Design and Optimization of Ergonomic Surgical Forceps for Skin Closure

A Major Qualifying Project
Submitted to the Faculty of
Worcester Polytechnic Institute
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Degree of Bachelor of Science

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Chapter 1 - Introduction

General Need Statement

Surgical forceps are one of the most commonly used tools in surgical procedures for grasping and manipulating various types of objects during operations. They have been used for centuries, and their current standard design has not been changed in decades (Sheikh, 2013). While they are effective, there is still significant room for improvement. Forceps used in the operating room are made with an uncomfortable and outdated design that does not allow for the full 360 degrees of tool rotation. There is a need for optimized ergonomic design of this tool to improve haptic interactions while grasping different objects during surgery, and to reduce slip between gloves and the tool's grips. The current design of forceps calls for a material that is strong and able to withstand the extreme heat of sterilization. The current material choice of stainless-steel allows for them to be reused and sterilized with ease, but creates a slippery surface on the forceps during operations leading to an increased chance of slipping and possibility of user error. It is essential that surgical forceps be optimized haptically and ergonomically to limit fatigue, slipping, and user and mechanical error in order to minimize complications during surgery to provide the safest possible outcomes for patients.

Project Goals and Procedures

The goals of this design project were decided on by the design team and the project advisors to address the current limitations of the industry-standard design of forceps. As a focus point for this project, the team decided to design a tool for skin closure applications by modeling designs based on Adson forceps. The design criteria that were decided on included: reducing slip, allowing for 360 degrees of rotation, ergonomics, haptics, and comfort of the overall design.

To create a design that could incorporate these features, the team made CAD models of forceps with different dimensions and grip textures. Each design varied by a certain percentage of the dimension for consistency. Once these designs were prototyped, they were tested using focus groups of resident surgeons and feedback from the project advisor, Dr. Dunn. Prototypes were used by these surgeons in non-oiled and oiled conditions to test the friction of the grip in simulated surgical conditions. The designs were also tested for their springiness and strength. This was to ensure that they were all able to withstand normal usage and to test their durability. The feedback received from these focus groups and mechanical tests was used to create a final prototype.

Report Preview

In this report, the team walks through all the relevant information and steps that were included to eventually settle on the final prototype and design. The literature review (Chapter 2) presents relevant background information to the limitations of current designs and background on necessary criteria for the new design. Important research includes material selection, sterilization, mechanical properties, and compliance to industry standards and the FDA. In the project strategy chapter the team discusses the client's need statement that was received from Dr. Dunn and other design requirements such as the focus on instruments for skin closure. The design process (chapter 4) that was implemented included consideration of alternative designs and Pugh charts that were utilized to analyze design choices that settled on a circular grip. Much of this design process and the decisions made were based on feedback from the project advisor and chief plastic surgeon at University of Massachusetts Medical Center (UMMC), Dr. Raymond Dunn. This feedback along with additional survey feedback from other plastic surgery residents is analyzed in Chapter 5, the Design Verification. In this section the team verified that the prototypes did improve upon the design criteria and resulted in positive feedback from experts in the field. After verifying the final prototype, the team performed further analysis into the Design Validation to discuss future applications and potential effects of use of this product. The team finalized the report with discussion about limitations such as access to industry level manufacturing practices, and limitations to the friction and springiness testing, and finally concluded with recommendations for future prototyping and manufacturing for ergonomic surgical forceps.

Chapter 2- Literature Review

2.1 Introduction to Relevant Background

Surgery and Skin Closure

Within the field of medicine, surgery plays a vital role in the treatment of injury and disease. Surgeries involving subcutaneous surgical procedures call for skin closure after completing the procedure in order to promote the healing of the open wound at the site and minimize infection. One of the primary functions of the skin is to protect the body from foreign microbiota to prevent infection and disease. Skin wounds provide a "moist, warm, and nutritious environment that is conducive to microbial colonization and proliferation."(Bowler et al., 2001). Surgical tools are expected to provide minimal chance of infection by being designed, used, and sterilized properly. Acute wounds, such as surgical wounds, "are expected to heal within a predictable time frame, although the treatment required to facilitate healing will vary according to type, site, and depth of a wound."(Bowler et al., 2001).Infection can cause wounds to heal improperly which can lead to "increased trauma, treatment cost increase, and general wound management to become more resource demanding"(Bowler et al., 2001). Maintaining sterile surgical equipment allows for minimal chance of microbiota from entering the site before the surgical wound is closed and gives patients the safest, efficient, most cost effective treatment available (Bowler et al., 2001).

One use of forceps is to assist in skin closure procedures. Sutures are often used to close surgical wounds after the subcutaneous operation is completed. Types of sutures include a simple interrupted suture, vertical and horizontal mattress sutures, and continuous sutures, while other skin closure techniques involve staples and adhesive strips and gel. Surgical forceps are used in most cases to retract the tissue so that the needle holder can thread the needle with the suture attached in the proper manner through the wound depending on which suture type is necessary. The goal for wound closure is to "prevent postoperative hematoma and minimize risk of infection" while leaving the most cosmetically acceptable scar possible (Bowler et al., 2001). If error were to occur in one or more of the aforementioned procedures, the risk of infection will increase leading to future personal and financial complications for the patient (Louie and Larson, 2018).

Types of Forceps Available and Manufacturing

There are many types of forceps used in the medical field. Different forceps are used depending on the procedure being performed. For each varying design of forceps there are different manufacturing processes in place. Forceps can be manufactured with clamps or without them, depending on their application. Forceps manufactured with locking clamps allow the surgeon to grip and hold an object in the operating area and maintain that grasp without having to be constantly holding the forceps or manipulating the amount of force being applied. Some types of forceps that are made with locking clamps include: hemostats forceps, splinter forceps, sponge forceps, needle holders, tubing forceps, and towel forceps.

Hemostat forceps are manufactured with “locking mechanisms called ratchets” (Waqaas, April 2012), which allow for the manipulation of the instrument and are used to grasp and clamp blood vessels and other things at the surgical site to prevent fluid flow, usually blood. Splinter forceps are made with “smooth or serrated tips, curved, straight or without ratchets” and are used for removal of pointed objects from the body, to handle sutures and to manipulate difficult to reach areas being operated on (Waqaas, April 2012). Sponge forceps are made with two circular tips relating to tongs which allow for “clamping, holding, gripping, twisting tissues, or inserting things into the body”(Waqaas, April 2012). Tubing forceps are made in order to place tubes into blood vessels during operations and are also known as tubing introducer forceps. Lastly, towel forceps are used to “hold or place pieces of towels or draped in the correct position during an operation” and are essential to the removal of these towels and drapes after the procedure is completed before skin closure (Waqaas, April 2012).

Forceps that are not manufactured with a locking mechanism are used to act as an extension of the surgeon’s “thumb and opposing fingers in the assisting hand to augment the instrument in the operating hand.” allowing for intricate manipulation and access to hard to reach areas (Louie and Larson, 2018). Similar to locking forceps, non-locking forceps are used to “grasp, retract, or stabilize tissue” as well as to “pack or extract sponges, pass ligatures, and stabilize and manipulate needles during suturing” (Louie and Larson, 2018). This design of forceps is what is primarily used in situations of skin closure following subcutaneous surgery. Dressing forceps can “be manufactured with straight, curved or with special angled tips” (Waqaas, April 2012) for varying types of surgical procedures . They are used for the application and removal of medical dressing on patients with a more forgiving version of dressing forceps are used in eye surgery. Tissue forceps are manufactured in a similar way to dressing forceps but are made with teeth which “provide better grip for holding tissues and are designed to avoid damaging the tissues.”(Waqaas, April 2012). Varying degrees of teeth are used in tissue forceps depending on how delicate the targeted area is. This project is focused on improving the ergonomics and haptics of non-locking tissue forceps used for the closure of skin or skin-like structures.

Area of Focus for this Report

Forceps are a small, handheld tool that are used in surgery for grasping tissues and objects that are not easily grasped with the fingers. They consist of two thin plates of material, usually a type of stainless steel, which are connected at the end, configured in such a way that it springs open when no force is applied. These two plates are joined by applying a force on either side with the thumb and index finger, gripped similarly to a pencil (Visenio, n.d.). Forceps are mainly distinguished from one another by their overall shape and the “tooth” at the tip of the tool. One of the most common toothed forcep types is “rat tooth” which consists of one tooth on one side, which sits in between two teeth on the other side when compressed. Adson forceps, which are used for skin closure, tend to have this style of tooth.

Figure 1: Rat Tooth Tips on Forceps (Amazon, 2016)

Toothed forceps are commonly used to grasp thicker, denser tissues, such as skin. Although many commonly used surgical forceps are toothed, there are also serrated forceps, which do not have a tooth on the end, but have small edges on the inside of the end for increased friction. These forceps are used less for thicker and larger tissue, but are used mostly for softer tissues, nerves, and vessels (Brisson, 2011). For this project, we will be focusing on toothed Adson forceps used for skin closure.

Typical Adson forceps are about 5 in x ½ in x ¼ in, within about ½ in (Mopec, 2021). The main characteristic of these forceps that make them favorable is the widened grip. A typical forcep has a grip width of about half that of Adson forceps, allowing for less finger to forcep contact, decreasing the control of the instrument.

Limitations of Traditional Forceps

Current forceps designs create problems for surgeons when manipulating and maneuvering them during operations which can lead to complications for the patient during and after surgery. It is essential for surgeons to be able to maneuver the forceps with the fewest possible degrees of movement and to be able to compress and retract the forceps without using too much or too little force. This feeling of the forceps is commonly referred to as springiness. Forceps should also be designed in a way that minimizes slipping due to bodily fluids present during operations. Having forceps with optimal degrees of movement and springiness would minimize user error, mechanical error, and fatigue. Commonly used forceps do not allow for enough rotation of the device about its long axis due to their squared edges and flat grips. This complicates the manipulation of the forceps during procedures, causing the surgeon to have to position their arm and forearm awkwardly with too many degrees of motion than is preferred. It also increases the chance for user and mechanical error because, if rotated too far about the long axis, there becomes an increased chance that the forceps will slip and over rotate possibly damaging delicate tissues in the process. Current forceps are manufactured using stainless steel or other heat resistant, strong metals yielding optimal composition for repeated sterilization and strength. However, those materials are not ideal for use in environments with slippery fluids, such as the operating area, causing increased chances for slipping of the surgical forceps during procedures. A new design for surgical forceps must incorporate all optimal aspects such as springiness, rotation, and grip in order to minimize or eliminate error during surgical procedures.

2.2 Background of Design Specifications

Sterilization

The Center for Disease Control or CDC outlines the guidelines for sterilization of medical equipment in, *Guideline for Disinfection and Sterilization in Healthcare Facilities (2008),* last updated in May of 2019. The need for sterilization of medical equipment is essential in healthcare facilities in order to eliminate the transmission of harmful microorganisms and pathogens between patients when under the care of medical professionals. Sterilization "destroys all microorganisms on the surface of an article or in a fluid to prevent disease transmission associated with the use of that item." (Rutala and Weber, 2008).

The CDC distinguishes levels of required disinfection and sterilization for medical equipment into three categories: Critical Items, Semicritical Items, and Noncritical Items, "according to the degree of risk for infection involved in use of the items" (Rutala and Weber, 2008). Surgical forceps fall into the 'Critical Items' category because they are surgical instruments "that enter sterile tissue or the vascular system" and have a "high risk for infection if they are contaminated with any microorganism" and could result in disease transmission (Rutala and Weber, 2008). Items in this category are subject to steam sterilization as long as the material can withstand extreme heat.

Steam sterilization, or autoclaving, is when "moist heat in the form of saturated steam under pressure is the most widely used and most dependable. Steam sterilization is non-toxic, inexpensive, rapidly microbicidal, sporicidal, and rapidly heats and penetrates fabrics" (Rutala and Weber, 2008) and is used in healthcare facilities on equipment able to withstand extreme heat. By delivering steam sterilization "moist heating destroys microorganisms by the irreversible coagulation and denaturation of enzymes and structural proteins"(Rutala and Weber, 2008). Pressure is added into the system to reach the optimal temperatures used in steam sterilization which are, 121℃ (250℉) and 132℃ (270℉), and the item must be "maintained for a minimal time to kill microorganisms" depending on the material of the item being disinfected (Rutala and Weber, 2008).

Regulating Bodies

The production of medical devices is overseen by different governing bodies. In the United States, the most prominent governing body for medical devices and healthcare in general is the Food and Drug Administration (FDA). Within the larger body of the FDA, the Center for Devices and Radiological Health (CDRH) is responsible for overseeing any body that is manufacturing, and/or importing medical devices for sale within the United States (U.S.A. Food and Drug Administration., 2020). The degree of regulation is dependent upon how the medical device is classified, Class I being the least risk, Class II presenting average risk, and Class III presenting the most risk. The FDA provides guidance on how to classify such a medical device, and then oversees the production and sale of the device.

The International Organization for Standards (ISO) creates and regularly reviews "formulas" for the design, manufacturing, and testing of products internationally. ISO presents less regulation to medical device production, and more guidance and standards for design and testing of medical devices (among many other things). ISO is an international body that gathers experts in the specified field to form a committee and decide upon the most agreed upon way of accomplishing certain tasks. Many different regulating bodies utilize ISO produced standards as a measure to govern.

Another body that provides such standards is ASTM International, formerly known as the American Society for Testing and Materials. This body also provides standards on an international level that provide guidance for the optimal ways to achieve designing and testing a wide range of goods, and has a large branch and focus on medical devices.

Materials

Forceps need to be created with two components in mind, one being the body of the forceps and the other being the grip. The materials used must be strong, durable, and able to withstand extreme heat for repeated sterilization. The 2019-2020 Major Qualifying Project (MQP), "*Design of Improved Scalpel Handles with Optimized Grips,"* explored the possibilities of using materials such as stainless steel, thermoplastic elastomers, silicone, neoprene, and acetal (Burke et al., 2020).

Stainless steel is widely used in the medical field for its compelling properties of ,"cost, strength, corrosion resistance and ease of cleaning" (Narayan, 2012). Stainless steel is a material known for having the ability to resist heat and corrosion due to the addition of chromium to its chemical makeup. It also has characteristics of high tensile strength, durability, formability, long lasting, and environmentally friendly." (Eagle Stainless, 2021). The two main types of stainless steel used in the medical industry are 316 and 316L. 316 L is the low carbon version of 316 stainless-steel. Both types cost about the same price. These two options can either be molded or 3D printed and can be easily overlaid with other additive materials. Adding a more flexible overlay material to a strong stainless steel base would allow for a grip aspect to be introduced optimizing user experience to reduce fatigue, slip, and mechanical error.

Springiness

Springiness is defined as the rate at which a deformed material goes back to its undeformed condition after a force is removed. The measure of springiness is not the same as the measure of firmness. While firmness describes the force required to close or bend something, springiness describes the elastic recovery. Springiness is a textural property measurement that is commonly used in the food industry. The graph below shows how springiness is measured and calculated (Stable Micro Systems, 2020).

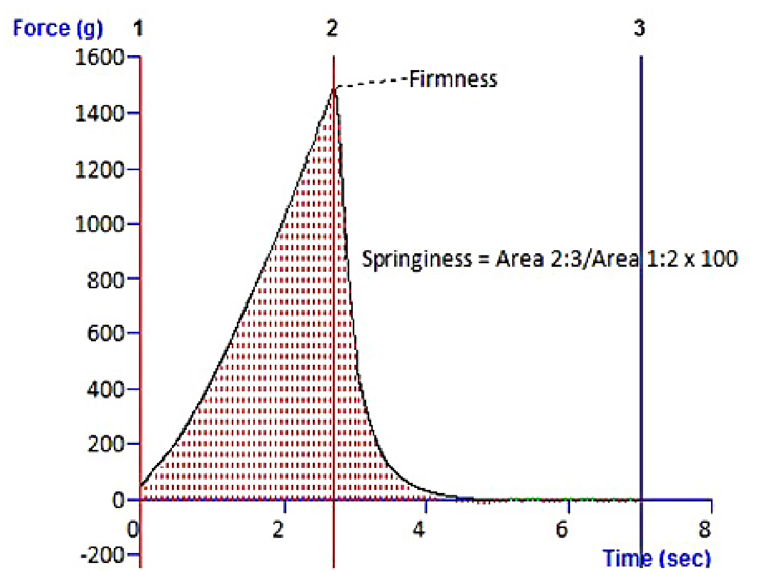

Figure 2: Springiness Calculations (Stable Microsystems)

To measure springiness, a device that performs uniaxial mechanical tests should be used, such as an Instron 4455. The device should be programmed to apply a compressive force first, before raising back up to the original position. While the motion is occurring in both directions, the force transducer measures the force that the test material is exerting on the plates. A graph similar to Figure 2 would be produced for the material. Using the graph, the springiness can be calculated as a ratio of the area under the curve while the plate is raising up to the area under the curve while the compressive force is being applied (Stable Micro Systems, 2020). A “perfect spring” would have a springiness ratio of 1, since it exerts the same force back on the plate as the plate puts on it. A material with no springiness would have a ratio of zero, since it would exert no force back onto the plate as it is returning to its original position. Most materials will fall somewhere in between zero and one.

Even though springiness is a metric that is often used in the food industry to quantify how food will feel in someone's mouth, it is applicable to this project because forceps need to "spring back" and have the right feel in a surgeon's hand. By using this metric as a way to quantify the feeling of forceps springing back in the surgeon's hand, insight can be gained into how to design for an ideal springiness.

Grips

An important aspect of the design of surgical forceps is the grip on the forceps where the surgeon will grasp the tool between the thumb and forefinger. Important considerations for the grips include increasing the coefficient of friction so that there is reduced risk for slipping of the surgeon's hand on the device. In a previous MQP by students at Worcester Polytechnic Institute (WPI), a team was tasked with redesigning the surgical scalpel grip and handle. The strategic approach of that team was " to achieve an ergonomic solution for a redesigned scalpel that has favorable haptic feedback due to its shape, mechanical, and material properties." (Burke et al., 2020). The way that this project team determined how to achieve the most ergonomic scalpel design for its uses in the operating room was to design an improved grip for the scalpel. This group also based some of their research off of a different MQP team from WPI who determined a "Golden Section Ratio" which describes optimal ratios of the dimensions of the design in order to optimize the fit to the different hand sizes of surgeons along with the distribution of forces that accompany this ratio and the resulting use of the scalpel. This will not be completely applicable for the use of forceps, however, provides a starting point for this project team to determine a new "golden section ratio" for surgical forceps, and determining force distribution when using this tool.

Texturizing played a large role in the design process of the grips of the team's surgical scalpels. Texturizing materials improve the friction and the grip on the surface. This can be accomplished by adding ridges, bumps, and other irregular and non-smooth additions to the surface of the tool. The team wanted to increase friction between the grips and the surgeon's hand (specifically surgical gloves). They determined that the ridges that aid in increasing friction should be consistent and consistently spaced for the haptics of the surgeon, but raised enough that they effectively reduce slip between a glove and the tool. Testing was done based on literature stating that diamond ridges were the most effective in providing the most friction, but testing in the application of grips for scalpels revealed that the optimal texturization method was that "The dot indentations into the surface showed a large reduction in surface friction, followed by the Hilbert Curve pattern. The ridges showed higher coefficient of friction, with the best results in the perpendicular orientation" (Burke et al., 2020). These same considerations will be utilized in the design process of the grips for surgical forceps.

After determining the basic pattern of the texturization on the grips, previous MQP teams conducted subsequent tests to determine optimal sizing and spacing with haptic considerations. This testing was also based on tests conducted under different conditions of use, such as testing the scalpel grips with the bare finger pad, and with gloves on. This kind of consideration will be integral to designing optimal grips for surgical forceps, especially under conditions of wearing sterile surgical gloves and with applications of the fatty tissues and other liquids that might interfere with the use of the forcep and increase potential for slip between the tool and the surgeon's hand.

Gold Standard

Surgical forceps have a generally standard design which has not changed significantly in decades. They typically range from about 11.4-25.4 centimeters long and up to about 1.3 cm in width (Mopec, 2021). They are mostly made of stainless steel which is known for its ability to be sterilized and it's strength. Since this general design has been in use for so long, it is proven to be effective in surgery and comfortable enough to function properly. However, this design is outdated in terms of ergonomic handling and range of motion. Standard surgical forceps have a flat, serrated grip for the fingers which can be slippery and restrict the rotation of the tool. In order to reach some tissues during surgical procedures, a surgeon must rotate their entire arm and sometimes contort their upper body due to the flat grip surface of standard forceps. This can be uncomfortable and even dangerous during certain surgeries, since not being able to maintain a firm grip on tissues can cause further complications. These limitations are important considerations for the "gold standard" of surgical forcep design to be reevaluated to better address the ergonomic nature of surgical forceps.

Chapter 3 - Project Strategy

3.1 Initial Client Statement

"The specific goal of this project would be to investigate, test and develop mechanical considerations required for improving the "pincer movement" in surgical forceps advancing and adapting recently studied ergonomic and haptic considerations developed at WPI for static surgery instruments."

3.2 Technical Design Requirements

Design Objectives and Functions

Pincer Movement: "Pincer movement" in this context refers to the ability to move the hand and wrist while performing a pincer grasp on an object, which in this case is while using surgical forceps. The pincer grasp is usually a term used in a child's motor function development, but in this case is a grip which uses the thumb, index finger, and sometimes the middle finger, such as the typical grip of a pen. This project is meant to increase the ergonomic and haptic design specifications of the surgical forceps. In order to do so, the design for this instrument must enhance the ability for pincer movement and create grip ergonomics that are more comfortable in a surgeon's non-dominant hand. A rounded grip, similar to that of a pencil, is likely to be the most effective option to fulfill this objective.

Ideal Springiness: The surgical forceps must also have an ideal springiness, or force to close the forceps. This objective is less quantitative and more qualitative. A surgeon determining their ideal springiness in a surgical forcep would be described as a general "feeling" for the strength of the forceps. This "feeling" can be quantified in the testing and calculations of springiness and force to close. Different surgeons may have different preferences for this objective, making it important to do a significant amount of testing in this area.

Ideal Dimensions: The length and width of the forceps are a considerable objective in the design, since having a good weight and balance in the surgeon's hand is essential to proper function. The grip surface of the forcep should land on the tips of the fingers, and the end of the forcep should lay in the purlicue. If the forceps are not long enough to reach the purlicue, the surgeon would lose a tremendous amount of control over the instrument. The forceps must also have a comfortable width for the surgeon. If they are too wide, the surgeon may have to extend their hand uncomfortably in order to close them. If they are not wide enough, it may be too easy to close them. The instrument must be comfortably positioned in the surgeon's hand such that it can effectively be used to grip tissue without compromising the grip of the instrument.

Grasping Ability: The main function of surgical forceps in practice is to grasp different types of tissues. The design for this project must be able to effectively grasp skin tissue, as we are focusing on forceps that will be used for skin closure. This means that the design must require a strong closing force so that it takes considerable force to close them. This way, there will be a stronger force on the tip of the forceps, creating a larger compressive force on the skin. Along with the strength of the forceps, the tip design is important to an effective grip on the skin. The rat tooth configuration that is common for Adson forceps is likely the best fit for skin closure specifically.

Ability to Elevate Objects: Another function of surgical forceps is using the tip to move tissues out of the way to work around them. This is typically done with the forceps fully compressed. In order for a forcep design to allow for this function, the space between the tip and the grip must be somewhat long and thin with no sharp edges. That way, they can fit in between small tissues in order to move them around and find tissues underneath without damaging anything they make contact with. This is a less important but convenient feature to consider for the forcep design.

