market by enabling for more accurate and precise injection technique. Surgeons and clinicians who consistently utilize the device will also experience less fatigue and higher comfort. In turn, physicians will have the capability of performing more procedures in a given time. This improves the overall efficiency of Botox injections.

6.5.5 Ethical Concerns

There are minimal ethical concerns associated with the device. More controversy is directed towards the procedure of Botox itself than the device. Because of the automated nature of the device, the necessary technical assessments were carried out to ensure its proper functionality. Our device improves the current procedure and patient experience of Botox injections. The syringe pump device will minimize physician error and any inconsistencies of injection volumes between aliquots. With constant flow rate and precise volume administration, patients will be less likely to experience post-procedural side effects as well.

6.5.6 Health and Safety Use

Our device will need to meet both FDA & ISO regulations in order to be implemented in a clinical setting. The design itself allows for improved patient safety due to the higher accuracy of injection volume and improved precision between aliquots. If the incorrect volume of fluid is about to be injection, the user will see that notification displayed on the device's LCD screen. The depth gauge and pre-injection aspiration are also further patient safety measures that our device possesses.

6.5.7 Manufacturability

Through mass production, the cost of the device would be significantly decreased. Electrical components of device could be downsized further through custom production of a PCB circuit. An independent manufacturer could be utilized to produce these PCB circuits. The plastic shell of the device and screw mechanism could also be 3D printed in

mass quantities. All of these factors make the device manageable in terms of

manufacturing.

Chapter 7-Final Design and Validation

7.1 Final Electrical Design

The coordinated electrical design functions as follows. The Arduino microcontroller code is uploaded to the microcontroller. The Arduino reads the potentiometer to set the desired volume for injection. After the volume input, the Arduino sends power to the motor to bring the syringe plunger clip to the top of the screw, hitting the upper limit switch. Once this is done, the Arduino switches the direction of the motor to send it down on the screw. In turn, the microcontroller reads the force sensor value. Once the syringe plunger clip comes into contact with the syringe plunger, the motor is stopped due to the force sensor reading. The user is then prompted to lock in the plunger to the syringe plunger clip. Following this, the Arduino sends power to the H-bridge, modulating the PID code to arrive at the set point designated from the initial setup. Every time the go button is pressed, the Arduino is prompted to dispense the same volume using the PID code to arrive at the set point. The circuit diagram for the final electrical design can be seen in Appendix A.

7.1.1 Arduino Microcontroller

The microcontroller initially used was an Arduino Uno, which supports an ATmega 328 chip from Atmel and a PCB board with header pins for easy breadboard connections. The Arduino Uno allows a user to program in the Arduino program, which supports a simplified version of Java that allows for 32Kbytes of in system self-programmable flash program memory. Another benefit to the Arduino microcontrollers is the vast library of user-generated code that can be tweaked and used for personal

operations. Using the support from the community library, most ideas can be implemented with ease by tweaking already generated code. Using the digital pins, one can send out signals through the Arduino to other devices in pulse width modulated (PWM) manner. This allows for the control of a variety of devices such as the motor being used in our applications as well as the LCD display. The Analog pins allow for the receiving of data from external sensors. These pins are used for our force sensor buttons and limit switches, in which the data received can be used to change operations. The Arduino outputs 5 Volts from each pin at a maximum of 20 mAmps. The Arduino is powered using 6V, but can be powered by higher voltages, such as a 9V battery due to its voltage dropping capabilities. Code is uploaded to the Arduino using a USB cable, and once a code is uploaded, the USB cable can be removed. As long as the Arduino is powered, the code will be continuously implemented until a fresh code is implemented.

7.1.2 DC Motor

The motor utilized in our design is a brushed DC motor with a quadrature encoder. Background on DC motors and encoders have been discussed in previous chapters, and will not be repeated in depth here. Using the 6 pins coming out of the motor assembly, our motor is supplied with a PWM signal and control the speed in a specific manner. The encoder pulses are sent to the Arduino to be processed in a PID fashion. This will allow for a specific set point to be set by the user depending on the desired volume to be dispensed. The PID function of the code enables the device to precisely dispense the specified amount of liquid. The parameters for the PID can be changed depending on certain criteria's. If a user does not desire an offshoot (when the motor corrects for going over the set point) the PID can be tweaked to prevent this. If a user

does not desire slow correction speeds, (as the PID loop slowly approaches the set point) the user can tweak the PID code to allow for faster, albeit prone to more offshoot operation times. Tweaking the proportionality, integral and derivative constants will allow for a variety of behaviors from the device, and a "goldilocks zone" can be reached with thorough tweaking, yet all the cons cannot be entirely eliminated.

