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DEPARTMENT OF MECHANICAL AND NUCLEAR ENGINEERING

EFFECTS ON SCALPEL CUTTING FORCES WITH ADDED VIBRATION AND COMPLIANT SCALPEL HANDLE

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ABSTRACT

This thesis for Schreyer's Honors College investigated the concept of using compliant vibrational tools for medical soft tissue cutting. Ultrasonic vibrations were applied to scalpels that had different compliant hinge geometries incorporated into the handle. The hypothesis of the thesis was if a compliant vibrational cutting tool was used, the amount of force required to make cuts will be reduced. Tissue deflection caused by the scalpel blade would be reduced if the force required to make the incision was reduced. When the deflection of the tissue is minimized, higher cutting accuracy and precision is possible. Having higher cutting and precision would benefit many different surgical procedures especially any invasive surgeries.

The objective of this thesis was to determine if the cutting forces could be reduced if a compliant hinge was added to the handle of a scalpel along with added ultrasonic vibration. The first task in achieving the objective was to design a compliant hinge geometry for the scalpel handles. Designs used in past experiments involving adding compliant geometry to needles were incorporated into the scalpel handle design. After the compliant geometry for the scalpel handle was designed, all the experimental mounting components and scalpel handles were fabricated. Using the fabricated components, vibrational cutting experiments were performed. Three different scalpel geometries were tested: no compliant hinge, single compliant hinge, and a double compliant hinge. Each geometry was tested with vibration added and no vibration added. Experiments were completed by cutting phantom gel which was used to resemble soft tissue. Cutting force and cutting depth were the parameters that were analyzed.

After the experiments were ran there was evidence that initial incision forces were reduced by between 17% to 42% when vibrations were added to a scalpel. The different compliant geometries led to different amounts of force reductions during the initial cutting with the double compliant hinge scalpel handle having the largest reduction. The force reduction of a scalpel handle with no compliant geometry with added vibration was only 17.06%. The force reduction of a scalpel handle with a single compliant hinge with added vibration was 39.26% and a handle with a double compliant hinge had a 41% reduction. After the initial incision was made, the added vibration and compliant geometry no longer had any effect on force reduction.

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Chapter 1

Literature Review

1.1 Description and Purpose of Surgical Scalpels

A scalpel is a small and extremely sharp bladed instrument used in a wide variety of surgical procedures to make precise incisions in the skin and in the underlying tissue of a patient. A scalpel is comprised of two main components: a handle and a blade. The handle of a scalpel is reusable, but the blade needs to be replaced after one procedure [1]. Scalpels are used mostly in invasive and excisional procedures. During invasive procedures, scalpels are used to cut through skin, muscle, and soft tissues to allow access to blood vessels and subcutaneous tissues during specific surgical operations. [2]. Excision surgeries involve the removal of a foreign body or foreign tissue from a patient. Such procedures include tumorectomy, lumpectomy, and mastectomy. The success of these procedures is dependent on making accurate and precise cuts with the scalpel. Failure to be accurate and precise can lead to several consequences including, but not limited to, additional surgeries, excessive bleeding of the patient during an operation, and even complications following the procedure. The importance of cutting precision can be seen in a study performed by McCahill et al. where they observed the percentage of women who needed to undergo reexcision following partial mastectomy. According to the research, 29.9% of patients needed to undergo reexcision after a partial mastectomy due to positive margins of malignant tissue that remained [3]. Scalpels need to have increased accuracy to reduce additional surgeries, and to reduce trauma experienced by patients. This may also lead to more cost effective medical procedures. The research outlined in this thesis investigates whether adding compliance and vibration to a scalpel will increase cutting accuracy and reduce the friction forces seen by the scalpel.

1.2 Current Vibration Techniques

Vibration techniques have been shown to have many benefits in a wide range of applications. Vibration techniques have been used in several different medical applications as well as other industries. Research is still ongoing to discover other benefits that could result from applying vibrations to different operations.

One industry in which vibration is used is precision machining. Vibration assisted machining (abbreviated as VAM) is a machining technique where a small amplitude vibration is added to the tool being used [4]. VAM is used in several different processes including turning, drilling, and grinding. Using vibration techniques in machining procedures has been shown to have several benefits due to reduced cutting forces such as improved surface finish, extended tool life, and better accuracy is able to be achieved [4].

Vibration techniques are also used in the medical industry. One instrument that is used in the medical field that utilizes vibration is the harmonic scalpel. A harmonic scalpel is an alternative instrument to a steel scalpel or an electro-surgical diathermy [5]. Harmonic scalpels are unique in the sense that they serve a dual purpose: cutting tissue and also cauterizing the tissue at the same time. Harmonic scalpels are similar to surgical diathermy, which cuts tissue and cauterizes via heat. When compared to surgical diathermy harmonic scalpels are better at cutting thicker tissue, generating less smoke during operation, and having better precision. There are several downsides since the harmonic scalpel takes longer to coagulate bleeding.

Coagulation can only occur when a cut is being made and maneuverability is not as easy as compared to other instruments [5]. The harmonic scalpel operates entirely from vibration. Vibrations ranging from 20 kHz to 60 kHz are applied to the tip of the scalpel as it cuts. The vibration results in protein denaturation at the site of incision. Protein denaturation occurs when the vibration causes intercellular friction, which leads to the breaking down of hydrogen bonds in the tissue. Protein denaturation coagulates blood cells rather than heat. The vibrations also are responsible for the cutting of the tissue. There are two different ways that the vibration cuts the tissue. The first method, mechanical stretching of the tissue beyond its elastic limit, occurs in high protein density tissue. The mechanical stretching is caused by the longitudinal motion of the scalpel blade between 60 to 100 μm occurring at the frequency of the vibration. The second method, which occurs in low protein density tissue, cuts via cavitation. Intercellular water vaporizes at low temperatures due to the mechanical vibrations resulting in the rupturing of cells at the site of incision [6]. The rupturing of the cells result in cutting. Harmonic scalpels are gaining popularity in the medical field. Currently, surgeries such as urology, tonsillectomy, thyroidectomy, and even plastic surgeries utilize this instrument.

The use of scalpels with applied vibration techniques will continue to be developed for a wide range of surgical procedures. One of the surgical procedures that has been investigated is optical surgeries. Cataract surgery is an extremely delicate procedure. Treatments require extreme precision and accuracy with minimal margin of error due to the delicate nature of the eye. Current methods are deemed very difficult due to the high level of skill needed by the surgeon. The surgeon has to apply a force with a scalpel in order cut through the collagen of the eye. The forces applied deflect the tissue and this deflection must be minimized. An experiment was conducted in which ultrasonic waves were applied to a scalpel blade and tissue deflection was observed. The scalpel was used in imitation cataract surgeries using silicon-based materials to mimic human tissue. A variety of frequency and amplitude ultrasonic combinations were used to identify an optimal combination that could be used in optical surgeries [7]. This work is ongoing and may result in the development of a new ophthalmic surgical device or a new technique that can be used in invasive surgeries.

1.3 Previous Research Involving Applied Vibration To Medical Equipment

Research has also been conducted to see the benefits of adding vibration and compliance to other medical instruments. Research done by Dr. Barnett et al. investigated the effects of added vibration to needles. A needle with vibration had puncture forces that were 29.5% less when compared to a normal needle [8]. Friction force experienced by the needle is also reduced by 48.3%. Adding compliance to the needle with vibration reduced friction forces even further with 71.0% reduction. In figure 1, there is a clear indication that vibration and compliance significantly reduce forces [8]. Vibration and compliance create larger cracks in the tissue, which enables the needle to pass without stretching the tissue as much as a smaller crack. Less stretching results in lower normal force between the needle and the tissue. Lower normal force yields lower friction force experienced by the needle.

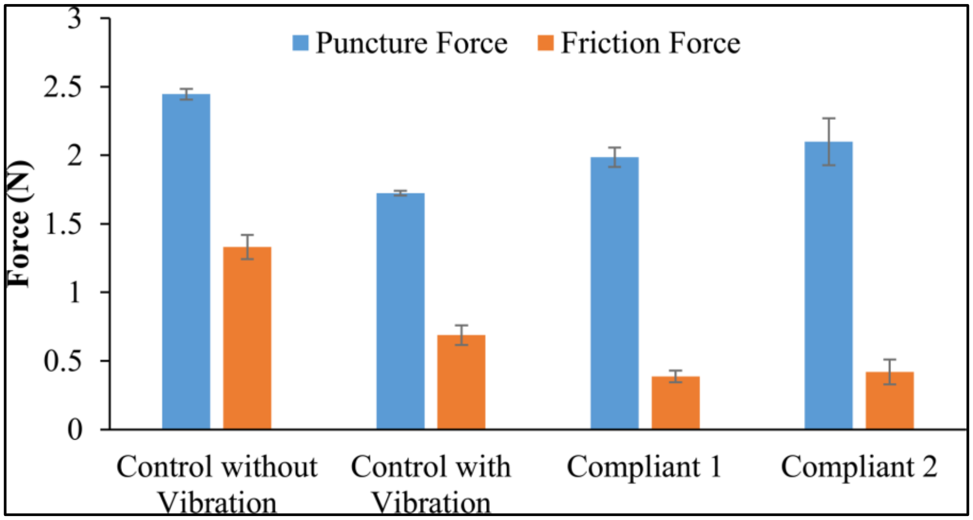

Figure 1 Results showing how vibration and compliance effect insertion and steady cutting forces of needles.

