Analog Design for Hypodermic Drug Delivery

WPI

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1 Abstract

In 2014, 8.9 million procedures were performed in plastic and reconstructive surgery, which has increased 10 fold since 1997. Within this field there is an increasing need for accurate and ergonomic delivery of hypodermic injections such as Botox™ and dermal fillers. To accomplish this task, the design team designed a completely analog delivery device that aids surgeons in accurate and efficient placement of hypodermic injections reproducibly and repeatedly, without fatigue for the surgeon.

The design is in two parts: a design for the ergonomic shell, and a design for the volume deposition mechanism. The ergonomic shell was designed to fit vertically within the hand and rest comfortably on the index finger and first web space. The volume deposition mechanism was designed to allow push button administration of a single aliquot of drug while preventing inaccuracy in volume and flow rate. Significant roadblocks prevented the creation of a final prototype device. However, based on the design process and outcomes, a set of future updates has been laid out to improve the design and integrate the deposition mechanism and shell.

2 Acknowledgements

The project team would like to thank our advisors, Dr. Aparajit Naram (University of Massachusetts Medical School) and Dr. Anjana Jain (Worcester Polytechnic Institute) for their continued assistance and guidance in the project

The design team would also like to thank Dr. Amy Peterson for the use of her 3-D printing facilities and access to her laboratory. In conjunction with Dr. Peterson the design team would like to thank Anthony D'Amico who aided us greatly with the 3-D printing process and parameters.

3 Authorship

This paper is written by Archit Parmanand with editing done by Archit Parmanand and Norman Harris.

4 Table of Contents

5 Table of Figures

6 Table of Tables

1 Introduction

Over the past 60 years, Botulinum toxin has been developed into an effective drug for use in cosmetic and reconstructive surgery. Botulinum toxin type A is commonly distributed as Botox, and is administered in widely varying circumstances, from facial wrinkles to Upper Motor Neuron Syndrome. The minute quantities used and the relatively high cost of production make the final Botox™ solution extremely expensive for the physicians and patients (Nigam, 2010).

Effective delivery of Botox™ and other, various, dermal fillers, are based solely on the physician's ability to inject the solution into the proper layers of the skin. While controlling the flow rate, applied amount, steadiness of syringe and needle, and numerous other patient interactions. User fatigue can also lead to medical conditions for the user, increasing the potential risks for the patient. This multifaceted delivery approach requires management of many variables and does not allow for accurately repeated results.

1.1 Current Standards for Delivery

Through the expertise of Dr. Aparajit Naram, at the University of Massachusetts Medical Center, the design team have been tasked with designing a device that will help alleviate these concerning extra variables, while allowing the physician to accurately deliver multi aliquot drug therapies to a patient.

The current standard has been used for decades to deliver small quantities of drug subcutaneously. This method involves use of a hypodermic needle and small syringe. The syringe is locked into the hypodermic needle via a pressure fit or "Luer Lok", and the drug is

loaded into the syringe via mechanical actuation of the syringe plunger. The drug is then ready to be deposited by the physician.

Deposition is again a fully manual process. By placing the index and middle finger on the wings of the syringe and actuating the plunger, the physician can control the serum's injection into the patient. He must do this while monitoring patient movement, depth of the needle, quantity and flow rate of dose, among other patient variables.

The device allows the user to insert a specific sized syringe into the device. The syringe is loaded into the device; a press of a lever or button activates the device to drive the syringes plunger a distance specific to the volume. When the device is pressed the plunger will fully descend, the mechanism will then fully recoil to its full extend allowing the device to be used to deliver the preset volume again. When the user is done, the syringe and needle can be safely and easily removed from the device and thrown away. The device itself never comes in direct contact with the patient or liquid involved in the procedure.

1.2 Project Scope

The fully analog solution has the ability to aid physicians across the globe. Cosmetic surgery is a 1.3 billion USD industry, with over 6 million patients receiving Botox™ treatments annually (American Society of Plastic Surgeon - ASPS, 2014). By reducing wastage and increasing the affectivity of delivery of Botox, the project will be aiding these patients and physicians both financially and medically.

Cosmetic Botox™ treatments can cost anywhere from 400 to 600 USD per treatment and as such every drop counts (Naram, 2014). By reducing wastage and run off, physicians and patients can see significant monetary gains over the course of their treatment. Per aliquot savings

can be estimated to be roughly 3-4 dollars (Naram, 2014). Over the course of one procedure the patient can receive anywhere from 10 to 20 aliquots. This brings savings of up to 80 USD per treatment or 13%-18% of the total cost of the procedure.

The device is also economically cost-effective because of its lack of electrical and digital components. With the lack of electrical components, the cost of manufacturing will be reduced, in comparison to the current devices on the market. This will benefit the user by reducing the upfront cost of purchasing the device and mitigating the long-term cost of replacing disposable parts.

The opportunity for designing and marketing this device stems from the lack of a clinical grade alternative to the current method of syringe and needle, leaving the current manual injection technique as the only option. The current method allows for significant error and, as mentioned above, leaves many variables unchecked.

1.3 Project Goals and Approach

The overall goal of the project is to create an ergonomic, analog drug delivery device that will allow for user, depth dependent application of multi aliquot drugs to a patient, safely and precisely.

These goals were achievable and were tracked via the design process. Using the general design process for development of the device, we were better equipped to handle the needs of the project and meet the goals of the advisor and sponsor Dr. Naram. In general we used checkpoint meetings to aid in communication with the advisors and display deliverables. These deliverables will are tracked by a Gantt charts that we populate using an agreed upon set of deliverables.

We used iterative design strategies using a base design to explore ergonomics, plunger actuation and other design facets. The main deliverables are:

- Initial ergonomic design
- Initial deposition mechanical design
- Combined ergonomic and mechanism design
- Finalized ergonomic and mechanism design for use with testing and further fine-tuning.

The goal for the project is to produce a final design for an ergonomic shell and mechanical deposition system that would be used for future manufacturing and production.

2 Background

Through examination of technical sources and other laboratory analogues, we look to support the design and technical considerations. This product, industry, and technical background built a basis of knowledge for the project and provided greater insight into the needs and objectives that the sponsors and team share. This section will discusses the scope and need for the project, and moves towards a description of the industry. Also included is a summary of the uses of Botulinum Toxin A, current methods of delivery and lab-grade analogues. Further description is given for the manufacturing of the device via 3D printing and potential mechanisms used throughout the iterative design process.

2.1 Project Scope and Need

As the industry grows and use of Botox™ and other hypodermic injections increases over time, there is continued room for improvement of methods to increase affectivity of treatments and methods of delivery. Within the scope of Botox™ delivery, the affectivity of treatment is very much based on the physician's skill and ability to reproduce the same action repeatedly for different spots around the face.

The device is specifically designed to increase efficiency and accuracy of delivery of Botox™ and other hypodermic injections. We are looking to improve the current standard of delivery and the basic syringe and hypodermic needle combination, so that the physician can focus his attention on depth dependent portion of delivery of Botox™ and other hypodermic drugs. The device aims to manage the multiple variables of drug delivery and will let the doctor focus primarily on accurate delivery with quicker, more precise treatments that provide longer-term affectivity without the risk of improper muscle paralysis and other hazardous side effects

(Werner et al, 2006). For the specific needs of Dr. Naram, we will be focusing on the use of the device with Botox™ injections, though any syringe delivered drug may be possible.

2.2 Industry Background

Cosmetic and reconstructive surgery has been a long-standing facet in the halls of medicine. Starting with early reconstructive procedures in 1917, Cosmetic and reconstructive surgery has grown significantly in the last century to improve the lives of millions across the globe.

With over 1.3 Billion USD in revenue, the industry continues to grow. The number of non-surgical procedures in the industry has gone up more than 500 percent from 1997 to 2013 and approximately 6.1 million patients underwent Botox™ procedures just last year (ASPS, 2014). There is continued growth in the use of Botox™ for cosmetic purposes as the cost of the procedure decreases with improvements in affectivity and technique of injection. This cost decrease is also aided by the use of Botox™ for non-cosmetic purposes and potential health benefits the treatment has to offer.

2.3 Botulinum Toxin Background and Use

Botulinum Toxin is a highly potent neurotoxin produced by the bacteria *Clostridium botulinum (*Montecucco et al. 2005*).* Its first reported clinical use was discovered in the 1960s when Dr. Alan Scott started formulating a solution that would allow for the harnessing of a neurotoxin that can cause muscle paralysis.

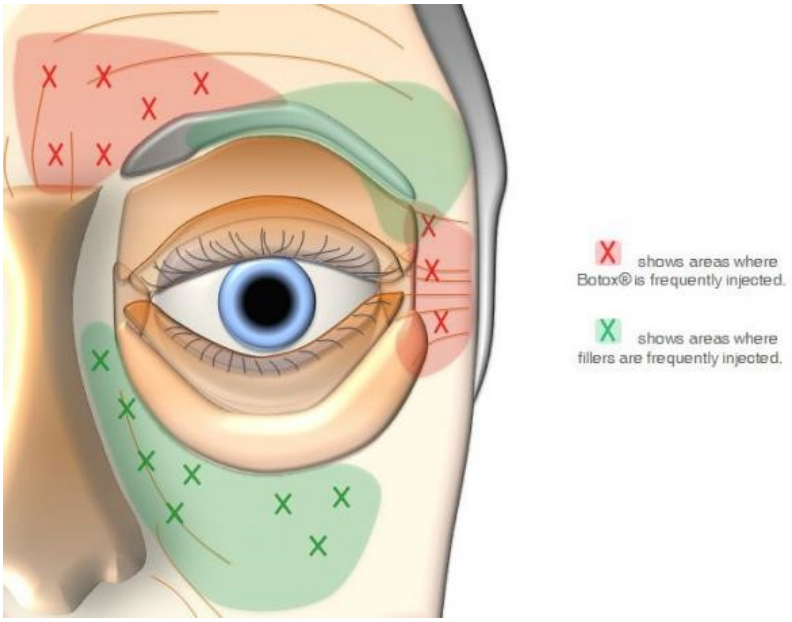

Figure 1: Injection locations for BTX-A and dermal fillers (Ortiz, 2015)

By 1985, using extremely small aliquots of less than 1 μg, Scott was able to use Botulinum Toxin type A (BTX-A) to treat a patients with spasms of the eyelids and those with "crossed eyes," a result of misaligned eyes (Flanders et al., 1987). As time went on BTX-A has grown into a multimillion-dollar industry within cosmetic and reconstructive surgery and nearly 6 million patients undergo Botox™ procedures every year. Injections into the face make up much of the market for the drug and clinical uses abound.

BTX-A was initially purified in 1928 by J. T. Snipe via isolation from its bacterial producer Clostridium botulinum (Snipe, P. et al., 1928). Its mechanism for disruption of neuromuscular disruption was subsequently isolated in 1949 by Arnold Burgen. Burgen's lab found that BTX-A would completely disrupt transmission of the neurotransmitter Acetylcholine via completely inhibiting its release into the synaptic cleft. This stops the signal for contraction from propagating and as such causes muscle paralysis (Burgen, A. et al., 1949).

Botulinum Toxin is the most acutely lethal neurotoxin and retains a median lethal dose (LD-50) of 1.3–2.1 ng/kg intravenously and 10-13 ng/kg intramuscularly (Arnon, S. et al, 2001). Thusly, it is important that delivery is accurate and does not enter the systemic bloodstream. Retrograde injection of BTX-A has been known to cause facial paralysis and further paralysis of muscle function. During treatment if the user injects BTX-A into the patient too quickly the drug can push against the normal flow of the bloodstream resulting in transmission of drug up the blood stream opposite its intended direction of flow. This opposite flow of drug can place the toxin into large blood vessels that then deliver the toxin to unintended muscles. This makes it crucial to ensure a flow rate that does not cause a retrograde movement of dilute solution from small venules into larger blood vessels.