Constraints

Sterilization: Must be able to withstand autoclaving, which typically is steam at greater than 250 degrees Fahrenheit, without deforming or failing.

Approved Material: For use in the operating room, any tool must be within the regulations specified by the FDA. This means that the material must be sterilizable and deemed safe for use. If the materials chosen for this design are able to withstand autoclaving and are capable of staying sterile during operation, the materials will be approvable by the FDA standards.

Forceps Specifications

Operational Ranges: This forceps design will have to operate within a very similar range to that of commonly used Adson forceps. Standard Adson forceps open to about 13mm and have the ability to completely close and elastically reopen to 13mm with exceptional consistency.

Limits: The forceps should not open past about 13mm, with small room for error. This is considered to be a comfortable range of opening for the fingers to effectively compress the forceps.

Tolerances: The forceps must consistently open to the same width, within 0.1 mm, to maintain a comfortable and effective grip width. The tips must also close to the same point, within 0.05 mm, to maintain an effective grasp texture with the rat tooth tip.

Precision/Accuracy: The forceps should effectively close with the single tooth smoothly contacting the gap between the double tooth side. This is crucial for effective tissue grasping. The forceps should also open to the same width, within at most 1mm for consistency in springiness.

Material Specifications: The materials used in this design must be able to withstand autoclaving and continue to maintain sterility throughout the length of a surgical procedure.

3.3 Design Requirements - Standards

In the project design strategy, the team considered accepted standards and regulations from established bodies, such as the International Organization of Standards (ISO), of medical devices and products used in surgical fields. Standards that will be taken into consideration and critical to this project are discussed below.

ISO 13485:2016 Medical devices- quality management systems- requirements for regulatory purposes. This standard was reviewed in 2020 and plays a huge part in the design and manufacturing of all types of medical devices. This will apply to all aspects of the team's approach to redesign of forceps because of the quality considerations. Quality is an integral aspect of the design steps to ensure that the product is functional, safe, and created in a repeatable manner while meeting all customer and regulatory requirements. This standard tracks all steps from material selection to the manufacturing process of the product. In conjunction with ISO 13485, ISO 14971:2019 Application of Risk Management to Medical Devices presents a formula for how the team will apply risk management techniques to reduce risk during production and manufacturing. While not all aspects of this project will be focused on the manufacturing of the forceps, understanding the application of these concepts during the design process is important in order to one day be capable of manufacturing the device which is the end goal.

The ISO Technical Committee (TC) 170 on surgical instruments writes and reviews standards for all medical instruments used in surgery including forceps (Bischoff, 2021). They have not written any specifically on the design and production of surgical forceps but ISO 9173 applies to dental forceps used for extraction (ISO, 2016). It has three parts focused on general requirements, design, and designation. This standard will also be helpful to guide the process of design of surgical forceps because similar considerations and design requirements will apply due to the correlation with the medical field and the constraints of sterilization.

3.4 Revised Client Statement

After collaboration with Dr. Dunn, other project advisors, and conducting further research, a more defined client statement was written.

"The specific goal of this project is to develop a final prototype of surgical forceps for improved ergonomics of forceps used in skin closure during surgery. The team will investigate, test and develop mechanical considerations and designs required for improving the ergonomics of the "pincer movement" in surgical forceps. The team will advance and adapt previously studied ergonomic and haptic considerations developed at Worcester Polytechnic Institute for static surgery instruments."

All mechanical, ergonomic, and haptic considerations will be applied to surgical forcep designs based strongly around Adson forceps used specifically for skin closure to settle on a final design and develop a final prototype.

3.5 Management Approach

Gantt Chart

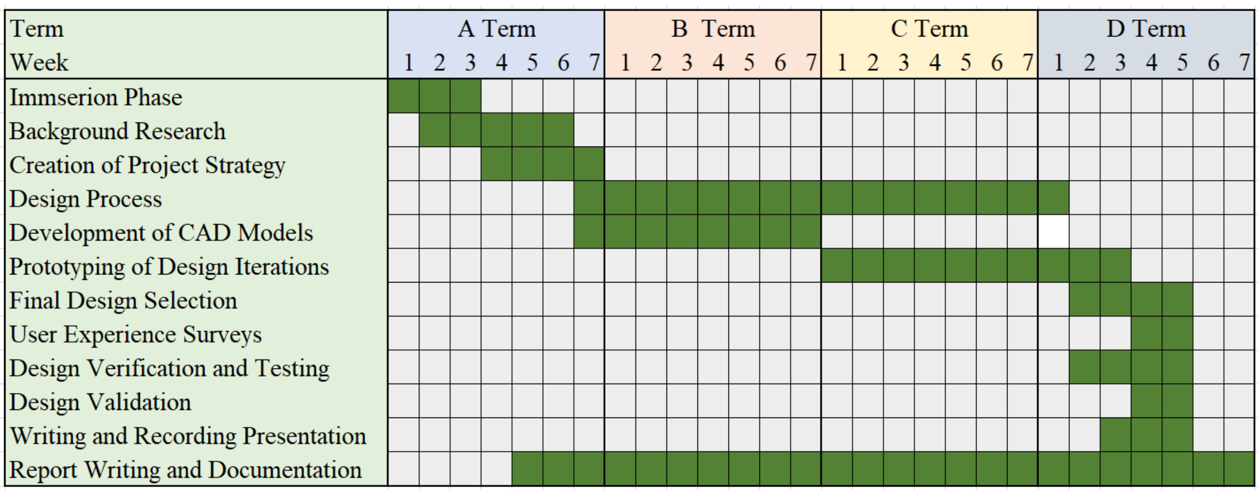

Figure 3: Gantt Chart

Work Breakdown Structure

1. Immersion
    a. Discussions with Dr. Dunn to understand expectations
    b. Reading previous MQPs to gain an idea of what we need to research
    c. Discussions with advisors to learn where to focus our research

2. Background Research
    a. Detailed notes on previous MQPs

b. Issues with existing forceps designs
c. Types of forceps
d. Forceps design
e. Sterilization
f. Regulating bodies
g. Materials
h. Springiness
i. Grips
j. Applications
k. Importance of forceps in wound closure
l. Current gold standard

3. Create Project Strategy
    a. Client statement
    b. Outline design requirements
    c. Write clear objectives for the final design
    d. List all constraints/functions/specifications
    e. Outline a management approach
        i. Create a Gantt Chart

4. Design Process
    a. Design selection
        i. Narrow down design alternatives using a Pugh Analysis to a final design concept to pursue
    b. Development of CAD models
        i. Rough CAD model of Dr. Dunn's outline
        ii. Create CAD models of varying lengths and thicknesses based on original
        iii. Update CAD with each iteration
    c. Prototyping of trial designs
        i. 3D printing
        ii. Several iterations
    d. Once shape is decided on, look into grip designs
    e. Trials with residents
    f. Narrow down designs using information from resident focus groups
    g. Produce a final prototype
    h. 3D print and assemble prototype

5. Design Verification
    a. Testing to ensure that the prototype meets all the design requirements

6. Final Design and Validation
    a. Discussion of how well the design meets all technical requirements and the final prototype specifications

Chapter 4 - Design Process

4.1 Needs Analysis

The goal of this project was to design surgical forceps that would function approximately the same as existing forceps except with a new design geared toward ergonomics and haptics. Based on this goal, the needs of the design are fairly straightforward. The design needs to function with the same specifications as existing forceps at the minimum, and must improve the ergonomics and haptics in some way. The design must be sterilizable in a typical hospital autoclave, must be able to improve upon the pincer motion, must be able to grasp skin for wound closure, and must show an improvement in the slipping of the existing grips in the surgeon's hand. Dr. Dunn requested that the design must also reduce the range of motion required to turn the forceps so that more fine movements can be made with less arm movement.

Though those are the basic requirements of this project, there are also some additional features that would be nice to accomplish. Some of these features would be an optimized version of the basic requirements listed above. This would include an idealized location of the grip along the length of the forceps, an ideal material for reducing grip slippage that is also sterilizable, ideal springiness, and a design that is optimized for mass production and manufacturing.

4.2 Alternative Designs

This project was unique because of the fact that the team's sponsor, Dr. Dunn, gave the team a rough design that he had already been working on as a starting point to base the project off of. This design features a rounded grip with two large humps and a narrower trough in the middle for the fingers to settle into. This grip would allow the user to roll the forceps slightly in their fingers to reduce the range of motion required to perform the pincer motion - one of the main requirements of this project. Figure 4 displays the grip design of the starting point that Dr. Dunn provided:

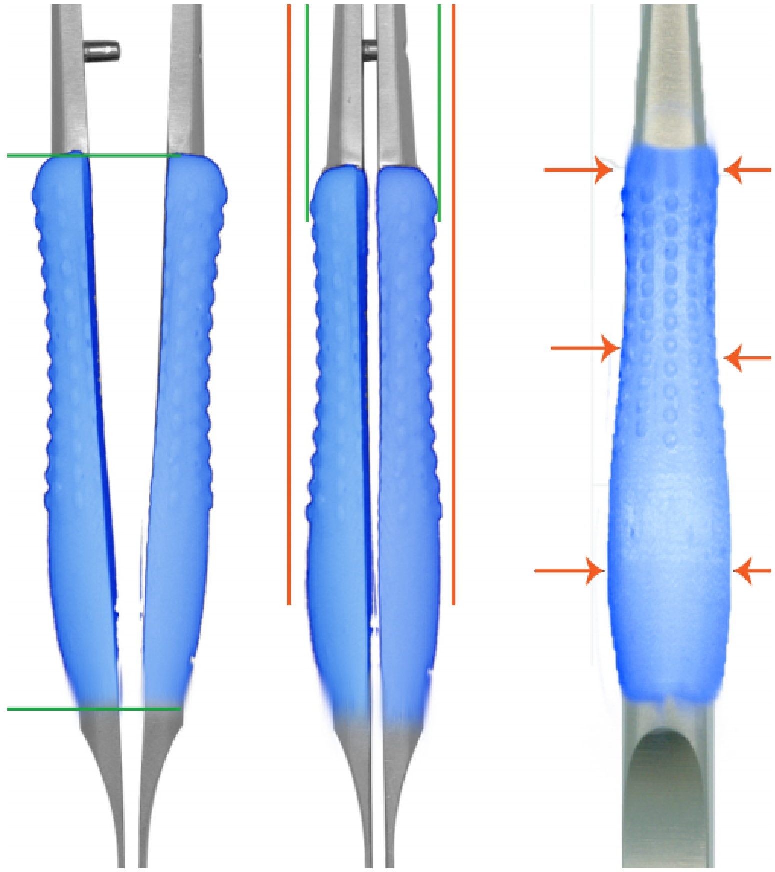

Figure 4: Design Concept 1- Rounded Uniform Grip

Dr. Dunn was adamant that this design was the most logical to proceed with, however the team carefully considered some alternate conceptual designs as well. When discussing ergonomic grips, the first thing that came to mind was the ergonomic pencil grips that are used to teach children the proper way to hold a pencil while writing. This is obviously a very different application, but the idea that the grip would force the fingers into a certain position seemed appealing since it could solve the design challenge of reducing slipping. Design concept 2 features a rounded shape with depressions for the fingers to settle into while in use. The design is made for a pencil, but the team believed it could be modified to fit the application of forceps if it was chosen as the leading design concept. The only issue with this grip style is that it is not uniform, so it would not allow the user to roll the grip between their fingers. Figure 5 shows the rubber pencil grips being used on a pencil:

Figure 5: Design Concept 2 - Rounded Non-uniform Grip

An additional pencil grip style that the team considered was a looped pencil grip. This design has specific loops for the fingers to rest in, and could even further improve the issue of slippage. Again, this grip would not be able to roll in the user's fingers, but could be modified to fit a forceps application. In Figure 6 is a photo of the looped pencil grip:

Figure 6: Design concept 3 - Finger Loop Grip

Lastly, the fourth design concept (Design concept 4) utilizes a hole in the middle of the grip for the fingers to rest in. The hole would be chamfered or filleted on the edge so as not to cause any scratching of the surgeon’s glove. The design would be modeled after the ergonomic guitar pick (shown below) and would simply be a hole drilled into the side of existing forceps to allow for slightly better gripping. This design again would not be able to roll in the user’s hand, but could be a simple modification to existing forceps that would not cause a huge change in the manufacturing process. Figure 7 shows the ergonomic guitar pick that served as the inspiration for this design concept:

Figure 7: Design Concept 4 - Rounded Hole Grip

4.3 Final Design Selection

The team began the design selection process by first creating a decision matrix with each potential design concept that was described in section 4.2. The decision matrix can be seen in Table 1:

Table 1: Decision Matrix for Alternative Designs

Criteria	Weight (1-5)	**Rounded Uniform Grip (1)**	Rounded Non-Uniform Grip (2)	Finger Loop Grip (3)	Rounded Hole Grip (4)
Ability to roll in hand	5	**1**	-1	-1	-1
Opportunity for haptic feedback	3	**1**	1	0	0
Ease of texture application	1	**1**	1	0	1
Feasibility for forcep application	4	**1**	0	1	1
Score	Out of 13	**13**	-1	-1	0

To fill in the decision matrix, each design criteria was given a weight based on its importance to the final design. The ability to roll the forceps in the surgeon's hand was ultimately the most important feature. Each concept was rated a 1, 0, or -1 based on how it compared to the typical forceps. If it was comparable it was given a 0, if it was worse than the existing forceps it was given a -1, and if it was better it was given a 1. The concepts were then totalled using the weighting factor and the final values were analyzed. Based on the needs analysis, alternative designs, and the decision matrix above, the rounded uniform grip concept was chosen as the concept to move forward with.

The team worked with Dr. Dunn to determine the rough shape of the grips and what type of forcep to focus on. Dr. Dunn requested that we work on ergonomically and haptically improving the Adson variation of forceps. In Figure 8 is a photo of the current industry standard for the Adson forceps:

Figure 8: KLS Martin Adson Forceps (12-368-12 model)

Dr. Dunn also provided the team with a rough sketch of general dimensions for a micro ball tip forcep design that he had been working with as a starting point for the design work on the Adson forcep. Although the micro ball forceps have different applications in surgical procedures, this outline was used to gain an understanding of what type of shape Dr. Dunn preferred for the grips. Those dimensions can be seen below:

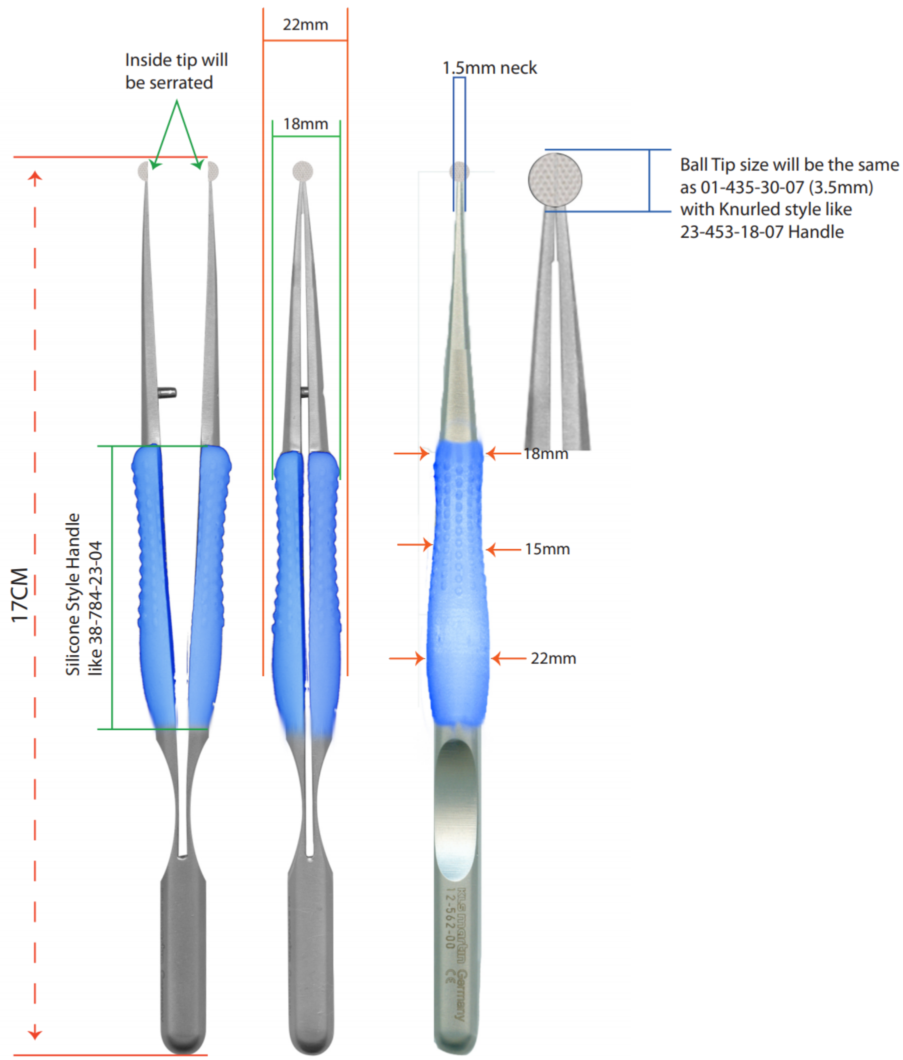

Figure 9: Dr. Dunn's Micro Ball Tip Forcep Dimension Outline

To kick off the design process, SolidWorks was used to model the "base" part of the forcep. This base follows the general shape of the forcep in Figure 9, and excludes the grip part. The base was made to the approximate dimensions of Figure 9, and the grip was excluded so that it could be made and attached as a separate part in SolidWorks. The rationale behind this approach was that the team would make the base and grip separately, and then would be able to mix and match different size grips and bases to determine the ideal size. The base part was created in SolidWorks using a series of planes, semicircles, and the lofted boss base tool. Half of the base was made first, then mirrored across another plane to create the typical forcep shape. Below are screenshots of the original base design in SolidWorks (Figures 10-12):

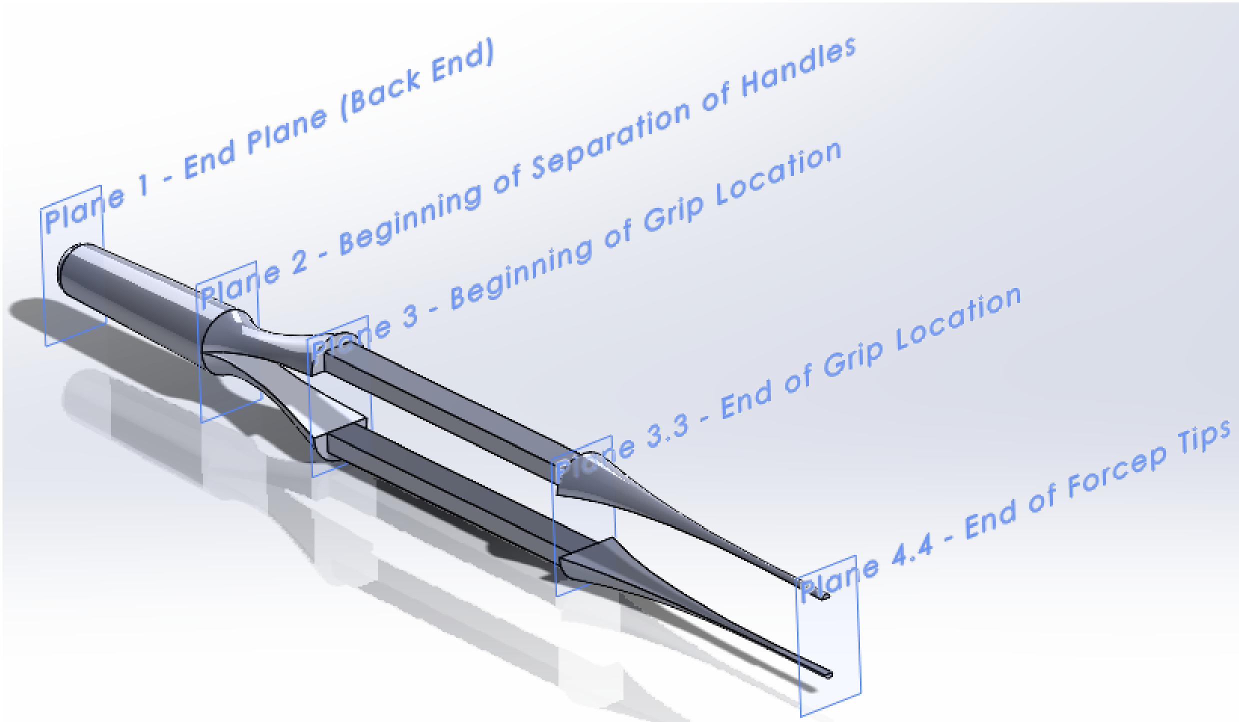

Figure 10: Angled View of Base Part With Planes

Figure 11: Top View of Base Part

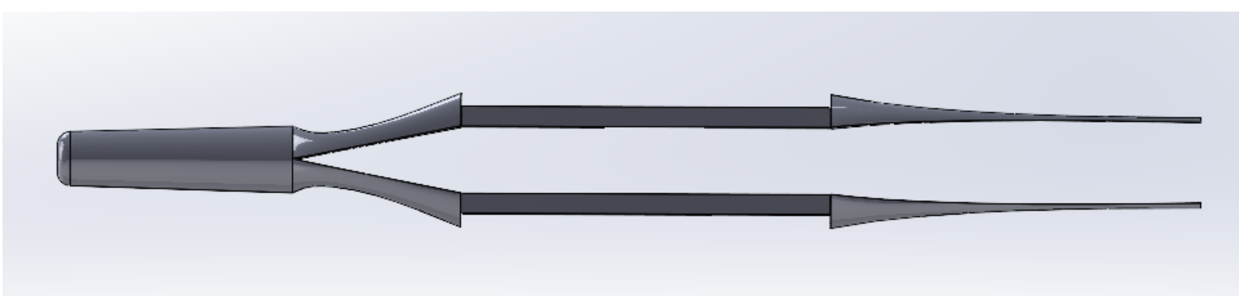

Figure 12: Side View of Base Part

Next, the grip was made based on the dimensions in Figure 9. It was during this step that the team realized that the dimensions listed in Figure 9 were not proportional to the widths in the photo. Below is a photo of the exact dimensions in SolidWorks:

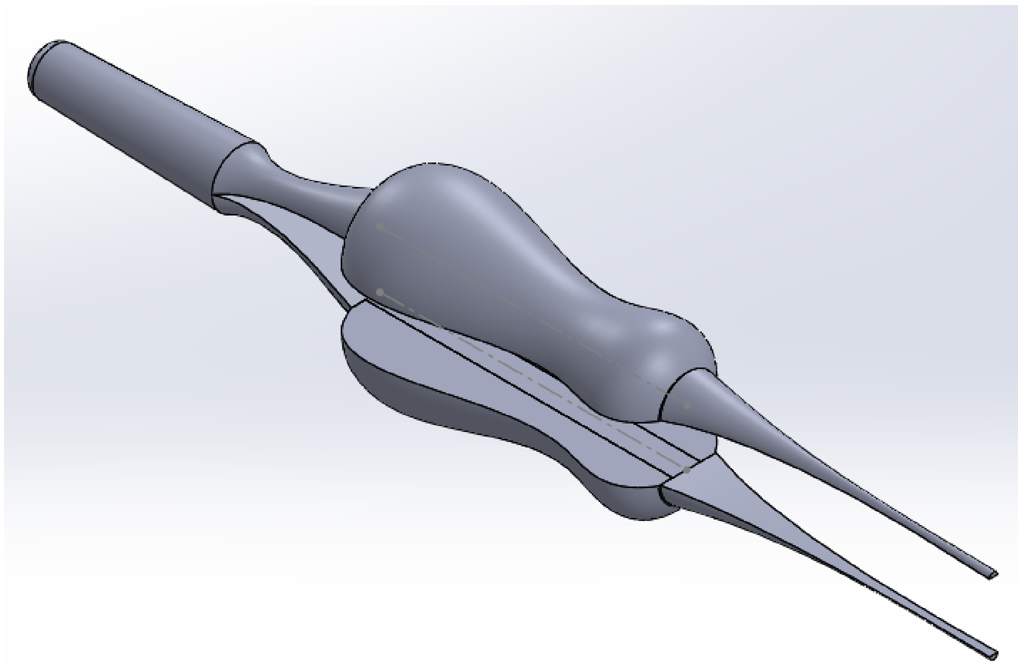

Figure 13: Forcep Base with the Exact Dimension Grip

The team assumed that this design would be ruled out since it looked somewhat impractical and “bubble” shaped. However, instead of disregarding it totally, the team decided to keep it as one of the possible designs to assess. To solve the problem of mismatched dimensions and widths in the outline that Dr. Dunn provided the team with, the photo was printed out to scale (ensuring that the overall length of the forceps in the printed photo was 17cm), and then the other dimensions were measured using a set of calipers. These dimensions were used to produce the “proportional dimensions” version of the forcep in Figure 9. Figures 14-16 show screenshots from SolidWorks of the proportional model:

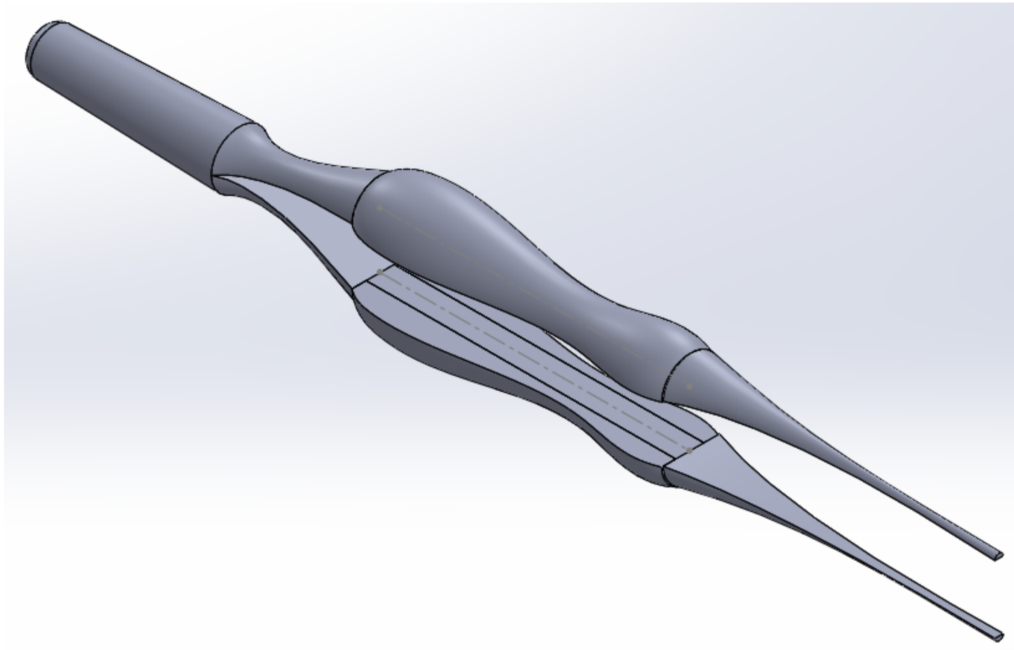

Figure 14: Proportional Model of Dr. Dunn's Dimension Outline

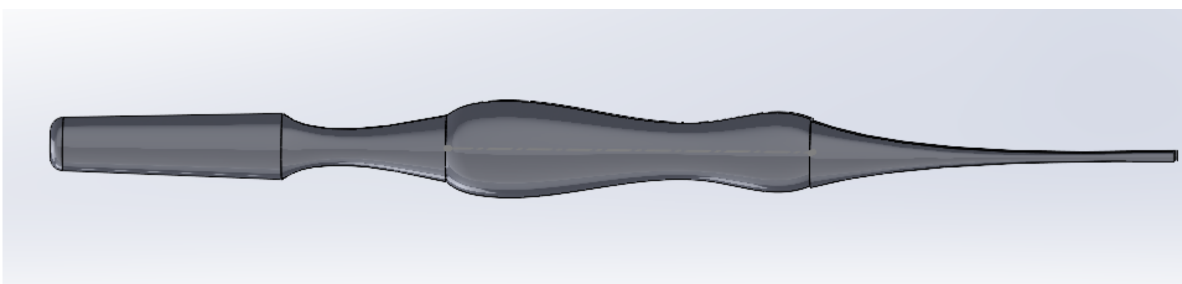

Figure 15: Top View of Proportional Model

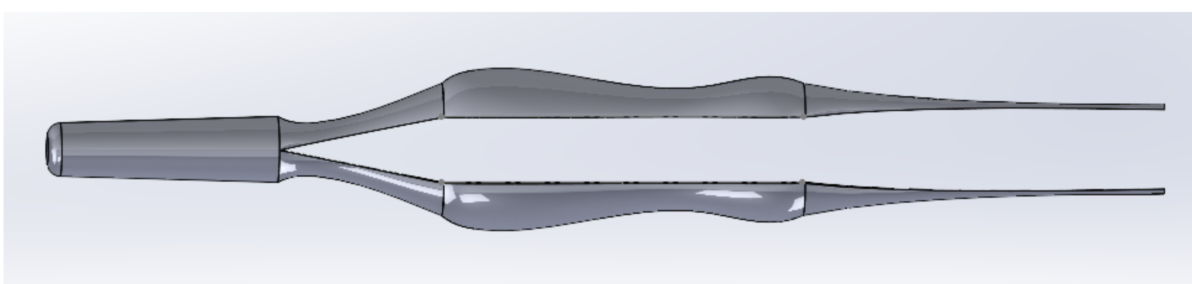

Figure 16: Side View of Proportional Model

Once the team had created the proportional model, a plan was outlined to create variations of the proportional model in order to test different sizes and widths of grips. The team decided to make four different lengths of bases and 16 different variations of grips - four different lengths (for each length of base) and four different widths of each length. This was done by starting with the proportional model of the base and saving it as a new .SLDPRT file in SolidWorks. Once it was open in SolidWorks as a new part, the distance between each plane in the model was increased or decreased to increase or decrease the total length proportionally. For the grips, the same process was repeated except the grips varied in length and width. To adjust the length, the plane distance was edited in the same way as the base parts, but for the width, the semicircle radius was increased and decreased for the large hump, the trough, and the small hump. This produced a variety of lengths and widths of grips and base parts. The grips and bases were combined into 16 total variations that can be seen in Figure 17 below:

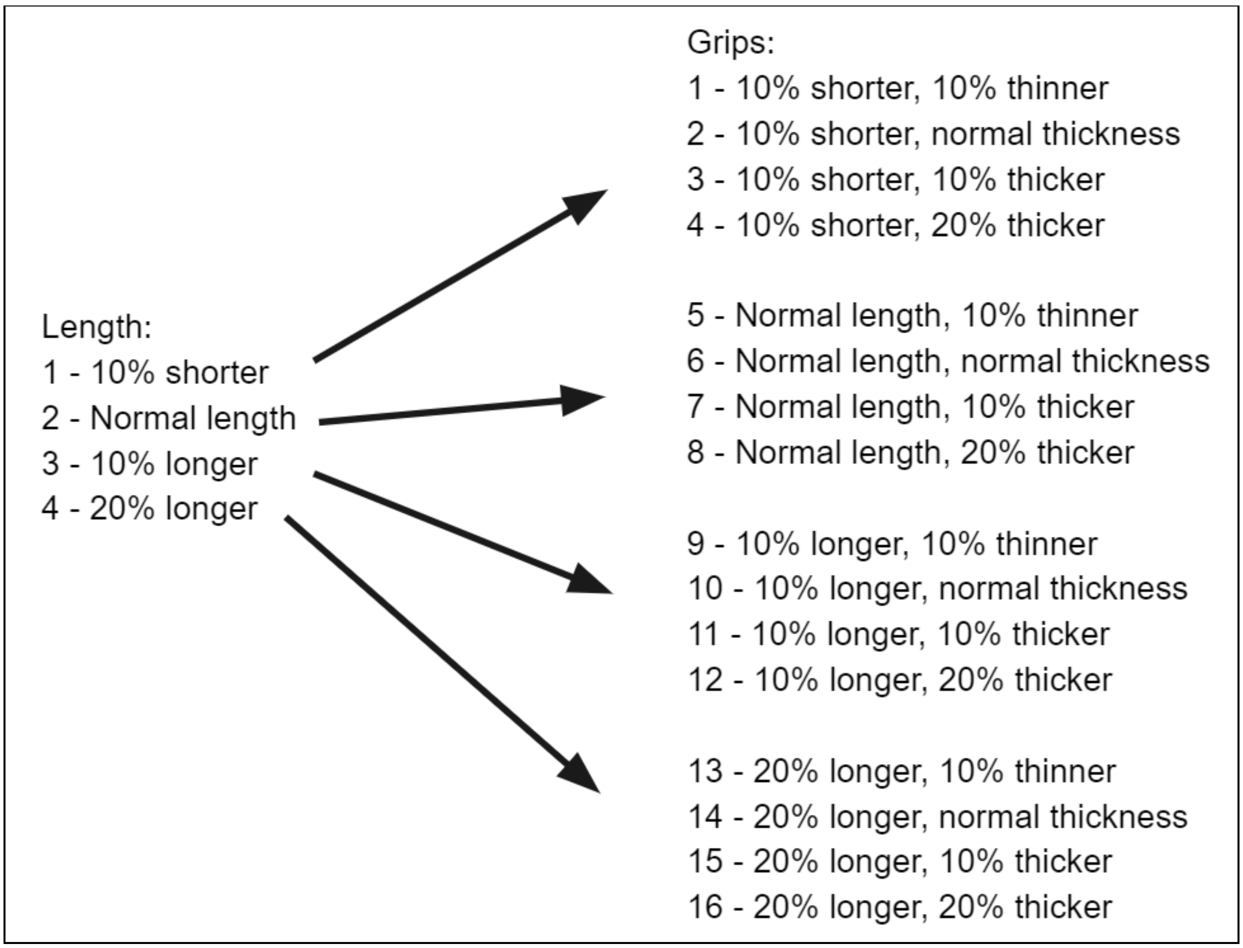

Figure 17: Outline of the Forcep Variations

These grips and bases were combined into the list of variations below, using the length number and grip number combination to distinguish them. Dr. Dunn's exact measurement model was included in this list of variations, leading to 17 models total. Variation 2-6 was the original proportional model to the outline that Dr. Dunn provided the team.

List of variations:
Dr. Dunn Exact Measurement Model
1-1
1-2
1-3
1-4
2-5
2-6
2-7
2-8
3-9
3-10
3-11
3-12
4-13
4-14
4-15
4-16

In SolidWorks, each base was mated to its corresponding grip sizes. Each base was assigned four different grip widths and there were four different base lengths to work with. In Figure 18 is the SolidWorks assembly that contains all 17 (16 variations of the proportional model and Dr. Dunn's exact model) in a side by side fashion so that the differences can be seen between them:

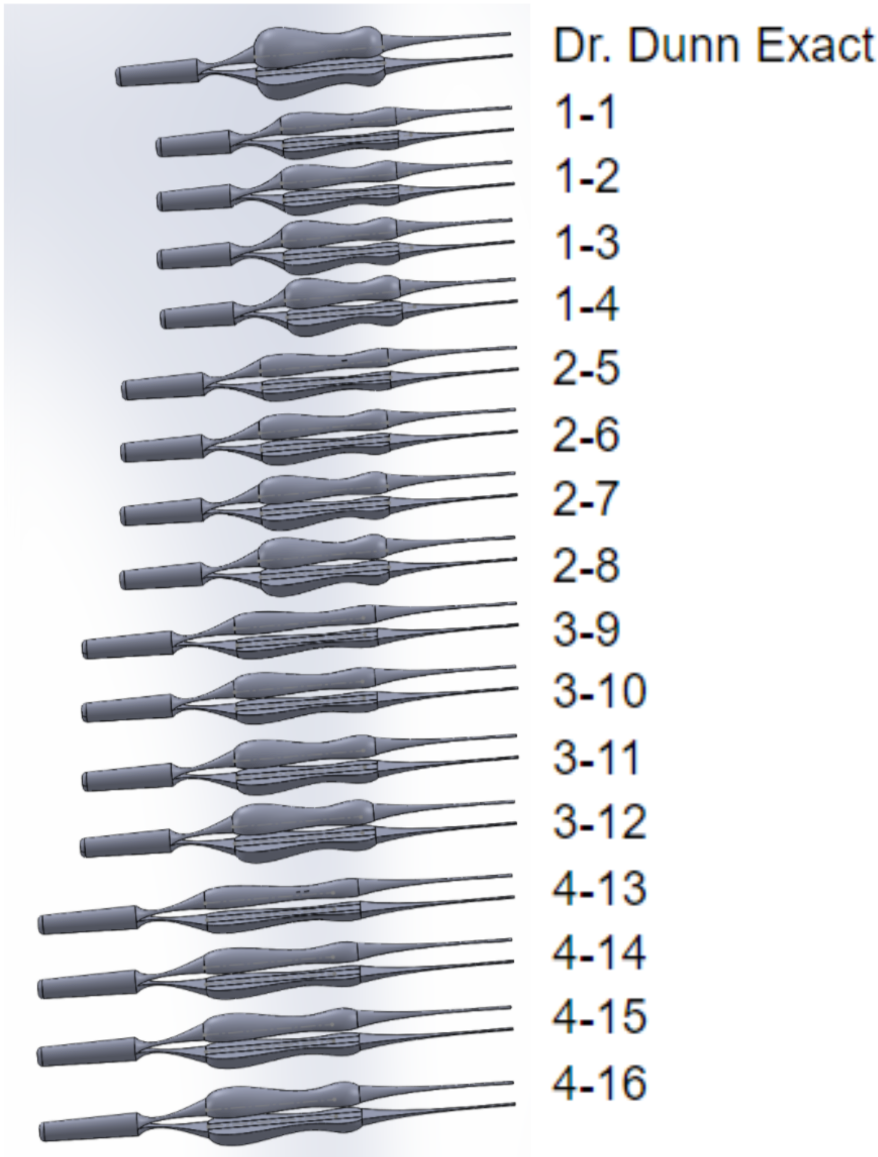

Figure 18: 17 Forcep Variations Labeled

Since it was difficult to visualize the actual size of these models, the following photo was edited to include length dimensions (Figure 19):

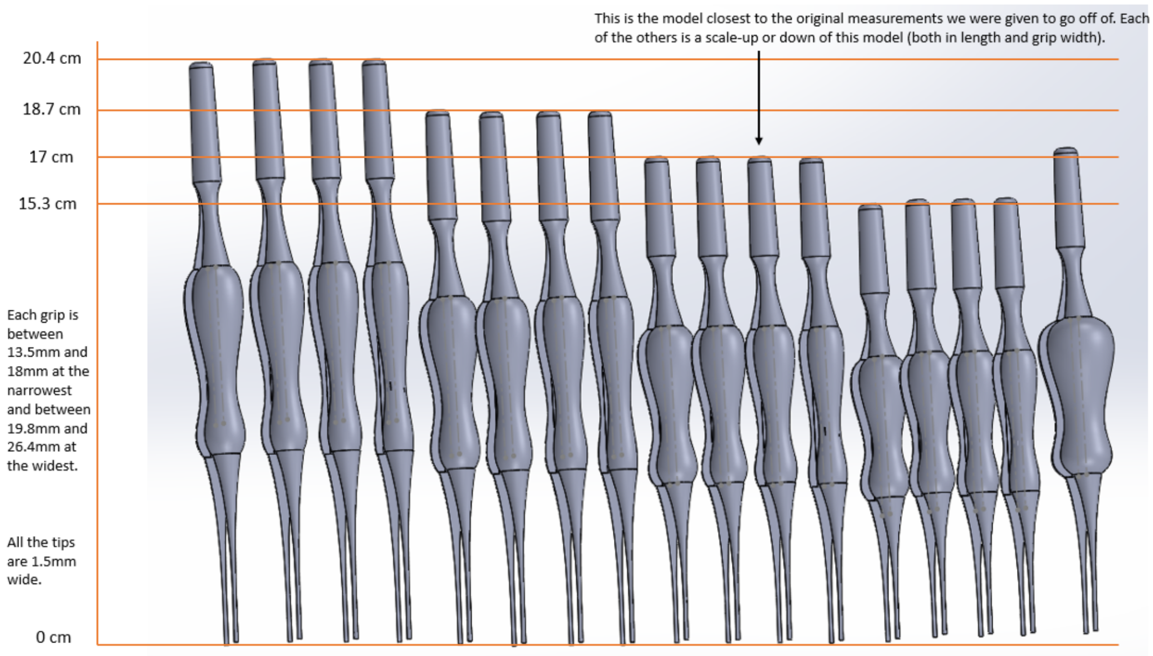

Figure 19: 17 Forcep Variations With Dimensions

Although the team knew that the final prototypes would not be 3D printed, using 3D printing as an iterative part of the design process was a valuable resource. The goal of 3D printing these 17 variations was to gain an understanding of how the grips felt in your hand, not to have ideal springiness, but they also needed to be somewhat functional. The issue that the team ran into with 3D printing these variations was that the stem of the forceps was not thick enough to hold up during light handling. Since they were breaking during light handling, it was difficult to feel how the grips functioned on the prints. To solve this problem, the team printed three test bases with different stem widths to conduct a feasibility test. These test bases were sent to Foisie Makerspace for printing. Figure 20 shows the PLA 3D printed test parts:

Figure 20: Test Bases Printed in PLA With Varying Stem Thickness

From this feasibility test, it was determined that the thickest stem size (blue) would be the best of the three tested for printing the other 17 variations since the others either failed or were too weak to hold. This stem thickness for 3D printing was 5 mm. However, the team felt that even this thickness was too flimsy, and decided to make the next variations even thicker. The stem thickness of the next iteration of prints was 6 mm, which the team expected to be more stiff and lead to a better prototype. Figure 21 is a photo of the 17cm long base piece in someone's hand for a size reference:

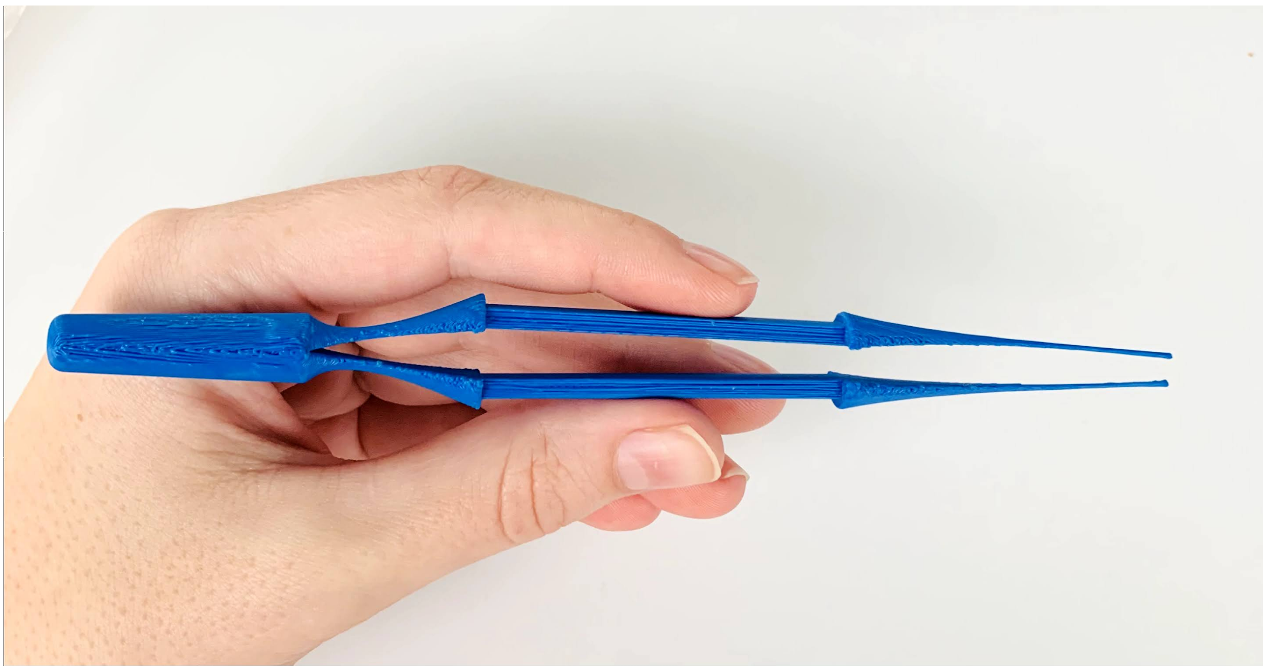

Figure 21: Photo of 17cm Test Base in Hand

Once the stem thickness of 6 mm was decided on for the 17 variations, they were sent to the WPI Foisie Makerspace for printing. The team decided to print the 17 variations in Nylon because of its additional stiffness and therefore closer resemblance of stainless-steel forceps. Once the variations were all printed, the support material had to be carved away using a wood carving knife. Figures 22-24 show photos of the variations and what the prints looked like directly off the printer:

Figure 22: Print Directly off the Printer and Carving Knife That Was Used

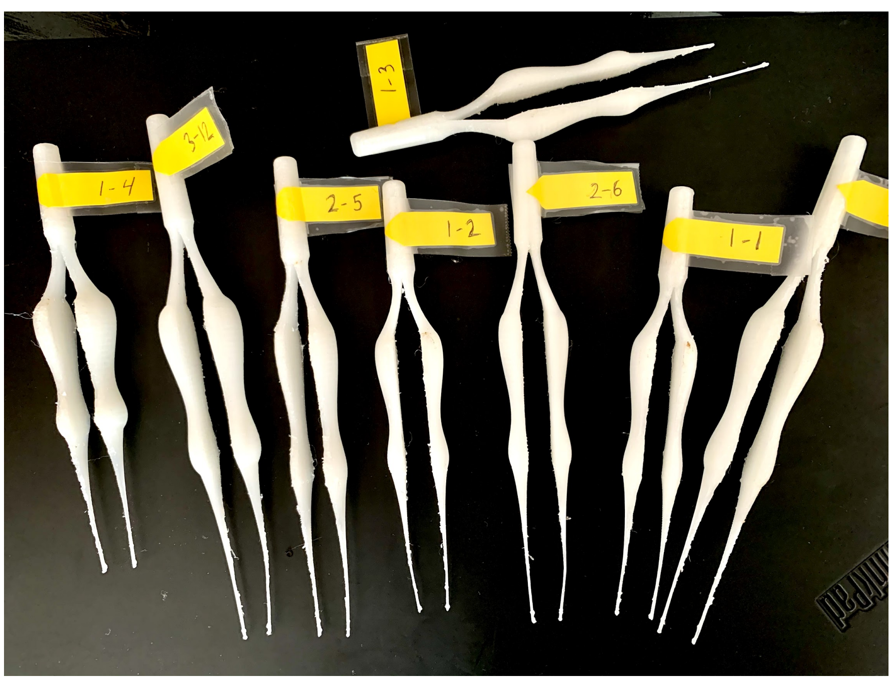

Figure 23: Forcep Variations Printed in Nylon and Labeled

Figure 24: Total Set of Forcep Variations

Some observations from these prints were that the tips were very flimsy due to the material being plastic instead of stainless-steel like the real forceps would be, and that some of the tips broke off while removing the support material from the prints. Though the 3D printed forceps did not function as well as real stainless steel models, this was a very valuable step in determining what variations the team would move forward with.