7.1.3 H-bridge

The H-bridge provides the user of our device with the ability to drive the motor in forward and reverse. Essentially this action enables the syringe clip to move up and down the lead screw. It is a simple circuit that can be built by the user, however, due to our size constraints; we have purchased an H-bridge at an inexpensive price. The H-bridge is used for bidirectional control of a motor from a microcontroller. It is the "middleman" of the operation, allowing the Arduino's unidirectional signal capabilities to be converted to bi-directionality, allowing for the DC motor to turn in both clockwise and counter-clockwise orientation. The direction of the motor changes based on a switch in the polarity of the voltage. The circuit has 4 switches, and when complete, and Switch 1 and 4 are closed, motor gets power and spins in one direction. When Switch 2 and 3 are activated, the motor starts turning in the other direction. This configuration allows for the H-bridge to switch on a gate for clockwise, or counterclockwise signal to the motor. Using this method, the single PWM signal is sent to the H-Bridge before the Arduino determines which direction the motor is to turn. It then sends this signal to the H- Bridge, activating the gate for that direction. Finally the PWM signal for that direction of rotation is sent to the motor.

7.1.4 Force Sensor

The force sensor utilizes piezoresistance to detect loads on the sensitive area. No force correlates to infinite resistance on the Arduino from the force sensor pin, and a full load reflects a 300kOhm resistor. Any value in between these two resistances is directly correlated with the amount of load that the force sensor is experiencing. Using this voltage divider configuration, varying amounts of forces on the sensitive area allow for varying amounts of voltages to be sent to the Arduino. The force sensor being used in our operations is very sensitive, with a max signal output at 1lb. Therefore, to the Arduino analog pin, no force on the sensor equals 0, and 1lb or more equals 1024. Any force in between is detected in a linear fashion. By placing this force sensor on the syringe-mounting piece, we can detect the volume.

The volume detection method uses a process that has not been implemented before for this method. The syringe mounting piece and the force sensor are forced to go to the "zero" point on the screw. The code sets this point as the zero state, after this, the motor rotates clockwise, forcing the housing and force sensor down on the screw towards the syringe plunger. During this time, the Arduino is reading the force sensor output with a 10msec refresh rate. At the time at which the force sensor comes into contact with the plunger, the Arduino detects the change, and stops the motor. Through thorough testing, the force sensor was calibrated to stop before a force necessary to dispense liquid out of a syringe was implemented. Therefore, using this method, the housing has come into complete contact with the plunger, at this point, the Arduino reads the number of pulses that was necessary for the housing to go from the zero state to its current distance. Using the total length of the syringe, the distance traversed, and the dimensions of the syringe,

the Arduino completes a calculation that calculates the actual volume in the syringe.

After this, every time the syringe dispenses the liquid, the volume is subtracted from the

syringe volume to display the actual volume left in syringe.

7.1.5 Limit Switches

Limit switches are well known in the industry as being safety stops. In our device,

limit switches were used at the end states of the screw to prevent the syringe housing to

move out of the screw. These programmable switches work by creating an open circuit

inside the switch assembly. Therefore, when the button is not pressed, the voltage across

the switch is 0 Volts. However, once the button is pressed, the voltage across the switch

becomes 5 Volts. The Arduino reads this change in voltage, and detects that the end stop

has been reached. The code therefore stops the movement of the mechanical assembly.

By ensuring immobility of the internal design mechanisms past a certain desired range,

the switches act as major counter-failure measures for our device.