Considerable research has been done to expand the use cases for BTX-A. BTX-A was initially used for treatment of Blepharospasm and Strabismus in 1980 (Flanders et al., 1987). From here the cosmetic and clinical uses would grow, allowing for use in treatment of hyperhidrosis (excessive sweating), chronic migraines, and Raynaud's phenomenon (Neumeister, M. et al, 2009) (excessive pain in the hands due to reduced peripheral blood flow). BTX-A's ability to function as an acetylcholine inhibitor is extremely efficient at relaxing muscle contraction and improving the above conditions.

2.4 Current Methods of Delivery

The equipment currently used for Botox™ delivery is a simple syringe and hypodermic needle (Naram, A, 2009). The needle, usually specialized 32 gauge hypodermics, for Botox™ or 25-27 gauge hypodermics for steroids and hormones, are locked into the syringe. The syringes, normally 1-5 mL in volume, features a female Leur lok couple that locks onto the male Leur lok

couple on the needle (U.S. Patent No. US6074373, 2000). This allows for user safety and ensures that the needle is securely fastened to the syringe.

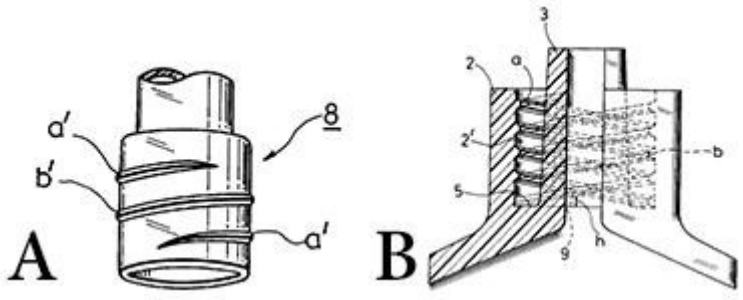

Figure 2: Leur Lok interlocking parts ***(U.S. Patent No. US6074373, 2000)***

The physician would then use this syringe and needle to load solution into the needle and remove any air from the system. This removal of air prevents introduction of air into the bloodstream, skin, or muscle. The handles of the syringe are held in the middle and index finger and the plunger is placed under the thumb. The physician would the place the tip of the needle within the skin, placing it at the needed depth for release of the drug.

At this point some physicians aspirate the point of injection, making sure that no major blood vessels have been pierced, though there is some contention as to if all physicians delivering Botox™ actually perform this step of the procedure. After the patient dependent depth has been reached, the physician manually actuates the cylinder, delivering a per-patient specified amount of drug to the patient. This would then be repeated upwards to 20 times based on the patient's needs.

This holding method is one of many ergonomic problems with the current method. For many physicians this stretched position is uncomfortable and unstable. With average "comfortable" human thumb reach being around 2.25 inches the method is an uncomfortable overextension for many physicians (Otten, 2013).

Based on this repetition (Westerblad, H. et al, 1991), it is important to note that fatigue can affect the physician's ability to repeatedly carry out accurate deliveries of Botox™. This is why it is one of the goals to make an ergonomic device with which the physician can deliver pharmaceuticals. Fatigue can eventually manifest into physical limitations for the physician, from simple problems such as wrist pain to as severe as carpal tunnel syndrome. Performing repetitive hand movements can increase an individual's risk of developing carpal tunnel syndrome, making the condition highly likely for physicians whose job involves high repetitions of thumb and wrist motion (Terrie, 2010). If we can reduce the fatigue caused by these repetitive actions, we can increase the accuracy at which the physician can operate. This method has been used since the inception of the treatment procedure and has shown significant room for improvement.

2.4.1 Existing and Alternative Devices

There are numerous laboratory grade devices that are available on the market to deliver accurate volumes in the laboratory setting. There also is a current patent on a Botox™ delivery syringe (U.S. Patent US2006025902, 2006). This particular device encapsulates the, pre-loaded, syringe within the device and through the use of a driving mechanism, propels the syringe's plunger in a stepwise manner. This allows the user to eject multiple aliquots or doses consistently and repeatedly. However, the main concern with use of these devices in a clinical setting is the lack of disposable parts and cost of custom syringe needle combinations. Within the clinical environment, concerns of cross contamination between patients and between batches of pharmaceuticals. Though labs do have these concerns, the sponsors would rather see a device

that would allow for use of conventional syringes and needles to be dropped in and actuated. The syringe would then be removed and disposed of in a sharps container.

2.4.2 Laboratory Alternatives

The current laboratory alternatives are very similar to the current standard in delivery for BTX-A. There are multiple options and makers, but all generally involve disposable tips, a plunger actuated delivery method and a selectable uptake and output amount. In particular, Sartorius produces an electronic pipetting device, titled, Picus® NxT. This device encompasses an electronic braking system in conjunction with a piston control system to control the accurate dispensing of liquid (Picus, 2014). This device also boasts an ergonomic and lightweight design and an aspirating function to reduce the amount of waste following use of the device.

Figure 3: Picture of the Picus® NxT in action (Picus, 2014)

Like many devices such as the device shown in Figure 3, a main concern and reason necessitating the design is that these types of devices are solely for laboratory use and not for clinical application. Aside from the incompatibility with clinical applications, there is a chance

that the internal volume uptake and deposition system of the device would come in contact with the solution and contaminate the device for use with different patients. This would require sterilization between uses, and would not be conducive to efficiency for a doctor with a large patient load.

2.4.3 Analog Clinical Designs

Filed as US patent US2006025902, Scott J Gerondale invented a single use fully analog device for delivery of Botox™ to a patient (U.S. Patent US2006025902, 2006). Though this device does meet some of the necessities of physicians that we interviewed, this would prove to be too costly to produce and use, and would likely increase the cost of the procedure past the already high 400-600 USD price per treatment.

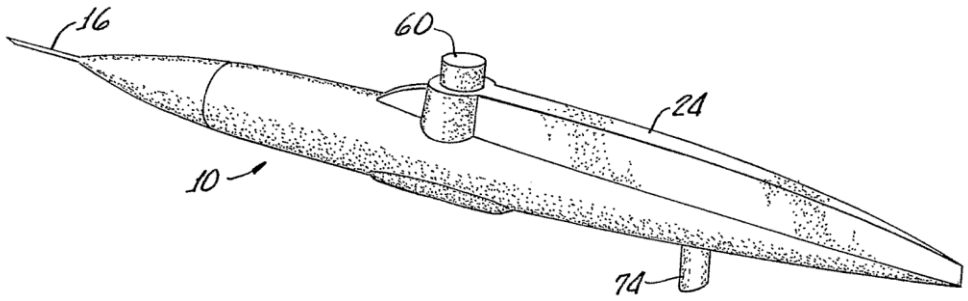

Figure 4: Design for single use ergonomic delivery device (U.S. Patent US2006025902, 2006).

The device is designed to be held similarly to a mechanical pencil with the needle (16) facing downwards to the skin and fingers gripping the syringe on the syringe body (10). With the press of the index finger on to the release mechanism button (60) the plunger (74) would be lowered, depositing serum into the patient. This device is one time use and does not allow for the

movement of the plunger back up the barrel, because of this there is increased wastage of serum and material, forcing doctors to repeatedly buy this specialized and hard to make devices.

The device intends to use the already available set of syringes and needles to deliver consistent doses and would require no additional repeated cost of supplies past the readily available syringes and hypodermic needles.

2.5 3D Printing and Rapid Prototyping

Three dimensional printing or additive manufacturing has allowed many companies and groups to rapidly prototype functional design elements. The additive manufacturing term was initially coined by Hideo Kodama in 1981 who developed a method for 3D printing that involved the exposure of a photo hardening polymer to UV light in masked of sections. This method has come to be known as stereolithography and can be employed to produce extremely accurate 3D models. However the monetary overhead and lead time can be prohibitive to operations that have a limited budget and time constraints, especially if they do not always need the accuracy offered by the stereolithographic method.

2.5.1 Fused Deposition Modeling

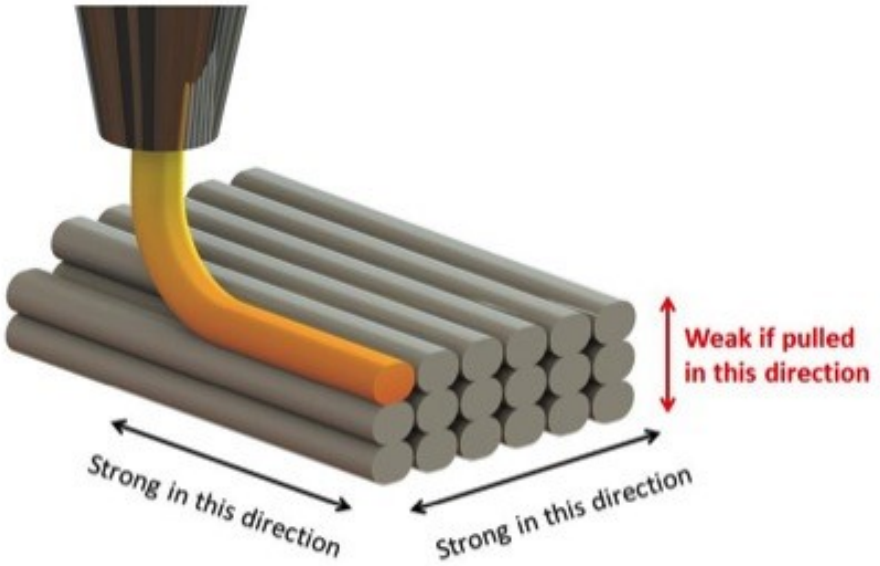

Figure 5: Fused deposition method (Ghose, 2015)

In the modern day, fused deposition modeling is used to achieve similar results, but with reduced overheads. In fused deposition modeling, a filament of polymer is heated and extruded through a ceramic head. Similar to the functionality of a hot glue gun, the polymer is deposited on a surface in subsequent layers, slowly forming layer after layer of connected polymer materials. This method produces a multi –layered object that is structurally stable in 2 out of 3 axis, as seen in Figure 5, and performs well under compressive loading. This method is simply faster than the stereolithographic method and, because of its lower overhead, is easier to access for most of the populace.

2.5.2 3D Printing Terminology

Within the subset of the 3D Printing industry, a company called MakerBot makes build-to-order 3D printing devices. These devices range in size and ability but in general allow for low cost creation of 3D models via fused deposition modeling. MakerBot offers 4 different printer

types and an amassment of different types of filaments in varying colors. To better understand 3D printing terminology we have included a table of commonly used 3D printing vocabulary that can be easily referenced.

Table 1: 3D Printing Terminology

Word	Meaning
Boat	1st initial layers used to evenly adhere filament to build platform
Build Platform	Plastic is extruded onto this platform. Platform moves downward as new layers are to be extruded.
Build Volume	Printable area reachable by the extruder head
Extruder head	User-controlled heated die that melted plastic is extruded from.
Filament	Spool of melted PLA or ABS plastic with 1mm diameter
Layer Height	Height of the deposited layer, controlled by the extruder head
MakerBot Replicator 2x	4th Generation 3D printer produced by MakerBot Industries
MakerBot Desktop	Software used to give instructions and build designs for use in the MakerBot Replicator 2x
Support Structure	Easily removable structure meant to support surrounding geometry

2.6 Analog Drive Mechanisms

2.6.1 Ratchet

The ratchet is a long standing mechanical device that allows for one way motion of a gear. In essence a ratchet has two main structures, an asymmetrical gear and a pawl. The gear is generally a sawblade-like gear that is anchored in its center via a tube or axel. The pawl is a small finger-like device that is spring-loaded to maintain constant contact with the gear.

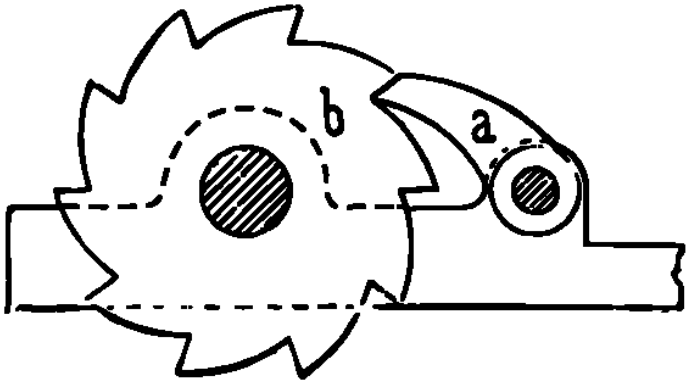

Figure 6 Simple pawl (a) and ratchet (b) mechanism (Band, 1894)

As you can see in the above figure, the pawl (a) prevents the gear (b) from spinning clockwise while allowing it to spin counterclockwise. When the gear is spinning counterclockwise the pawl slides over the face of the gear, pushing over the tooth due to its spring-loaded nature. If the gear was to rotate backwards, the pawl would catch on the steepest edge of the gear tooth and prevent any further motion.