A similar research study was conducted where the effects of vibration and compliance added to scalpels were tested. The research conducted by Jessica Barrett found that vibration reduces the insertion force of a size 10 scalpel blade by .834 N [9]. The steady cutting force was also reduced by .469 N. Jessica's research showed cutting forces of a scalpel could be reduced by adding vibration and compliance. Slits were cut in the scalpel blade and the blade acted as the compliant hinge as seen below in figure 2. Scalpel blades are made from hardened steel, stainless steel, or high carbon steel for sharpness and edge retention. All of these steels are very rigid and not very flexible. Compliant hinges need to be made of a material that is flexible in order to operate properly. Having a rigid compliant hinge hampered movement. Therefore, the results were not as expected.

Figure 2 Compliant scalpel made to test compliance on the blade and vibration with scalpels.

One final issue with the research that will be addressed in these experiments is the mounting system used to secure the scalpel blade to the scalpel handle. A very large metal clamp was used to secure the scalpel blade. This setup can be seen in figure 3. The large clamp attached to the end of the scalpel acted as a damper. By dampening the system the vibrations applied to the scalpel were most likely not as efficient as expected.

Figure 3 Experimental set up used in earlier scalpel compliant testing. A large clamp was used to secure scalpel blade. The large mass acted as a damper.

1.4 Compliance Concepts

Two researches mentioned in section 1.3 utilize compliance concepts. Two rigid structures joined together by a thin hinge area is a compliant hinge [10]. The hinge area is made out of a flexible element. Use of compliant hinges is a different approach at linking rigid members. Normally, rigid body mechanisms consist of rigid links connected at movable joints. However, compliant hinges work by deflection of flexible material between the two members. Applications of using compliance hinges is ongoing and several benefits have already been discovered. One of the benefits that is utilized in both of the instruments listed above is a compliant hinge's ability to store energy in the form of strain energy [10]. The flexible member stores energy that is similar to the way a spring stores potential energy. Potential energy in the compliant hinge can be converted into kinetic energy, which in the research mentioned before, results in the transfer of motion that is caused by vibration.

Compliant hinges can be modeled in a variety of different ways. One of the most common models used for compliant hinges is the pseudo rigid body model. A pseudo rigid body model is a way of modeling the compliant hinge as two rigid members connected by a flexural pivot point between them [11]. Flexural pivots are modeled as kinematic joints at the center of the flexible segment using torsional springs to represent the member's stiffness. A compliant hinge is can be represented with two rigid bodies with a torsional spring between them.

The accuracy of this model is dependent on the size of the flexible member relative to the length of the rigid members. Accuracy of the model decreases as the size of the flexible member increases. The pseudo rigid body model will be used to model the compliant hinges used in my research.

1.5 Cutting Techniques and Blade Selection for Research

A series of different compliant geometries and non-compliant scalpels were tested by making incisions into tissue simulant. Slide cutting with size 10 scalpel blades will be used in the experiments to simulate consistently, typical real-life scenarios. Forces will be measured and analyzed to determine the effects of compliance and vibration on the scalpel.

There are three main cutting techniques for scalpels: scrape cutting, slide cutting, and press cutting [1]. Slide cutting was replicated in this research since slide cutting is the most common incision method and it is the easiest to mimic. Slide cutting is well suited to skin incisions because it allows accurate depth control and precise direction and length control. Cuts are made through this method by sliding the blade against tissue along the cutting edge of the blade. Thus, the cutting direction is perpendicular to the applied pressure of the scalpel.

Scalpel blades have different numbers which are dependent on the size and geometry of the blade. During the duration of this research project No. 10 Stainless Steel Surgical Scalpel Blades from Havel's Inc. will be used [12]. The No. 10 scalpels are the most common type of scalpel blade used since the blade has a large, curved cutting edge. No. 10 scalpels are most often used to make incisions in the skin and subcutaneous tissue, as well as cutting other soft tissues [13]. Procedures that use the No. 10 scalpel include coronary bypass procedures, thoracic operations, and hernia repairs to harvest the artery, to open the bronchus, and to repair the inguinal hernia [13].

1.6 Research Overview

Scalpels are used very frequently in surgical procedures. Accuracy is extremely important to avoid complications. Accuracy can be improved by reducing incision forces. This research project will investigate adding vibration compliance to scalpel handles. Experimentation is performed to determine if cutting forces are reduced. This research is different from previous research projects because three different compliant geometries will be investigated using ultrasonic. The compliant geometry will be located in the scalpel handle.

Chapter 2 describes the process of how the fixtures used were designed and machined for each experimental setup as well as explanations for experimental methods. Experimental methods are also be explained. Chapter 3 details the experimental results. Chapter 4 summarizes this research project, gives the final results, and outlines any future work that could further this concept of applying vibration and compliance to scalpels. Through continuation of this work, methods could be developed to reduce scalpel incision forces. By doing so, patient safety will be improved and will make surgeries much more cost effective.

Chapter 2

Experiments and Methods

2.1 Experimental Parameters

The research conducted for this thesis involved running the same experiment with varying parameters. The varying parameters were the geometry of the scalpel handle and whether or not vibration was applied to the scalpel. The experiment utilized No. 10 scalpels as the cutting tool. The first set of parameters that were tested was a scalpel handle with no compliant geometry and no added vibrations. This set of parameters provided a control group of a No. 10 scalpel. The second set of parameters was a scalpel handle with a single slit compliant geometry and no added vibrations. The third set of parameters was a scalpel handle with a double slit compliant geometry and no added vibrations. The fourth set of parameters was a scalpel handle with no compliant geometry with added ultrasonic vibrations. The fifth set of parameters was a scalpel handle with a single slit compliant geometry with added ultrasonic vibrations. The sixth set of parameters was a scalpel handle with a single slit compliant geometry with added ultrasonic vibrations. Specific details of each experiment's parameters are shown in Table 1.

Table 1 Complete Experimental Procedures

Experiment No.	**Compliant Geometry**	**Vibration Frequency**	**Number Trials**	**Rate of Incision**	**Target Cut Depth**	**Tissue Simulant**	**Measurements**
1	None	N/A	6	3 mm/s	12 mm	Polyvinyl Chloride Phantom Tissue	Force (N) Depth of Cut (mm)
2	Single Slit	N/A	6	3 mm/s	12 mm	Polyvinyl Chloride Phantom Tissue	Force (N) Depth of Cut (mm)
3	Double Slit	N/A	6	3 mm/s	12 mm	Polyvinyl Chloride Phantom Tissue	Force (N) Depth of Cut (mm)
4	None	26,000 Hz	6	3 mm/s	12 mm	Polyvinyl Chloride Phantom Tissue	Force (N) Depth of Cut (mm)
5	Single Slit	26,000 Hz	6	3 mm/s	12 mm	Polyvinyl Chloride Phantom Tissue	Force (N) Depth of Cut (mm)
6	Double Slit	26,000 Hz	6	3 mm/s	12 mm	Polyvinyl Chloride Phantom Tissue	Force (N) Depth of Cut (mm)

The six variations of parameters for the experiment were completed using the same apparatus, which is shown in figure 4. The piezo actuator supplied the vibration for the trials that required applied ultrasonic vibrations. The linear motor moved the scalpel configuration through the tissue simulant, which was placed on a force sensor, at the set incision rate.

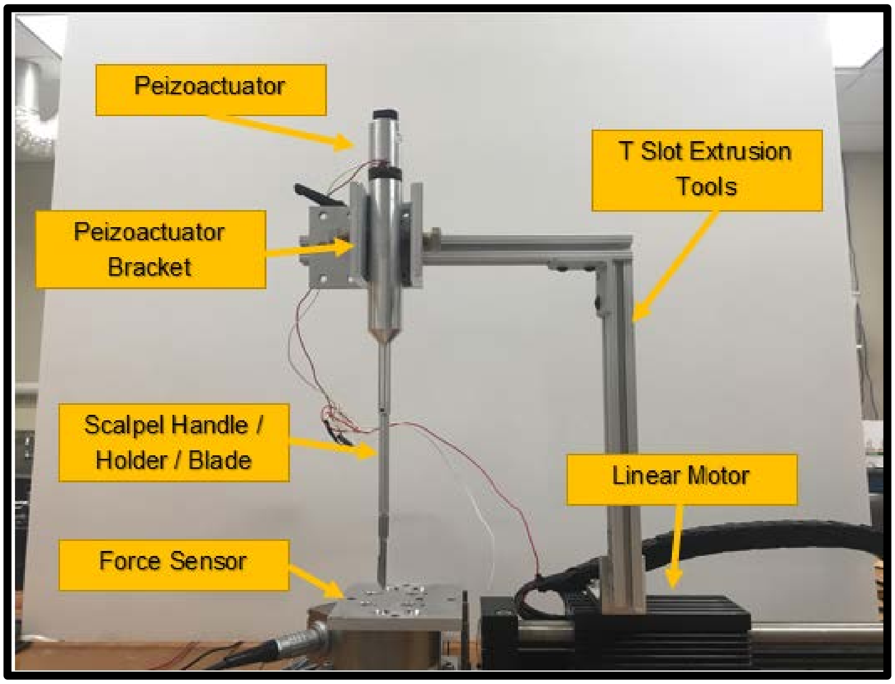

Figure 4 Apparatus used during experiments. Each component is labeled.