7.1.6 Pseudo-code

The technical code is shown in Appendix B, however, a pseudo-code will be

displayed here to explain the processes undergone:

- Interrupt pins are defined for encoder feedback from the motor. These are used for the encoder pulses being counted.
- Everything is initialized and defined for later use in the code.
- The Liquid Crystal display library is included in the code. This allows for LCD function use.
- The LCD pins are initialized for use.
- The case structures are stated to set the states at which the code will jump to a different portion of the code to run the section specified. In this case, 5 cases are defined.
  - SET_VALUE state allows the potentiometer to be used to set the volume to be dispensed by the device.

- VOLUME state forces the motor to turn counter clockwise at a PWM of -100, which allows the motor turn at a safe, yet quick fashion to reach the top of the screw to go to its zero state. The motor stops when the syringe housing hits the top limit switch.
- ZERO state is when the motor starts moving clockwise at a PWM of 100, allowing the force sensor to be activated and ready to stop the motor when the force sensor detects the syringe. The pulses from the encoder are counted at this state to calculate the volume. The motor stops once the threshold set for the force sensor is reached. This value is between 0 and 1024 due to the Arduino Analog pin restriction.
- GO state is when the volume set in SET_VALUE state is dispensed. This uses the PID code defined in the GO section to dispense the predetermined volume. This state can be repeated until the user turns off the device or the bottom limit is reached.
- ENDED state is when the end of the screw is reached, signifying that there is no more liquid in the syringe, and the housing cannot go any further in the housing to dispense liquids. This will be activated either by the code detecting no liquid, or by the limit switch at the bottom of the housing.
- Void setup function is used to set all the setup requirements. This is where the encoder interrupt rise functions for detecting the encoder pulses are written. Furthermore, the serial monitor is activated for debugging purposes. Lastly, the H-bridge outputs are initialized for its use and the LCD screen size defined.
- The PID loop is defined in this section of the code with the proportionality, integral and derivate functions and the math pertaining to this all defined.
  - The PID function is initialized, with all its criteria specified.
    - For the integral function, the dt number is initialized, which calculates the total time in mSeconds.
    - The error is calculated by finding the target setpoint (the amount to be dispensed) and subtracting this value with the currentvalue (current pulses from encoder)
    - The integral value is the current integral + the error multiplied by the dt.
    - Derivate is found by subtracting the error by the previous error, then dividing the total by dt.
    - The output is calculated by summing the products of the kp value with the error, the ki value with the integral, and the kd value with the derivative.
      - The kp, ki and kd values are all set at the beginning of the code when the PID fine tuning is being done.
  - This code is run in a loop whenever the PID function is called.
- The drivemotor function constrains the speed of the motor within -255 to 255, with the negative values sending a counterclockwise pwm to the H-bridge, and positive values sending a clockwise pwm to the H-bridge
  - The rest of the code defines these values for the H-bridge.

7.2 Final Mechanical Design of Device

For this project a traveling lead screw mechanism was selected. This works by converting the rotational motion of the motor into linear motion that is used to push the syringe plunger. While the lead screw rotates, a stabilization rod runs through the lead nut

and prevents rotation of the lead nut. This then causes the lead nut to travel up and down the lead screw. In addition to this, the custom syringe clip piece is attached to the lead nut. The syringe clip is compatible with one and three mL syringes and has a hinged mechanism for the clip so it is not lost. The final piece is the force sensor, which is how the electrical components communicate with the mechanical ones. The force sensor is there to stop the mechanism before fluid is dispensed when the syringe plunger is reached. In addition to this, the number of rotations past and remaining on the lead screw can be calculated because of the force sensor, which can then be used with the syringe dimensions to perform the volumetric calculations.

7.2.1 Lead Screw

As mentioned in chapter four, a linear actuator is a mechanical device that converts rotational energy provided from a motor into linear motion. While this is not the only use for a linear actuator, it is the one that will be focused on because it is most applicable to this project. A linear actuator works by using "an external, non-linear force to drive some kind of piston back and forth." (Anaheim Automation) One basic type of linear actuator uses sections of a cogged belt or roller drive chain to operate pulleys. The pulleys than perform some kind of work, such as lifting an object. Other basic linear actuators use electric motors with mechanical conversion systems.