When the gear is rotated in reverse the pawl must travel from the top edge of the tooth to the steep edge of the next tooth. This slight backwards rotation is called backlash and can prevent complete immobility of the ratchet during a reversal of motion. Its mitigation however is simple and can range from reducing the distance between teeth, to increasing the spring force to put greater pressure on the pawl to increase friction of the unit.

This system is beneficial to the design process as it provides a unidirectional movement of the gear. Implementation into the device would provide a unidirectional drive for the deposition mechanism, making for a safer device and increased simplicity for users.

2.6.2 Rack and Pinion

A common linear actuator, a rack and pinion allows for rotational motion to be converted to linear motion. The mechanism employs a linear gear bar and a symmetrical gear. In the name rack and pinion, the rack refers to the linear gear bar while the pinion refers to the circular gear.

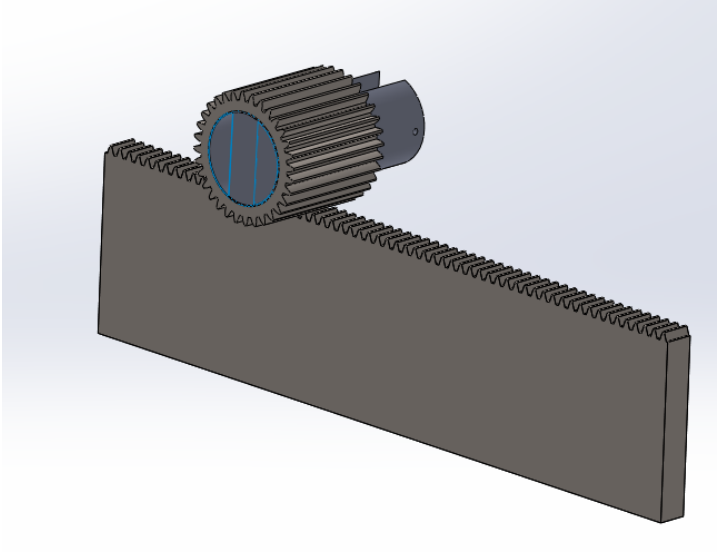

Figure 7: Rack and Pinion CAD drawing

Rotation of the gear/pinion engages the teeth on the gear bar/rack. This affectively allows the rotational force of the gear to be turned into a linear force applied by the bar (Sclater, 2013). Clockwise rotation of the pinion means movement of the rack to the left or upwards. While the counterclockwise rotation of the pinion means movement of the rack to the right or downwards. This mechanism has minimal backlash when the teeth are engaged as the teeth of both the gear and the rail are almost always engaged at a given point, this prevents back movement in the

mechanism and no inaccuracy in its desired range of movement (AGMA, 2005). The unit can however suffer from backlash upon initial insertion of the rail into the gear's rotational radius.

The rack and pinion is a very simple machine and as such is very cost effective to implement. Creation of a mechanism with 3D printing can be quick and easy. Implementation into the device could provide a useful mechanism for conversion of a ratchet or geared button press into a linear up and down movement.

3 Project Strategy

3.1 Client Statement

To develop design plans and implement a design strategy we initially gauged the client's needs with a written client statement. As we progressed through the project analysis and background research, the project was further able to define the scope and evolve the client statement to specifically meet the objectives of the client.

3.1.1 Initial Client Statement

Initially the team aimed to create an analog drug delivery device that would allow for the user to easily control the transfer of multi aliquot drugs to a patient. The team's sponsor and client through the University of Massachusetts Medical Center in Worcester, Massachusetts, Dr. Aparajit Naram, expressed the need for this device in his clinic and wanted to design this product for future production and retail. To better understand the needs and objectives we approached Dr. Naram with an initial statement that would summarize his clinical needs and device objectives. The initial client statement was as follows:

> "The overall goal is to create an **analog drug delivery device** that will allow for **depth dependent application of multi aliquot drugs to a patient.** The device allows the user to **insert a specific sized syringe into the device**. The syringe is loaded into the device while holding down a "loading" button **that "informs" the device of the starting size** of the syringe with plunger. The device has a dial allowing the user to set a **predetermined volume** to be delivered which activates the device to drive the syringes plunger a **distance specific to the volume**. When the plunger is pressed the plunger will fully recoil to its full extent

allowing the plunger to be used to deliver the preset volume again. When the user is done, the **syringe and needle can be safely and easily removed** from the device and thrown away. The device itself **never comes indirect contact with the patient**."

- Initial Client Statement (9/04/2014)

3.1.2 Further Analysis of Client Statement

The original client statement, while detailed, lengthily described the specific design fundamentals of the device rather than explaining the client's needs and overall objectives for the design of the device. The revised client statement needed to encapsulate an ideas that would address the objectives that Dr. Naram conveyed without including more design process oriented considerations. The statement concisely needed to mention:

- Analog nature of the device
- Quick and safe delivery of drug to patient
- Efficient and accurate delivery of drug to patient
- Ergonomic design of device
- Accurate volumetric control
- Minimization of drug loss

The statement and goals needed to encapsulate these basic objectives to properly portray the client's objectives as well as convey the project's novelty as a clinical aid and medical device.

3.1.3 Revised Client Statement

After further deliberation, research, and meetings with the sponsor the team was able to narrow down the client's needs and objectives for the design and manufacturing of a drug delivery device. The revised client statement demonstrated the sponsor's specific needs of a device that can perform specific tasks accurately and efficiently:

> "The sponsor would like an **analog hypodermic drug delivery device** that allows for **quick, efficient, and accurate delivery** of multi aliquot pharmaceuticals to the patient. The **device is to be ergonomic** and aid the physician in **accurate placement** and **volumetric control** of drug application while **minimizing drug loss**."

-Revised Client Statement (10/02/2014)

The client statement was better able to encapsulate the overarching goals of the device and was able to portray the role of the device within the clinical environment. By working with Dr. Naram, the project team was able to better identify the novel features of the proposed device in comparison to the current "gold standard" methods.

3.2 Identifying Design Objectives

After identifying the client statement, we moved towards fleshing out the sponsor's objectives into broader categories of information. The project team was able to categorize the objectives into two key categories. The primary objectives were formed to address Dr. Naram's most important goals that he laid out in the initial interview. The secondary objectives were laid out to support the overall design of the device and further detail the facets of the initial design objectives.

3.2.1 Initial Objective Identification

Through weekly meetings with Dr. Naram, the design team was able to agree on functionalities of the device through examinations of the Client statement.

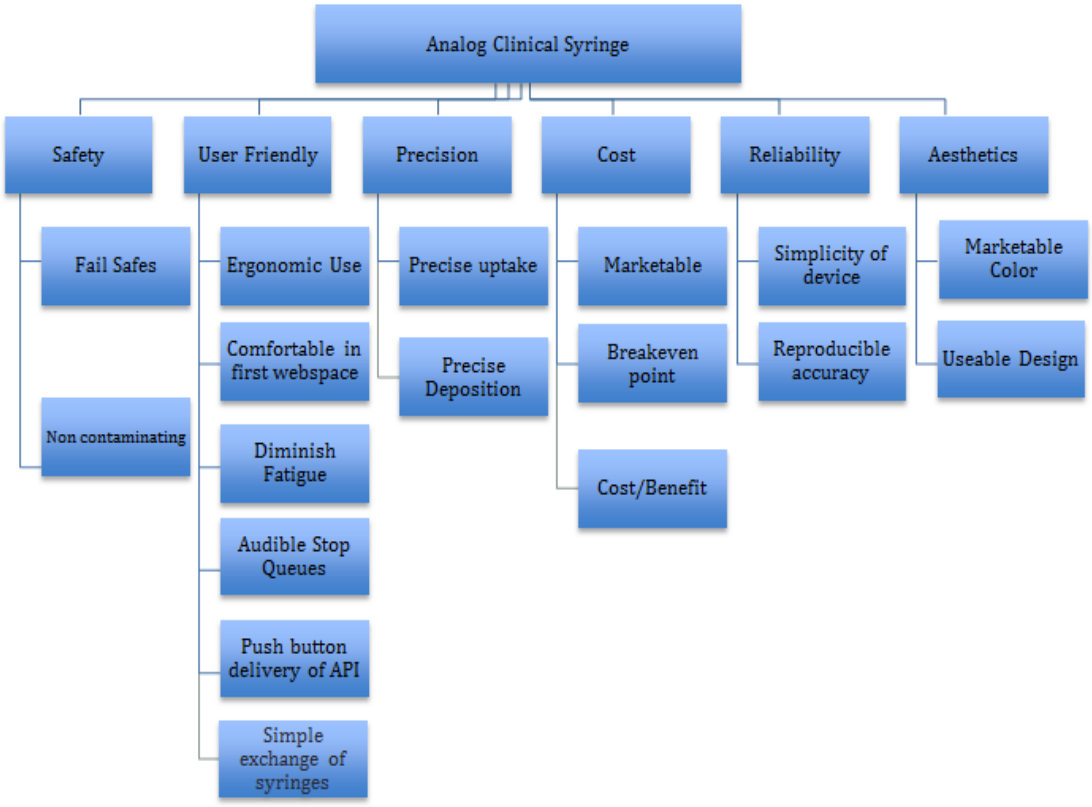

Figure 8: Objectives tree organized by overarching category

The goal of the development of this objective tree was to give direction to the requirements of the project. The project team used it as a basis for developing the primary and secondary objectives and were able to use its branches as descriptors when talking to the client/sponsor. Using the listed objectives as a basis for discussion, the project team was then able to form and populate a pairwise analysis chart.

Table 2: Pairwise Analysis of Design Considerations

	Safety	User Friendly	Precision	Cost	Reliability	Aesthetics
Safety	X	1/2	0	0	1/2	0
User Friendly	1/2	X	0	0	1/2	0
Precision	1	1	X	1/2	1	1/2
Cost	1	1	1/2	X	1	1
Reliability	1/2	1/2	0	0	X	0
Aesthetics	1	1/2	0	1/2	1	X
TOTAL	**4**	**3.5**	**0.5**	**1**	**4**	**1.5**

Dr. Naram populated the chart with his answers and the totals were tabulated. The team was able to focus their priorities on various design concepts. Safety and reliability of the device was of the utmost concern; this was closely followed by user friendliness. The team did not rank the secondary objectives further and allowed the conversations with Dr. Naram and client statements to drive decision making in regards to importance of secondary objectives.

3.2.2 Re-evaluation of Device Objectives

It can be noted that the Dr. Naram was more interested in the aesthetics of the device than the precision. The team came to the conclusion that there was considerable overlap between reliability and precision with little difference in key secondary objectives i.e. reproducible accuracy.

There was considerable misunderstanding as to how the options were presented; though precision of uptake and deposition definitely mattered, these were viewed as secondary to the device's ability to accurately dispense drug and reproduce said results, as denoted in the initial

objectives tree. The objective tree was then remade, specifically to combine these two primary objectives.