2.2 Experimental Components

No. 10 scalpels and scalpel handles, which were manufactured specifically for this thesis, were used to simulate a scalpel. The scalpel and handle were held in an apparatus made up of clamps and T-Slot extrusion tools. A STC Series Linear Motor from Dunkermotoren was used to move the scalpel apparatus. A PDUS200 Ultrasonic Driver from Micromechatronics, Inc. was used to provide vibrations to the scalpel. An ATI Industrial Automation Gamma IP65 Force/Torque Sensor was used to collect data on the forces the tissue simulant was experiencing. The linear motor, ultrasonic driver, and force sensor were all connected to a lab computer. Utilizing a LabVIEW program, all three were able to be controlled. The tissue simulant were 120mm x 60mm x 30mm blocks of polyvinyl chloride phantom tissue. The tissue simulant was secured to the force sensor via double-sided tape.

The STC Series Linear Motor from Dunkermotoren was used to move the scalpel configuration. This particular linear motor was chosen due to its ease of use, convenient mounting platform, and integrated bearing and encoder. The rate of incision and distance of travel could all be set for the motor utilizing LabVIEW. Figure 5 shows a detailed and labeled drawing of the linear motor.

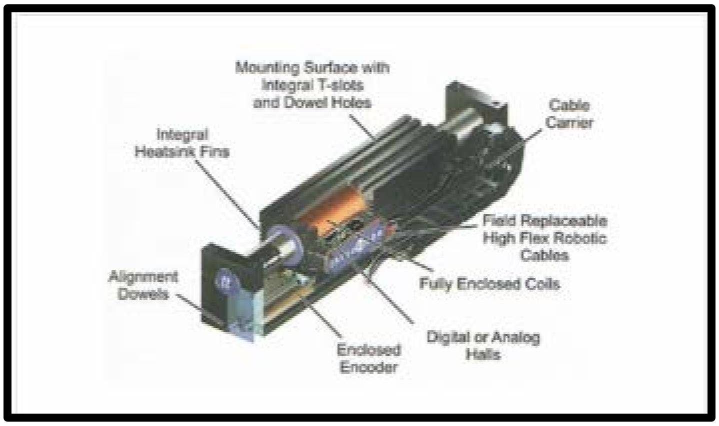

Figure 5 STC Series Linear Motor from Dunkermotoren

The ATI Industrial Automation Gamma IP65 Force/Torque Sensor was used to record all of the incision forces. This sensor provided high sensitivity. The resolution of the force sensor is ± 1/160 N . High sensitivity is important when observing and recording incision forces since the forces being recorded are not great in magnitude. The sensor was secured to an adjustable stage, which is only adjustable in the direction perpendicular to the linear motor. Both of these components can be seen in Figure 5. Figure 7 shows the different directions the sensor was able to record.

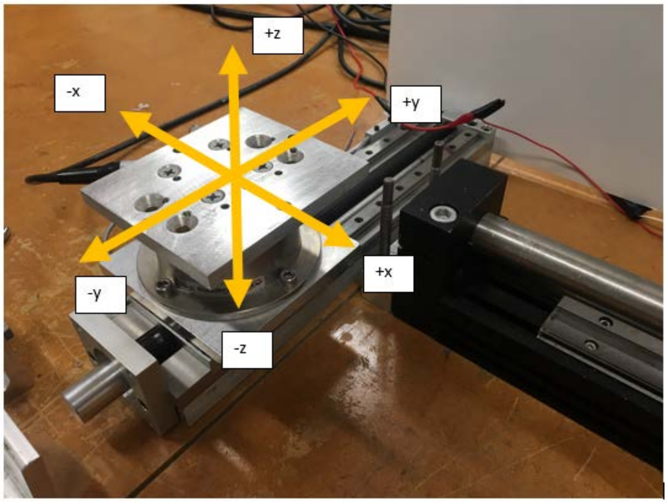

Figure 6 Picture shows which direction on the force sensor is represented by which force in LabVIEW.

The tissue simulant was secured to the force sensor using double sided tape. The tissue simulant was made out of Polyvinyl chloride phantom gel since the mechanical properties are similar to that of subcutaneous tissue. This gel was created using a 5:1 ratio of plastic softener from M.F. Manufacturing Company. A PDUS200 Ultrasonic Driver from Micromechatronics, Inc. was used to provide the ultrasonic vibrations for when the parameters of the experiment involved added vibration. This piezo actuator was able to deliver a ultrasonic frequency and maintain resonance via frequency tracking which made the piezo actuator ideal for this experiment. When the actuator operated at the resonance frequency of the actuator the movement and vibrations produced were maximized. A range of frequencies needed to be specified with a minimum point and a maximum point for the actuator to look for a resonance frequency between this range. Figure 7 shows the results of a frequency sweep. When setting the frequency range, the range should enclose a section where the angle peaks and the magnitude goes from a minimum to a maximum. In figure 7, the range was set between 25600 Hz and 26400 Hz in order to capture the resonance frequency at 26000 Hz.

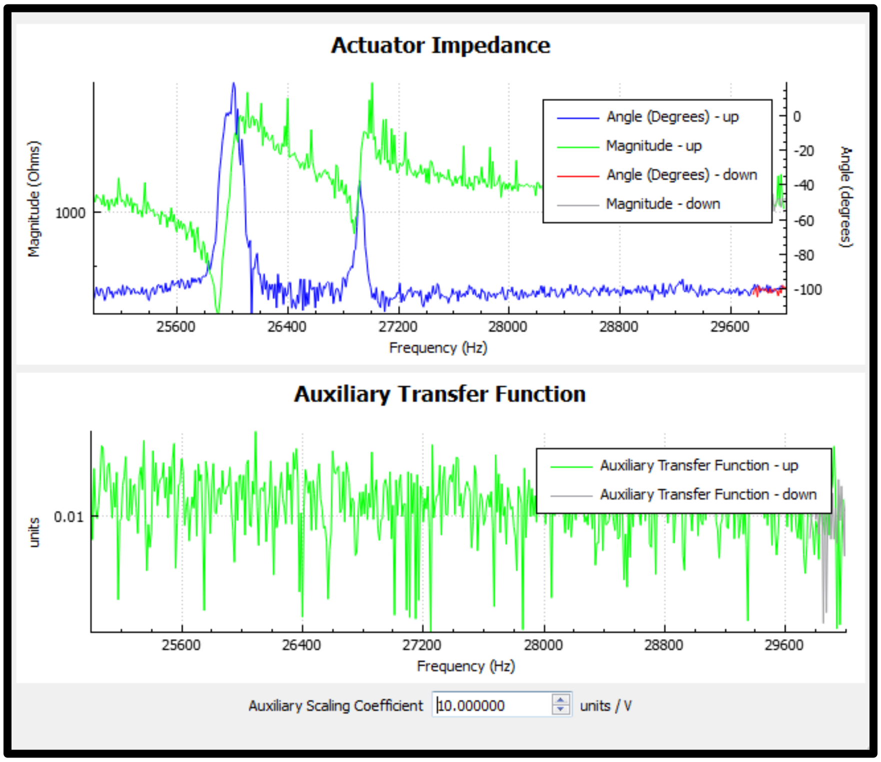

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Figure 7 Frequency sweep results. These results were used to set the range of frequencies that the ultrasonic driver would look at to find the resonance frequency. The resonance frequency can be seen at 25 KHz due to the peak in the angle curve.

2.3 Manufactured Experimental Components

Five different components needed to be manufactured for the research experiments. Components that needed to be machined included scalpel handles, a holder for the scalpel blades, and a mount for the piezo actuator. The designs were drawn as 3D models utilizing SolidWorks, as shown in figure 8.

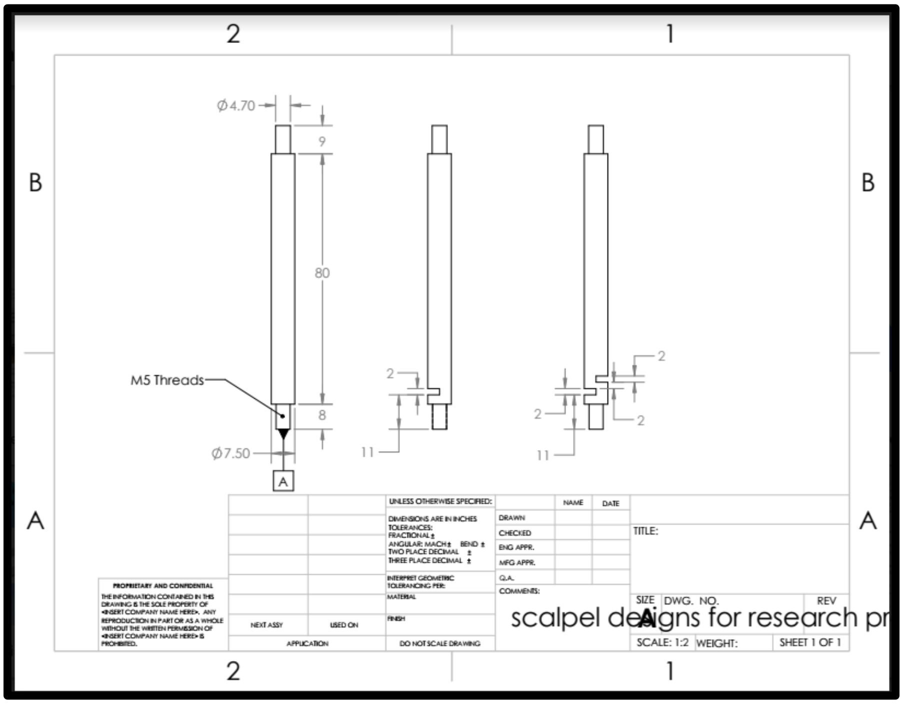


Figure 8 3D Model of the three different scalpel handles to be manufactured. Left to Right: No compliant geometry, single slit geometry, double slit geometry. The units are in mm.

