VetMed: 3D Printed, Patient-Specific Incline Plane For Management of Class II Malocclusions

Final Report

BME 301

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Abstract

Class II malocclusion is a common genetic skeletal deformity among dogs that affects the dental interlock between teeth. The mandibular (lower) jaw is shorter in length than the maxillary (upper) jaw, causing the lower canines to puncture and damage the upper gum palette. The current treatment works to safely correct the malocclusion through tipping orthodontics. However, this process is both expensive and timely, making it an inaccessible procedure for most pet owners. With an improved workflow and simplified design, this procedure can be available for all pet owners and affected animals. The final design is made to be patient-specific, needing four measured variables; bridge length, two ellipse dimensions, and the incline plane angle, which would cut down the workflow for the veterinarian as well as making it user-friendly for the veterinarian to change. Upon the design's simplicity, 3D printing in titanium (Ti64) allows for the device to withstand the maximum canine biting force. Compression testing showed no deformation when tested with a force of 926 N. Additionally, testing the newly simplified workflow document with students with varying skill level in Solidworks resulted in proving that the new workflow process is more efficient than the previous way of treating class II malocclusion. In the future, the device and workflow will be tested on patients with class II malocclusions. Furthermore, plans are made to patent the workflow process with WARF and potentially create a company to be intermediates with veterinarians to help treat class II malocclusions.

I. Introduction

a. Impact

Class II malocclusions are a common genetic skeletal deformity that affects 10% of purebred dogs; most commonly, Golden Retrievers, Labrador Retrievers, Standard Poodles, and German Shepherds [1][2]. With this condition, the dog's lower jaw is relatively shorter than the upper jaw, causing the lower canine teeth to be misaligned. This abnormal alignment diminishes the functionality of the bite. Not only is this painful, but if it is not corrected, it can lead to dental attrition, gum diseases, oronasal fistula, and the destruction of the gum pallet and tissue[2].

According to the Veterinary Medical Ethics of the American Veterinary Medical Association (AVMA), "Should the health of the patient require correction of such genetic defects, it is recommended that the patient be rendered incapable of reproduction" [3]. However, from a genetic perspective, malocclusion is an inherited condition that is an autosomal recessive mutation [4]. As shown in Figure 1, even if the breeding of visibly affected dogs is stopped, this does not stop the carrier puppies from mating with another carrier puppy and passing the condition onto their offspring.

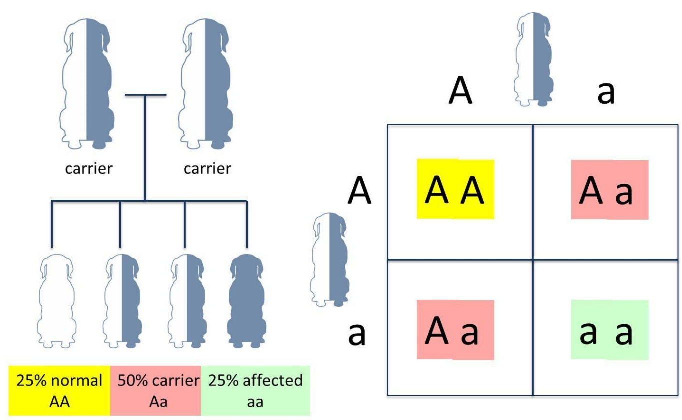

Figure 1: *Punnett square that predicts the variation and probabilities of the offspring from a crossbreed of two heterozygous recessive parents [4]. Twenty-five percent of the puppies will visibly have malocclusions and if bred, they will pass the mutated information on. Fifty percent of the litter will carry one abnormal gene from one parent and a normal gene from the other, making them carriers. They will look normal but have the chance of passing on malocclusions if bred with another carrier. The other 25% will be unaffected and will not pass the trait onto future generations [5].*

To stop the reproduction of affected dogs is an unrealistic solution due to the high chance a dog could be a carrier of the mutation. Additionally, the dogs affected, Golden Retrievers, Labradors, Poodles, and German Shepherds are among the most popular dog breeds in the US, making it even more difficult to stop the spread [6]. Overall, there needs to be an easily accessible and efficient veterinary treatment that works to correct class II malocclusions, so that every dog diagnosed has an opportunity for correction.

b. Existing Treatments

The position statement of the American Veterinary Dental College (AVDC) states that "the goal of veterinary orthodontic procedures of companion animals is to alleviate pain and provide a healthy and functional occlusion" [7]. The current treatments used to treat class II malocclusions utilize intrusive or tipping orthodontics.

Intrusive orthodontic procedures are focused on removing the painful contact point in class II malocclusions. Methods include either extracting or shaving the problematic tooth followed by vital pulp therapy to maintain tooth structure. These procedures, however, do not provide a long-term solution, as they decrease the functionality of the teeth and bite. Dog's teeth are needed to serve as weapons and as tools for cutting or tearing food, so it is important that the teeth stay intact.