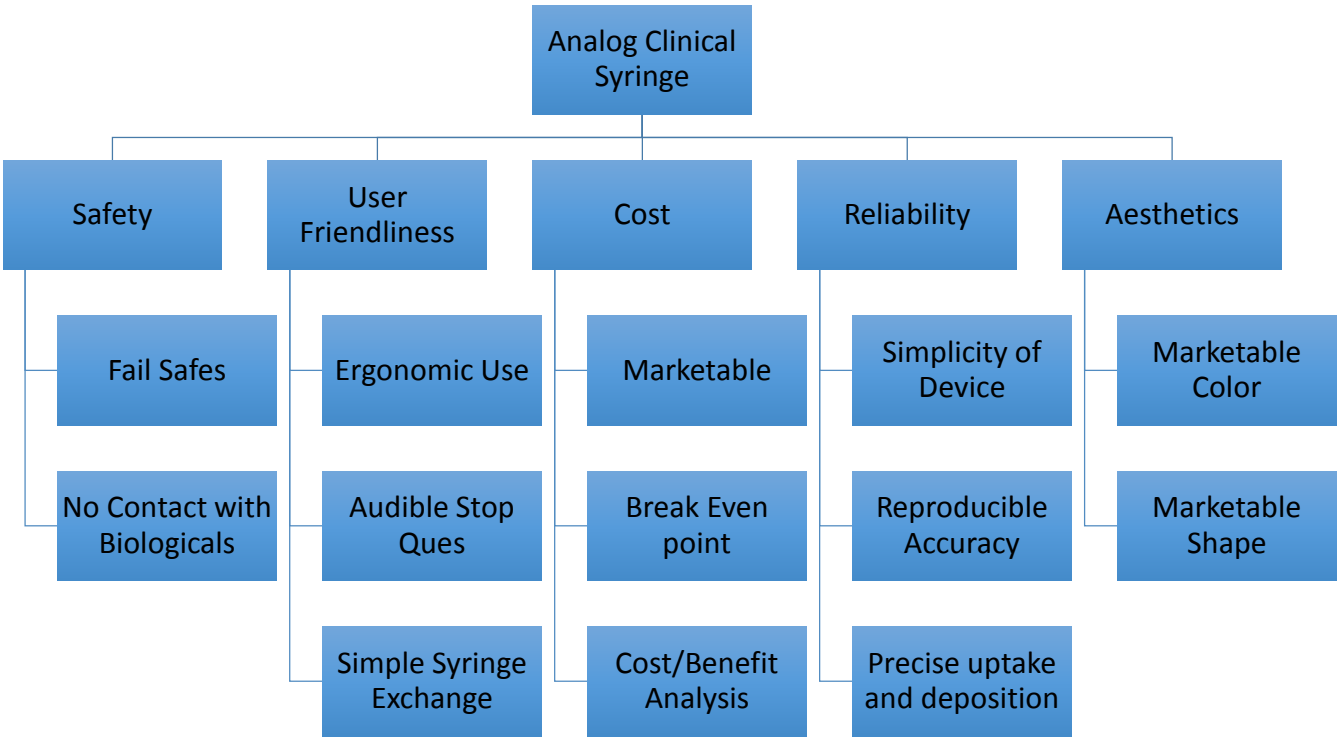

Figure 9: Updated objectives tree showing Primary and Secondary Objectives

The objective tree was pared down significantly, removing overlapping statements in ergonomic use and reconstituting reliability to consist of both the precision and reliability primary objectives of the previous trees. We also removed more obvious secondary objectives such as useable design in the aesthetics primary objectives.

3.3 Primary and Secondary Objective Extrapolation

The primary objectives were made using the updated objectives tree found in Figure 9. In total, after revision of the objectives tree, the project had five main objectives:

- Safety of the device
- Reliability of the device
- User friendliness of the design
- External aesthetics of the device
- Cost of the device

The objectives are listed and discussed in that specific order that Dr. Naram

3.3.1 Device Safety

Because the device is for use with active pharmaceuticals, it was deemed necessary that the device be operated as safely as possible and present any risks to the patient or the doctor.

3.3.1.1 Physical Safety Fail Safes

It was very important to Dr. Naram that there were fail safes in place to prevent over delivery of drug to the patient as this can cause paralysis of areas around the injection site. The project team also wanted to ensure that it was not possible to introduce air into the blood stream, reducing the chance of damage to arteries and tissue in the area of injection.

3.3.1.2 Contamination Prevention

As this device is also to be used very frequently within the span of a day, the project team wanted to ensure that the device did not come into contact with any patient bio fluid, active pharmaceutical, or other biologically contaminating source. This is the basis for the project team using designs that employed a system that uses existing syringes that can be thrown away

without contaminating the device's internal systems. With this in mind, the client wanted to be able to wipe the device down with isopropyl alcohol between uses as the only of sterilization.

3.3.2 Reliability of Design

On the pairwise analysis chart, the sponsor ranked reliability on the same level as the safety of the device. After reforming the tree and including the previous precision branch of the tree, the project team was able to concisely categorize objectives that dealt with the accurate and precise deposition of pharmaceuticals by the device.

3.3.2.1 Simplicity of a Completely Analog Design

By working with Dr. Naram, the design team identified the necessity for a mechanically driven option for hypodermic injection. This design objective was stipulated to underline the necessity for a simple easy to use device that would reliably perform over and over again, without repeated input.

We also considered that the response time of a fully mechanical device would be considerably less than that of an electronic one, thus allowing for repeated use without having wait for the added start up, batteries, and limited use times inherent with electrical devices.

3.3.2.2 Accuracy and Precise loading and deposition

Due to the multiple aliquots nature of Botox, multiple volumes of solution are injected into each patient. The device needed to able to repeatedly (precisely) and accurately dispense the user-determined volume of drug per aliquot. The project team aimed to test the viability of the uptake and deposition mechanism while it is external to the device, and then repeat viability testing while the system is within the device to ensure optimum performance. The project team wanted to ensure accuracy of volume deposition for all steps in the design and make sure that the

system is accurate outside of and within the device. The project team sought to compare performance to a lab grade analogue by comparing volumetric output at a given set point.

One of the many problems with the current method of hypodermic drug delivery is the unreliable flow rate upon injection of solution into the patient. This can become a serious problem if the user accidentally injects a drug solution too quickly into the patient. For example, injecting a solution of Botox™ too quickly can cause retrograde injection of the drug into the patient's blood stream. This increases the possibility of paralysis, blindness, and other major health complications.

3.3.3 User Friendliness of Design

The next highest rated objective was user friendliness of the device. This user friendliness was encapsulated in ensuring that the device had an ergonomic design, was able to give feedback during use via audible cues, and must allow for quick loading and unloading of syringes of varying size and volume.

3.3.3.1 Ergonomic Design

Through personal communication with the client, Dr. Naram, it was concluded that the ergonomics of the device design was an imperative. In essence, the device needed to be easy to handle for the user. This was important because over the course of a single day a user may see upwards of twenty patients, and depending on the particular needs of the patient a single session can last 15-20 minutes. The current method of drug delivery, use of a syringe and needle, has a tendency to cause fatigue in the user over extended use and treatment sessions. The design is aimed to alleviate the user's fatigue and prevent any errors that can be attributed to fatigue.

To accomplish this the client has expressed a need for the device to fit comfortably within the first web space of the user's hand. This means that the device would be placed between the thumb and the index finger much like the form of a pencil. This positioning would allow for ease of use and accurate placement of the hypodermic needle, allowing physicians to repeatedly inject the control volume at the correct positions and depths over long periods of use. The project team planned to have an initial ergonomic concept that was present to Dr. Naram for his thoughts. The project team then developed the product through iterative redesign based on the feedback of the UMASS physicians and plastic surgeons.

3.3.3.2 Reusable and Versatile Design

Through the background research and correspondence with Dr. Naram, the project team recorded the application of Botox™ through varying gauge needles and syringe volumes. Taking this into account, the design will be able to use common syringes of 1-5 mL in volume delivery and allow for accurate deposition of active pharmaceuticals through 25-32 gauge hypodermic needles. This allows the device to accommodate different practices that use a varying manufacturer of syringes and hypodermic needles.

Because the device is reusable within the clinic and between patients, it must obviously never come in contact with any active pharmaceuticals or patient bio fluids. Within the stipulations of Dr. Naram, the device will be readily cleanable with isopropyl alcohol or any other antibacterial product. As there is no need for sterility of the device, there is no need for further cleaning or autoclaving.

3.3.3.3 Device Feedback

As seen in the pairwise analysis chart in *Table 1*, the sponsor would like to have a very user-friendly device. Dr. Naram would like to see a method of notification and user feedback for different aspects of the device use and drug delivery process.

To increase user friendliness the sponsor would like to have the device provide some sort of feedback for when a single aliquot is complete or the syringe is empty. Feedback would improve user accuracy and patient to doctor interactions. This would play a key factor in safety of the device, and overall marketability to physicians.

3.3.4 External Aesthetics

The 4th highest objective in the pairwise comparison chart was the Aesthetics of the device, specifically the color and shape. This objective focuses in on the need for the device to marketable to plastic surgeons as a method of more accurate delivery. This means that the device must provide function and form, and as such the external shell will have to not only be ergonomic, but must add to the appeal of the device.

3.3.5 Cost and Marketability

The cost of the device will be very dependent on the internal components. The overall cost to produce a device will be lower for a fully mechanical device than a device that uses, batteries, LCDs, and drive motors. This reduction in costs plays directly into marketability. If a device that is accurate to the needs of a physician can be produced for a lower cost, it can be sold a lower price point. The device aims to be cost effective; it is with this cost effective design that Dr. Naram intends to drive sales of a final product.

3.3.5.1 Post-injection Drip Drug Loss

While keeping a consistent volume per injection site is important for safety and patient satisfaction, the device will also save small amounts of the drug in the barrel being wasted by run off or minute over-injection. Following a single injection a phenomenon occurs in where there is drug loss due to post-injection drip. This occurs at some level after each injection and over the course of one treatment session can add up to a significant amount of waste. This runoff is likely induced by capillary action caused by removing the needle from the patient's facial tissues.

The sponsor has communicated to the project team that, while this may be a difficult area of waste to overcome, he would like to see the device negate this form of loss. According to the research and discussions with Dr. Naram, over the course of a single session the patient and physician may see savings upwards to 80 USD; this savings can not only help market the device but can help patients a more effective treatment for the cost.

3.4 Constraints

Through further development of the objectives we categorized the constraints into three main areas: Safety, Manufacturability, and Usability. Using these categories, the project team were then able to further expand the objective tree, focus discussion during meetings with the sponsor, and build criteria for gauging affectivity of designs.

3.4.1 Safety Constraints

Safety of the device was of the utmost concern, as Botox™ is a very strong neurotoxin if used improperly. Because of this the device:

- Must be sanitized with isopropyl alcohol
- Not be able to come in contact with active pharmaceuticals or bio-fluids

3.4.2 Manufacturing Constraints

The goal of this project is to offer a final prototype that can be used for further manufacturing. This means that we must have taken into account design of the device for future manufacturing via extrusion/machining/molding.

- Ergonomic design that reduces yield loss of materials
- Material used is wear resistant and economical for production
- Tolerances within device manufacturing do not require high precision machining

3.4.3 Usability Constraints

Working with the project objectives the project team identified the need for numerous constraints and guidelines for usability. These constraints were taken from the interviews with Dr. Naram and were extrapolated from his initial design documentation that he provided.

- Ergonomic one-handed design
    - Must be placed in the first web space
    - Must not cause fatigue over long periods of use
    - Cannot interfere with repeated injection of hypodermic needles
- User defined volume delivery
    - Must give accurate results with low variance (±5%) from the set value
    - Must deliver solution at rates lower than that of peripheral arterial blood flow (<.1 cc/sec)
    - Must not block site of volume left in syringe
- Simple exchange of syringes and needles
    - Must allow for sub 20-second removal and replacement of spent syringes/needle combinations.

- Must allow use of 1-5 mL syringes and 25-32 gauge needles

These constraints were used as a driving force for innovation in the design. As the project progressed most constraints were kept the same unless otherwise noted.

4 Initial Designs

To begin work on the project initial concepts we used Solidworks to conceptualize designs. The goal of these initial designs were to field initial reactions to certain shapes, sizes, and hand placements for the device. Key concepts in these devices included:

- Easy initiation and termination of injection
- Pencil like-grip
- Holder allows easy access to syringe
- Visible syringe volume
- Holder allows for variable syringe volumes

Keeping these initial stipulations in mind the project team worked to design the following ergonomic outer shells. These shells were presented in their electronic form to clients for review. After their review, the comments for each device were noted and further stipulations and design ideals were fleshed out.