The three scalpel handles were machined at the Penn State University Learning Factory based off of the 3D models. The three scalpel handles were machined by turning down 3/8” stock Al 6061-T6 to size on a lathe. There were two ends on each of the three handles. On the one end for each handle the end was turned down to a smaller diameter than the diameter of the rest of the handle. This end was turned down so that the handle could fit in the hole of the actuator and be secured. The opposite end for the three handles was turned down and threaded using a M5 die. The threading was done so the scalpel holder could be screwed onto the end of the handle. Each handle then had a different type of compliant geometry added. The different geometries can be seen in figure 8 and figure 9. One handle had no compliant geometry added, the second one had one slit, and the third one had a double slit added. The compliant geometry was done by cutting slits with the band saw.

The scalpel blade holder was also manufactured in the learning factory. A normal scalpel blade handle was taken and the front portion of the handle (the part where the blade is attached) was cut off using the band saw. The portion that was cut off was then drilled and tapped. This would allow this part to be able to screw onto the handles manufactured earlier. The final products can be seen in figure 9.

Figure 9 Final machined parts. Top left: double slit compliant geometry scalpel handle. Top middle: single slit compliant geometry scalpel handle. Top right: no compliant geometry scalpel handle. Bottom: Scalpel blade holder.

A bracket also needed to be manufactured in order to hold the piezo actuator. This was accomplished by welding two 90 degree angles together. Once the two angles were welded together, it formed a u shape. Once they were welded, the weld was grinded down to have a flush surface. The sides of the u shape were then drilled and tapped. The drilling and tapping allowed a bolt to be used as a set screw on both sides. A picture of the bracket can be seen in figure 4. The bracket is seen holding the piezo actuator.

2.4 Experimental Procedure

The same experiment was conducted to see if vibrations and compliant geometry would reduce cutting forces. During the experiment, two different parameters were varied to test the effects on cutting forces. The two parameters that were varied was the scalpel handle geometry and whether or not ultrasonic vibrations were added. There were three different types of geometries that were tested (no compliant geometry, single slit, and double slit). Each of the varied scalpel handle were tested with and without vibrations. This was conducted to observe if the added vibrations were the cause of the results or the geometry or both. Each set of parameters were tested with six experimental trials to ensure consistent results. The experimental procedure that was used during test is as follows:

1. The scalpel apparatus was set up using the magnetic rail track and metal components found in the lab. The tissue simulant was placed on the force sensor and was secured using double-sided tape.
2. The following test parameters were set.
    - The scalpel blade is positioned so that the target initial cut depth is 12 mm
    - The actuator runs at 26kHz (supplying 90V)
    - Rate of incision is 3 mm/s
3. Using LabVIEW data recording was activated followed by the activation of the linear motor.

4. The scalpel blade proceeded to cut through the entire length of the tissue simulant and then the recording of data was stopped.
5. The process was repeated for six different set of parameters. Each set of parameters was tested with six individual trials. The six sets of parameters were as follows:
    - No Compliance No Vibration
    - No Compliance W/ Vibration
    - Single Compliance No Vibration
    - Single Compliance W/ Vibration
    - Double Compliance No Vibration
    - Double Compliance W/ Vibration
6. For each trial, the x-direction forces were recorded in Newtons. The depth of cut for each trial was also recorded in millimeters. Cutting forces and depth of cut were used to compare the effect of the different sets of parameters and to test the hypothesis of this thesis.

Chapter 3

Experimental Results

This thesis hypothesized that applying ultrasonic frequency vibrations and adding compliant geometry to scalpels would decrease the force exerted on the tissue during scalpel incisions. To test this hypothesis, the experiments outlined in Chapter 2 were performed and the cutting forces resulting from scalpels with no vibration and scalpels with ultrasonic vibration were determined and recorded. Six different data sets were acquired; no compliant geometry with no added vibration, no compliant geometry with added vibration, single compliant hinge geometry with no added vibration, single compliant hinge with added vibration, double compliant hinge geometry with no added vibration, and double compliant hinge with added vibration. The results were graphed showing displacement (mm) vs. cutting force experienced (N). On each graph, the six different tests for the six different sets of parameters were plotted. The graphs can be found in Appendix A. However, a sample graph can be seen below in figure 10.

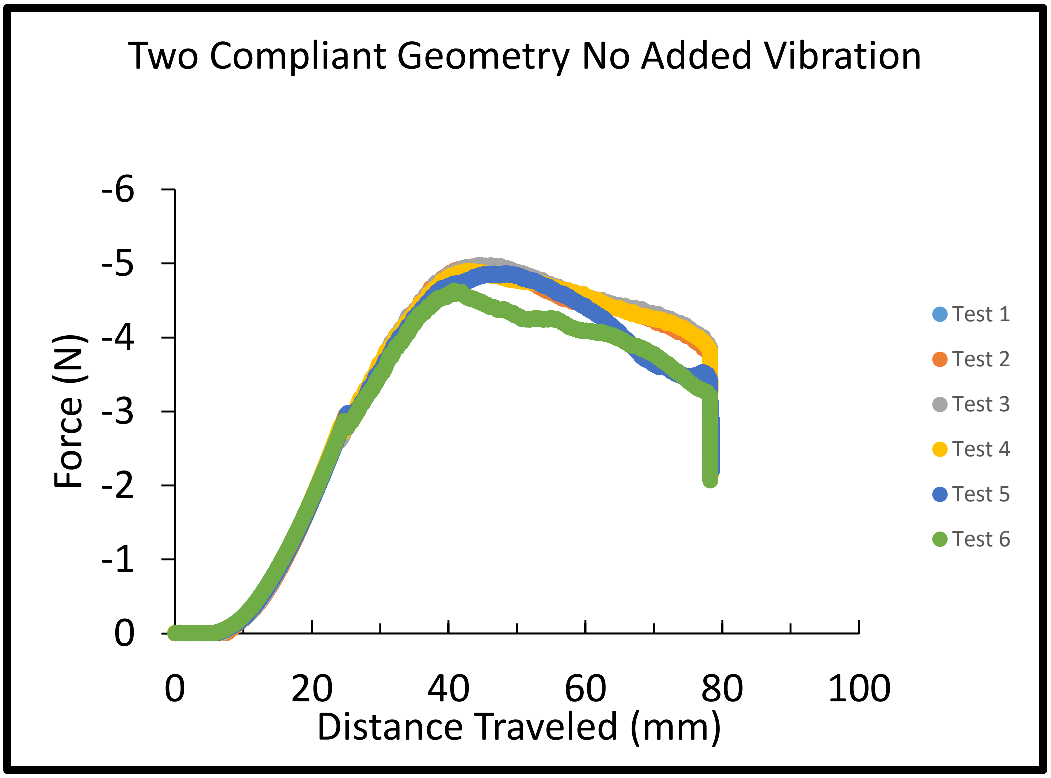


Figure 10 Sample graph of cutting force vs cutting distance

All of the graphs showed a similar cutting profile which was to be expected. While the scalpel initially begins to cut the tissue sample, the force experienced increased until a maximum was reached. Once the maximum was reached, the cutting force experienced begins to steady. The observed cutting profile occurred because the scalpel blade experienced a large normal force when initial contact was made with the tissue. The scalpel blade deflected the tissue sample before a crack finally formed in the tissue sample. The sudden decrease in the force on the force per distanced travel graph indicated when the blade formed a crack in the tissue sample and the blade transitioned from deforming the sample to actually cutting the sample. Once the scalpel blade broke through the tissue, the scalpel blade experienced a cutting force and frictional forces (caused by the interaction between the tissue sample and the blade). These two forces are less than the normal force, which is why the graphs leveled off or decreased after the maximum point was reached.

The cutting depth of the scalpel blade for each of the trials varied slightly due to the different set of parameters. The varied cutting depth meant that the cutting forces varied slightly regardless of the vibration added or the compliant geometry. To account for the slight variation in cutting depth, force per depth of cut was the measurement used to compare the different trials from the different set of parameters. Figure 11 compared the force per depth of cut at three different locations on the tissue sample for the six different set of parameters. The bottom axis labeled which bars were associated with which set of parameters. The three different locations of the sample where the data was taken from was represented by the bars. The force per depth of cut was gathered by dividing the force experienced at a certain point on the sample by the depth of the cut at that point. The depth of cut was determined by using a caliper. The force per depth of cut was determined at three points on each tissue sample. The three points were 10 mm, 30 mm, and 50 mm. These points captured the initial cutting forces as well as the steady cutting forces. Error bars were added to each of the three bars for each of the set of parameters. The error bars showed the variation of each of the six trials for that sample. Force per depth of cut was reduced at 10 mm whenever vibration was added to each of the scalpel handle geometries when compared to no vibration added. Also, the experiments that involved added vibrations had larger error bars. The larger error bars are due to larger variations in the measurements obtained from the different trials. When vibration is added to the scalpel blade, the movement of the blade is not very predictable. Therefore, there was variation in the cutting forces experienced by the scalpel blade.