This project uses another type of linear actuator known as an electromechanical linear actuator with a traveling-nut. This assembly is ideal for this project because it is an inexpensive, small assembly and is moved easily. Traditional linear actuators used in industry are large and expensive systems. In this design, a lead screw is connected to a

motor. The lead screw rotates with the motor shaft. In many cases a gearbox is used as well. Gearboxes are used to size down the rotation of the motor that is converted to the lead screw. This enables a smaller motor operating at a higher RPM to be geared down and provide a higher torque than normally possible. In addition to the screw, there is a nut on the screw that is constrained from rotating. This constraint causes the nut to travel up and down the screw instead of rotating with the screw. (Anaheim Automation)

Screw linear actuators also have a static loading capacity. This is the load that the actuator can support when the motor is turned off. The breaking force of the actuator varies with the angular pitch of the thread and the overall design of the threads. (Anaheim Automation)

For this project, a custom lead screw was purchased from the company Thomson. After determining the forces involved with the device, the proper lead screw and nut could be determined. The screw that was purchased is a precision, stainless steel screw. This screw has a diameter of ¼ inch with a lead of 0.25 and a lead accuracy of 0.003 in/ft. While the loads in this assembly are well below the limitations of stainless steel, purchasing the nut needed more careful consideration. The MTS4-2516 flanged nut was purchased which has a design load of 25 pounds and an efficiency of 76 percent. In addition to this, the nut is made of acetyl plastic and is internally lubricated with a polytetrafluoroethylene (PTFE) coating to limit friction. This coating enables the assembly to have a friction coefficient of 0.08 – 0.14. The lead nut will then be stabilized by a rod that goes from the motor, through the nut flange, and to the device housing. Overall, these specifications are more than what is necessary for this application.

Additionally, a lead screw design reduces noise and vibrations felt by the user when compared to ball lead screw mechanisms (Thomson).

7.2.2 Syringe-Plunger Clip

In order to push and pull the syringe plunger, a custom part had to be made. The most cost effective way to design this part was to design it in SolidWorks and have it 3D printed. Not only did this part have to move the plunger but it also needed to be free from the plunger so number of revolutions to the top of the plunger could be determined, and therefore the volume in the syringe. Adding the length constraint for the project a typical linear lead screw mechanism was not ideal.

The lead-nut to plunger attachment offsets the top of the plunger above the lead screw itself. This was done first by creating a cylindrical attachment that connects to the lead-nut. Next, a portion of the top of the cylinder was cut to create a flat space. Then an additional rectangular back was added to the piece, with a cylindrical hole cut out of the middle so it could be attached to the nut. Then two posts were added to the top of the piece. Another U-shaped clip piece was created to then fit between the posts and the back of the piece. The syringe plunger head sits against the rectangular back while the clip secures the syringe head in place.

Dr. Naram pointed out that the clip piece could be easily lost and so another mechanism was necessary. To accommodate this, a hinge was added to the device. Another rectangular cut was made on the inside of a post that extended into the back of the piece. Next a small rod is inserted into the post and through a hole in the clip. This way the plunger clip can be opened while installing the syringe and during the volume

calculation and locked in place when the device is in use. In these ways the additional

attachment was able to meet all the constraints.

7.3 Final Device Shell Design

Figure 23: Final CAD Design

Our final prototype came in at 98.34 grams with a total length of 277.78 mm, and

surface area of 96343.07 mm^2. For this design we split the total prototype into 6 parts.

First we split the motor holder from the syringe holder. The total motor holder weighed

74.17 grams, while the syringe holder weighed 69.88 grams. From there the motor holder

was split into 3 pieces, the bottom portion, and the top portion was split into 2. The top

half of the upper portion of the device would be responsible for hiding the motor weighed

16.31 grams, with a length of 60 mm, width of 30 mm, and height of 80 mm. The bottom

potion of the top motor which would allow access to the screw mechanism and syringe

placement weighed a bit more at 20.79 grams, with a length of 60 mm, width of 30 mm,

and height of 112.16 mm. The bottom portion of the motor holder was only 1 part, and

had a height of 192.16 mm. From here we split the syringe holder into 2 pieces with an

even 50/50 distribution. Dimensions for both were the same except for the fact that the

top portion of the syringe holder would have two 5 mm button cutouts on the top. Both parts weighed 10.91 grams, had a height of 83.62, length of 34.82 mm, and had an outside radius of 17.38 mm, as well as an inside radius of 5.2 mm. The last piece was the depth gauge, which was modified from the previous model. This depth gauge had a weight of 0.233 grams, surface area of 674.815 mm^2, height of 70mm, length of 16.171mm, and a width of 1.250. The outside circle had a 8mm radius, while the inner circle diameter was 11 mm.