4.1 Dumbbell Device

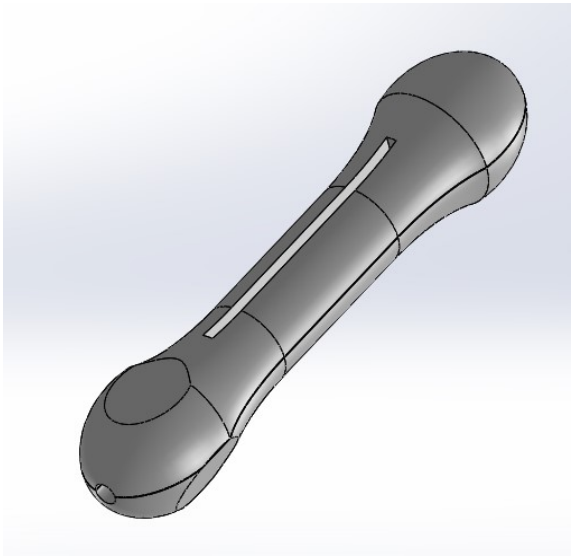

Figure 10: Initial Ergonomic Dumbbell Device

This initial device was meant to be held much like a pen. The device shaft would lay within the first web space and delivery of a specified volume of drug would be triggered via a press of the index finger. The device employed the use of a delivery volume window to allow for ease of viewing of the syringe as it was used by the device.

The ergonomic shape of the device provided three distinct surfaces for resting of the thumb, index, and middle fingers, similar to ergonomic pen grips found on modern pens. Syringes would be placed inside by opening the device in a clamshell fashion, and placing the syringes within a predetermined area of the shell. Because this was such a rough model the design facets that the design was intended to meet were weighted towards ergonomic possibilities and not towards possible mechanisms designs

4.2 Wedge Device

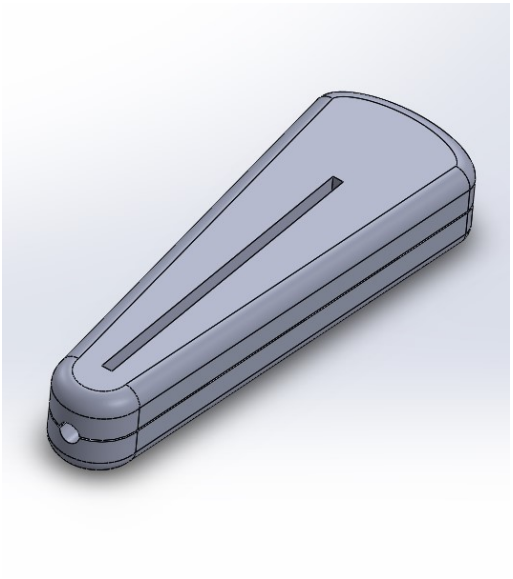

Figure 11: Initial Ergonomic Wedge Design

This initial device was also meant to be held like a pen. The device would be held flat with index finger on the left face, thumb on the right face, and index finger supporting the device tip from the bottom. The upper part of the body (farthest away in Figure 11) was meant to rest on a user's first web space and provide greater surface area for finger contact. The shape also included an injection volume window and syringes would be placed inside via a clamshell like opening of the device. The focus of this design was to gauge the client's liking of different shell shapes and aesthetics.

4.3 Initial Design Client Feedback

The project team brought the devices to the client seeking feedback on ergonomics, design choices and further sought to formulate design facets. In doing so, the client was able to give the project feedback and better steer the design process.

Though the dumbbell device shell did meet some client needs, there were some problems with this initial device. For example. The pen like grip made mechanical drives extensively hard to design, and created unsurmountable problems within the already tight internal space constraints of a hand held device.

This wedge design, much like the dumbbell device, had considerable drawbacks. The device was significantly less ergonomic than needed though it provided increased internal space for mechanical drive systems. The grip was initially considered greater to that of the dumbbell device but the device would not be a good one-size fits all use for various sizes of physicians' hands.

The client feedback also gave cause for refocusing design efforts. From Dr. Naram's comments and feedback a new design constraint was implemented. Not only did the analog device have to be held within the first web space, but it also was meant to be held upright in the same manner used by pipettes. The first iteration design had been focused on pen like devices that would not have met the client's needs and would have been increasingly hard to design. Refocusing efforts onto a more upright pipette like device opened up new options for device design. The new goal was to take the previous design facets that had worked for the initial designs and apply them to a new upright device.

5 Second Iteration of Design

Based on the feedback from the client there was a necessity for a significant redesign. The client wanted the scope of the project to focus on an Ergonomic design for repetitive day in and day out use of the device. The stability of the device within the first web-space was also key. By moving towards an upright design for the device, similar to lab grade pipettes, future conceptual designs would be better able to provide first web-space stability while also providing ergonomics for reduced fatigue. Using these new design parameters the project moved forward into a new iteration of design.

5.1 New Design Concepts

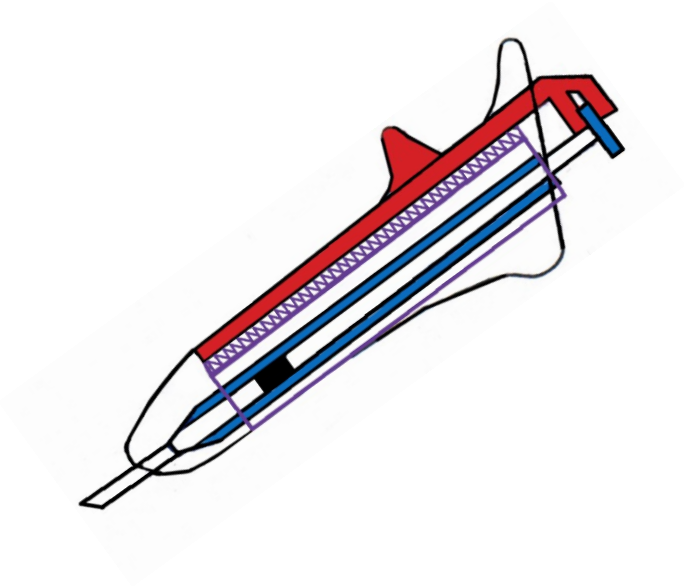

Figure 12: Initial Concept for Second Iteration of Design

Adhering to the stipulations mentioned previously, a new conceptual idea for the device was created. Figure 12 shows a cross section of the proposed device with color-coded sub-assemblies. Main features in this new design are an introduction of a ratcheting drive mechanism, a new mechanism for loading the syringe and a new ergonomic design.

5.1.1 Drop in Syringe

In the previous figure, the syringe is shown in blue. It is meant to be loaded into the syringe from the top, removing the need to open or close the device like in previous design iterations. This drop in method would allow for greater safety to the physician or physician's assistant and would require less cleaning of the device as less internal volumes of the device would be exposed to the patient clinical environment.

5.1.2 Introduction of Drive Mechanisms

In Figure 12, the drive mechanism is shown in red and purple. This proposed mechanism is similar to the rack and pinion and ratchet systems described in chapter 4. As the red plunger is depressed, so too is the plunger on the syringe to which it is attached. The mechanism only allows for one way movement and this adds some safety to the design, as it prevents air from getting into the injection if the plunger were to be reversed. This method also prevents the surgeon from moving the mechanism backwards without his/her knowledge, preventing the over or under injection of serum and increasing the physician's efficiency.

This ratcheting mechanism also benefits the device by preventing loss of serum on removal of the device from skin. Within the client's initial requirements was a necessity to prevent post injection drip. By preventing the movement of the plunger after removal of the needle from the patient's skin, the post injection drip is mitigated.

5.1.3 Ergonomic Design

The black outline in Figure 12 shows the basic silhouette of the ergonomic shell of the device. This design was made to feel similar to laboratory grade pipettes and included features like an index finger catch and a rest for the first webs-space and thumb. The design was to work in an upright fashion with the thumb on the red plunger and the rest of the hand wrapped around

the device similar to the method shown in Figure 3. Through the client feedback the design team knew that this was a design facet that needed considerable refinement but saw this initial design as a good starting point for further revisions and iterations.

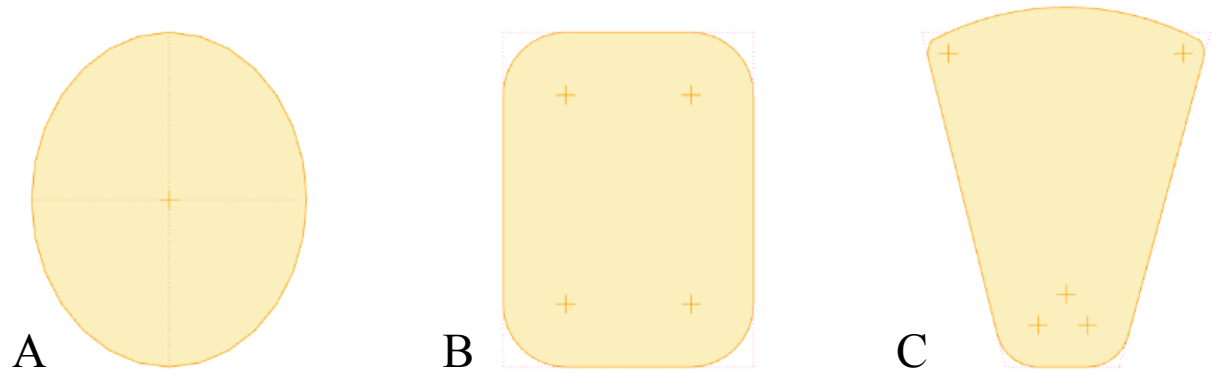

Figure 13: Top down Cross-Section of Ergonomics Shell

Further design consideration in this stage were also made for design of the shell's barrel shape. The mid portion of the device was to be shaped in a way that provided better grip and comfort than that of a square piece of stock. Cross section A was shaped to mimic the shape of a can or pill bottle. Cross section B was shaped to mimic that width of a telephone. Cross section C was made to be a combination of the two featuring a design similar to current market laboratory grade pipettes (Picus, 2014).

By presenting these design options to the clients, the design team was better able to build out clay models for their consideration. The three cross sections shown in Figure 13 show the proposed shapes. These shapes were proposed under the pretense that their rounded nature would provide better contact area with the physician's hands and would be easier to grip than a square or tubular structure.