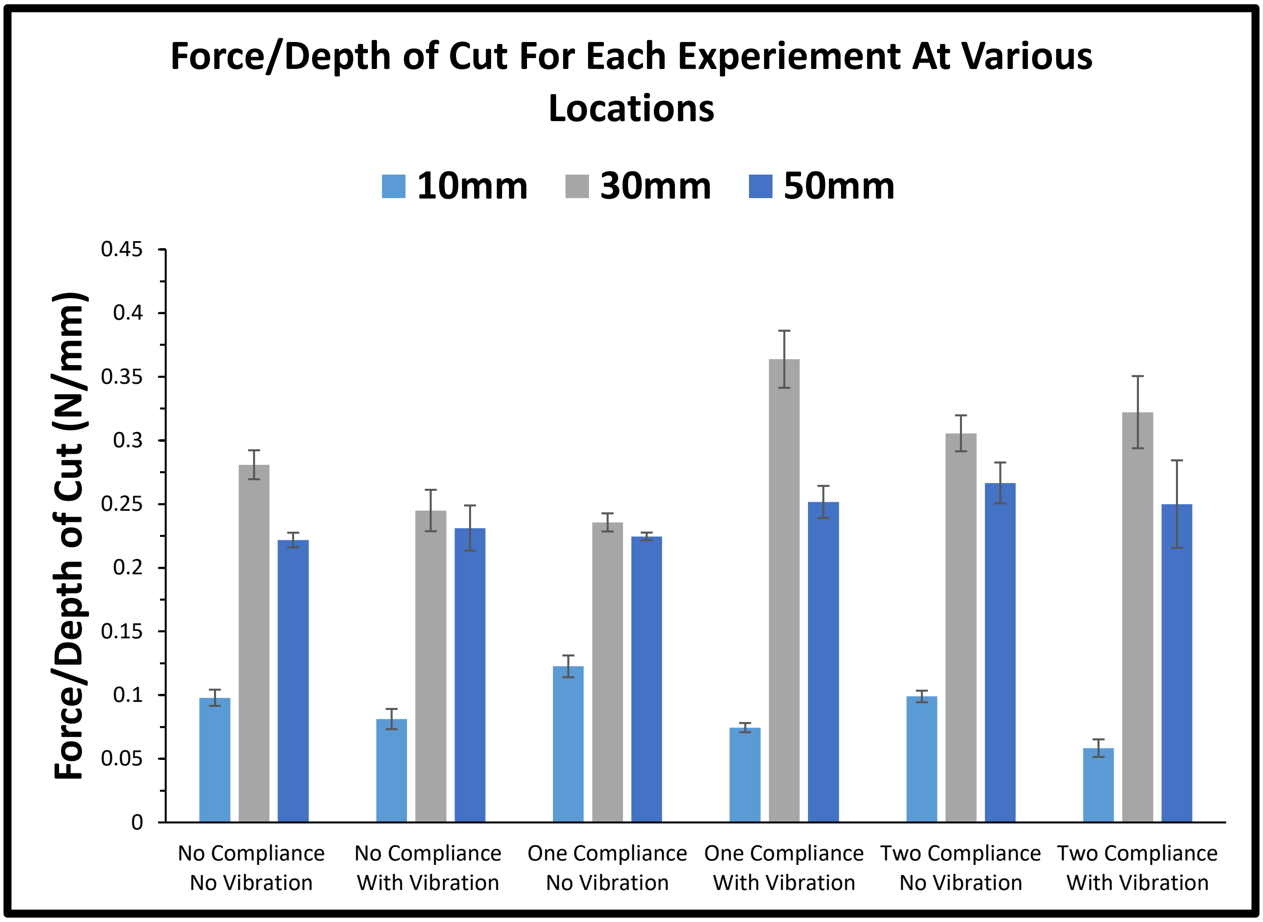


Figure 11 Force Per Depth of Cut For The Different Experiments

The initial incision forces per depth of cut were reduced when vibrations are added for all the different compliant geometry configurations. As shown in Table 2, the initial incision forces per depth of cut were reduced when vibration is applied to the scalpel. Table 2 shows the average force per depth of cut for the three different scalpel handles that were test with and without applied vibration. The force per depth of cut values used in table 2 were the values obtained when the scalpel blade cut 10 mm into the tissue sample. When the scalpel blade was located at 10 mm, the values obtained were reflective of the initial incision forces. The average force per depth of cut in the table were obtained by taking the averages of the force per depth of cut of the six different trials for each of the different set of parameters. The reduction of initial cutting forces per depth of cut was most likely due to the added vibration assisting in the formation of a crack in the tissue sample. When the scalpel blade began to cut into the tissue sample the blade had to first form a crack in the tissue sample. The added vibration reduced the amount of force required to create the crack in the tissue sample, therefore leading to a reduction in force per depth of cut during the initial incision. Initial incision forces were reduced by a minimum of 17.06% and as much as 41.00%.

Another observation that can be drawn from table 2 was that the different scalpel handle geometries had an impact on the amount of force per depth of cut reduction. The scalpel handle with no compliant geometry only saw a 17.06% reduction in force per depth of cut when vibration was added. The scalpel handle that had the single compliant hinge saw a 39.26% reduction and the handle with a double compliant hinge saw a 41.00% reduction. Whenever compliant geometry was added to the scalpel handle, the vibration added was much more effective in reducing the force per depth of cut. The scalpel with the handle containing the double compliant hinge was the most effective at reducing the initial incision's force per depth of cut. The compliant geometry in the scalpel handles helped to propagate the vibration to the scalpel blade. This will result in the scalpel blade to have much more movement. More movement results in less force required for initial crack formation.

Table 2 Difference in Initial Incision Force Per Depth of Cut With and Without Vibration Added.

Compliant Geometry	*Average Initial Incision Force/Cutting Depth Without Vibration*	*Average Initial Incision Force/Cutting Depth With Vibration*	*Difference in Incision Forces/Cutting Depth (Green = reduction, Red = increase)*
No Compliance	.09790 N	.08120 N	.01670 N , 17.06%
Single Compliant Hinge	.1226 N	.07445 N	.0482 N , 39.26%
Double Compliant Hinge	.09893	.05836 N	.0406 N , 41.00%

The initial hypothesis for the thesis was that cutting forces would be reduced throughout the entire length of the cut if vibration and compliant geometry were applied to the scalpel handle. As mentioned earlier, the incision forces, the forces experienced when the scalpel blade cut 10 mm into the sample, were reduced with vibrations and added compliant geometry during the initial cut. The hypothesis did not hold up though for the remainder of the cut when forces were compared for the different set of parameters at cutting lengths of 30 mm and 50 mm. When vibrations were added, regardless of the compliant geometry, the cutting force per depth of cut was either nearly identical or higher than the cutting force per depth of cut observed without vibrations.

Table 3 looks at the average force per depth of cut for the different scalpel geometries with vibration added and no vibration added. Figure 12 is a visual representation of the values in the furthest right column of table 3. The averages were obtained by taking the average of the six different trials for the six different set of parameters that were tested. The average force per depth of cut values in table 3 were from when the scalpel cut 30 mm and 50 mm into the tissue sample. The furthest right column shows the difference in force per depth of cut when vibration was added versus when no vibration was added. The values highlighted in green indicated a reduction in force per depth of cut when vibrations were added. Red indicated the opposite. Figure 12 is a visual representation of the difference between the force per depth of cut when vibration was added and force per depth of cut without vibration added. The vertical line represents a difference of zero Newtons. If the vibration reduced forces then the bars are green and to the left of the vertical line. If the vibration increased forces then the bars are to the right of the vertical line and are red. The difference between the force per depth of cut with vibration added and no vibration is minimal for all the different sets of parameters at cutting distances of

30 mm and 50 mm. In addition, added vibration both increases and decreases the force per depth of cut so there is no correlation.

Table 3 Difference in Incision Force Per Depth of Cut With and Without Vibration Added at 30 mm and 50 mm For The Different Experiments. The green indicates that vibration reduced force per depth of cut. Red indicates that vibration increased the force per depth of cut.