These 17 variations were brought to Dr. Dunn, who felt and inspected each one. Ideally, the team would have been able to put this iteration of prototypes in front of more surgeons to gain more feedback, but with the restrictions from the COVID-19 pandemic, even being able to have Dr. Dunn assess these variations was a victory. With his background in plastic surgery and vast experience using forceps in his day to day job, he was able to provide insight on the most logical designs to move forward with, and the designs that were not applicable for skin closure. These seven were the 1-1, 1-2, 2-6, 2-7, 3-11, 4-15, and 4-16.

An interesting aspect of these choices was that four of the seven actually had the exact same proportions to each other: the 1-1, 2-6, 3-11, and 4-16. These were proportional in every way: grip length, width, and overall length. The team did not inform Dr. Dunn of this relationship ahead of the meeting to assess the prototypes so as not to introduce any bias. Though he was not aware that these four all had the same proportions to each other, he still picked out these four (along with the other three that he saw potential in). This told the team that there was something about those proportions that was successful. The team decided to call this specific group the “Golden Ratio” for the forcep grips. Table 2 summarizes the ratios of the variations that Dr. Dunn selected:

Table 2: Golden Ratio Values

	Grip Length (mm)	Large Protrusion Width (mm)	Trough Width (mm)	Small Protrusion Width (mm)	Overall Length of Forceps (mm)
Model 1-1	49.5	12.6	8.1	10.8	153.0
Ratio (W/L)		**0.25**	**0.16**	**0.22**	
Model 2-6	55	14	9	12	170.0
Ratio (W/L)		**0.25**	**0.16**	**0.22**	
Model 3-11	60.5	15.4	9.9	13.2	187.0
Ratio (W/L)		**0.25**	**0.16**	**0.22**	
Model 4-16	66	16.8	10.8	14.4	204.0
Ratio (W/L)		**0.25**	**0.16**	**0.22**	
Model 1-2	49.5	14	9	12	153.0
Ratio (W/L)		0.28	0.18	0.24	
Model 4-15	66	15.4	9.9	13.2	204.0
Ratio (W/L)		0.23	0.15	0.20	

The team decided it would be beneficial to conduct another feasibility test of the grips overlaid on existing forceps. Using the seven variations that were selected by Dr. Dunn, the prototypes were deconstructed to isolate the grip part from the stems and tips. This was done using a miter saw and clamps to ensure safety. Then, pulling from Dr. Dunn's personal collection of forceps, the grips were matched up with a set of forceps that were close to their original length (meaning that the grips from longer forceps bases were paired with longer existing forceps). Figure 25 shows the deconstructed prototypes next to their paired existing forceps:

Figure 25: Deconstructed Forcep Prototypes With Their Paired Existing Forceps

These grips were then glued to the existing forceps using hot glue. The grips were placed as close to the natural gripping location of the forceps as possible. Figure 26 displays the deconstructed grips glued onto the existing forceps:

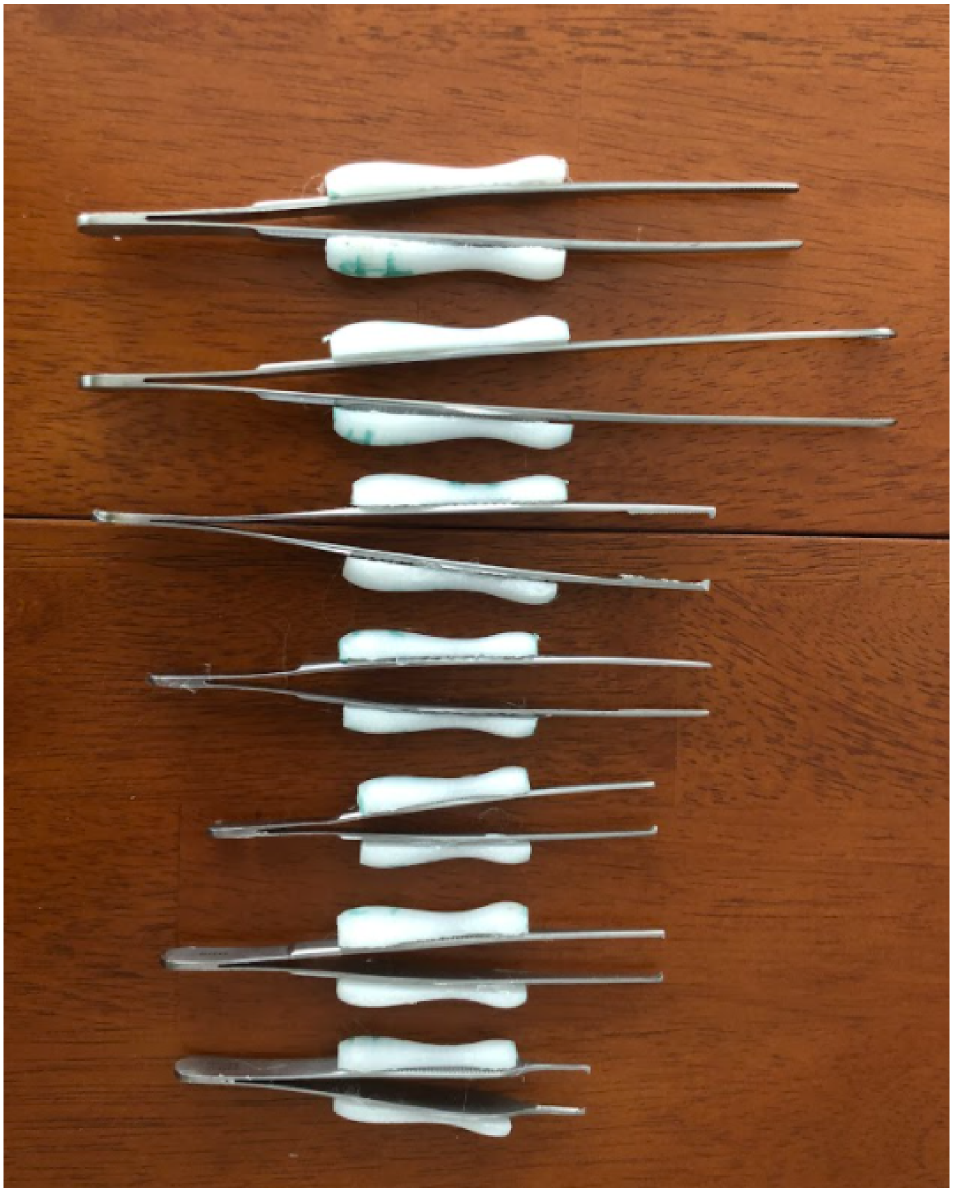

Figure 26: Deconstructed Forcep Prototypes Glued Onto Existing Forceps

The purpose of this test was to help narrow down the finalist prototypes even further. These overlaid prototypes were again brought to Dr. Dunn for his review. From this meeting, it was determined that the team would move forward with the four that fit the Golden Ratio for forcep grips: 1-1, 2-6, 3-11, and 4-16. The next iterative step was to make the grips tapered to fit better onto the overlaid forceps. This was done in SolidWorks by adding two additional planes to the grip model and adjusting the lofted boss base feature to include two small rectangles on the ends. This gave the four grips a tapered look, which can be seen in the screenshots (Figures 27-29) from SolidWorks below:

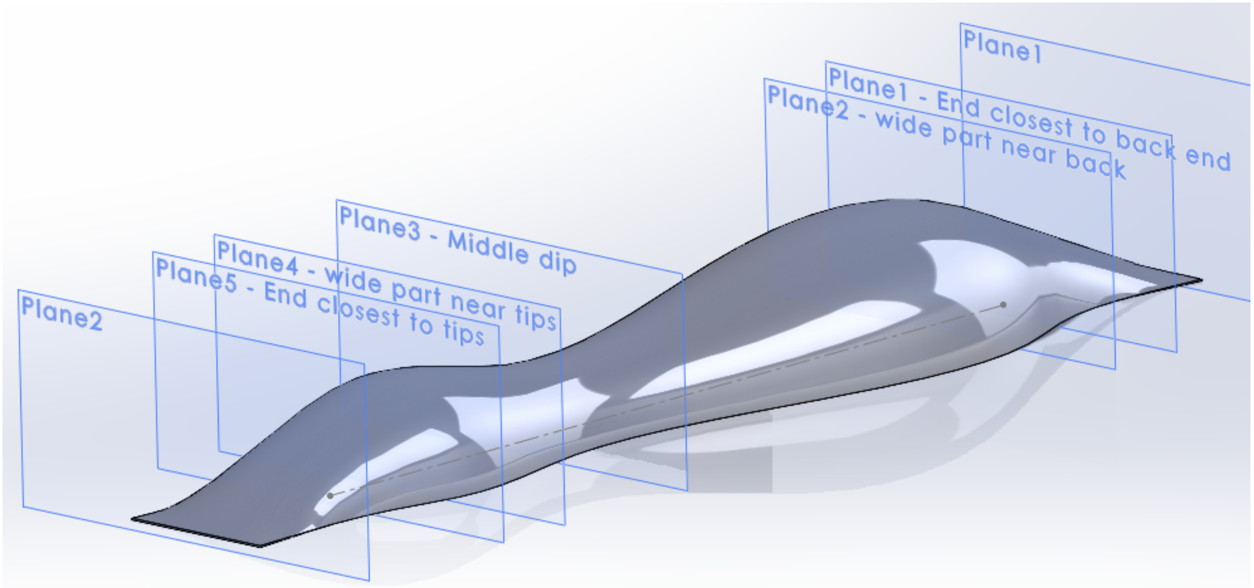

Figure 27: SolidWorks Model of Tapered Grips

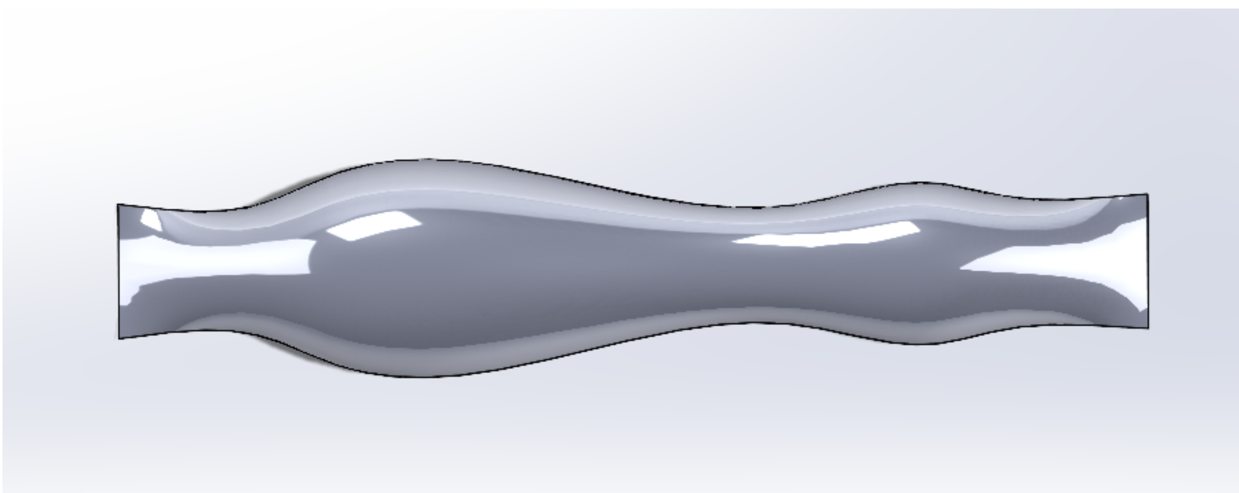

Figure 28: Tapered Grip Model Top View

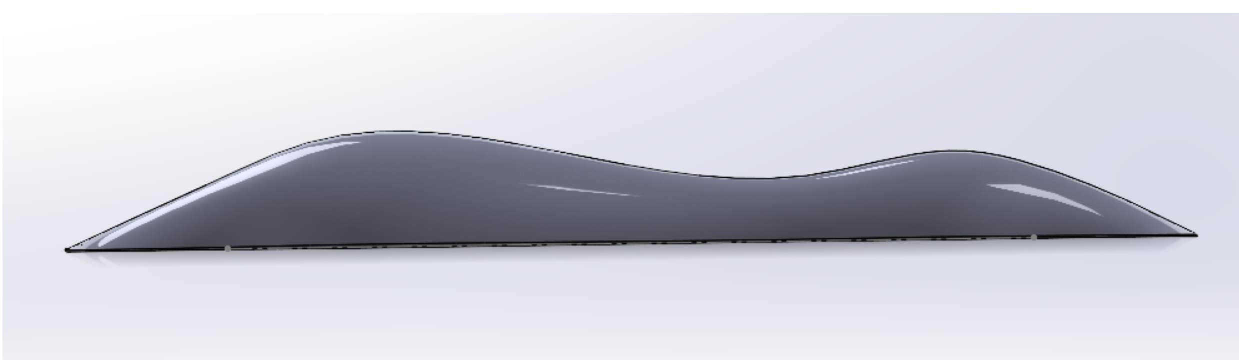

Figure 29: Tapered Grip Model Side View

Once this tapered design was finalized, the four files were sent to the WPI Foisie Makerspace for printing in PLA since the stiffness was not an important factor when only printing the grips, and PLA was the fastest to print. Figure 30 shows the four variations (left to right: 1-1, 2-6, 3-11, 4-16):

Figure 30: Tapered Prints of the Golden Ratio Grips

While making these grips in SolidWorks, the team decided to purposely leave the tapered ends a bit wider than was needed so that the prints could be sanded down to the exact size of the forcep they will be overlaid on. Below in Figure 31 is a photo of the grips after they had been sanded down with 120 grit sandpaper:

Figure 31: Tapered Prints After Sanding

The grips were then paired up with existing forceps that they would be overlaid on. Below are photos of the tapered grips and their respective set of forceps as well as those same grips glued to their set:

Figure 32: Tapered Grips With Their Respective Set of Forceps

Figure 33: Tapered Grips Overlaid on Existing Forceps

When this iteration of prototypes was brought to Dr. Dunn, he approved of all of them. However, since the team had previously decided to focus on Adson forceps only, it was the most reasonable choice to continue working with 1-1 and 2-6 since they were the shorter two variations. Adson forceps tend to be shorter than the other types of forceps the team had used in the first few iterations of the overlaid prototypes, so 1-1 and 2-6 fit the length of the Adson forceps the best. Due to this decision, the team solidified the plan to continue pursuing the 1-1 and 2-6 variation and leave the 3-11 and 4-16 as a recommendation for future redesigns of larger styles of forceps. Three pairs each of the 1-1 and 2-6 tapered grips were printed in PLA while the team waited for the 12 pairs of Adson forceps to come in the mail from KLS Martin. Below in Figure 34 is a photo of the six pairs after being labeled:

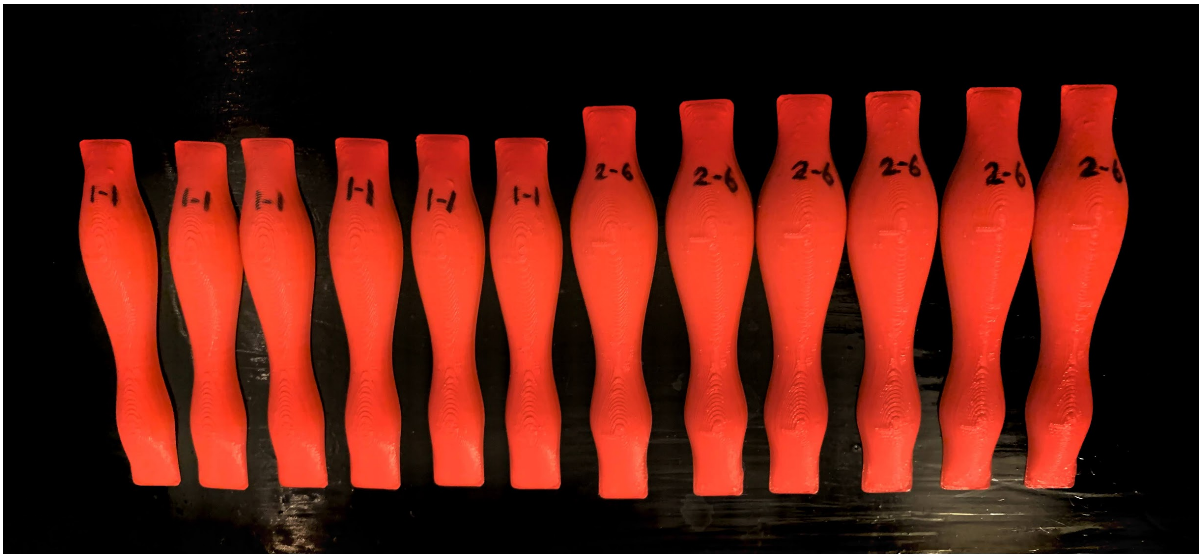

Figure 34: 1-1 and 2-6 Tapered Grips With Labels

Once the Adson forceps arrived, the team realized that simply glueing them on would not be sufficient for a working prototype, since the Adson forceps were slightly wider than both of the grips and it would interfere with the ergonomic and haptic motion of rolling the forcep in the user's hand. Since it would interfere with the motion that the team was trying to improve, it was determined that the excess material would need to be removed. The excess material can be seen in Figure 35:

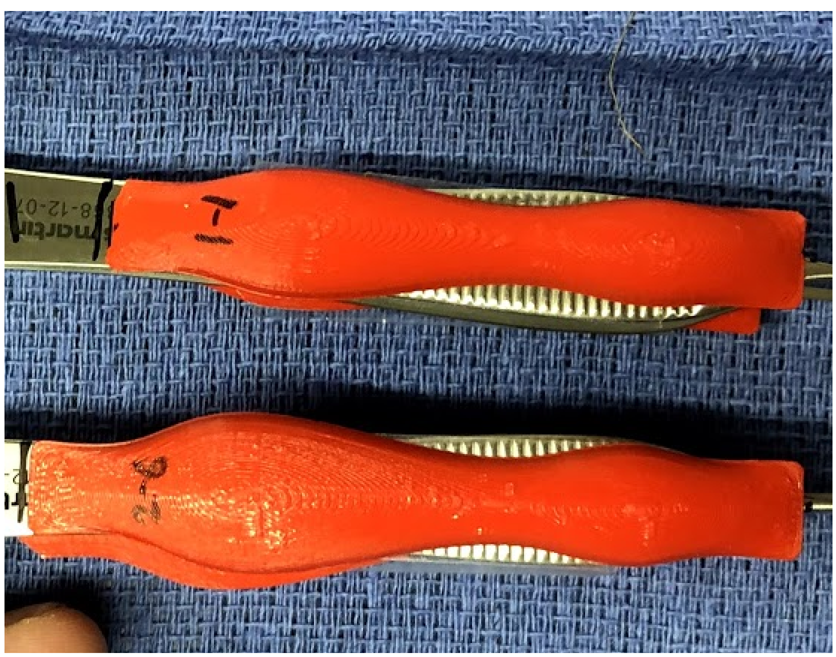

Figure 35: Excess Stainless Steel Material That Would Interfere With Ergonomics

In order to remove this excess material, the exact location of the grips needed to be recorded. The Adson forceps and tapered grips (1-1 and 2-6) were brought to Dr. Dunn to determine where the grips should be placed. This step was important to determine the exact desired location of the trough where a surgeon's fingers sit in the grip. This location affects the balance of the tool in the surgeon's hand as well as the necessary force to close the forcep tips and grip materials. Below are photos of Dr. Dunn assessing and marking the forceps, as well as the final grip location for each variation marked in Sharpie on the stainless steel itself so that it can be easily repeated:

Figure 36: Dr. Dunn Assessing the Grip Locations

Figure 37: Adson Forceps Side View with Proper Grip Location

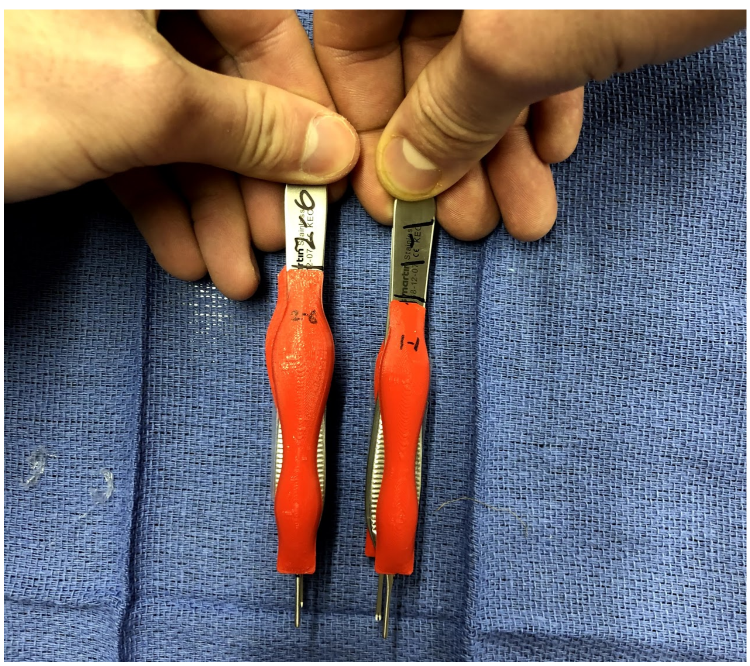

Figure 38: Adson Forceps Top View With Proper Grip Location

The marked location of the trough along the base of the Adson forceps remained constant between different grip sizes so although length and width of the grip may vary, the surgeon's fingers will always fall at the same location along the forcep. Once the exact grip locations were marked on the stainless steel Adson forceps, the outline was marked with sharpie to indicate where exactly to grind the stainless steel away. An angle grinder was used to remove the excess material. Using the final Adson forceps with the excess material removed, the tapered grips in each size were overlaid and glued on using gorilla glue. Figures 39-41 show the tapered grips overlaid on the Adson forceps:

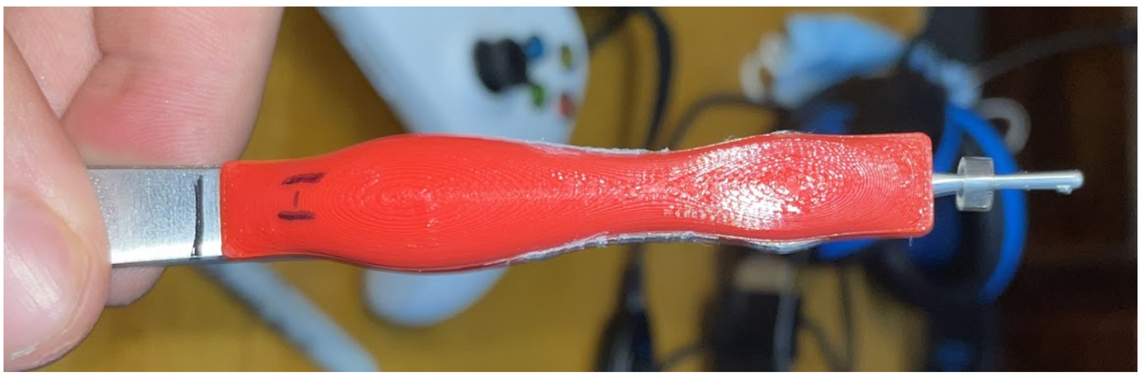

Figure 39: Adson Forceps After Grinding, Before Filing Grip Tip

Figure 40: Top View of 1-1 and 2-6 Grips Overlaid on the Ground Down Forceps

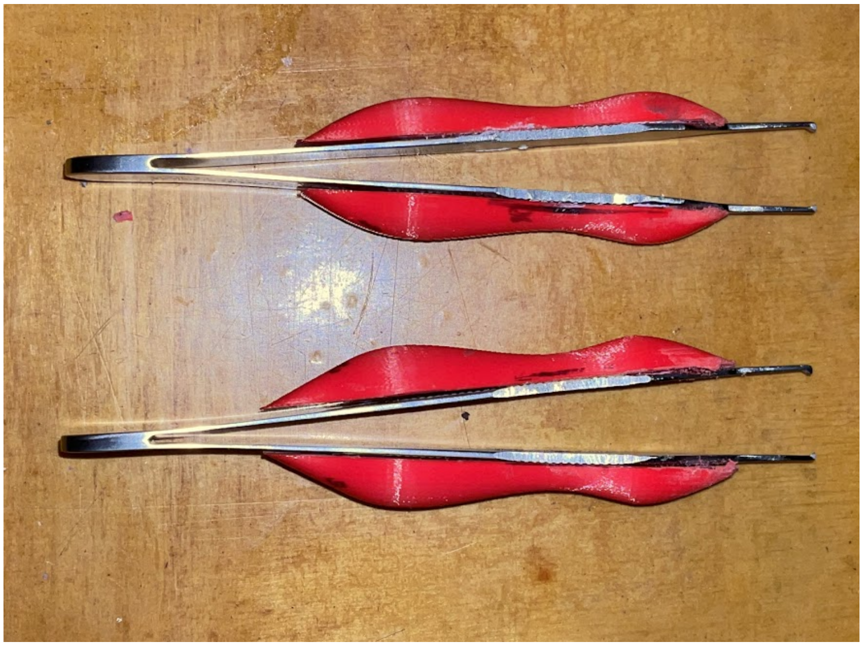

Figure 41: Side View of 1-1 and 2-6 Grips Overlaid on the Ground Down Forceps

One aspect of the above prototypes that Dr. Dunn expressed displeasure in was the fact that the grips were more oval shaped than circular. This reduced the rotational aspect of the design. To solve this problem, the team edited the SolidWorks model to include a slot that would fit around the ground down forceps instead of over. Figure 42 shows the change in shape with and without the slot:

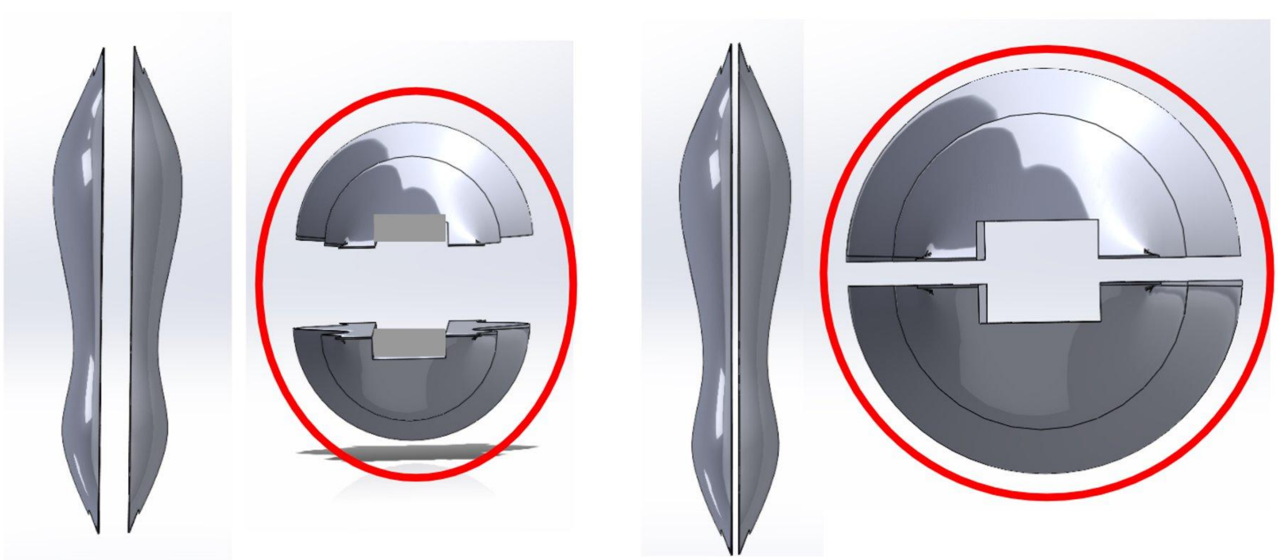

Figure 42: Grip Shape Before and After Slot Was Added

Next, the team added a grip texture to the SolidWorks model. The texture "Checkered Knurl" was chosen based on previous MQP work (Burke et al., 2020). Below is the height map that was used in the model:

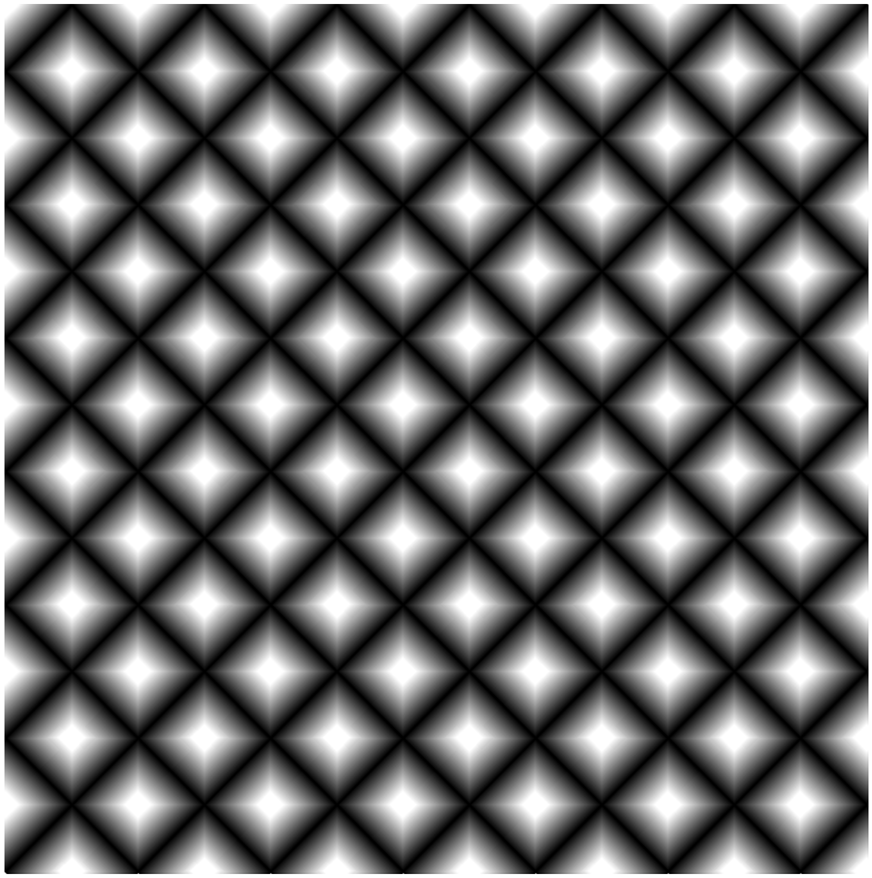

Figure 43: Checkered Knurl Height Map

This texture height map shown in Figure 43 was kept consistent between the models, but the size and offset distance was varied to allow for testing of the optimal size of the texture. The sizes were as follows:

- Texture 1: smallest with 0.5mm offset
- Texture 2: medium with 0.75mm offset
- Texture 3: largest with 1.0mm offset

The size of the height map and the corresponding textured grip can be seen in Figure 44:

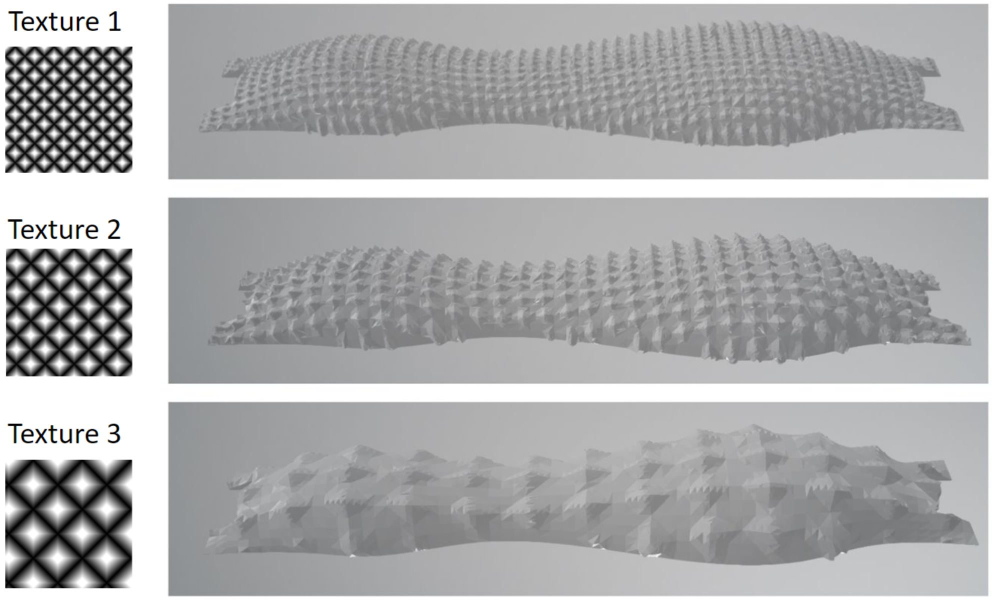

Figure 44: Height Map With Corresponding Textured Grip

These variations were 3D printed in PLA and glued on the ground down Adson forceps. Below, the full set of 1-1 and 2-6 variations with each texture can be seen in Figure 45:

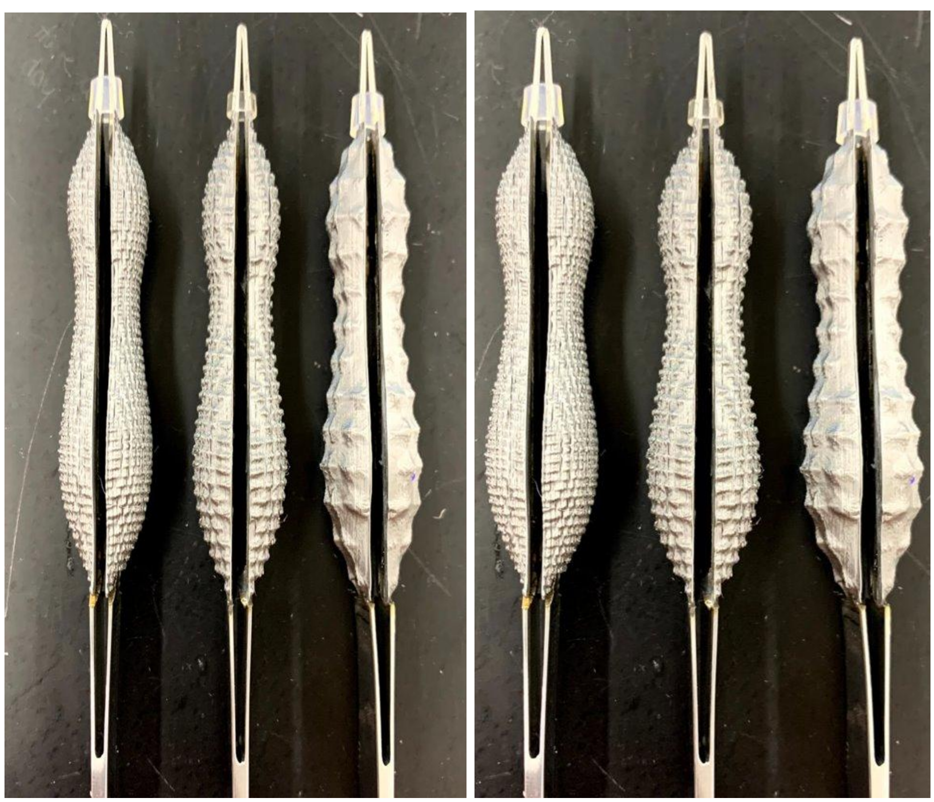

Figure 45: Final Set of 1-1 and 2-6 Variations With All Three Textures

After the user experience surveys had been performed and the data analyzed, it was found that the 2-6 with the texture 2 overlay was the leading design variation. Photos of the final design are shown in Figures 46-47:

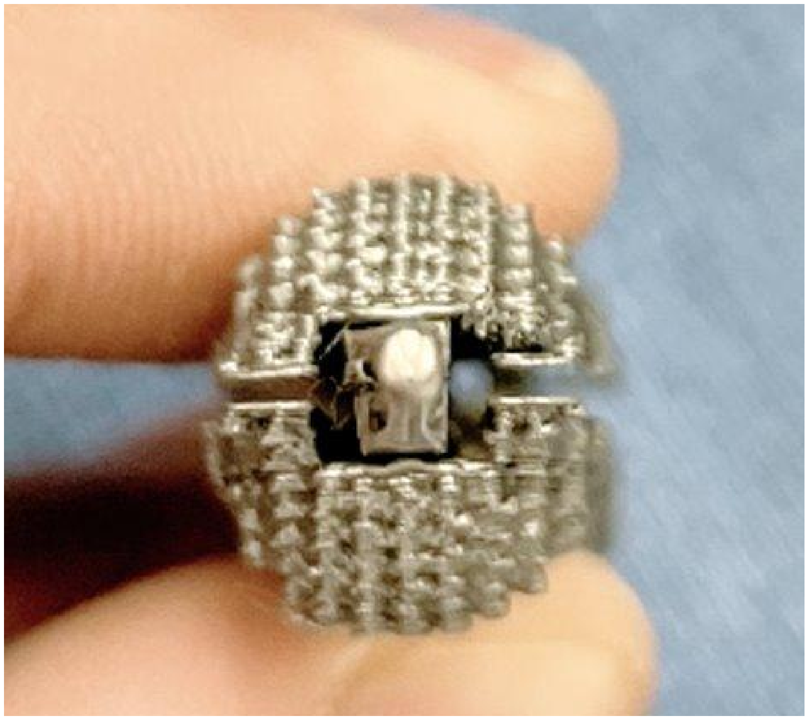

Figure 46: End View of the Final Design

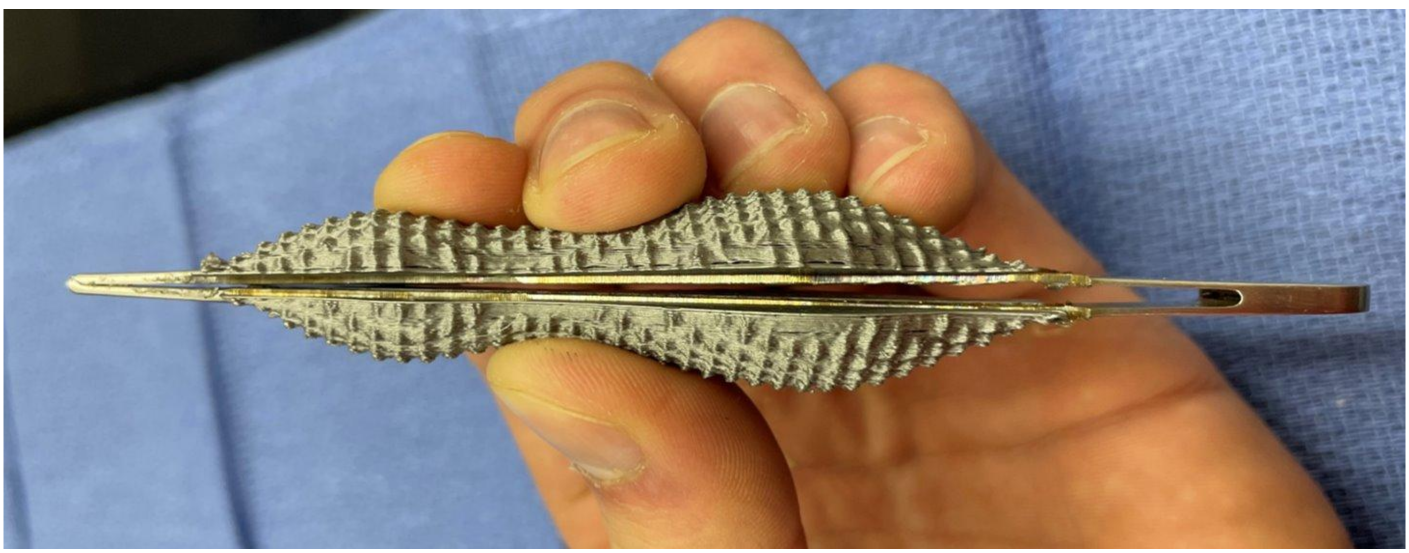

Figure 47: Side View of the Final Design

Specific Measurements for the final design are found below in Table 3:

Table 3: Final Prototype Measurements

Total Grip Length	55mm
Overall Forcep Length	120mm
Distance from Tip to Trough	45mm
Large Protrusion Width	14mm
Trough Width	9mm
Small Protrusion Width	12mm
Texture Size and Offset Distance	Medium with 0.75mm offset

Chapter 5 - Design Verification

5.1 Introduction to Verification Testing

The team conducted multiple different types of tests in order to prove that the final prototype improved upon the design specifications determined at the beginning of the project. These specifications were to improve the ergonomics and haptics of the forceps for skin closure, determine the ideal dimensions of grip length, determine the ideal springiness and force to close, and to reduce slip between the grip and users glove hand. User experiments were conducted on the final design of the forceps at UMass Medical Center with nine resident surgeons and the Chief of Plastic Surgery, Dr. Dunn, to gather quantitative data from professionals working in the field. The data was analyzed so that the team could confirm or deny that the final design was an improved concept compared to the existing Adson forceps. Throughout the entirety of the project the team would meet with Dr. Dunn after creating different iterations of prototypes to move the project forward allowing the team to create subsequent prototypes.

5.2 Friction Testing

The first test conducted was designed to test the coefficient of friction for each of the three grip textures. To begin, two pieces of foam were cut to the size of a hand and had slots cut into them in order to properly seat them on the Instron 5544 for later use as seen in Figure 48. The pieces of foam were chosen because they had a stiffness that closely mimicked what a user's hand would feel like.

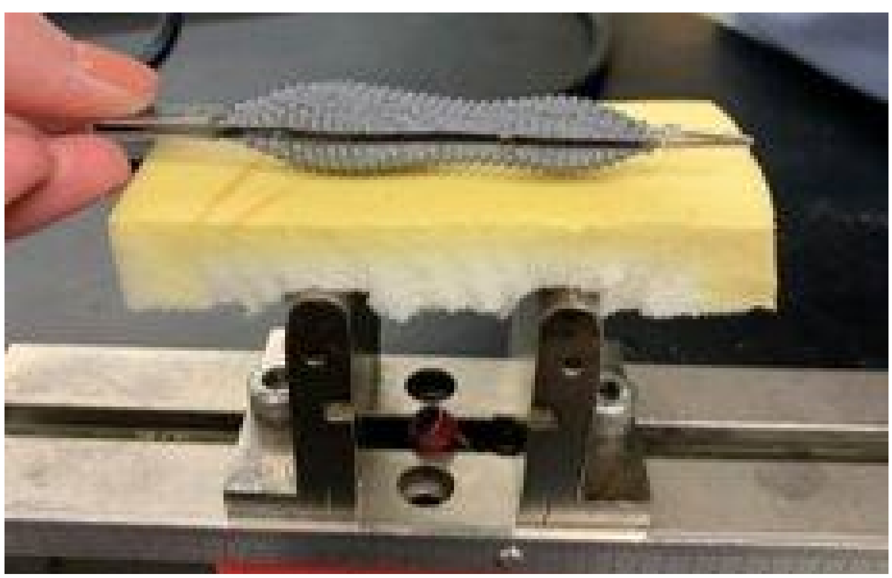

Figure 48: Foam Cutout on Instron

Next, each piece of foam was overlaid with latex gloves to closely reproduce what the forceps grips would experience while being held by a medical professional. When the gloves and foam were completed, they were placed on the Instron 5544 and subjected to a 4 point bending test. A tare load of 3N, representing the normal force, was used as the force to close the forceps for all three textures. Once the load was set, a 20N maximum load spring scale was attached to the forceps with a string by a loop around the proximal end of the forceps. One of the team members held the spring scale directly in line with the forceps laterally to keep the force in the x-plane only as seen in Figure 49.

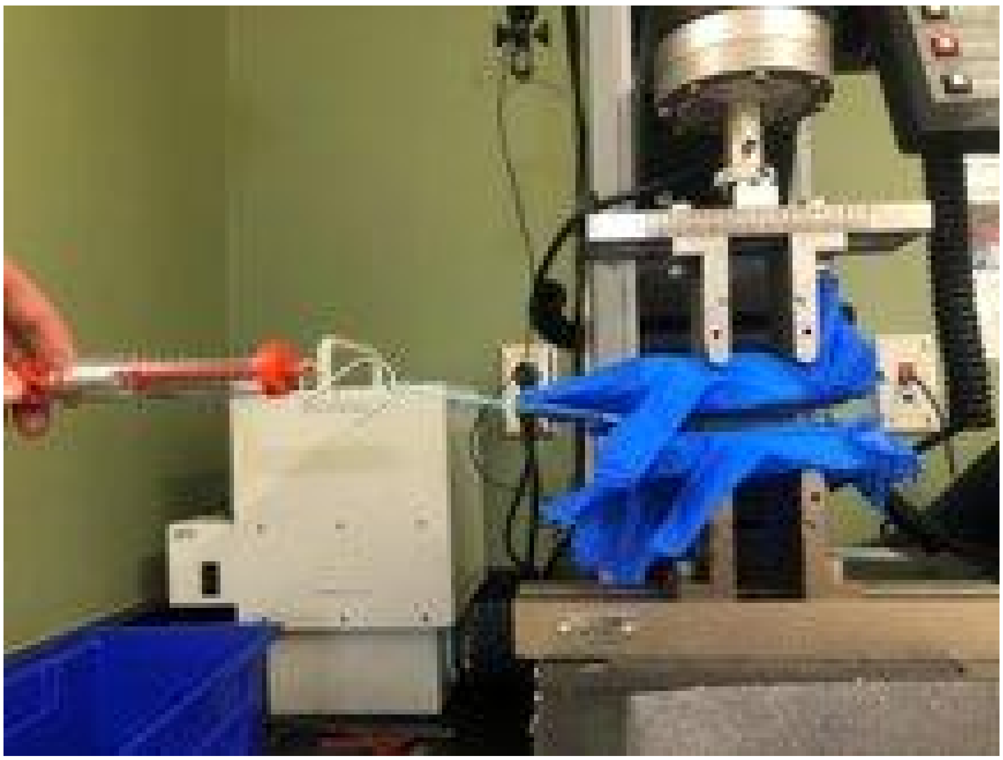

Figure 49: Slip Test Using Spring Scale

One team member pulled the spring scale while another team member was looking at the forceps to see the instant the forceps began to move. At the very instant the forceps started to slide, the teammate watching the forceps would alert the teammate holding the spring scale to take the reading of the spring scale at that very moment. That measurement taken was used as the force of friction. Using the the measurement recorded and the equation $F_{friction} = Fnormal * \mu$ to determine the coefficient of friction which is denoted in the equation as μ. The test was conducted three times for each texture to get a larger data set. The test was completed once with the gloves and forceps being dry, without any substance on them. The test was then done a second time three more times for each grip texture, this time collecting data for the coefficient of friction with the gloves and the forceps lathered in canola oil. This was done to mimic the various bodily fluids that the forceps would be exposed to during a surgical procedure.