Tipping orthodontics uses an incline plane to guide the misaligned teeth to the correct position by utilizing controlled tipping mechanics. When the dog closes its mouth, the teeth will hit the incline plane with the force of a bite. Due to Newton's 3rd law, this force moves the crown in one direction, while the root of the tooth resists motion [8]. A moment force is created at the apex of the root, and over time repeated motion will slowly guide the canines into the desired position. In figure 2, the root of the tooth stays in the same place so there is no damage done to the buccal bony plate.

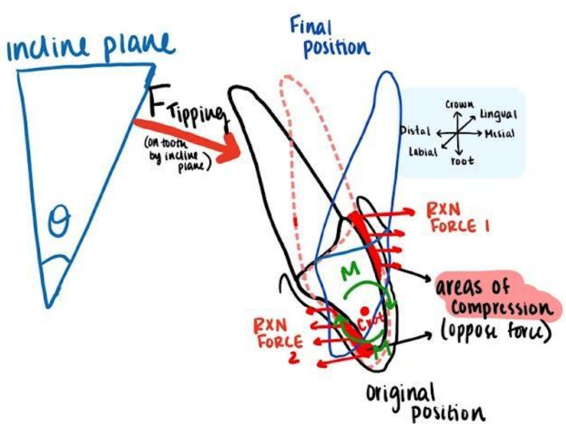

Figure 2: *Controlled tipping mechanics combined with the incline plane. The moment force created at the apex of the tooth M = F x d.*

Dr. Graham Thatcher has been working to perfect an inclined plane device that is non-intrusive to the rest of the patient's mouth with a height, size, and angle of incline that is patient-specific [2]. Figure 3 shows the incline plane device attached to two teeth of the mandibular jaw, with built-in incline plane ramps on the sides. To produce this device, Dr. Graham first takes a Computed Tomography (CT) scan of the canines' jaw. Then, this data is saved in the Digital Imaging and Communications in Medicine (DICOM) format, and the file is outsourced to a software engineer to produce a 3D printed version of the patient's jaw. Using the printed jaw as a reference, Dr. Thatcher carves out an initial mold of the incline plane using a bis-acryl composite material. This carved model is sent to a software engineer who uses software to transform the hand-carved incline plane model into a 3D printable model. The Fall 2020 BME Design group printed this device in Dental LT resin, however, it was not able to withstand the bite force and this material broke after two weeks of treatment [9].

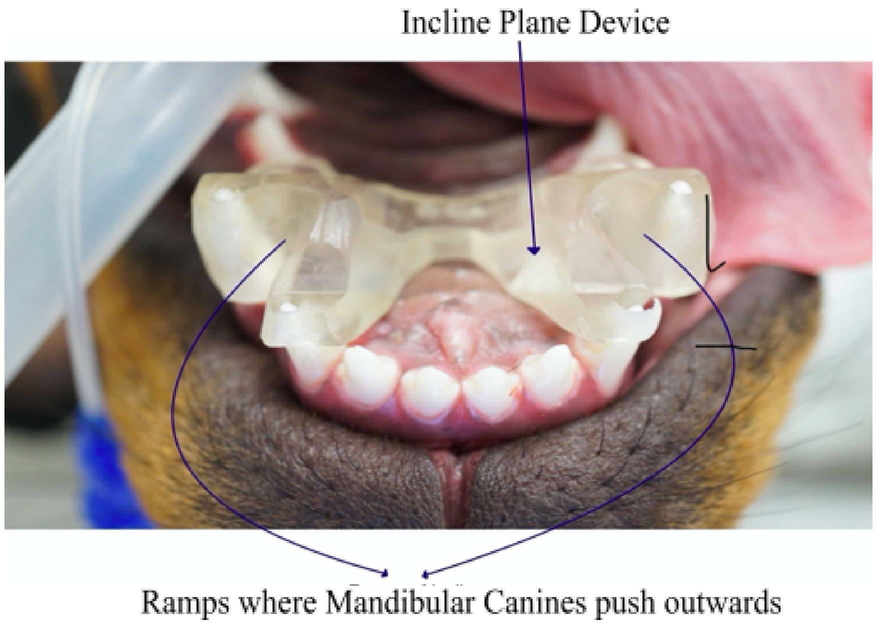

Figure 3: *Incline plane device.*

Dr. Graham Thatcher is not the only veterinary orthodontist working to perfect the workflow and the design of an incline plane. Another treatment involves single tooth incline planes. The same controlled tipping mechanics are applied with the use of incline planes. However, the difference is, that instead of the device being one piece, there are two single incline planes attached directly to the maxillary canine and the second and third incisor teeth [10]. These incline planes are placed and fabricated in the dog's mouth while they are intubated. A light-cured acrylic denture base material is cut and placed strategically around the maxillary teeth. This strategic placement involves shaping, contouring, and smoothing around the teeth to create the incline plane with no sharp edges and the desired shape. Each surface is light cured for 20 seconds. Figure 4 shows the two single, separate patient-specific incline planes created on both the maxillary canines.