Cutting Distance on Sample	Geometry	No Vibration Force Per Depth of Cut	Added Vibration Force Per Depth of Cut	Force Per Depth of Cut Reduction
30 mm	No Compliance	0.2809	0.2450	-0.0359
	Single Compliant Hinge	0.2356	0.3637	0.1281
	Double Compliant Hinge	0.3056	0.3222	0.0166
50 mm	No Compliance	0.2218	0.2312	0.0094
	Single Compliant Hinge	0.2246	0.2517	0.0271
	Double Compliant Hinge	0.2666	0.2500	-0.0166

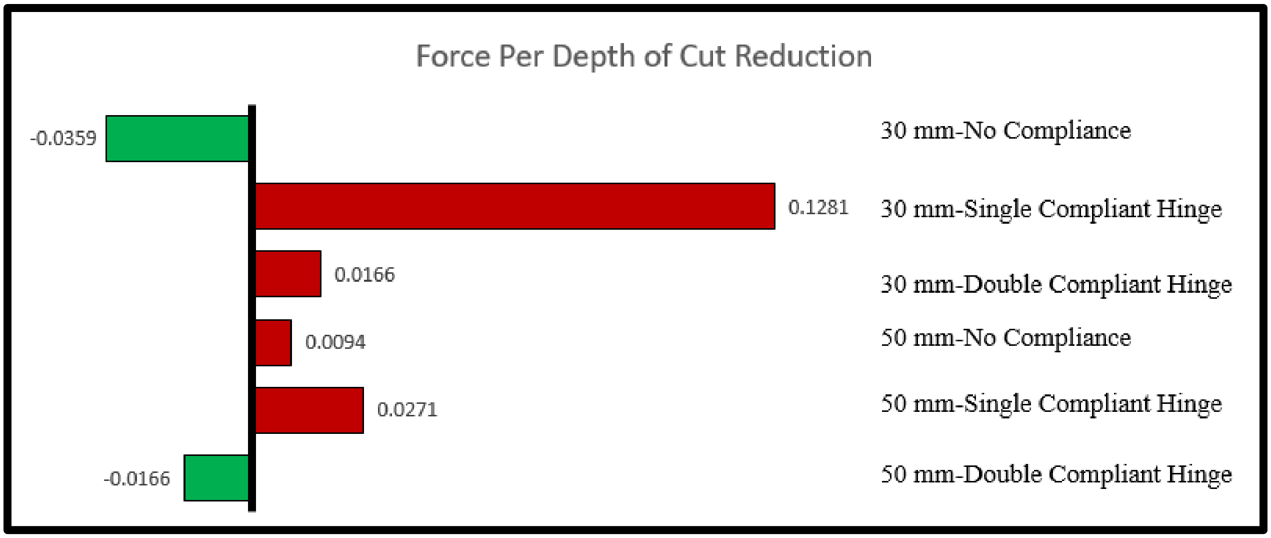


Figure 12 Graphical Display For Table 3. The graph is showing how added vibrations doesn't have a reasonable effect on the force per depth of cut.

Although adding vibration and compliant geometry to the scalpel handle reduced force per depth of cut during the initial incision, the force per depth of cut was mostly unaffected for the remainder of the incision. The reason behind this may be due to the fact that the added vibration and compliant geometry have no effect on the frictional forces caused by the tissue on the scalpel blade. During the initial incision, the added vibration and compliant geometry helped reduce the forces required to form a crack. Once the crack was formed in the tissue sample, the frictional forces between the tissue and the blade as well as the cutting forces remained unaffected. The frictional forces were not affected by the added vibration. Also, the added vibration helped in the formation of the crack in the tissue sample in the very beginning of the incision. However, the added vibration did not help in the crack propagation since the force per depth of cut remained unaffected.

Chapter 4

Discussion and Conclusion

4.1 Summary and Conclusions from this Work

Scalpels are used in a variety of surgical procedures, and the accuracy of scalpel cuts is vital to the success of the surgery and limiting complications. Scalpel cuts can be made more accurate by reducing the forces necessary to make an incision. Six different experiments were completed through this thesis work that investigated if adding vibration and compliant geometry could potentially reduce forces of scalpel incisions. Different compliant geometries were tested to see if different geometries would affect forces differently.

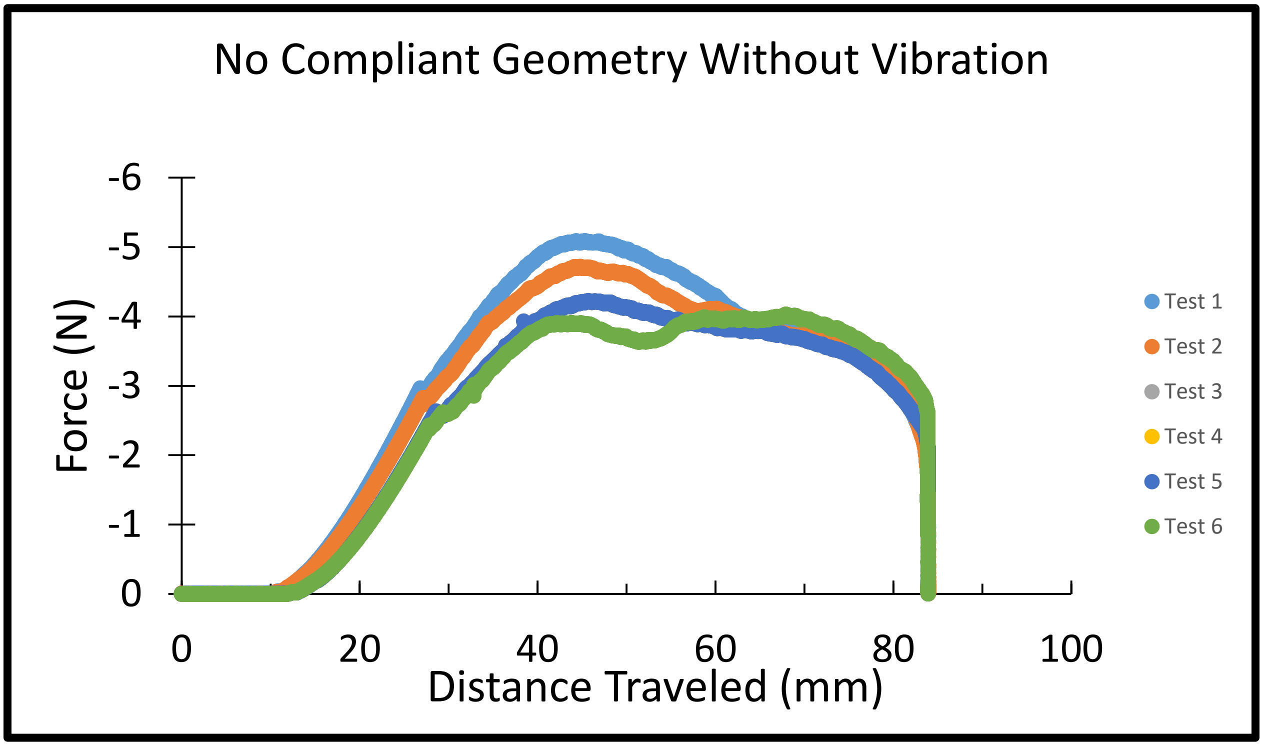
After completing the experiments and analyzing the results, there were three conclusions that could be taken away from the results. The first conclusion that was reached was that initial incision forces can be reduced when vibrations are added to a scalpel. Force reductions of anywhere between 17% to 42% were observed when vibration was added to the scalpel. The force reductions were most likely due to the vibrations assisting in the crack formation stages of the initial incision which reduced the forces required. The second conclusion that was determined was that different compliant geometries led to different amounts of force reductions during the initial cutting. The force reduction of a scalpel handle with no compliant geometry with added vibration was only 17.06%. The force reduction of a scalpel handle with a single compliant hinge with added vibration was 39.26% and a handle with a double compliant hinge was 41% reduction. The added vibration assisted with crack formation in the tissue sample due to the movement of the scalpel blade. The added vibration causes the movement of the blade. Added compliant geometries helped translate the movement caused by the actuator to the scalpel blade. The double compliant hinge was the most effective at reducing forces because the double compliant hinge is the best compliant geometry to translate the vibration. The third conclusion that was determined was that after the initial incision was made, the added vibration and compliant geometry no longer had any effect on force reduction. Once the crack was formed in the tissue during the initial incision, the only force experienced by the scalpel was the frictional force between the tissue and the scalpel blade and a cutting force. The added vibration and compliant geometry didn’t reduce the frictional forces or the cutting forces, therefore there was hardly any force reductions. The only force reduction observed was the reduction in force required to cause a crack in the tissue during the initial incision.