Chapter 8-Conclusions and Final Recommendations

Our device properly addresses the issues for physicians associated with the high frequency of procedures performed daily. With an automated design, physicians do not face the negative consequences of excess procedures on their manual dexterity. As shown through the testing results, our automated syringe pump is efficient and accurate for administering Botox injections, while simultaneously ensuring patient safety. The device's ergonomic design and proper functionality allow for it to be implemented in clinical environments. Future iterations of the design should incorporate a printed circuit board (PCB), metal coatings for the screw mechanism, and a modified version of the device shell to further improve ergonomics.

8.2 Design Benefits

True success of the device lies in its capacity to properly meet physician and patient need alike. Our design will not only improve injection technique for clinicians, but also serve to minimize pain of the injection procedure for patients. By comfortably fitting within the first webspace of the hand, it is less likely for the user to experience fatigue, as is the case with the conventional syringe and plunger method. The improved ergonomics of the device will enable physicians to perform the procedure with greater ease. Overall, our design will allow physicians to facilitate injections more quickly, while still maintaining accuracy. This way, they can focus more of their attention to their interactions with the patient. Patients will in turn reap benefits of a shorter, less painful procedure. The syringe pump device will minimize physician error and any inconsistencies of injection volumes between aliquots. With constant flow rate and

precise volume administration, patients will be less likely to experience post-procedural side effects as well.

The biomedical science industry in general with benefit from our clinical syringe pump device as well. With automated control over the amount of fluid dispensed, the device makes injections more accurate and precise between aliquots. The medical industry can lessen stress placed on physicians by accepting the more efficient technology presented by our automated syringe pump. The design's pre-aspiration setting and depth gauge also enhance patient safety during injection procedures. The depth gauge will allow for the physician to set an unvarying needle depth. Before administration, the syringe pump will be equipped with an aspiration feature in order to ensure that the needle is not inserted within any blood vessels of the patient.

8.3 Future Recommendations

With the design concept proven to be functional, future projects should focus on improving the aesthetics and further testing of the device. Given greater funding and time, the following modifications should be made to enhance the design.

8.3.1 Electrical Components

At the current time, the functional electric components of the design are too large to fit into the printed shell of the device. Given more time and funding, a printed circuit board (PCB) could be custom-made to be mounted within the shell. The Arduino microcontroller should also be replaced with a Texas Instruments microcontroller. Although this microcontroller would be more difficult to program, it would maintain a longer lifetime and use a much lower power supply.

8.3.2 Mechanical Components

The major mechanical mechanisms of the device should be improved upon in the future to allow for better functionality. The motor to screw coupling should be constructed out of metal. With a metal finish, the mechanism would have greater stability as it moves during use of the device. The screw to syringe mount should also be made out of metal in order to improve the accuracy of the design. The clip used to hold the syringe in place should be automated in future versions of the design. This way, once the force sensor detects a syringe, the clip would automatically close. By doing so, the device would require no user input or handling to secure the syringe. Finally, a screw with more threads could be chosen for the mechanical mechanism. With more threads comes higher accuracy, although such a screw requires more funding. The motor currently occasionally stalls because the internals are not constrained entirely. By increasing the speed of volume calculations steps, this stalling could be easily overcome.

8.3.3 Device Shell/Exterior

For better ergonomics, it would be best to modify the CAD model. The lower syringe-containing portion of the device should be more towards the 50 percent mark of the total device length. This way, the curvature of the design where the user is meant to hold the device would be more natural. The weight of the device would be more equally dispersed as it is held. In order to achieve this modification, the bottom portion would have to be edited so that there would be space for the lead screw. Overall, this change would improve the comfort of the device for the clinician. For the user to visually confirm that the correct volume of Botox is being injected, we plan to make the bottom shell portion of the device transparent.