Figure 4: *Single incline plane devices made out of light cured acrylic denture base material.*

To treat mild to moderate malocclusions, another form of an incline plane, a crown extension can be used. In figure 4, the semi-translucent blue core build-up material is formed around the mandibular canine so that the incisive tip no longer impacts tissue. The same tipping orthodontics are used, as the patient closes its mouth, the crown extension makes contact with the upper gum of the patient, and reaction forces act upon the extension, tipping the canine into the desired position. Initially, the patient will not be able to fully close the mouth, the extension should be visible and pointing outwards [2].

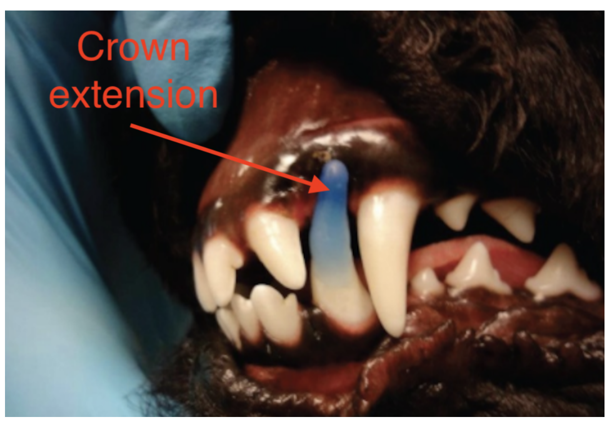

Figure 5: *The blue piece is a crown extension composite in a patient. It acts as an extension of the lower mandibular canine, tilting the tooth into a correct position.*

c. Problem Statement

Class II malocclusions negatively affect the quality of life of dogs and if left untreated, the dog is at risk for infections, tissue damage, and irreversible tooth damage. Dr. Graham Thatcher has produced a 3D printed patient-specific incline plane, which safely corrects class II malocclusion in dogs. However, the process is time-consuming and complex, making the procedure expensive for pet owners. In addition, there is limited flexibility between patients, Dr. Graham has to restart the whole design process for each patient. To create an easily accessible and efficient veterinary treatment, there needs to be an improved workflow and design of the incline plane device. This workflow will be patient-specific and only use measurements, reducing the time needed for the treatment process.

II. Background

a. Research

Biology and Physiology

Normal Occlusion

Occlusion is the dental interlock between the maxillary (upper) and mandibular (lower) canines. Figure 5 displays a normal, functional occlusion. The mandibular canine fits in between the upper third incisor and the maxillary canine. In addition, the crown of the tooth is pointed outward allowing for the jaw to close without puncturing the gum. Abnormal alignment between one or many teeth is described as a malocclusion.

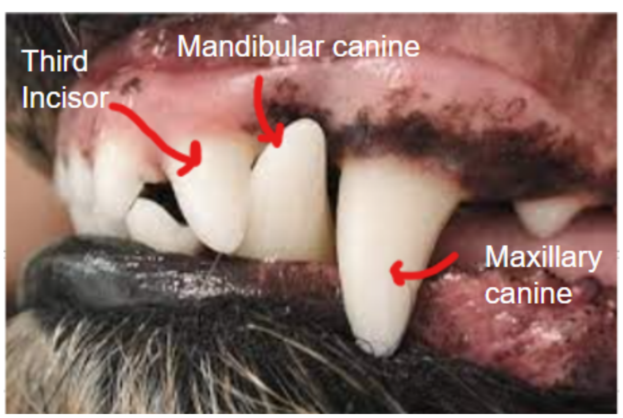

Figure 6: *Normal occlusion in a dog with the mandibular canine correctly aligned, causing no damage to the gum tissue.*

Class II Malocclusion

Malocclusions are caused by discrepancies in the length of the mandibular or maxillary jaw with respect to normal jaw lengths. Specifically, a class II malocclusion is diagnosed when the mandibular (lower) jaw is shorter in length than the maxillary (upper) jaw, often referred to as an overbite. In figure 6, the mandibular canine is pointing inward and puncturing the roof of the mouth, causing damage to the gum and palatal tissue. In addition to pain, the jaw does not close correctly and normal jaw movement is inhibited. This often leads to poor quality of life for patients.