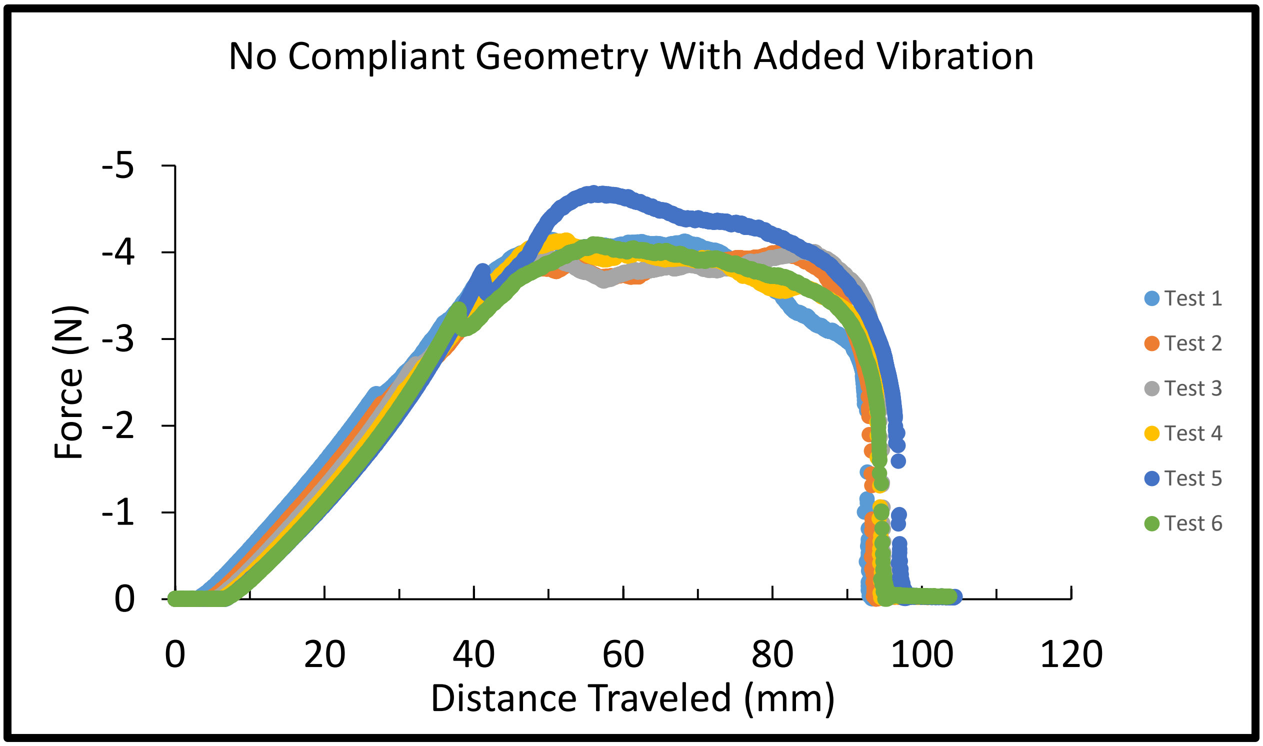
4.2 Directions of Future Work

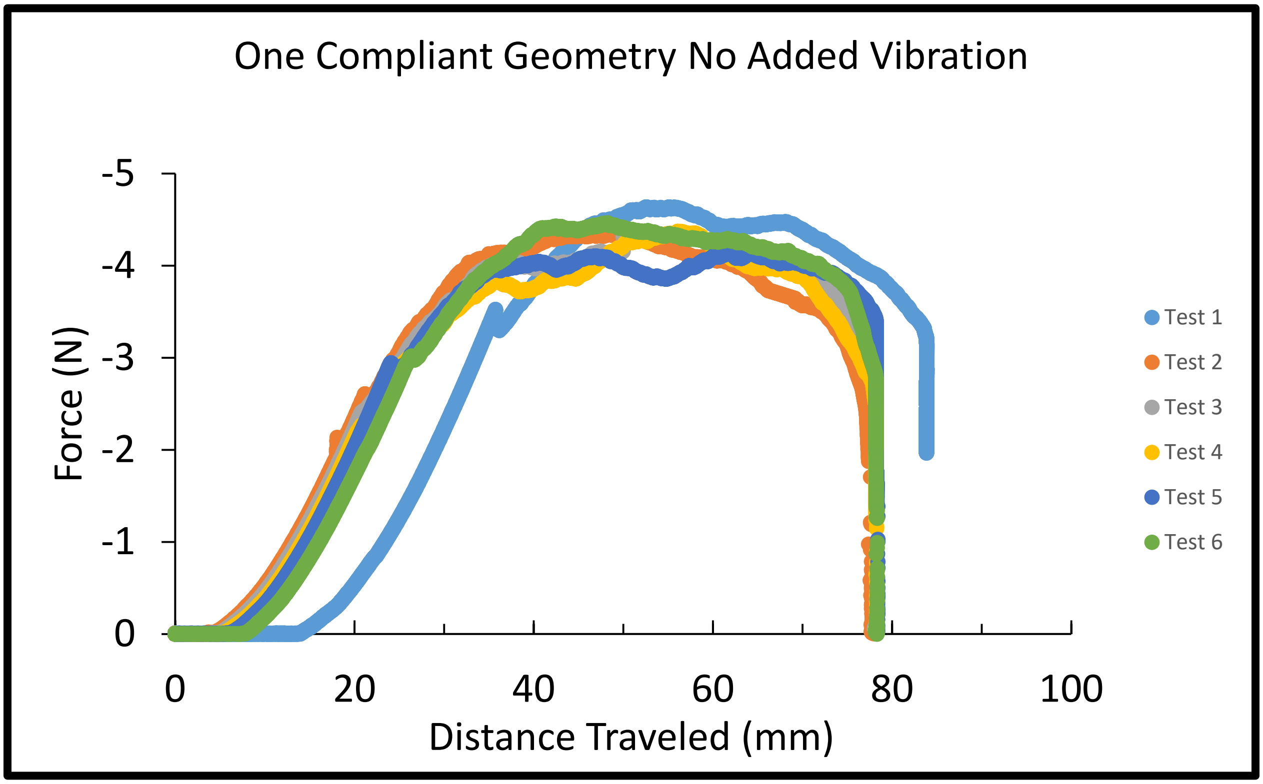
Future goals of this research includes several different aspects to help improve the results that are gathered. One goal would be to manufacture more scalpel blades to experiment with. The scalpel handle could be manufactured with different materials which could improve the compliant ability of the handle. In addition, different types of compliant geometries could be tested and different locations of the compliant geometry could be tested. Another goal would be to test different applied vibration frequencies. During this thesis only one frequency was used. Different frequencies could result in different results. Also, different tissue simulants could be tested on. One final goal would to manufacture a much more accurate apparatus to test the hypothesis. While constructing the apparatus and scalpel blades, the tools and machines that were available made precision manufacturing very difficult. While dealing with such small forces and movements, any manufacturing error could have a large impact on results. The findings from this thesis work, in conjunction with future work, can be used to create surgical equipment that requires less force to be exerted. Through such efforts, patient safety and comfort can be improved and surgical complications can be reduced.

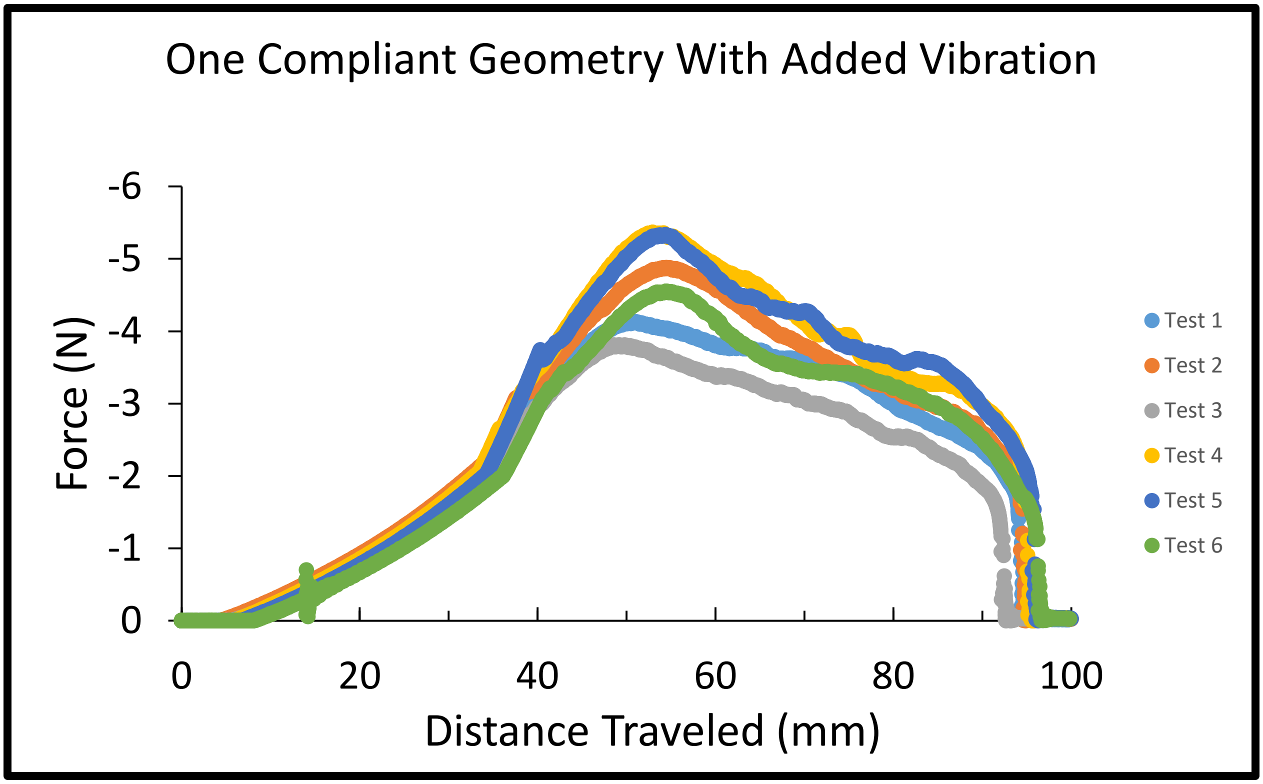
Appendix A

Force VS Displacement Graphs






One Compliant Geometry No Added Vibration
Force (N)
-5
-4
-3
-2
-1
0
0
20
40
60
80
100
Distance Traveled (mm)
Test 1
Test 2
Test 3
Test 4
Test 5
Test 6