5.2 CAD Modeling of Second Iteration

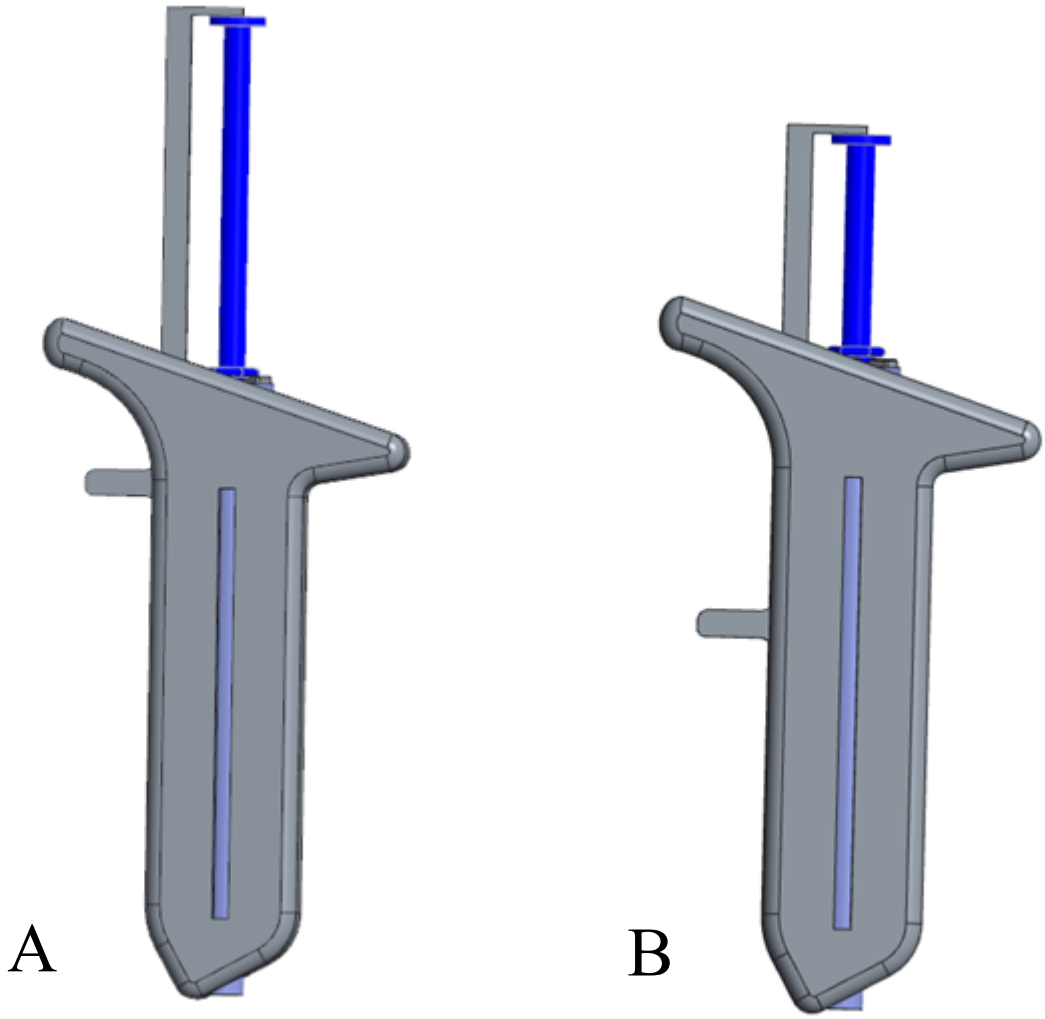

Figure 14: CAD model of second iteration at initial (A) and intermediate (B) extension

By extrapolating the concept design for the device, the project was able to produce CAD models in PTC CREO Parametric 3.0. This software allowed the design team to change ergonomic facets in a fashion more simple than Solidworks allowed, and as such allowed the project to tailor designs to the client's needs much quicker than previously thought. This 3D model also served in giving the design team a better understanding of the internal volumes of the device.

Through CAD modeling the project team was also able to show how the proposed mechanism would work. As shown in Figure 14, a 1 inch movement of the device plunger from (A) to its final position in (B) produces a 1 inch movement in the syringe plunger. This device design succeeds in changing the location of the thumb place to an area closer to the syringe body, allowing for better control of the device and more comfortable ergonomics.

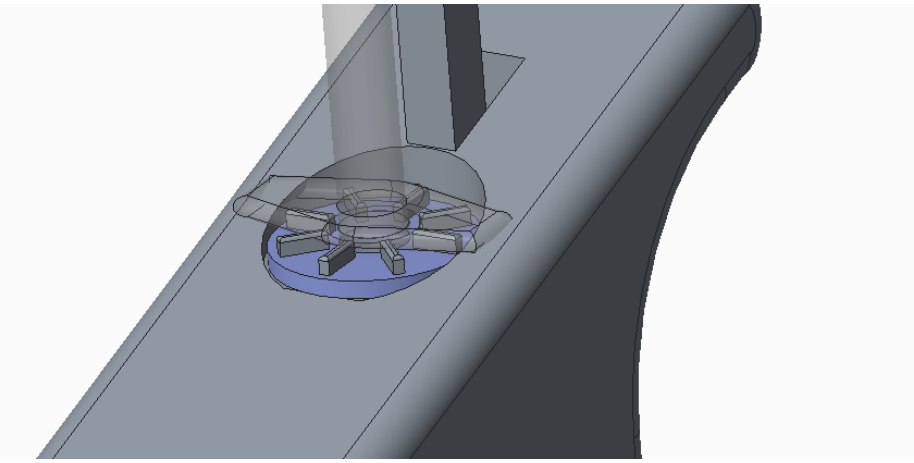

Figure 15: Closer look at syringe insertion point

The CAD model also provides a better look at the drop-in syringe design as well as how the ratchet/rack and pinion drive mechanism works, as you can see in Figure 15. The CAD model also afforded the project team the ability to begin 3D printing a model for use as a proof of concept piece.

5.3 3D Printing of Device Shell

Printing for the device was managed done on a MakerBot Replicator 2x. This device featured a possible 100 micron resolution and 9.7" x 6" x 6.1" possible build volume, making it ideal for uses in prototyping the design. By converting the CAD model into point data the project team was able to place the design into MakerBot Desktop, and then print it on the MakerBot Replicator 2x using the following parameters.

Table 3: MakerBot Replicator 2x Print Settings

Parameter	***Input Value***
Filament Type	MakerBot ABS
Extruder Temperature	230 °C
Build Plate Temperature	115 °C
Resolution Preset	High (.15 mm Layer Height)

These parameters were based on initial print parameters set as default to the device. Small changes to extruder temperature and build plate temperature were made to better adhere ABS boats made under each device shell. Full procedures can be found in Appendix A section 9.1 Procedure for Printing of CAD Model. Initial prints failed repeatedly due to filament feeder malfunctions and creep caused by the heated plate and slower deposition rate caused by higher resolution. This was combatted using a slurry of acetone and ABS recommended by Anthony D'Amico of Peterson Lab. This slurry allowed for better bonding of ABS to the build plate while reducing the creep caused by the heated plate by creating a small barrier layer of ABS slurry that acted as a buffer layer. Procedure for Slurry creation can be found in Appendix A section 0

Procedure for ABS Slurry Creation.

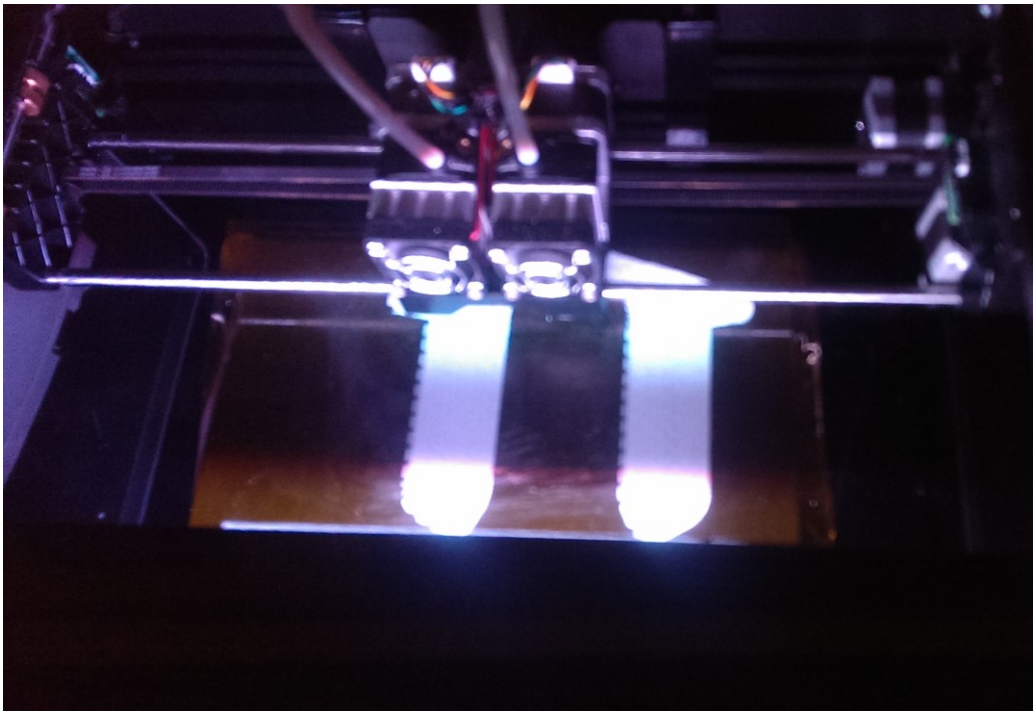

Figure 16: 3D printing of second iteration design

This printed device shell was made in two parts to show the potential inner workings of the device via presentation of the lateral cross-section of the device. When put together, the shell also showed a potential final size and ergonomics of the device. These models were brought to the client for feedback and detailing potential future changes.

5.4 Clay Modeling for Ergonomic Design

After the initial devices were shown and discussed with the client, focus was turned to the ergonomic design. The shell would dictate the ability to implement mechanical drive systems and would in essence drive device creation. Because of this, the project team needed to ensure that the ergonomic design was comfortable for the physicians.

To achieve this goal of ergonomic comfort, the design team formed multiple clay model shell designs. They used shapes similar to the cross sections found in Figure 13 to offer a better baseline for ergonomic shell design. To make these clay device shells, modeling clay was procured and shaped into tubes of 1.5 inches in diameter and 5 inches in length. A scaled cut out of Figure 13 was placed on the cross sectional face of each tube and the tube was then molded to each shape. A cap was placed on each piece resembling the upper portion of the second iteration design. A clay model of the actual device was made as well to further aid in rapidly changing the ergonomic layout. Each of these designs was then presented to the client for feedback.

5.5 Second Iteration Client Feedback

User feedback for the second round of devices was positive and provided a progressive method for creating the final iteration of the device. Using the models, the design team were able to gauge the design on ergonomics, drive functionality, balance and aesthetic appeal. These four categories would be employed to further drive change within the device and these parameters also relate back to the initial design concepts seen in Figure 9. There were a number of take away messages from this round of client feedback and the new design parameters provided the design team with pertinent feedback that better aided the project team in creation of the final shell and drive devices.

5.5.1 Ergonomic Feedback

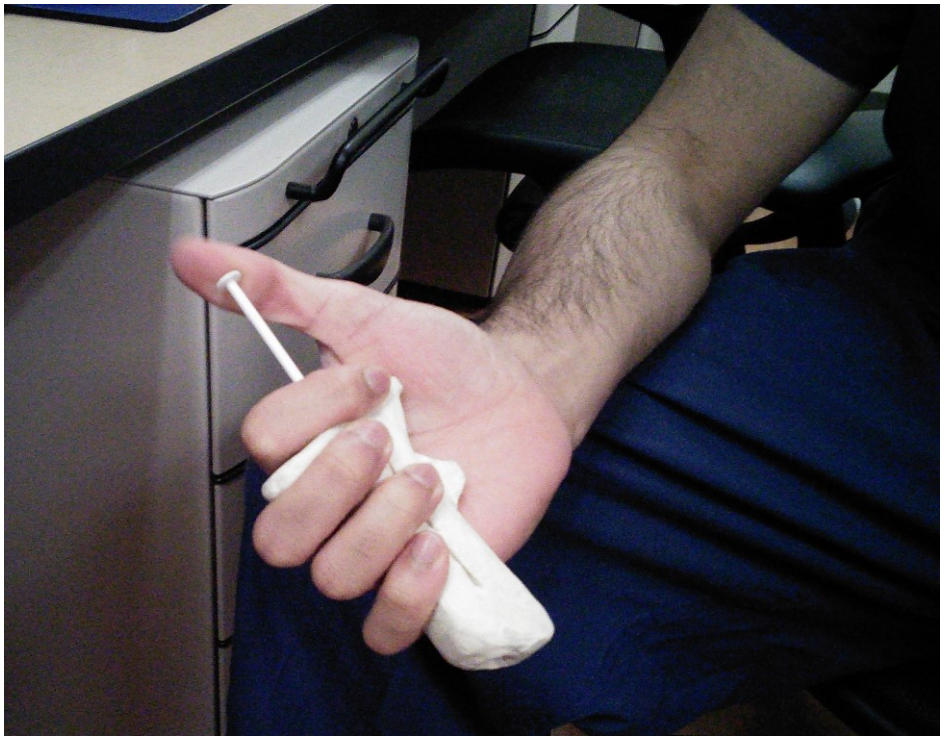

Figure 17: Clay model testing of the ergonomics of the second iteration design

The ergonomic feedback the shell received was beneficial to reshaping the device. The project team first approached the client with the clay mockup of the design pictured in Figure 17. The project team immediately realized a key concept that the design lacked. The ergonomics of the device did not readily suggest how it was to be held. This meant that, as a new user, surgeons like Dr. Naram would not be able to hold the device properly. In fact in the above figure, Dr. Naram is incorrectly holding the device. His thumb is extended when it should be placed on the plunger featured lower on the device. In Figure 17, the client's index finger is above the index finger catch instead of the intended location of under the catch. After this misinterpretation of the devices ergonomics, it became an imperative that future designs have more obvious placements for the thumb and index finger, to prevent misuse of the device by a new user.