8.3.4 Patient Testing

Due to time constraints, we were unable to be approved for and subsequently carry out testing on cadavers or even patients. This way we could further ensure that the device is suitable in a clinical environment.

8.3.5 Market Exposure/Sales

In order for this device to be successful on the market, we need to find the right clients who will help further the products awareness. To do this our team has devised a marketing plan that will lead us to a licensing contract with a major medical device company. The first thing that we need to do is to continue to gather feedback from clinicians. Not only should our study involve major hospitals, but we should also include private practices in our survey. An example of our survey can be found in the appendix. After conducting this survey and making the proper modifications to the device, we would then develop our leads within the original clinicians we surveyed. After this we would work with them to see who are the leading manufacturers that supply the rest of their commonly used devices. Once we have developed a list of potential buyers, we would continue to market our devices at conferences where we knew that they would be attending. By cold calling these companies, as well as developing email campaigns, we believe that our device would quickly be picked up for a licensing deal with a major medical device company. Once we were able to get a deal, we would also continue to work with them to suggest further modifications to the device.

8.3.6 Further Applications of Device

The device can be used in the future for a variety of applications for which precision volumetric injections are desired. This may vary from laboratory use to clinical uses for which the product is specifically catered. The device may also be adapted for other common types of drug installations. Our current design focuses on incremental volume injections due to the nature of the application. However, the syringe pump has the capability of being used for various other injection types including steroid or even fat grafting. With this later application, the device would need to be set with a standard flow rate. The device could also be altered to hold a greater volume of fluid for injection into the patient.