For each of the trials, the resulting forces and calculated coefficients of friction were averaged and are shown in Table 4. The coefficients of friction circled in red in Table 4 show that the second grip texture was found to have the highest coefficient of friction compared to texture one, texture three, and the regular Adson forceps under both non-oiled and oiled conditions.

Table 4: Friction Testing Results

	Texture 1		Texture 2		Texture 3		Regular Adson	
	Non-oiled	Oiled	Non-oiled	Oiled	Non-oiled	Oiled	Non-oiled	Oiled
Force to close (N):	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Force to slip (N):	2.0	1.1	2.5	1.7	2.4	1.5	1.7	0.8
Coefficient of friction:	**0.67**	**0.37**	**0.83**	**0.57**	**0.80**	**0.50**	**0.57**	**0.27**

This confirms that, compared to the normal Adson forceps, adding a grip will decrease the overall slip factor of the forceps. This provides medical professionals with a safer alternative, reducing the possibilities of user error during surgical procedures.

5.3 Force to Close Testing

The second test conducted was done in order to quantify the optimal force needed to fully depress the forceps at the ideal finger placement locations and offsets of +- 1.5 cm. As seen in Figure 50, the middle mark on the forceps shows the point of preferred finger placement location and was determined from feedback from Dr. Dunn and nine surgical residents who participated in user experience surveys.

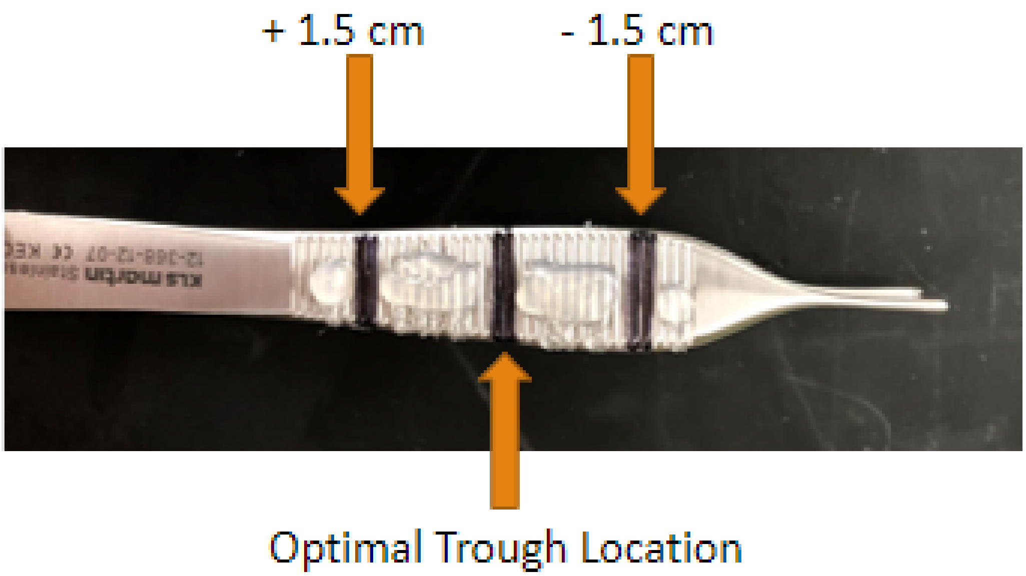

Figure 50: Locations of Trough Placement

This preferred finger location translated to the trough placement of the grips that the team designed. The other two marks show the offset locations which were placed +/- 1.5 cm from the optimal trough location and were used to examine the difference in force necessary to close the forceps when moving proximally and distally along the length of the forceps. Hot glue was added to the forceps to ensure the three point bending test was conducted accurately so the forceps did not slip when the force was applied. The experimental setup is shown in Figure 51:

Figure 51: Force to Close Testing

The upper anvil on the Instron was jogged down and centered in between the dried hot glue around each of the markings. The Instron was then finely adjusted until the forceps were fully depressed and once this point was reached the force measurement from the Instron was recorded from the Bluehill software. This procedure was followed for each of the three markings on the forceps. At the optimal trough location, the resulting force to close the forceps was found to be 6.14N. This measurement was utilized to make future design recommendations for where the trough of the grips should be located. The measurements recorded for the offset markers were used to prove that the force to close varies significantly with adjustments to the trough locations. The results from this experiment can be seen in Table 5:

Table 5: Force to Close Testing Results

Location of applied force:	Average force (N):
-1.5cm	4.45
Optimal (center)	6.14
+1.5cm	7.87

5.4 User Experience Surveys

The team provided Dr. Dunn and nine surgical residents with sets of the latest prototype iteration of the 1-1 and 2-6 forceps with all three textures overlaid as well as a pair of traditional Adson forceps. Using those forceps, the surgeons would be able to participate in the user experience surveys. The participants completed a simple task with the forceps in which they grasped a small object and rotated it. The instructions and the worksheet to be filled out can be found in Appendix A. The experiment was performed in a dry condition for one survey and coated in oil in the second survey to simulate bodily fluids encountered in the operating room. Each participant graded their experience regarding slippage, comfort, ergonomics, and haptics on a scale of 1 to 7 with 1 being the worst rating and 7 being best. The data received from the participants on each prototype was compiled and weighted based on the importance level to the overall design and use. The results of this are shown in Tables 6 and 7 below. The total scores from the residents were calculated out of the perfect score of 7 to determine which prototype the surgeons preferred as the most optimal prototype. Prototype 2-6, texture 2 received the highest weighted score of 5.67 in the non-oily test which told the team that this prototype was overall the most optimized in the areas of slip, comfort, ergonomics, and haptics. In the oily testing, the 2-6, textures, 2 and 3 tied for the highest scores in this trial proving that these prototypes are the preferred designs to minimize slip, and optimize comfort, ergonomics, and haptics compared to the traditional Adson forceps.

Table 6: Non-Oiled Test Results

Non-oily testing:	Weight of Criteria:	Grip 1-1, Texture 1	Grip 1-1, Texture 2	Grip 1-1, Texture 3	Grip 2-6, Texture 1	Grip 2-6, Texture 2	Grip 2-6, Texture 3	Classic Adson Forceps
Criteria:		Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):
Slip between fingers and grip (1 being very slippery, 7 being no slip whatsoever)	5	1.07	1.65	1.96	0.94	1.96	1.96	1.69
Overall comfort of forceps in your hand (1 being uncomfortable, 7 being comfortable)	3	0.99	1.10	0.96	0.99	1.18	1.07	0.89
Ease of use to perform the given task	4	1.39	1.68	1.64	1.39	1.71	1.39	1.59
The feel of the grip texture in your fingers	2	0.57	0.77	0.68	0.63	0.82	0.68	0.57
TOTAL (out of 7):		**4.02**	**5.20**	**5.24**	**3.95**	**5.67**	**5.10**	**4.74**

Table 7: Oiled Test Results

Oily testing:	Weight of Criteria:	Grip 1-1, Texture 1	Grip 1-1, Texture 2	Grip 1-1, Texture 3	Grip 2-6, Texture 1	Grip 2-6, Texture 2	Grip 2-6, Texture 3	Classic Adson Forceps
Criteria:		Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):
Slip between fingers and grip (1 being very slippery, 7 being no slip whatsoever)	5	0.714	1.43	1.43	1.43	1.79	1.79	0.714
Overall comfort of forceps in your hand (1 being uncomfortable, 7 being comfortable)	3	0.429	0.643	0.643	0.643	0.643	0.643	0.429
Ease of use to perform the given task	4	1.14	1.43	1.43	1.43	1.71	1.71	1.14
The feel of the grip texture in your fingers	2	0.286	0.571	0.714	0.429	0.714	0.714	0.143
TOTAL (out of 7):		2.57	4.07	4.22	3.93	4.86	4.86	2.43

The final question on the user experience surveys asked the surgeons to rank the forceps from their favorite forceps to their least favorite forceps. The table below, Table 8, shows the averaged rankings between the nine surgeons. The 2-6 forceps with texture 2 overlaid was the overall favorite for the study. The rankings of the forceps with different textures followed the trend that they were chosen in the order of decreasing coefficients of friction. It is important to note that none of the surgeons knew about this data as the data for the coefficients were not disclosed to the surgeons prior to this survey.

Table 8: Comparative Forceps Ranking Results

Forceps Ranked in Order From Best to Worst:
2-6 Texture 2
Classic Adson Forceps
1-1 Texture 2
1-1 Texture 3
2-6 Texture 3
2-6 Texture 1
1-1 Texture 1

A more detailed breakdown of the individual responses and unweighted survey results can be found in Appendix C. After compiling the results of the user experience survey, the scores for each model were weighted and averaged. Based on these averages, the 2-6 with texture 2 was the model with the highest average score. Next came the traditional Adson forceps, followed by the 1-1 model with texture 2. A one-sided unpaired t-test was run between each model and the classic adson forceps to find the statistical significance of our data. It was then found that the 2-6 model with texture 2 was favored over the traditional Adson forceps with 91% confidence. The 2-6 model with texture 2 was the model with the highest user experience survey results and the highest coefficient of friction, making it the clear front runner out of all the ergonomic models.

Chapter 6 - Final Design and Validation

6.1 Final Design Objectives and Tasks

The design project began as an obtuse idea to improve upon the current design of surgical forceps. The team conducted research into forceps use in medical and surgical applications and discovered that forceps are one of the most commonly used surgical tools, however, one of the least focused on for innovation and optimization. This project aimed to tackle that issue by addressing the following objectives:

- Design forceps that are appropriate for skin closure in plastic surgery applications.
- Improve the haptic capabilities of the forceps overall design and grip. Reduce slip between the forceps grip and surgical gloves.
- Improve ergonomics of the forceps design with primary focus on the grip by designing a grip that allows for 360 degrees of rotation in between the fingers (reduce the overall motion of the arm/rotation around the shoulder for the user).
- Create a design that is manufacturable, focusing on practicality and cost reduction. Select materials that are FDA compliant and will hold up under repeated sterilization by autoclave.

To meet these objectives, the team worked over the course of one academic year, or four terms according to the WPI school system. The design team members met on a twice-weekly basis to discuss project goals, objectives, and divide up deliverables to ensure that progress was constantly being made on the project. The team met with their academic project advisor, Dr. Raymond Page on a weekly basis to discuss feasibility of ideas, help with brainstorming, and documentation of the design process. The design team met with Dr. Raymond Dunn of University of Massachusetts Medical Center (UMMC) on a bi-weekly basis to discuss practical applications of plastic surgery to the design process, receive feedback on prototypes, and discuss applications and next steps of each design. Each of these meetings were instrumental to progressing the forceps designs and allowing for so many iterations and design options.

Objective 1: Design forceps that are appropriate for skin closure in plastic surgery applications.

To meet this objective, it was imperative that the team work very closely with their sponsor Dr. Dunn at UMMC who is the head of plastic surgery. Therefore, Dr. Dunn had extensive knowledge in the field of plastic surgery, the specifications necessary for a surgical instrument, and specifically how the current forceps design could be improved upon. Much of this optimization would come from the “feel” or the balance of the instrument in the hand of a surgeon. There was discussion of the forceps needing to close with a certain applied pressure from the finger without too much resistance but with just enough spring back. Given this background and the necessary components to design a product that would be applicable for skin closure in plastic surgery, the following task sequence was performed:

1. Discuss the necessary components of the design to gain an understanding of purpose and direction of the design.
2. Pitch design concept to Dr. Dunn and other advisors. Record feedback regarding practical application to surgery and skin closure. Make conceptual alterations as necessary.
3. Create drawings of design in SolidWorks and 3D print prototypes at the WPI Foisie Innovation Studio.
4. Bring prototypes to Dr. Dunn for feedback on the haptics, shape and specifications, and ergonomic feel.
5. After a basic understanding of design needs is met, bring forceps prototypes to focus groups of plastic surgery residents to gain a deeper understanding of surgeon preferences from more than just one test subject. Record all data and findings.
6. Test commonly used forceps designs for their springiness using a Bluehill program and Instron 5544 in the laboratories of Goddard Hall at WPI. Use these values to find the desired springiness of forceps. (This value would hypothetically be utilized in the manufacturing of the full forceps, however, for the scope of this project will not be utilized in the final design.)
7. Repeat steps 1-5 as necessary and make alterations to the most recent prototype design(s). Print a new prototype and get feedback. Continue the process with focus on the components that qualify the forceps design for skin closure (size, balance, springiness).

Objective 2: Improve the haptic capabilities of the forceps overall design and grip. Reduce slip between the forceps grip and surgical gloves.

The haptics of a design involve “the use of technology that stimulates the senses of touch and motion” (Oxford, 2021). The primary points of focus in an improved forceps design are the balance of the instrument in the user’s hand, the general feel and pattern of the grip, the material choice of the grip, and the proportions of the design.

1. To determine the optimal balance point of forceps, the group began by determining the approximate location of the center of mass on each prototype. This location was compared to the location preference of Dr. Dunn and other plastic surgery residents through the use of user trials and focus groups.
2. After gathering qualitative and quantitative data from various subjects and from the balance point of each instrument, new prototypes were made by placing the dip of the trough of the grip in the determined best location for balance of the instrument.
3. For material choice of the grip, the materials were researched and considered primarily based on the FDA-approved options, and ability to be sterilized through autoclaving.

Then the further choice was based on the haptic feel of the material in a hand. For this reason, silicone and Thermoplastic Elastomer (TPE) were selected as the preferred grip materials.

4. Grip patterns were tested based on prior research from a previous MQP regarding scalpel grips and how to reduce slip between the user and the instrument using different textured patterns (Burke et al., 2020).
5. Continue with the process of grip selection and user experience testing using surgical gloves and oiled and non-oiled scenarios. Use these conditions to mimic the environment of the surgical field as best as possible.

Objective 3: Improve ergonomics of the forceps design with primary focus on the grip by designing a grip that allows for 360 degrees of rotation in between the fingers (reduce the overall motion of the arm/rotation around the shoulder for the user).

One of the most desirable aspects of this new forceps design, in the opinion of the project advisor Dr. Dunn, is the ability to fully rotate the instrument in between the user's fingers without additional arm movement or rotation of the trunk (upper body). This reduces user fatigue and allows for ease of use within the surgical field. This objective was achieved through many iterations of prototyping as discussed in Objective 1. Designs were created in SolidWorks and discussed and tested by the design team, Dr. Dunn, and surgical residents in focus groups. The main aspect of this task was to ensure that the grip was designed as a cylindrical base such that the forcep could be completely rotated in a single motion.

1. Create conceptual designs of grips and bring them to advisors for feedback.
2. Adjust grips conceptual designs as necessary.
3. Draw conceptual design of grips in SolidWorks and send to the WPI Foisie Makerspace to be 3D-printed.
4. Gather qualitative and quantitative feedback from advisors and plastic surgery residents through surveys and discussion. Focus this feedback on the rotation of the instrument in between the fingers.
5. Perform iterations of designs focused on the round shape of the grip to enhance rotation.

Objective 4: Create a design that is manufacturable, focusing on practicality and cost reduction. Select materials that are FDA compliant and will hold up under repeated sterilization by autoclave.

In any design project it is important to keep the end goal of production and manufacturing in mind. If a design becomes too impractical to produce then it will never reach any markets or be manufactured. Things that could prevent next steps of a design would be an impractical material selection, or a design that is too difficult to mass produce by cost-effective means. This objective was met by researching common processes for manufacturing metal and silicone medical devices such as cast molding and machining, and factoring this reasoning into all design decisions.

Data Analysis involved in the design process that was relevant to meeting design objectives includes the following:

1. Data from the surgical resident focus group on proportions and haptics (Appendix B).
2. Data from slip testing and UX focus groups (Section 5.2, Section 5.4, and Appendix B).
3. Data from springiness testing to lead to recommendations (Section 5.3).
4. Comparison between preferred grip location based on the surgeon's preferred balance points, and the resulting force to close (Section 5.3).

6.2 Economics

This project was undertaken with the final goal of designing a product that would eventually be mass-manufactured and hopefully become an integral tool in every operating room. Dr. Dunn made it clear that following the final design prototype of this product he hoped to have it manufactured and sold to surgeons across the nation. This design could have a significant economic impact on hospitals and medical facilities as this design is composed of two different materials would therefore likely have a slightly higher cost than the typical adson forceps that were previously being utilized. Additionally, any new product that is not widely accepted and purchased will have slightly higher costs until it becomes the accepted standard to the applicable market. Medical professionals and hospitals would need to weigh the benefits of this ergonomic forceps design to the slightly less expensive and widely accepted option. The team and its advisors feel confident that this design's benefits outweigh the slightly higher cost.

It is the team's belief that to get this product off the ground and as a success in the market that individual doctors will make the biggest difference. Currently, surgeons such as Dr. Dunn are unhappy with the typical design of surgical forceps and other similar tools such as surgical scalpels that are not designed with ergonomic and haptic considerations. They have resorted to creating their own prototypes for the sake of surgical precision and to reduce their arm range of motion to make a cut that could be easily accessed by the rotation of the instrument in between the fingers. The team has also considered the impact of clinical representatives to clinics and hospitals around the nation. If prominent medical professionals begin to prefer a new product such as this surgical forceps then that could convince whole practices, and hospitals to eventually make the shift to this improved design.

6.3 Environmental Impact

The environmental impact of this new design of forceps becoming popular in the medical field should be minimal. Typically, the forceps used for skin closure during plastic surgery are Adson forceps that are made solely of stainless steel. This new design includes a silicone grip overlaid on top of the design of the stainless steel forceps. Incorporating two materials into one product will likely require a slight increase of materials in comparison to the alternative. Additionally, this will impact the providers of these two materials and possibly account for a larger carbon footprint through additional shipping and possibly extra packaging. This will produce extra waste.

The sterilization process of this new forceps design will be the same process as is currently used for forceps as all of the involved materials are not susceptible to break down under the high temperatures of the steam sterilization. Therefore this will not produce additional waste and cause negative environmental impact. Overall, there are not necessarily positive environmental impacts to switching to this design of surgical forcep, however, the negative impacts are very minimal, if any.

6.4 Societal Influence

This product will have a direct effect on the skill and precision that a doctor or surgeon executes during procedures. According to the goals and objectives of this project, this product will give the user a significant increase in the range of motion of the instrument with less effort and movement of the arm, shoulder, and trunk. According to the project advisors and the projections of the design team, this ease of execution could result in better patient outcomes and fewer mistakes during surgery, not to mention, less fatigue to the user. Therefore, the project team predicts that if this product were to be utilized by surgeons that it could aid the surgeon's stamina during a procedure and even go so far as to provide more precision and accuracy while using the instrument and improving the livelihood of the patient. Conversely, if the instrument were to miss the objectives of more ease to the surgeon (user), or somehow interfered with the job of the surgeon then that could result in very negative influence for the user and/or the patient. This is a major consideration when going to focus groups and collecting feedback for the product.

Additionally, any time a professional switches away from a widely accepted method or instrument, there is a learning curve associated with the product. There would need to be a lot of emphasis on practicing with this new instrument in labs and other applications before it was used in a surgery on a live patient. The negative impact of making a mistake on a patient during a surgical procedure could be catastrophic and needs to be avoided at all costs.

Another aspect of societal influence of this device would be to consider the jobs that would be created to further perfect this instrument, start the manufacturing processes, and to mass-produce the forceps to multiple practices and hospitals. An exciting new product could produce many jobs to provide it to many consumers. Additionally, could spark further innovation around this product and other similar products. For example, the concept for this project design stemmed from a new ergonomic scalpel design. Similarly, the use of this product could lead to other innovation around similar products.

6.5 Political Ramifications

If this product were to be deemed as the new standard in forcep design, then it would hypothetically be purchased and utilized world-wide. Considerations would need to be made regarding the patent and licensing of the product to determine who would be allowed to produce this and similar products such as the similarly designed scalpel with similar grips (Burke et al., 2020). Since forceps are such a commonly used tool in medical applications, a huge market exists for them so it would be important to discuss the licensing of the design. If, for example, a single medical device manufacturing company had the rights and ability to manufacture this product then that would result in rapid growth for the company and huge sales and an economic boost to the area and possibly nation in which the company resides. A singular license to one manufacturer/company could also result in negative ramifications as that manufacturer could drive prices up for the sake of monetary gain with no consideration for improving healthcare through distribution of the product.

6.6 Ethical Concerns

One ethical concern with the use of this new forceps design would be the associated risk of switching surgical techniques for the user. The use of forceps is not necessarily considered a high risk part of surgery, unlike the use of scalpels to create incisions. However, improper use of the forceps could still result in unwanted outcomes during surgery for the patient. Surgeons need to be incredibly precise with all of their movements within the surgical field as the human body is incredibly delicate and could be harmed by many different means. It is necessary to require that surgeons practice their surgical technique with this altered instrument prior to use in surgery.

A second ethical concern would be to allow for the licensing and allowances of this product to many different companies and countries to allow for the product to be widely accessible. This is important because the newly designed product could result in improvements to health care and better patient outcomes. Limiting this improvement to one region of the world instead of a widespread reach would raise major ethical concerns about limiting innovation due to high prices and/or inaccessibility.

6.7 Health and Safety Issues

During the material selection stage of the design process, the team wanted to ensure that the entire product was completely sterilizable and FDA approved for use in medical applications. Sterilizability is one of the most pressing health and safety issues associated with medical instruments because of the sensitivity of the human body to foreign bodies. If pathogens were to live on the forceps or in crevices within the design, the use of the instrument in an open body cavity would infect the patient and could result in infection and even death. Included with the sale of the product will be clear instructions for sterilization of the tool in between uses to prevent the transfer of germs. A specific concern related to sterilization is to consider the crevices that will exist within the textured grips of the final design. This grip texture was selected based on its ability to minimize user error through increasing the coefficient of friction between surgical gloves and the instrument. However, this texture presents extra opportunity for pathogens to remain on the instrument. A component of sterilization for this instrument may include some kind of pressurized wash or scrubbing to occur prior to autoclaving the instrument.

6.8 Manufacturability

Throughout the design process, all choices were made with the end goal of manufacturing in mind. Such design choices include the overlay of the silicon grips on top of the smooth forceps design to allow for manufacturing by way of die-casting and then subsequently overlaying the grip through injection molding. Another project group with more of an academic focus in manufacturing and industrial engineering worked in conjunction with this design team to discuss broad manufacturing options and to aid the design team in making recommendations regarding reproducibility of the ergonomic forceps design.

Another aspect of manufacturability for a medical device is the ability to get FDA approval- not only of the product but of the manufacturing processes. The following standards and regulations were considered over the course of the project:

ISO 11737-1, 2, and 3: This standard involves the sterilization of health care products through the determination of the number of microorganisms on reusable tools in health care. This standard does not apply to monitoring the health care environment but only to monitoring this reusable instrument. This standard was addressed during the material selection of silicon and stainless steel which are both completely sterilizable.