From use of the clay shell models the project team were also able to better understand how the barrel shape made a difference to the physician. Ideally, the device would fit firmly in the first web space with consistent contact though the palm and a slight tapering as it sits within the hand. The assumption was underscored as the project team proceeded through the feedback with Dr. Naram. From the shapes mentioned in Figure 13, the first two received negative feedback as they were too small to be placed in the hand and stay stable, the first oval cross section, or too large and sharp without enough taper, the rounded square cross section.

The third cross section received favorable feedback. The taper designed allowed for continuous contact with the hand and allowed Dr. Naram to easily balance it within his fingers. It was noted that the client also wanted to place his index finger above the index finger rest instead of underneath. IT was also noted that the slightly rounded front and rear of the design aided in keeping the device firmly gripped within the hand.

5.5.2 Drive and Volume Delivery Design

The feedback for the volume delivery portion of the device was greatly beneficial in steering the project away from the 1:1 movement ratio design mechanism. Because a one inch movement on the device plunger meant a one inch movement on the syringe plunger, the design was really only moving the positioning of the hand and thumb while keeping the large range of motion needed to administer a dosage. The design team also surmised that keeping the same large range of motion would likely continue to exacerbate the pain and discomfort caused by fatigue of repeated injections.

6 Final Design

The final design was broken into two separate designs. The first was the ergonomic shell of the device. The second was the drive and volume delivery mechanism of the device. Both were conceived with the constraints the other may have in mind.

6.1 Ergonomic Device Shell

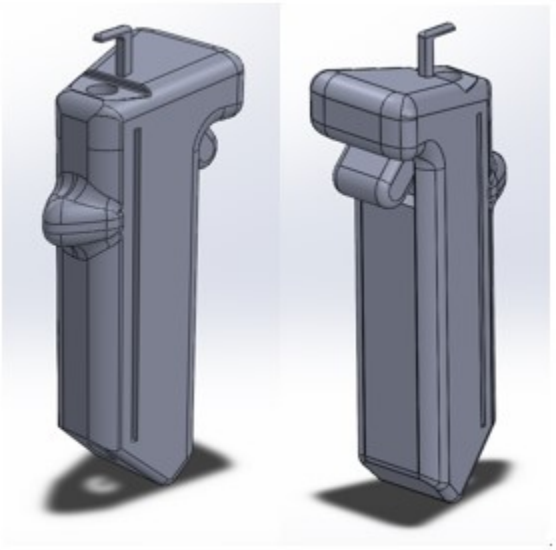

Figure 18: Final design for ergonomic device shell

The final design for the device shows many of the device facets exhibited in the previous design iterations while addressing the previous design problems that the design team face in the initial and second iterations. There are six key design features that the design revolves around:

- Index Finger Rest and Placement
- Thumb Rest and Placement
- Ergonomic Design
- Volume Window
- Syringe Drop In
- Fitting a Ratcheting Design

The index finger is placed on the top of the bump featured on the front of the device. In the previous design, the client had mistakenly pinched the index finger rest between his index and middle finger, offering him more stability when using the device. The design team carried this device facet forward and placed it in such a way that it lined up the index finger and base of the thumb on the shell. This focus a single style of grip getting rid of the previous confusion associated with the design.

The index finger rest also allows for better control of the devices rotation and movement in space. By pinching the finger rest between the proximal phalanges of the index and middle finger, users can prevent movement and slippage of the device.

The thumb rest and thumb placement is partially dictated, as previously mentioned, by the index finger placement. The first web space can be placed readily under the thumb rest and can be removed when the physician seeks to inject the volume. The trigger is rounded to comfortably fit and work under the pressures of repeated depression by the thumb.

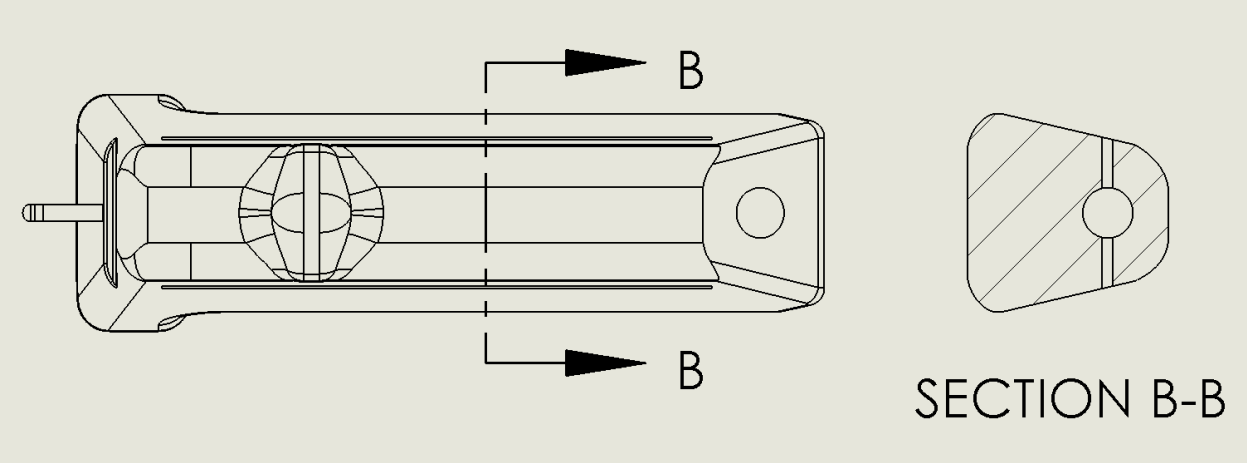

Figure 19: Final design section view of ergonomic shell

The Ergonomic design is taken form the feedback received on the clay models the design team created previously. This design is similar to the last section view seen in Figure 13, and has

been compressed slightly to better meet the ergonomic needs of the client and fellow surgeon. This design provides a greater usable surface area, increasing stability in the hand, and fits well within the volume that the hand can comfortably control.

The volume window was a design facet that continues from the first iteration of designs. The client always wanted to be able to see how much of the device volume has already been used and this window prevents the physician or surgeon from having to guess how much serum they have injected over the course of the treatment. This window increases safety for the patient and provides peace of mind to the surgeon or physician who is delivering injections using the device.

Syringe drop in was carried over as a design facet from the second iteration device. This design facet makes loading and unloading of the syringe significantly easier and prevents potential internal contamination of the device as it no longer requires the device to be open when exchanging syringes. It also reduces the time needed for reuse of the device after expenditure of an initial syringe.

Design concepts for the internal volume deposition mechanisms had to be kept in mind while designing the shell of the device. The upper portion of the device was developed to comfortably house any such mechanism by having a wider and more spacious upper end than in previous designs. With this space in mind, an internal mechanism was developed that would safely and efficiently fit within this space.

6.2 Ratchetting Drive Mechanism

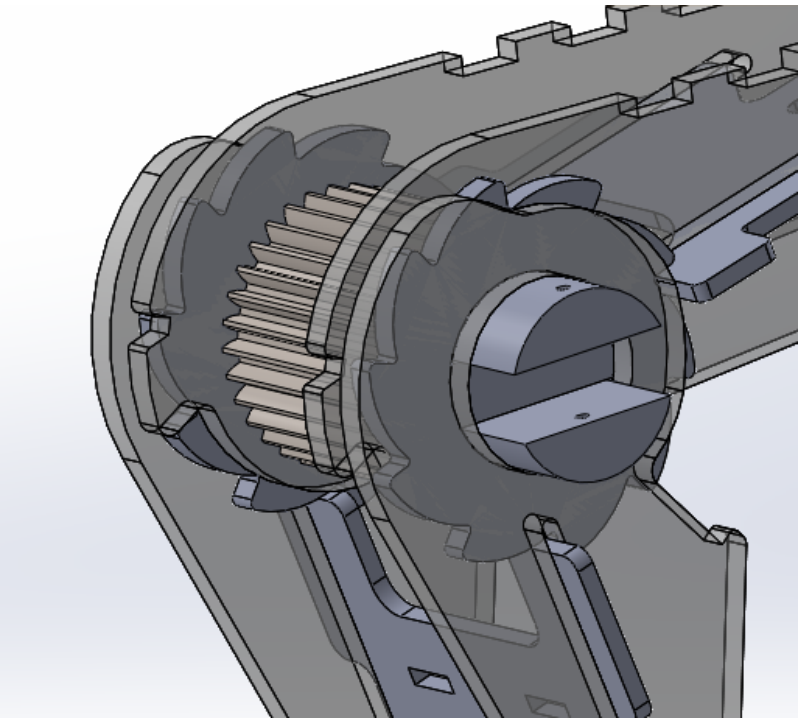

Figure 20 Ratchet Mechanism Design

By adopting a ratchet like design for the driving mechanism, the user cannot turn a push of a button into the downwards movement of the plunger. The mechanism works similar to that of a normal ratcheting trailer hitch, except one side is not fixed and a spring now prevents the over extension of the device past the limits of the device. In essence, the ratchet can only move one asymmetrical tooth at a time, allowing for only one aliquot to be delivered per gear press.

To achieve syringe plunger depression, the ratchet was coupled with a rack and pinion like rail set up. This set up allowed allows the device to change the rotation of the gear in the middle of the ratchet device into the downward movement of the rail.

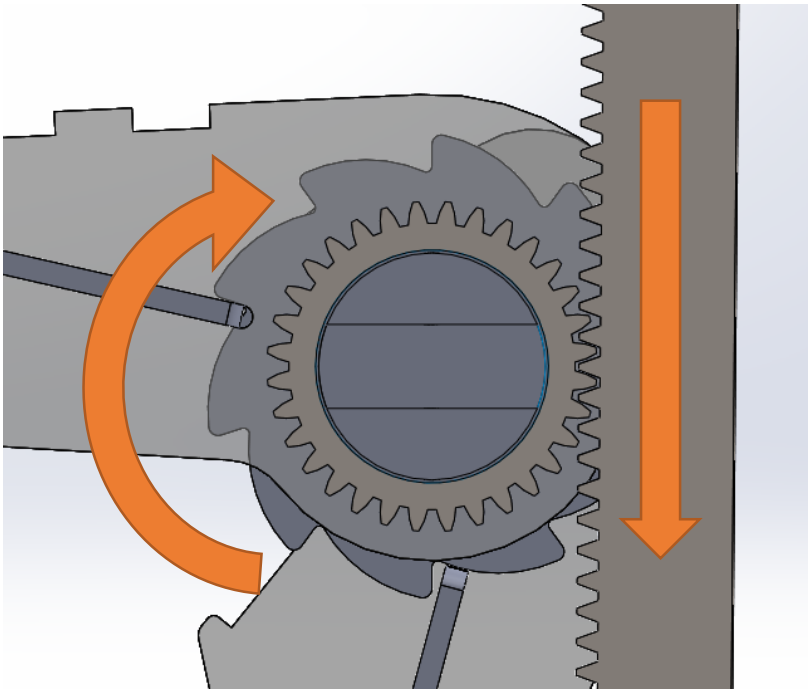

Figure 21: Ratchet and rail combine to depress plunger

Every time the button is depressed the casing moves downward. The spring tensioning of the casing then pulls the assymetrical wheels of the ratchet up as the pawl is now engaged. When the pawl is engaged, the gear around the center of the ratchet seen as a beige tubular gear in Figure 20, spins clockwise, pulling the rail down and with it the syringe plunger.