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Appendix A: Circuit Diagram
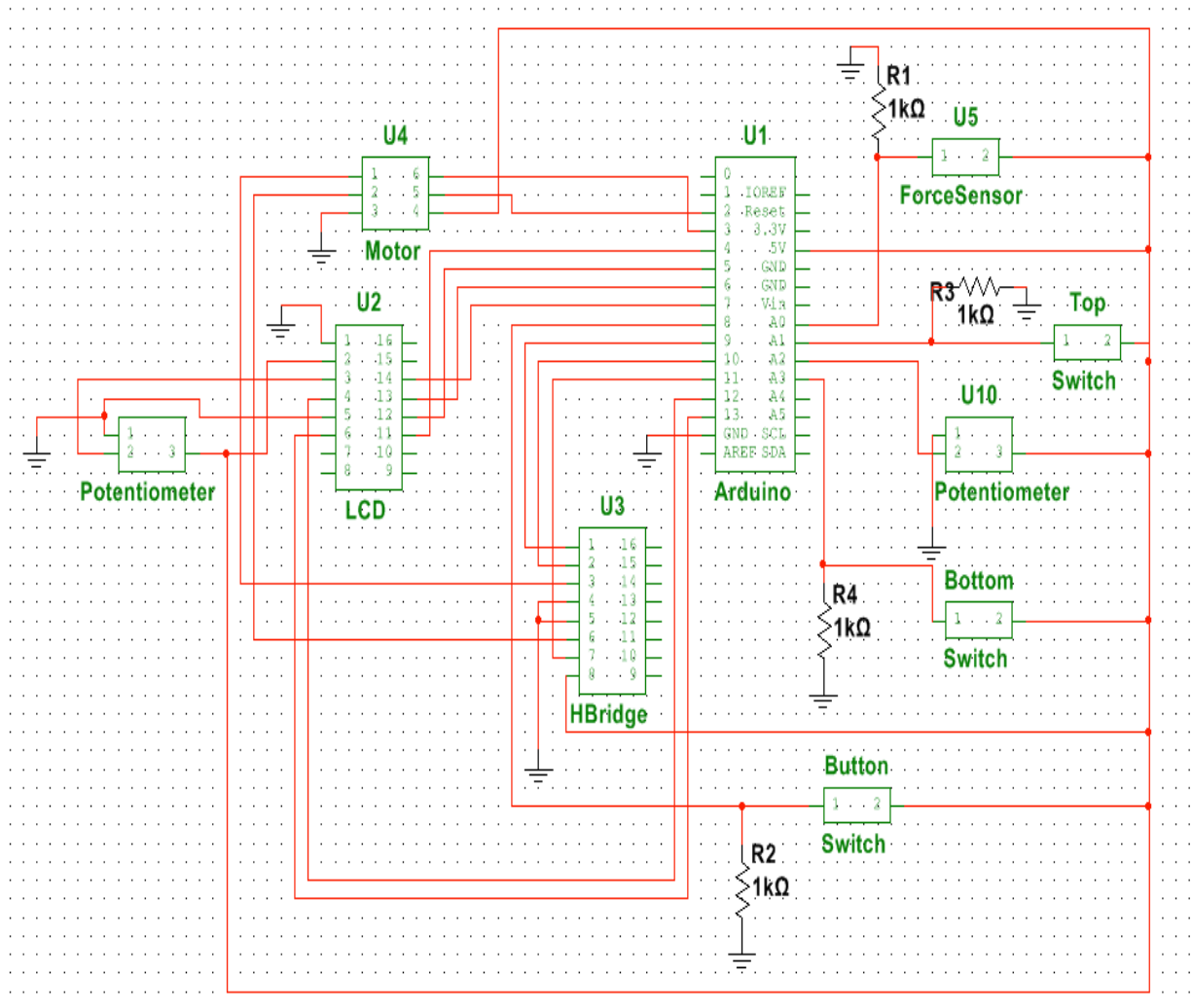
Appendix B: Arduino Code

```
long pulses, A_SIG=0, B_SIG=1;
const int motorPin = 9;
const int forwardPin = 10;
const int reversePin = 11;
const int buttonPin = 8;
const int toplimit = 15;
float kp = 0.9;// propotional constant
float ki =0; // integral constant
int kd = 20; // derivative constant
float error;
float pterm;
long actual;
long constrained;
long setpoint;
const int defaultSetpoint = 25;
long Volume;


#include <LiquidCrystal.h>

// initialize the library with the numbers of the interface pins
LiquidCrystal lcd(12, 13, 5, 4, 6, 7);

typedef enum {SET_VALUE, VOLUME, ZERO, GO, ENDED} state;
state currentState = SET_VALUE;

void setup(){
 attachInterrupt(0, A_RISE, RISING);
 attachInterrupt(1, B_RISE, RISING);
 Serial.begin(115200);
 pinMode(motorPin, OUTPUT);
 pinMode(forwardPin, OUTPUT);
 pinMode(reversePin, OUTPUT);
 pinMode(buttonPin, INPUT);
   // set up the LCD's number of columns and rows:
 lcd.begin(16, 2);
 // Print a message to the LCD.
 lcd.print("Volume uL");

}
```

```
long integral = 0;
long previousError =0;
long previousTime =0;
long pid(long currentValue, long target, float kp, float ki, float kd){
  long time = millis();
  long dt = time - previousTime;
  long error = target - currentValue;
  integral = integral + error *dt;
  long derivative = (error - previousError)/dt;
  long output = kp*error + ki*integral + kd*derivative;
  previousError = error;
  previousTime = time;
  return output;
}

void driveMotor(long speed){
  //Constrains speed to be between -255 and 255
  speed = constrain(speed, -65, 65);
  //Writes the speed to the enable pin
  analogWrite(motorPin, abs(speed));
  if(speed > 0){
    digitalWrite(reversePin, LOW);
    digitalWrite(forwardPin, HIGH);
  } else if( speed < 0 ){
    digitalWrite(forwardPin, LOW);
    digitalWrite(reversePin, HIGH);

  }
}


void loop(){
  static long lastButtonPush = 0;
  if (digitalRead(buttonPin) == HIGH) {
    if (millis() - lastButtonPush > 200) {
      switch (currentState) {
        case SET_VALUE:
          currentState = VOLUME;
          break;
        case VOLUME:
          currentState = ZERO;
          break;
        case ZERO:
          currentState = GO;
        case GO:
          pulses = 0;
```

```
      break;
    case ENDED:
      currentState = SET_VALUE;
      break;
    }
  }
  lastButtonPush = millis();
}


  switch (currentState) {
    case SET_VALUE:
      readPot();
      break;
    case VOLUME:
      Serial.println("volume detect");
      volume();
      break;
    case ZERO:
      Serial.println("calculating");
      zero();
      break;
    case GO:
      motorStuff();
      break;
    case ENDED:
      Serial.println("ended");
      break;
  }
}


void motorStuff() {
  Serial.print("Volume");
  Serial.print(Volume);
  Serial.print(", ");