ISO 13485:2016: This standard involves putting quality management systems in place during the manufacturing of medical devices and is instrumental to ensuring an effective and repeatable process for producing medical devices. It includes everything from the incoming materials and parts of the product, to how every component is handled and treated prior to, during, and after manufacturing. This is essential to ensure the safety of the product and to make sure that it meets regulatory and customer requirements.

The AAMI in conjunction with ANSI, a non-profit organization that produces voluntary standards regarding medical instruments provides helpful guidance in the development of medical instruments within the areas of healthcare technology management, medical device manufacturing, and sterilization. This guidance was taken into account while making manufacturing recommendations and in designing the product.

Chapter 7 - Discussion

The model that the team produced was generally determined to be more ergonomically effective than the existing Adson forceps commonly used. Compared to the flat and wider industry standard Adson forceps, the team's design allowed for more comfortable and effective pincer movement. This improves the range of effective motion for the user to grasp tissue. The team's design also has a more haptically favorable grip surface, with two extrusions and one "trough," which tailor to the natural curve of the hand much more comfortably and ergonomically than the flat surface of the existing model. Since the designs have the same tip design, the grasping of the tissue by the forceps themselves is just as effective as that of the existing design, which is desirable. Finally, compared to the rippled grip design on the existing Adson forceps device, the checkered knurl grip surface on the team's design has a higher coefficient of friction, allowing for a more secure grip in surgical conditions.

This project strived to create a new design for surgical forceps grips, specifically Adson forceps for skin closure, that focuses more on the ergonomic properties of the tool. Current designs used commonly in operating rooms tend to have flat grips with small ridges. To create forceps that are more ergonomic, it must feel more comfortable and balanced in the user's hand. A flat surface to grip is not very comfortable for turning the hand and rotating while being held. This new design must be more rounded and feel more comfortable on the fingers when turning and rotating, which was a major consideration. Finding the best balance point in the hand is also a strong consideration when designing new forceps. Finger placement on the grip of the forcep is crucial for the user so that they can have the most effective grip on the tissue being grasped. Another problem with the current design that was taken into consideration was the friction of the grip surface. As mentioned above, the current design features small ridges for grip strength. This is not as effective as possible, as the stainless-steel can still be slippery despite these ridges. This design also strived to create a grip pattern on the ergonomic surface that reduces friction significantly, even under wet and slippery conditions, which are common in the operating room. These problems with the current forceps design were the most significant that we used when creating the new design.

The objectives of this project were to create an Adson forceps design that enhances the pincer movement while having ideal springiness and dimensions. The design created in this project enhances the pincer movement greatly. With two "protrusions" and a "trough," the design allows for the user to rotate the device in their hand with much more fluidity and range than the commonly used flat design. The rounded grip area allows for the fingers to more comfortably grip tissues, along with allowing more control at a larger range of angles. The team had Dr. Dunn quantify and identify which designs of forceps were too springy or not springy enough. Using this evaluation, the team was able to choose an ideal design using stainless steel to maintain this ideal springiness. The team had Dr. Dunn examine several different dimensions of forceps prototype iterations to find an ideal length and width of forceps grips. After this examination, it was determined that there was a ratio of length and width between these grips that was most comfortable. This was identified as the “golden ratio” which is a ratio of 0.25 between the large protrusion width and length, 0.16 between the trough width and length, and 0.22 between the small protrusion width and length. Out of the golden ratio designs, the smallest two designs (1-1 and 2-6) were found to be the most effective for the Adson forceps, as they fit the overall length of the forceps more comfortably. For skin closure, it was decided that this size of grip would be ideal since standard Adson forceps are relatively small.

The constraints of this project were to ensure that our design was able to be sterilized safely and be made out of approved materials. In order to make sure our design was sterilizable, the team ensured that the final materials used could withstand the heat of an autoclave. The base material of the design, stainless steel, is known to be able to withstand this heat and maintain sterilization afterwards. For the grip surface, silicone and thermoplastic elastomer (TPE) were chosen since they are also able to withstand an autoclave process and maintain sterilization. These materials were also chosen because they are both approved for use in the operating room.

The forceps models were given to Dr. Dunn and the resident surgeons at UMass Memorial for user experience surveys to be rated from 1-7 in different scenarios. The result of this study showed that the 2-6 grip design with texture 2 is the favored design out of all seven that were tested. This is believed to be because it has the ideal dimensions for the application with the texture that was tested to have the highest coefficient of friction. The next best performing model in the surveys was the industry standard Adson forceps. This is believed to be because some of the resident surgeons in the study are newer to the field and therefore less experienced in the operating room. This could account for some surveys gravitating towards this model, since this is the model that they have learned with for the past few years.

During mechanical testing, each forceps grip texture was tested for coefficient of friction. Texture 2 was found to be the grip with the highest coefficient of friction, meaning it was the most effective grip for reducing slip. The next most efficient grip texture was texture 3, followed by texture 1. This is speculated to be because the texture 2 model has the best elevated area compared to the other textures. Dr. Dunn mentioned that texture 3 had too much “smooth” area, making it more slippery, which is reflected by the friction results. The texture 1 was determined to not have enough smooth area, making it smooth in essence. This is also reflected by the friction results. Based on this, the 1-1 and 2-6 with the texture 2 are the favorites for slip reduction.

The other mechanical test performed on the forceps was an ideal springiness test. This was done to identify the ideal force to close a set of forceps for future use and designs. The offset tested closest to the tips was identified to have the lowest force to close, the base mark was a bit more force to close, and the mark closest to the base was the largest force to close. This is because the force is based on a moment reaction from the base of the forceps. The further from the base of the forceps, the less force is required to close them. However, less force does not necessarily mean better. From consulting with Dr. Dunn, the base (middle) mark was the ideal placement for the trough of the grip, which is where the finger rests to close the forceps. This means that the ideal springiness is the medium force to close, or about 6.14 N. Using stainless steel for forceps bases, this springiness is definitely attainable for future designs, and should be considered when designing a new model. That is, the ideal force to close value should be attained at the location on the forcep where the user would place their fingers.

This design project is limited by the time available to test more materials and methods of manufacturing. If there were more time available, the team could experiment with cast molding of silicone and thermoplastic elastomers. These materials would be more ideal for mechanical testing of friction, as they are more realistic for operating room application. The project was also limited by the inability to produce a new stainless steel prototype for the base of the design. The prototypes used in this project were stock Adson forceps which were ground with an angle grinder, and the PLA grips were glued on. If there were a new steel prototype, a new size and shape for skin closure forceps could be developed with ergonomic grips easily attached with no manual adjustment to the metal. With no manual adjustment to the stainless steel forceps themselves, the springiness and alignment of the forceps would not be in jeopardy. Despite these project limitations, for design verification and validation, the Adson forceps with PLA grips sufficed.

Chapter 8 - Conclusions and Recommendations

Surgical forceps are such a commonly utilized medical instrument, and yet, have sorely lacked any engineering advancements or optimization for years. Surgeons and other medical professionals have issued complaints about the discomfort with using the current design of forceps for hours on end and the restricted motion that comes with using a flat instrument that requires you to grab tissue or other objects from multiple angles. It is the hope of the design team and its advisors that this project could serve a part in progressing innovation for surgical forceps and many other medical instruments that have been otherwise neglected for such a long time.

The end product of this design project is an improved surgical forcep design for skin closure in plastic surgery using the base dimensions of an Adson forcep. One of the more important aspects of this design to focus on and that could be incorporated into any forcep design and even into other medical or everyday instruments and tools would be the design of the grip. This grip allows for a full range of motion of the instrument just with the rotation of your fingers. There is less need for the user to adjust an entire body position or rotate the shoulder to awkward angles to position the tip of the forcep just right. This innovation could lead to future innovation in a variety of other fields, but especially within the medical field where it is so important to reduce surgeon fatigue over long operating times and to increase precision wherever possible.

The final design for this project, the 2-6 model with texture 2 (checkered knurl 0.75mm offset), is the design with the most ideal dimensions and texture for enhanced pincer grasp and reduced slip for skin closure application. This conclusion was reached after iterations of designs along with surgeon feedback and mechanical testing. This design has potential to become an industry standard for use in the operating room. It would increase ergonomic and haptic feedback and greatly reduce slip in not only skin closure, but in many other surgical applications as well. Using the golden ratio of grips, the dimensions could be adjusted for forceps of any size to fit any application with precision. The grip surfaces are also applicable to many designs, which would be able to effectively reduce slip on any model of grip.

Due to certain limitations on this project, the team was unable to achieve everything they set out to. If the team were allotted more time and resources, more testing and prototyping could have been done using different methods of manufacturing and different materials. Cast molding was a type of prototyping that would have been interesting to attempt. This would open the material selection to materials such as silicone and thermoplastic elastomers. These materials would be able to undergo multiple cycles of autoclaving, a requirement in operating room sterilization, and would have different haptic properties. Also, the grip surface would be able to have more resolution and different slip reduction properties. These are important considerations for an operating room ready prototype, which the team would recommend future teams look into in the future.

The design of the stainless steel forceps is also an aspect of the project that the team was unable to analyze. The forceps used for this project were standard Adson forceps which were angle grinded into the shape the team needed to overlay the printed grips onto. If the team were able to produce stainless steel forceps in the shape required for overlaying without manual alteration, the springiness and alignment properties of the forceps would not have been compromised. This would be important to look into for future projects as well, as this would also be important for a prototype to be operating room ready.

A final recommendation for future teams on this project is to look into the effectiveness of different offsets of checkered knurl patterns. Since the 0.75 and 1.0mm offset patterns were the most effective of the three, a pattern with an offset between these would be worth looking into and analyzing. This could increase the coefficient of friction on the grip, possibly reducing slip even more. Finding the ideal offset which is also ideal for manufacturing resolution is an impactful consideration for all ergonomic grips in this application.

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Appendices

Appendix A: Instructional Packet for User Experience Survey of Forceps Prototypes

This appendix displays the packet of instructions that each participant in the User Experience (UX) testing received prior to completing the survey. Each participant received their own packet and was instructed to read through the instructions carefully prior to testing. Detailed instructions were critical to the integrity of this testing because due to the COVID-19 pandemic, the design team was unable to meet with these participants in-person. There were a total of 10 participants in the UX surveys. Nine were plastic surgery residents, and one was the project sponsor and chief of plastic surgery, Dr. Dunn.

User Experiment Survey of Seven Different Forceps Designs

Purpose:

The purpose of this survey is to gather data for the Major Qualifying Project (MQP), Design and Optimization of Ergonomic Forceps for Skin Closure. This project was completed by a student team from Worcester Polytechnic Institute (WPI) in the Biomedical Engineering Department and the Mechanical Engineering Department in conjunction with the University of Massachusetts Memorial Medical Center (UMMC). This project was advised by Dr. Raymond Page (WPI), Dr. Raymond Dunn (UMMC), and Dr. Kristen Billiar (WPI). Any data that you provide towards this project will aid the team in analyzing the effectiveness of various designs of forceps for use by medical professionals in many clinical settings. Thank you for your participation!

Instructions:

Please perform the following task by following each of the steps listed below with each of the seven provided forceps. Perform the task, once under normal circumstances, and again with olive oil or another similar oil coating each set of forceps. (This simulates bodily fluids that would be present during surgery.) Ensure that in normal circumstances there is no oil or moisture present in the testing field.

Step 1:
Choose a small item that can be manageably grasped with the forceps (i.e. a piece of cloth, a slice of chicken, or a paper clip, in our case we chose a piece of foam) laying it on a flat surface in front of you (Figure 1).

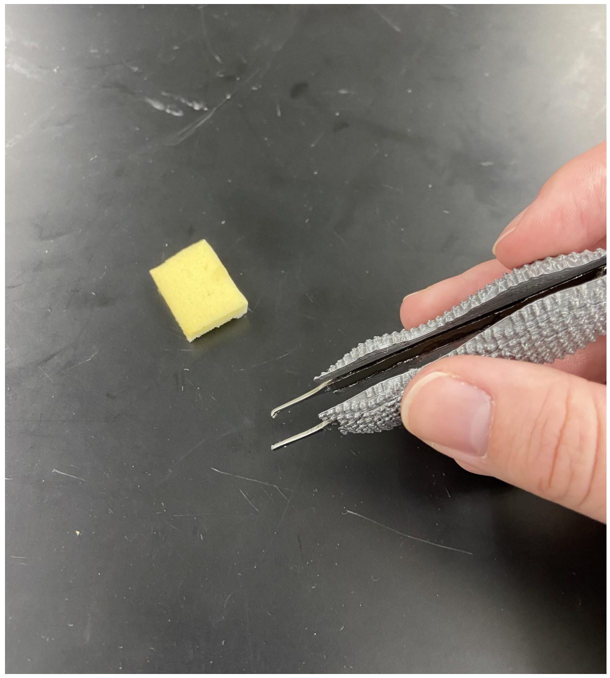


Figure 1: Selection of Small Object for Grasping

Step 2:
Don surgical gloves prior to testing the forceps. Hold the forceps using your non-dominant hand as you normally would during clinical applications (Figure 2).

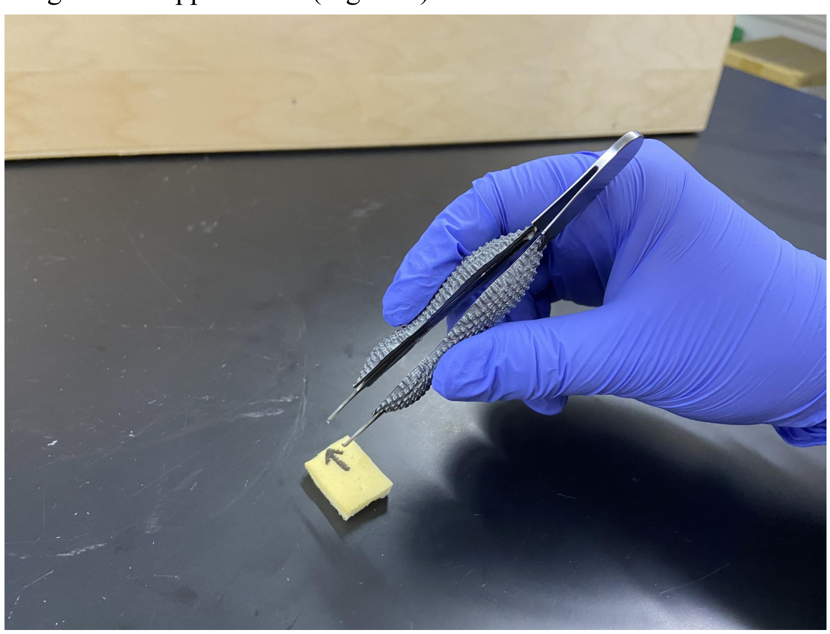


Figure 2: Setting Up the Workspace

Step 3:
Grasp the item with the forceps and lift it into the air (Figure 3).

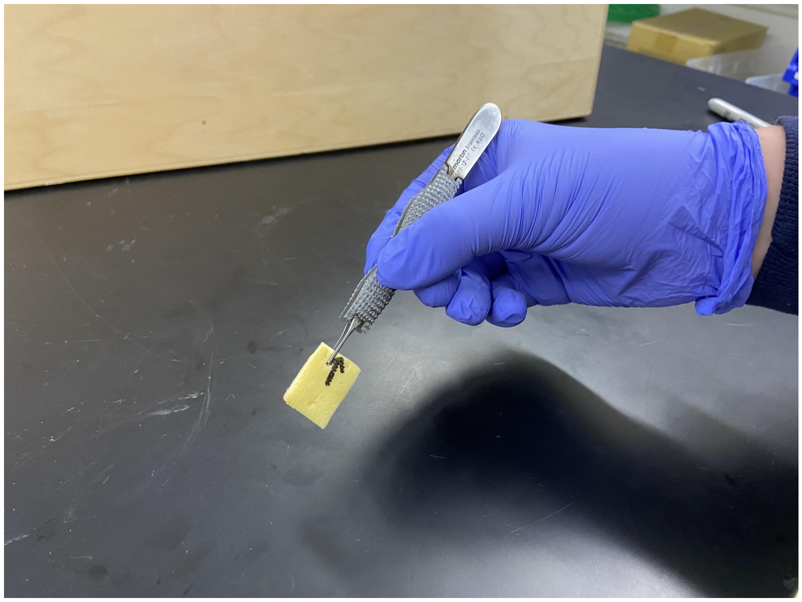


Figure 3: Lifting Object Using Forceps

Rotate the item, setting it down at approximately 180 degrees rotated from its original position back onto the flat surface in front of you (Figure 4).

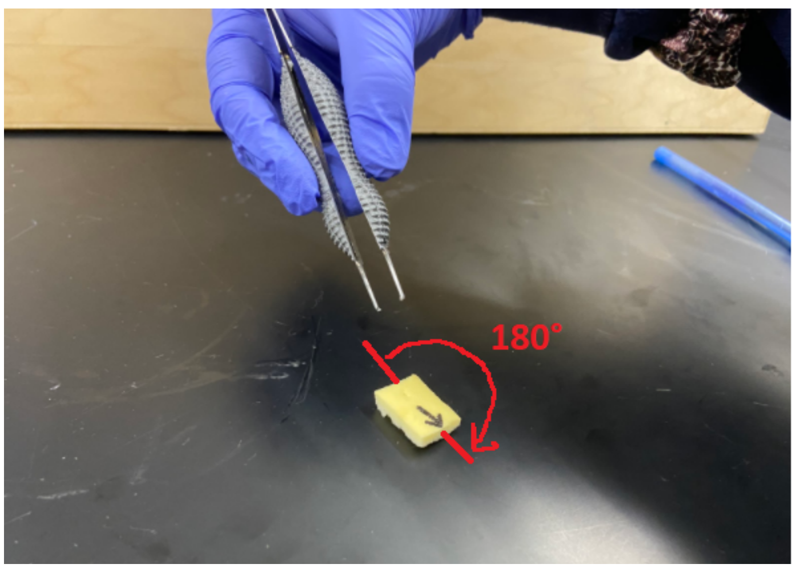


Figure 4: 180° Turn

Step 4:
Grasp the item with the forceps and lift it into the air (Figure 3).
Flip the item over, setting it down on the back surface from its original position onto the flat surface in front of you (Figure 5).

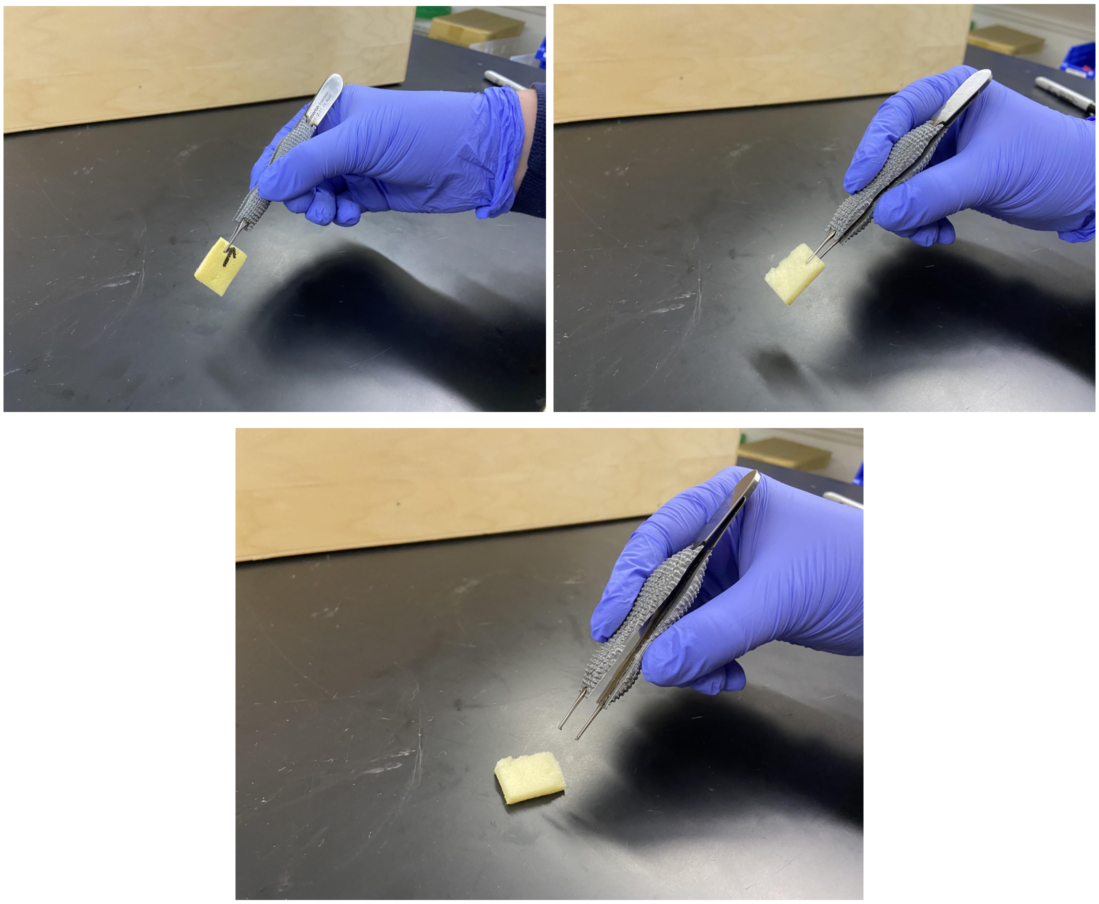


Figure 5: Flip the Object

Step 5:
Please rate the following aspects of this user experiment on a scale of 1 being an awful experience, and 7 being a great experience (Tables 1-3).

Step 6:
Following all of the user experiments (both oily and non-oily) please fill out Table 4 giving your overall ranking of all of the designs of forceps ranking them as 1 being your least favorite forceps for overall use, and 7 being your preferred forceps for overall use (Table 4).

Potential Alteration of User Experiments:
For the sake of ease and time, you may choose to not perform the user experiments using the oiled gloves and forceps. (Ignore Table 3.)

User Experience Participant Worksheet:

Name of Participant:

Age of Participant:

Gender of Participant:

Participant Profession (as is relevant to use of forceps):

Non-Dominant Hand (Left or Right):

Small item chosen for grasping:

Oil type used during experiments:

Table 1: Grading Scale for User Experiments

1	2	3	4	5	6	7
Awful			Neutral			Great!