This method also offers safety to the doctor. Because the movement of the syringe plunger only begins when the casing is lifted (after the the button is pressed and allowed to return to its initial position) the Surgeon can avoid misinjections by not letting go of the button. This way if it is accidently pressed while in the incorrect position, the position of the needle can be corrected and the contents then released. The button also cannot be partially pressed as it would then return to the start position without disengaging or reengaging the ratchetting system

6.3 3D Printing of Prototype

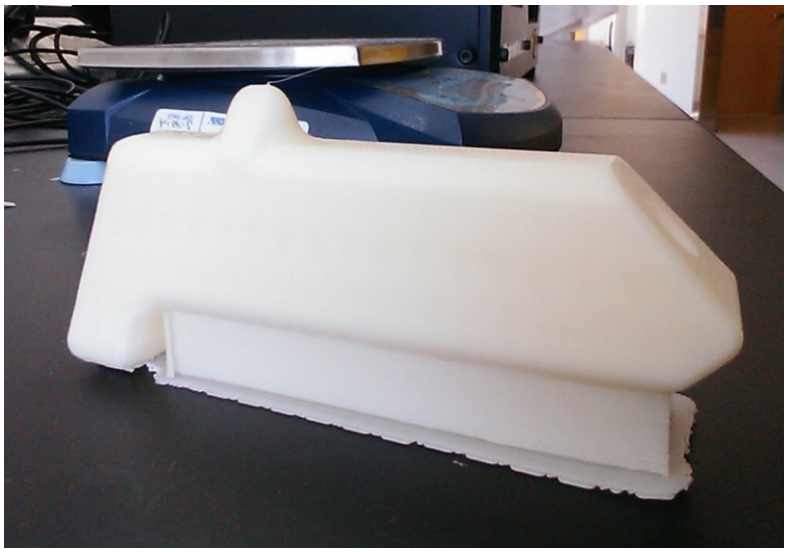

Figure 22: Printed Shell of final ergonomic design

Printing of the prototype shell was achieved via methods described in Appendix A using the presets found in Table 3. This model featured only shell components and no components from the mechanical volume deposition mechanism. The model was initially printed on a boat to promote even adherence to the print surface, and support material was used to procure an even print. Both boat and support material were then sanded down and removed.

6.4 Proof of Concept Model

A proof of concept model for the mechanism was built to provide a basis for future design and production. The project was limited by the resolution of the 3-D printer and the creation of device size model wasn't possible. To prove that the concept worked and provided an efficient methods to meet the goals the concept was built in 2:1 scale.

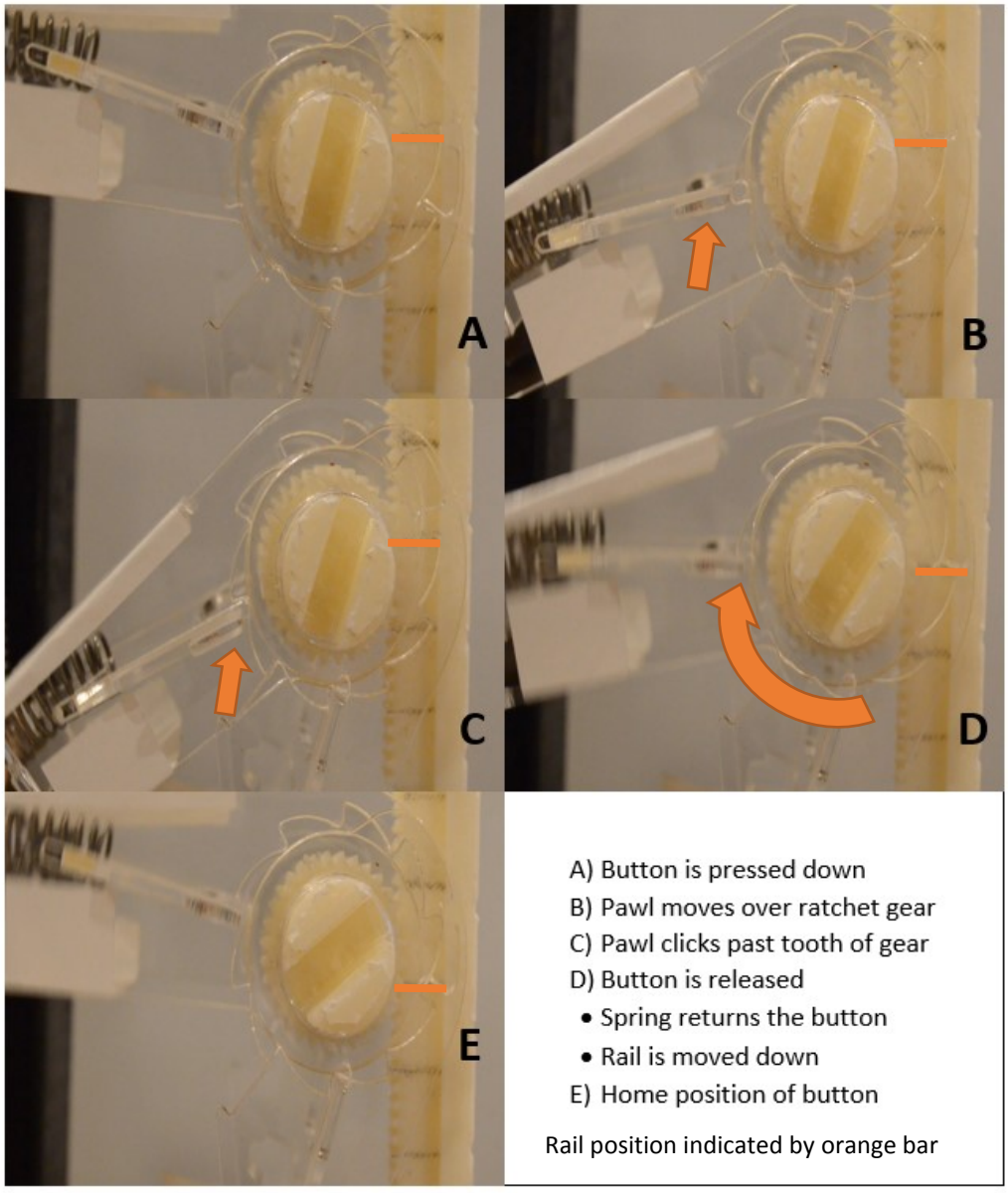

Figure 23: Proof of Concept Model showing the ratchet functionality of the deposition mechanism

As shown in Figure 23: Proof of Concept Model , the model functions and displays the method of interactions that the ratchet design uses to achieve the plunging of the device. A single press of the scale proof of concept model's lever is tantamount to a single aliquot being delivered to the patient.

7 Conclusions and Future Recommendations

7.1 Ergonomic Design

The goal for an ergonomic design was to develop a product to aid a physician in accurate hypodermic injection administration. The idea was to employ a design that allowed for a simple, comfortable, and intuitive injection experience. . To aid in the process of developing ergonomics clay models were made to better understand surgeon preferences and grip sizes. Rapid prototyping via 3D printing was employed to rapidly create models and scale replicas of the ergonomics. Through multiple iterations of device shells, a final shell was settled upon.

The final design created, employed all the design facets that were discussed throughout the iterative design process. These include, ergonomic design, volume delivery window, and easy to use press button location and an overall simple and safe design. The design proposed can also still be tweaked using CAD software such as Solidworks or PTC CREO Parametric 3.0, and as such will continue to get ergonomic updates as feedback from the client continues.

Future updates to the design of the shell will be dictated by further physician input, and will be carried out at the availability of surgeons at UMass Medical. Improvements to the design can then be handled within the CAD Software based on the already available files as mentioned above.

7.2 Volume Deposition Mechanism

The goal for the volume deposition Mechanism was to safely and accurately deliver acute quantities of serum to a patient at the press of a button. The Strategy was to employ a design that allowed for a simple and accurate mechanism, which would have some feedback for the surgeon. Through rapid prototyping and iterative design a deposition mechanism was made by coupling a ratcheting mechanism to a rack and pinion like device. Together this mechanism offered a simple, safe and adjustable way to deliver volumes of drug to a patient.

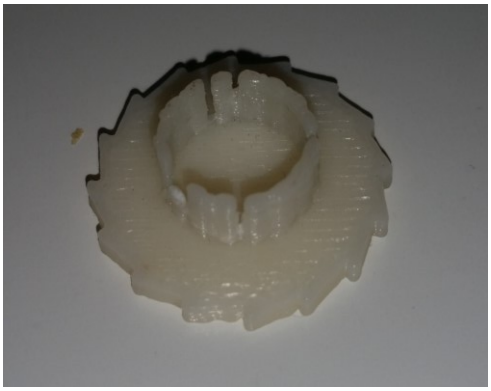

Figure 24: Common printing defect at small scales

Further improvement of this design will come from an improvement in 3D printing. The current method is limited by accuracy of the 3D printing head in terms of making small gear teeth and material walls. The gear shown in Figure 24 for example shows a wavering and inconsistent wall structure for the asymmetrical gear used in the ratchet device. The resolution for these prints was increased from a layer thickness of .15 mm to .10 mm. Even with these resolution increases, the produced pieces did not have the required shape or sturdiness needed. These problems were difficult to overcome in the short period of time provided within the scope of the project and will have to be left to future iterations to fix. By creating these parts in more

accurate 3D printers, smaller pieces would be possible and a full scale down of the mechanism would be attainable.

7.3 Further Testing

Further testing would have to be carried out to substantially flesh out the device's use parameters. Because of the problems with scaling down the drive mechanisms, no tests have been done to quantify the accuracy of the mechanism at scale. Though the mechanism does display great promise in its reproducibility and consistency of movement, further testing of the device on skins and hydrogels would allow for further quantification of the abilities of the device at scale.

Due to the limitations in filament types (ABS plastic only), choosing the device materials was also pushed out of the scope of this project. However, in the future this aspect could definitely be addressed. Considerations in design have already been made for replication with 3D printers and considerations would have to be made when switching to injection molding. Material choice would also have to be taken into consideration as ABS is not safe for use with common cleaning solutions of alcohol and would not be FDA approved (Food and Drug Administration, 2014).

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9 Appendix A

9.1 Procedure for Printing of CAD Model

1. CAD models were exported from Solidworks/CREO Parametric 3.0 in the .STL file format.
2. MakerBot Desktop software was started and allowed to load
3. .STL files were then imported into the MakerBot Desktop software via the ADD FILE button.
4. If prompted by software objects were moved to the platform
5. If needed objects were rotated to the correct orientation of printing
6. If multiple objects were printed, steps 1-5 were repeated.
7. Objects were positioned on print bed with ample space between objects using the movement tools.
8. Setting were calibrated using the SETTINGS Buttons
    a. MakerBot ABS was selected for the left nozzle
    b. MakerBot ABS was selected for the right nozzle
    c. Color-Matched was selected for the Raft and Supports
    d. A appropriate resolution was selected for the object to the printed
    e. If high was selected Advanced options button was clicked
        i. Under quality layer height was set to the appropriate value
        ii. Under temperature the Left and Right Extruder temperatures were set to 230°C and the build plate was set to 115 °C
    f. Save settings was pressed

9. File was exported using the EXPORT PRINT FILE button
    a. File was allowed to load
    b. Print Preview was selected to ensure no improper geometry was seen
        i. If print preview was incorrect, step 7 was repeated and then step 9 was tried again.
        ii. If print preview was correct, the window was closed using the Close button
    c. File was exported using Export Now button in the Export window.
        i. File was saved as .x3g file type to SD card used with MakerBot System
10. SD Card was placed in SD Card slot for MakerBot
11. Build from SD Card was selected on MakerBot
12. Using the up and own arrows, the correct file from the SD Card is selected
13. Print is initiated via pressing the central OK button.

9.2 Procedure for ABS Slurry Creation

1. .5 gram of scrap ABS extruded filament is weighed on a scale
2. ABS is crushed and broken via folding and placed into a 100ml beaker
3. 60 ml of acetone is added to the beaker
4. 5 minutes of time is elapsed to allow for the melting of the ABS into the acetone
5. Slurry is mixed using glass rod until mixture is evenly off white in color
    a. If pieces of ABS are still present, additional acetone may be added until pieces are dissolved.
6. Slurry can now be dabbed on to surface of kapton taped build plate via Kimwipe.