  lcd.setCursor(0, 1);
  lcd.print("Volume uL");
  lcd.setCursor(1,1);
  lcd.print(Volume);
  lcd.print("           ");



  long motorSpeed;
```

```arduino
  // stop moving once we get to the setpoint
  if (setpoint - pulses > 5) {
    motorSpeed = pid(pulses, setpoint, kp, ki, kd);
  } else {
    motorSpeed = 0;
  }
  driveMotor(motorSpeed);
  Serial.print(" Pulses");
  Serial.println(pulses);
  Volume = (Volume - (pulses/14.822));
}

void readPot() {
  long sensorValue = analogRead(A2);
  sensorValue = map(sensorValue, 0, 1023, 0, 1000);
  sensorValue= sensorValue- (sensorValue % 25);
  sensorValue= defaultSetpoint + sensorValue;
 int actualsensorValue= sensorValue;
  setpoint= (actualsensorValue * 14.822);
  Serial.print("Volume uL");
  Serial.println(sensorValue);
  // set the cursor to column 0, line 1
  // (note: line 1 is the second row, since counting begins with 0):
  lcd.setCursor(0, 1);
  // print the number of seconds since reset:
  lcd.print(sensorValue);
  lcd.print("          ");

}


void volume() {
  driveMotor(-100);
  lcd.setCursor(0,1);
  lcd.print("Zeroing");
if (digitalRead(toplimit) == HIGH){
  driveMotor(0);
  pulses = 0;
  lcd.setCursor(0,1);
  lcd.print("Press GO");
  lcd.print("          ");

  }
}

void zero() {
```

```
 int forceValue = 0; //variable to store the force sensor value in
 //read the analog in value
 forceValue = analogRead (A0); //reads analog a0 pin for force
 Serial.print ("sensor = ");
 Serial.println (forceValue); //print number to serial port
 delay(10);

if (forceValue > 100) {
 driveMotor(0);
 //Volume = ((totalpulses - pulses)/14.822);
 //Volume= pulses; used for calibrating the total pulses for the screw length tests
18399
 Volume= (18399 - pulses)/14.822;
 Serial.println ("Volume uL");
 Serial.println (pulses);
 Serial.println (Volume);
 lcd.setCursor(0, 1);
 // print the number of seconds since reset:
 lcd.print("Volume uL");
 lcd.setCursor(1, 1);
 lcd.print(Volume);
 lcd.print("          ");
}
 else if (forceValue <100) {
  driveMotor(60);
  lcd.setCursor(0,1);
  lcd.print("Calc Volume");
  lcd.print("          ");

 }
}


void A_RISE(){
 detachInterrupt(0);
 A_SIG=1;

 if(B_SIG==0)
 pulses++;//moving forward
 if(B_SIG==1)
 pulses--;//moving reverse
 //Serial.println(pulses);
 attachInterrupt(0, A_FALL, FALLING);
}
```

```
void A_FALL(){
 detachInterrupt(0);
 A_SIG=0;

 if(B_SIG==1)
   pulses++;//moving forward
 if(B_SIG==0)
   pulses--;//moving reverse
 //Serial.println(pulses);
 attachInterrupt(0, A_RISE, RISING);
}

void B_RISE(){
 detachInterrupt(1);
 B_SIG=1;

 if(A_SIG==1)
 pulses++;//moving forward
 if(A_SIG==0)
 pulses--;//moving reverse
 //Serial.println(pulses);
 attachInterrupt(1, B_FALL, FALLING);
}

void B_FALL(){
 detachInterrupt(1);
 B_SIG=0;

 if(A_SIG==0)
 pulses++;//moving forward
 if(A_SIG==1)
 pulses--;//moving reverse
 //Serial.println(pulses);
 attachInterrupt(1, B_RISE, RISING);
}
```