Table 2: User Experiment of Non-Oily Testing of Forcep Designs

Non-oily testing:	Grip 1-1, Texture 1	Grip 1-1, Texture 2	Grip 1-1, Texture 3	Grip 2-6, Texture 1	Grip 2-6, Texture 2	Grip 2-6, Texture 3	Classic Adson Forceps
Criteria:	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):
Slip between fingers and grip (1 being very slippery, 7 being no slip whatsoever)							
Overall comfort of forceps in your hand (1 being uncomfortable, 7 being comfortable)							
Ease of use to perform the given task							
The feel of the grip texture in your fingers							

Table 3: User Experiment of Oily Tests of Forcep Designs

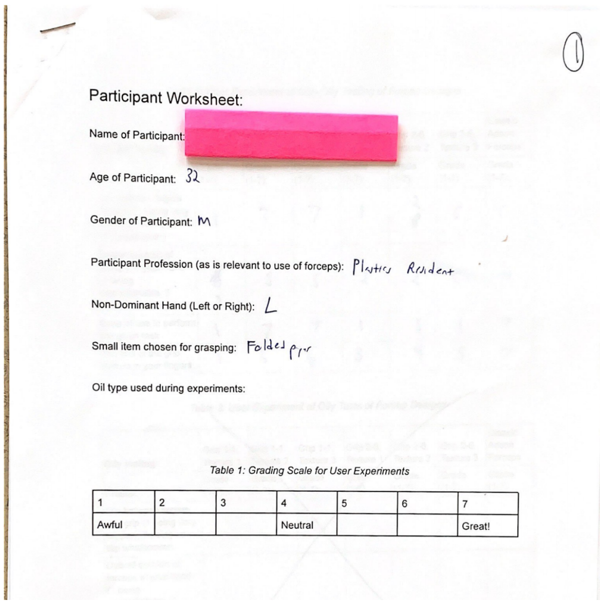
Oily testing:	Grip 1-1, Texture 1	Grip 1-1, Texture 2	Grip 1-1, Texture 3	Grip 2-6, Texture 1	Grip 2-6, Texture 2	Grip 2-6, Texture 3	Classic Adson Forceps
Criteria:	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):
Slip between fingers and grip (1 being very slippery, 7 being no slip whatsoever)							
Overall comfort of forceps in your hand (1 being uncomfortable, 7 being comfortable)							
Ease of use to perform the given task							
The feel of the grip texture in your fingers							

Table 4: Ranking of Overall Performance of All Forcep Designs

Forceps:	**Rank:**
Grip 1-1, texture 1	
Grip 1-1, texture 2	
Grip 1-1, texture 3	
Grip 2-6, texture 1	
Grip 2-6, texture 2	
Grip 2-6, texture 3	
Classic Adson Forceps	

Appendix B: Data From User Experience Surveys

Subject 1:



1

Participant Worksheet:

Name of Participant: [redacted]

Age of Participant: 32

Gender of Participant: M

Participant Profession (as is relevant to use of forceps): Plastics Resident

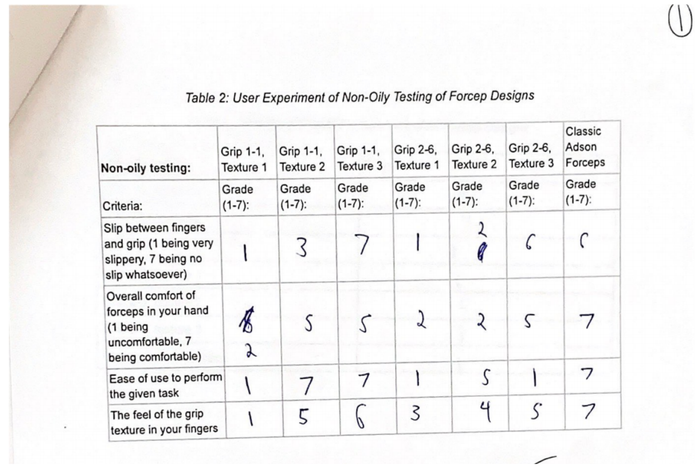
Non-Dominant Hand (Left or Right): L

Small item chosen for grasping: Folded paper

Oil type used during experiments:

Table 1: Grading Scale for User Experiments

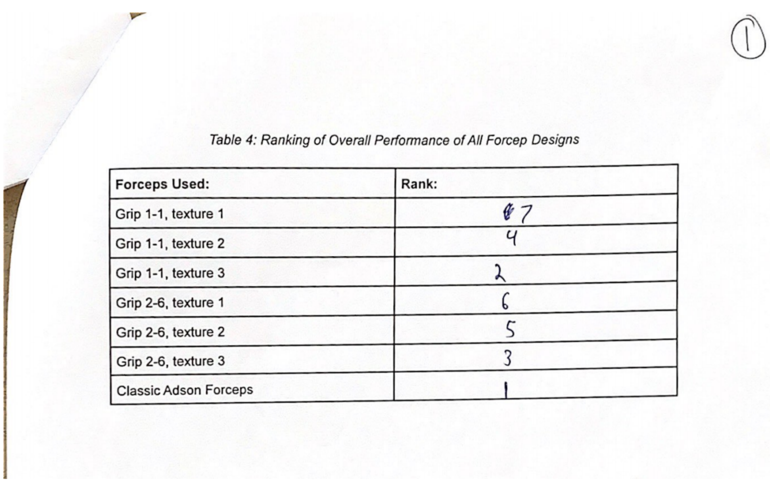
1	2	3	4	5	6	7
Awful			Neutral			Great!



1

Table 2: User Experiment of Non-Oily Testing of Forcep Designs

Non-oily testing:	Grip 1-1, Texture 1	Grip 1-1, Texture 2	Grip 1-1, Texture 3	Grip 2-6, Texture 1	Grip 2-6, Texture 2	Grip 2-6, Texture 3	Classic Adson Forceps
Criteria:	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):
Slip between fingers and grip (1 being very slippery, 7 being no slip whatsoever)	1	3	7	1	2	6	6
Overall comfort of forceps in your hand (1 being uncomfortable, 7 being comfortable)	2	5	5	2	2	5	7
Ease of use to perform the given task	1	7	7	1	5	1	7
The feel of the grip texture in your fingers	1	5	6	3	4	5	7



1

Table 4: Ranking of Overall Performance of All Forcep Designs

Forceps Used:	Rank:
Grip 1-1, texture 1	7
Grip 1-1, texture 2	4
Grip 1-1, texture 3	2
Grip 2-6, texture 1	6
Grip 2-6, texture 2	5
Grip 2-6, texture 3	3
Classic Adson Forceps	1

Subject 2:

②

Participant Worksheet:

Name of Participant:

Age of Participant: 33

Gender of Participant: M

Participant Profession (as is relevant to use of forceps): Resident physician

Non-Dominant Hand (Left or Right): Left

Small item chosen for grasping: Small paper square

Oil type used during experiments:

Table 1: Grading Scale for User Experiments

1	2	3	4	5	6	7
Awful			Neutral			Great!

②

Table 2: User Experiment of Non-Oily Testing of Forcep Designs

Non-oily testing:	Grip 1-1, Texture 1	Grip 1-1, Texture 2	Grip 1-1, Texture 3	Grip 2-6, Texture 1	Grip 2-6, Texture 2	Grip 2-6, Texture 3	Classic Adson Forceps
Criteria:	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):
Slip between fingers and grip (1 being very slippery, 7 being no slip whatsoever)	2	3	4	3	7	7	6
Overall comfort of forceps in your hand (1 being uncomfortable, 7 being comfortable)	4	5	4	4	7	7	2
Ease of use to perform the given task	6	6	6	6	6	6	2
The feel of the grip texture in your fingers	4	4	5	6	7	6	2

②

Table 4: Ranking of Overall Performance of All Forcep Designs

Forceps Used:	Rank:
Grip 1-1, texture 1	6
Grip 1-1, texture 2	5
Grip 1-1, texture 3	3
Grip 2-6, texture 1	4
Grip 2-6, texture 2	1
Grip 2-6, texture 3	2
Classic Adson Forceps	7

Subject 3:

(3)

Participant Worksheet:

Name of Participant:

Age of Participant: 30

Gender of Participant: M

Participant Profession (as is relevant to use of forceps): RESIDENT

Non-Dominant Hand (Left or Right): L

Small item chosen for grasping: PAPER SQUARE

Oil type used during experiments: N/A

Table 1: Grading Scale for User Experiments

1	2	3	4	5	6	7
Awful			Neutral			Great!

(3)

Table 2: User Experiment of Non-Oily Testing of Forcep Designs

Non-oily testing:	Grip 1-1, Texture 1	Grip 1-1, Texture 2	Grip 1-1, Texture 3	Grip 2-6, Texture 1	Grip 2-6, Texture 2	Grip 2-6, Texture 3	Classic Adson Forceps
Criteria:	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):
Slip between fingers and grip (1 being very slippery, 7 being no slip whatsoever)	5	~~2~~ 5	6	2	5	6	7
Overall comfort of forceps in your hand (1 being uncomfortable, 7 being comfortable)	7	~~4~~ 6	6	6	6	6	3
Ease of use to perform the given task	7	~~6~~ 7	7	6	7	6	7
The feel of the grip texture in your fingers	7	~~8~~ 6	4	5	6	5	5

(3)

Table 4: Ranking of Overall Performance of All Forcep Designs

Forceps Used:	Rank:
Grip 1-1, texture 1	1
Grip 1-1, texture 2	2
Grip 1-1, texture 3	5
Grip 2-6, texture 1	4
Grip 2-6, texture 2	3
Grip 2-6, texture 3	6
Classic Adson Forceps	7

Subject 4:

4

Participant Worksheet:

Name of Participant:

Age of Participant: 28

Gender of Participant: F

Participant Profession (as is relevant to use of forceps): PLASTIC SURGERY RESIDENT

Non-Dominant Hand (Left or Right): Left

Small item chosen for grasping:

SMALL SQUARE OF THE PARCHMENT THE STERILE GLOVES COME IN

Oil type used during experiments:

N/A

Table 1: Grading Scale for User Experiments

1	2	3	4	5	6	7
Awful			Neutral			Great!

4

Table 2: User Experiment of Non-Oily Testing of Forcep Designs

Non-oily testing:	Grip 1-1, Texture 1	Grip 1-1, Texture 2	Grip 1-1, Texture 3	Grip 2-6, Texture 1	Grip 2-6, Texture 2	Grip 2-6, Texture 3	Classic Adson Forceps
Criteria:	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):
Slip between fingers and grip (1 being very slippery, 7 being no slip whatsoever)	4	5	3	6	7	3	6
Overall comfort of forceps in your hand (1 being uncomfortable, 7 being comfortable)	5	5	3	6	6	4	7
Ease of use to perform the given task	4	4	2	4	6	2	7
The feel of the grip texture in your fingers	5	6	1	5	6	1	6

4

Table 4: Ranking of Overall Performance of All Forcep Designs

Forceps Used:	Rank:
Grip 1-1, texture 1	5
Grip 1-1, texture 2	3
Grip 1-1, texture 3	7
Grip 2-6, texture 1	4
Grip 2-6, texture 2	2
Grip 2-6, texture 3	6
Classic Adson Forceps	1

COMMENTS:

WHEN I PICK UP AN ADSON, I ALWAYS GRAB IT WITH THE TINES ORIENTED PROPERLY. I FOUND THAT WHEN I PICKED UP THE OTHER FORCEPS, MY NONDOMINANT HAND HAD TROUBLE ORIENTING THE TINES PROPERLY. I HAD TO LOOK AT THE INSTRUMENT IN MY HAND & REORIENT IT TO BE ABLE TO DO THE TASK.

Subject 5:

5

Participant Worksheet:

Name of Participant:

Age of Participant: 27

Gender of Participant: Female

Participant Profession (as is relevant to use of forceps): Resident

Non-Dominant Hand (Left or Right): L

Small item chosen for grasping: Paper square

Oil type used during experiments: N/A

Table 1: Grading Scale for User Experiments

1	2	3	4	5	6	7
Awful			Neutral			Great!

5

Table 2: User Experiment of Non-Oily Testing of Forcep Designs

Non-oily testing:	Grip 1-1, Texture 1	Grip 1-1, Texture 2	Grip 1-1, Texture 3	Grip 2-6, Texture 1	Grip 2-6, Texture 2	Grip 2-6, Texture 3	Classic Adson Forceps
Criteria:	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):
Slip between fingers and grip (1 being very slippery, 7 being no slip whatsoever)	3	7	7	3	7	7	2
Overall comfort of forceps in your hand (1 being uncomfortable, 7 being comfortable)	3	7	5	3	7	5	6
Ease of use to perform the given task	5	7	6	5	7	6	6
The feel of the grip texture in your fingers	5	7	6	5	7	6	6

5

Table 4: Ranking of Overall Performance of All Forcep Designs

Forceps Used:	**Rank:**
Grip 1-1, texture 1	6
Grip 1-1, texture 2	1
Grip 1-1, texture 3	3
Grip 2-6, texture 1	7
Grip 2-6, texture 2	2
Grip 2-6, texture 3	4
Classic Adson Forceps	5

Subject 6:

6

Participant Worksheet:

Name of Participant:

Age of Participant: 27

Gender of Participant: F

Participant Profession (as is relevant to use of forceps): PRS

Non-Dominant Hand (Left or Right): Right

Small item chosen for grasping: Paper

Oil type used during experiments: —

Table 1: Grading Scale for User Experiments

1	2	3	4	5	6	7
Awful			Neutral			Great!

6

Table 2: User Experiment of Non-Oily Testing of Forcep Designs

Non-oily testing:	Grip 1-1, Texture 1	Grip 1-1, Texture 2	Grip 1-1, Texture 3	Grip 2-6, Texture 1	Grip 2-6, Texture 2	Grip 2-6, Texture 3	Classic Adson Forceps
Criteria:	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):
Slip between fingers and grip (1 being very slippery, 7 being no slip whatsoever)	2	4	5	2	4	5	
Overall comfort of forceps in your hand (1 being uncomfortable, 7 being comfortable)	3	4	3	3	5	3	
Ease of use to perform the given task	6	6	6	6	6	6	
The feel of the grip texture in your fingers	5	6	7	5	6	7	

6

Table 4: Ranking of Overall Performance of All Forcep Designs

Forceps Used:	Rank:
Grip 1-1, texture 1	2
Grip 1-1, texture 2	6
Grip 1-1, texture 3	4
Grip 2-6, texture 1	1
Grip 2-6, texture 2	5
Grip 2-6, texture 3	3
Classic Adson Forceps	7

Subject 7:

7

Participant Worksheet:

Name of Participant:

Age of Participant: 35

Gender of Participant: F

Participant Profession (as is relevant to use of forceps): resident physician

Non-Dominant Hand (Left or Right): L

Small item chosen for grasping: thumb tack

Oil type used during experiments: N/A

Table 1: Grading Scale for User Experiments

1	2	3	4	5	6	7
Awful			Neutral			Great!

7

1= bad 7= good

Table 2: User Experiment of Non-Oily Testing of Forcep Designs

Non-oily testing:	Grip 1-1, Texture 1	Grip 1-1, Texture 2	Grip 1-1, Texture 3	Grip 2-6, Texture 1	Grip 2-6, Texture 2	Grip 2-6, Texture 3	Classic Adson Forceps
Criteria:	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):
Slip between fingers and grip (1 being very slippery, 7 being no slip whatsoever)	3	7	6	2	7	6	5
Overall comfort of forceps in your hand (1 being uncomfortable, 7 being comfortable)	6	6	2	6	6	2	6
Ease of use to perform the given task	6	6	6	6	6	6	7
The feel of the grip texture in your fingers	4	7	2	4	7	2	5

7

Table 4: Ranking of Overall Performance of All Forcep Designs

Forceps Used:	Rank:
Grip 1-1, texture 1	4
Grip 1-1, texture 2	2
Grip 1-1, texture 3	6
Grip 2-6, texture 1	5
Grip 2-6, texture 2	3
Grip 2-6, texture 3	7
Classic Adson Forceps	1

extra thoughts: while easier to rotationally manipulate + grip, I do slightly miss the haptics/proprioception of knowing "which end is up" in terms of the teeth on a classic adson.

Subject 8:

8

Participant Worksheet:

Name of Participant:

Age of Participant: 32

Gender of Participant: M

Participant Profession (as is relevant to use of forceps):

MD resident

Non-Dominant Hand (Left or Right):

left

Small item chosen for grasping:

wrapper

Oil type used during experiments:

Table 1: Grading Scale for User Experiments

1	2	3	4	5	6	7
Awful			Neutral			Great!

8

Table 2: User Experiment of Non-Oily Testing of Forcep Designs

Non-oily testing:	Grip 1-1, Texture 1	Grip 1-1, Texture 2	Grip 1-1, Texture 3	Grip 2-6, Texture 1	Grip 2-6, Texture 2	Grip 2-6, Texture 3	Classic Adson Forceps
Criteria:	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):
Slip between fingers and grip (1 being very slippery, 7 being no slip whatsoever)	2	3	5	2	3	5	5
Overall comfort of forceps in your hand (1 being uncomfortable, 7 being comfortable)	4	4	4	6	6	6	5
Ease of use to perform the given task	2	3	5	4	5	6	5
The feel of the grip texture in your fingers							

8

Table 4: Ranking of Overall Performance of All Forcep Designs

Forceps Used:	**Rank:**
Grip 1-1, texture 1	7
Grip 1-1, texture 2	5
Grip 1-1, texture 3	3
Grip 2-6, texture 1	6
Grip 2-6, texture 2	4
Grip 2-6, texture 3	2
Classic Adson Forceps	1

Subject 9 and Dr. Dunn (shared form):

(9)

Participant Worksheet:

Name of Participant: [redacted]

Age of Participant: 32

Gender of Participant: M

Participant Profession (as is relevant to use of forceps): PRS Resident

Non-Dominant Hand (Left or Right): L

Small item chosen for grasping: Paper

Oil type used during experiments: X

Table 1: Grading Scale for User Experiments

1	2	3	4	5	6	7
Awful			Neutral			Great!

(9)

Tom | Dunn ★ ran out of papers, combined on this sheet

Table 2: User Experiment of Non-Oily Testing of Forcep Designs

Non-oily testing:	Grip 1-1, Texture 1	Grip 1-1, Texture 2	Grip 1-1, Texture 3	Grip 2-6, Texture 1	Grip 2-6, Texture 2	Grip 2-6, Texture 3	Classic Adson Forceps
Criteria:	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):
Slip between fingers and grip (1 being very slippery, 7 being no slip whatsoever)	3 | 4	~~8~~ 4 6	7 / 6	3 / 2	6 | 6	5 | 6	2 | 1
Overall comfort of forceps in your hand (1 being uncomfortable, 7 being comfortable)	4 | 6	~~7~~ 6 / 4	7 / 6	4 / 6	5 | 7	6 | 7	3 | 1
Ease of use to perform the given task	4 | 5	~~8~~ 5 6	6 / 6	4 / 6	6 | 6	6 | 6	6 | 3
The feel of the grip texture in your fingers	2 | 4	~~8~~ 3 6	7 / 6	2 | 5	4 | 6	6 | 6	2 | 1

Table 3: User Experiment of Oily Tests of Forcep Designs

Oily testing:	Grip 1-1, Texture 1	Grip 1-1, Texture 2	Grip 1-1, Texture 3	Grip 2-6, Texture 1	Grip 2-6, Texture 2	Grip 2-6, Texture 3	Classic Adson Forceps
Criteria:	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):	Grade (1-7):
Slip between fingers and grip (1 being very slippery, 7 being no slip whatsoever)	2	4	4	4	5	5	2
Overall comfort of forceps in your hand (1 being uncomfortable, 7 being comfortable)	2	3	3	3	3	3	2
Ease of use to perform the given task	~~4~~ 4	~~4~~ 5	5	5	6	6	4
The feel of the grip texture in your fingers	2	4	5	3	5	5	1

Dr. Dunn

Prediction Last Q

Maybe Different

Each Q Separately

6

Analyze data on Last question

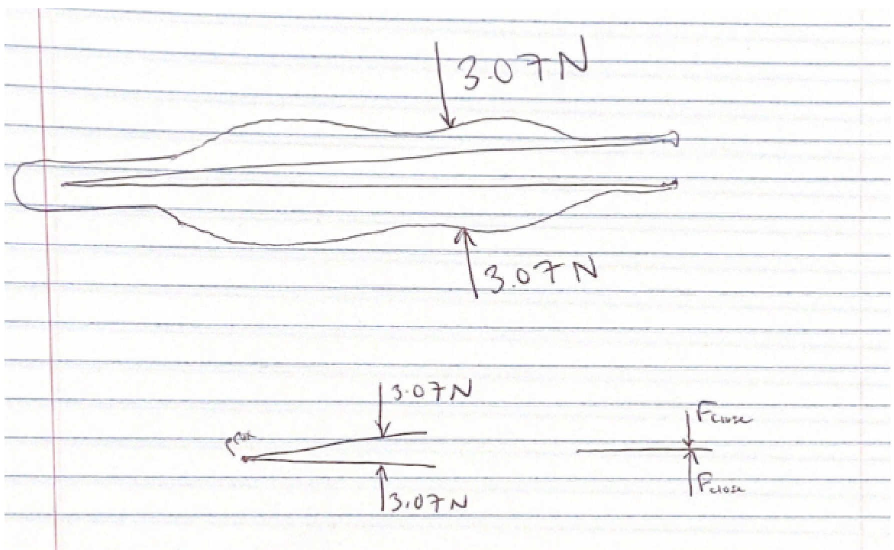
(9)

Table 4: Ranking of Overall Performance of All Forcep Designs

Forceps Used:	Rank: Tom	Dr. Dunn
Grip 1-1, texture 1	7	6
Grip 1-1, texture 2	3	4
Grip 1-1, texture 3	2	5
Grip 2-6, texture 1	6	3
Grip 2-6, texture 2	1	1
Grip 2-6, texture 3	5	2
Classic Adson Forceps	4	7

Appendix C: Free Body Diagram of Force to Depress Forceps

FBD:



Appendix D: Feedback from Dr. Dunn

Forcep designs that were primarily eliminated (obvious "no" choices):

A. *1-3: The base design of the forcep was not completely inappropriate, however, the grip length along the handle was too short to be held comfortably.*
B. *1-4: This design was described as "awful" due to the grip length being much too short and the length of the valley in which your fingers sit was too small. It is obvious that all the dimensions were shrunken down to match the short length of the base of the forcep and this is not desirable. The width of this design, however, was appropriate.*
C. *2-5: This design reminded Dr. Dunn of the same issues as design 1-1 in which the design was too thin for skin closure.*
D. *2-8: Because of the reduced length this design feels too stubby in the surgeon's hand and is not applicable to surgical applications comfortably. The length of the forcep worked, however, the grip length was too short.*
E. *4-13: This design was obviously not proportional. It was too thin for how long it was- especially in the cleft between the two humps where the surgeons fingers grip the device. There was no haptic helpfulness from this grip design.*

Forcep designs that were under consideration ("maybe" options):

A. *1-2: This design was described as "not that bad" and proportionally correct for the sizes given in this application. This design was on the fence for moving forward with prototyping.*
B. *3-10: Proportionally okay, the length and 'feel' of the forceps were not as ideal as the "yes" options.*
C. *3-12: This design felt too enlarged for its "shrunken down" proportions.*
D. *4-14. Proportionally okay. Proportionally okay, the length and 'feel' of the forceps were not as ideal as the "yes" options.*

Forcep designs that were considered good designs and should move forward with the next step of prototyping ("yes" options):

A. *1-1: This design was very long and slim and not applicable for skin closure in plastic surgery. However would be a great application for ophthalmology. We were able to move forward with prototyping using this variation as well due to its similarity to the Adson Forceps.*
B. *2-6: This design was proportionally pleasing for applications of skin closure in plastic surgery. This design was on the fence as a "maybe" and a "yes" option. Move forward with prototyping.*

C. *3-11: This design had a good feel in the surgeon's hand but wasn't quite as refined of a feel as other designs. Move forward with prototyping for testing.*
D. *4-15: The spacing of the cleft in which the surgeon's fingers sit was appropriate. The width of the grips is also good for a steady hold in the hand. The 4-16 design was very similar and slightly better in proportions. Do not move forward with prototyping for this design.*
E. *4-16: Very similar to the 4-15 but feels a little more refined. The longer forcep length was appropriate for the wider dimensions. The only concern is that perhaps the length of the forcep is too long.*