One Compliant Geometry With Added Vibration
Force (N)
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-5
-4
-3
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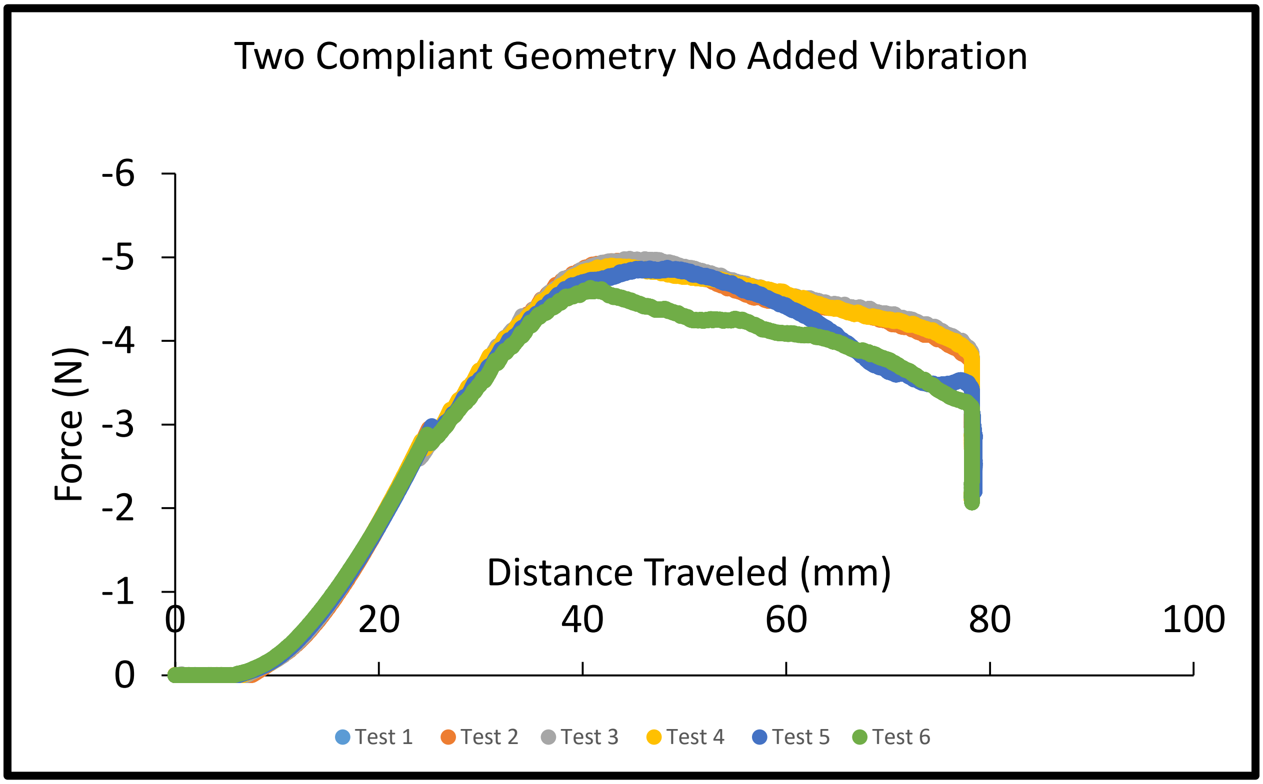
Test 2
Test 3
Test 4
Test 5
Test 6


Two Compliant Geometry No Added Vibration
Force (N)
-6
-5
-4
-3
-2
-1
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Distance Traveled (mm)
0
20
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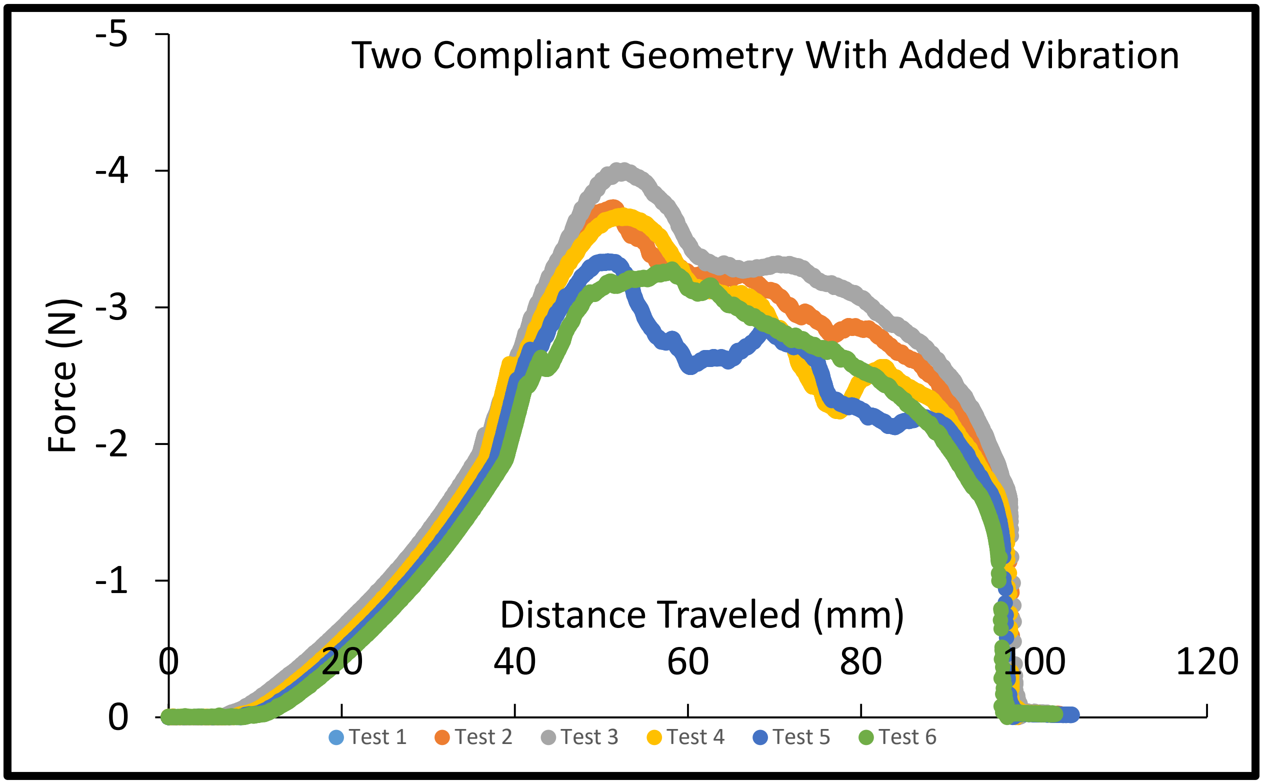
80
100
● Test 1
● Test 2
● Test 3
● Test 4
● Test 5
● Test 6


Two Compliant Geometry With Added Vibration
Force (N)
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-4
-3
-2
-1
0
Distance Traveled (mm)
0
20
40
60
80
100
120
● Test 1
● Test 2
● Test 3
● Test 4
● Test 5
● Test 6

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ACADEMIC VITA

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Education

- The Pennsylvania State University - Schreyer Honors College
- Bachelor of Science, Mechanical Engineering, May 2018
- Minor in Business
- Honors in Mechanical Engineering
- Thesis Title: Effects on Scalpel Cutting Forces With Added Vibration and Compliant Scalpel Handle
- Thesis Advisor: Dr. Jason Z. Moore

Work Experience

Duraloy Technologies (High Alloy Steel Foundry) Scottdale, PA
Internship May 2016-Present

- Led dozens of improvement projects to improve safety and efficiency of production.
- Designed several machines and devices to assist in production and to improve efficiency.
- Data entry and calculations for metal alloy densities and shrink factors used to improve yield.
- Proficient knowledge in both static and centrifugal casting processes.
- Assisting in R&D, testing, and implementation of new technologies and manufacturing processes.
- Modeling castings in Solidcast to check for shrink and improve yield.
- Tensile testing, Stress rupture testing, and material analysis testing of metal samples.

Supervisor: Zachary Clark

Camman Light Industries Derry, PA
Shipping and Receiving Manager and Assembly Team June 2014-January 2016

- Design and build shipping containers for different styles of lighting fixtures.
- Responsible for the shipping and receiving of all orders and managing inventory level.
- Prioritizing jobs and seeing that objectives were met.
- Assemble lighting fixtures with a team based off technical drawings from Solid Works.

Supervisor: Keith Enos

Kennametal Young Engineers 2013 Graduate Latrobe, PA
Gate Team Leader

- Planned, developed, and implemented a project solution following Kennametal's gate process.
- Utilized PowerPoint and AutoCAD to give formal presentations.
- Attended lectures given by Kennametal engineers about their field of work.

Grants Received

- Schreyer Honor College Scholarship

SKILLS

Microsoft Word, Microsoft Excel, Microsoft PowerPoint, AutoCAD, Solid Works, Matlab, Inventor, Solidcast, Power Tools and Welding Certified (PSU), Python, German Proficient

AWARDS/HONORS

- Eagle Scout
    - Project completed at Latrobe Christian Missionary & Alliance Church
    - Designed and constructed a new emergency exit including a cement ramp and railing system
    - Extensive landscaping to eliminate a safety hazard near a children’s playground
- Nation Society of Leadership and Success
-