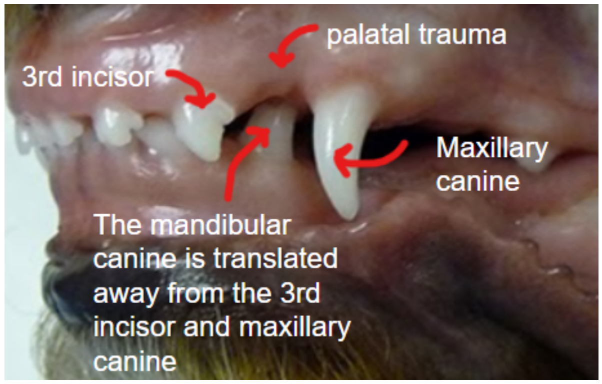

Figure 7: *Class II Malocclusion in a dog.*

Design Research

Existing Patent

US5151027A is an expired patent for a veterinary orthodontic fixture useful in correcting lingual displacement of the mandibular canine teeth of an animal [8]. This device utilizes incline planes attached to the maxillary canine to tilt the mandibular canines into a normal position where they will not interfere with the gingival tissue of the maxilla (Figure 7). This device does not inhibit the normal growth of the patient's jaw, and it is cemented to the teeth to fit snugly on the maxillary canines.

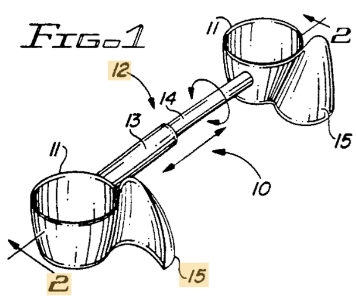

Figure 8: *US5151027A Patent used to correct class II malocclusions in dogs. This expired in 2009.*

Titanium 3D Printing

Titanium is a good dental material due to its strength, biocompatibility, and corrosion resistance. Titanium 3D printing allows the doctor or veterinarian to make a patient-specific device that is specifically suited to the patient's needs. Titanium 3D printing also reduces material waste since only the exact amount of titanium needed is used [11]. A titanium 3D print is created by placing titanium powder on a bed which is then fused into the desired piece using a laser [12].

b. Client Information

Dr. Graham Thatcher is a Veterinary Orthodontist and a former Assistant Professor of Dentistry and Oral Surgery at the University of Wisconsin-School of Veterinary Medicine. Dr. Thatcher has been working with tipping orthodontics and especially incline planes.

c. Design Specifications

Incline Plane and Material

In Veterinary orthodontics, incline plane devices are attached directly to the patients' teeth to gradually correct class II malocclusions by tipping orthodontic mechanics [2]. Thus, it is essential that the device's material must be able to last intraorally for 6-8 weeks. The incline plane will provide a force equal to and opposite to the bite force of the dog that will create a moment force to tip the tooth. So the material of the device has to withstand the potential maximum bite force of a dog, 926 N with repeated and continual stress synonymous with eating [13]. In addition, the device should ideally withstand face traumas as these treatments are often implemented in puppies. Therefore, a strong biocompatible material needs to be considered to achieve these specifications.

The ability to 3D print an incline plane will potentially lower production costs to under $200 and reduce manufacturing time. The current incline plane has a manufacturing time of two to three weeks. 3D printing will reduce the need for anesthetics and CT scans for each patient. Hence, the material chosen should be compatible with 3D printers while still being capable of withstanding the stresses applied. Lastly, the incline plane device must span the distance between both maxillary canines (13-58 mm) [13], fit around the mandibular canines (5-22 mm) [13], and have the proper incline plane angle to push the malocclusion out of the patient's mouth (45-60 degrees). All these dimensions would vary from patient to patient and vary over a broad range. The incline plane angle is determined from patient to patient based on the degree of malocclusion determined solely by the veterinarian [2]. The average tooth width for a dog's mandibular canine is 11mm, and the average distance in dogs from maxillary canine to maxillary canine is 38mm [13]. To match the standards of human orthodontics, dimensional errors must be under 300-500 micrometers to be considered acceptable for treatment use [14].

Software/Workflow

Having software that is easily operated will be optimal for the design fabrication process. This allows for veterinarians with little computer-aided design skills to personally manipulate the device. Having the veterinarian able to manipulate a Standard Triangle Language (STL), such as a Solidworks file, will allow them to make each device patient-specific. The manipulations of the STL file needs to be simple where altering the file will take 30 minutes. Each manipulation would be based on specific dimension measurements (listed above) taken by the veterinarian, which should also take 30 minutes. In addition, the elimination of a software engineer allows for faster fabrication periods, reduced cost, and more accessible treatment for a greater number of patients. Furthermore, simplifying the number of variables needed to be manipulated to make the software more easily operated, while also reducing the need to intubate and scan each patient's mouth. Similarly, creating a step-by-step reference guide to aid in the operability of the software chosen to create the design, such as Solidworks. Finally, the software must be archived in an STL file to be compatible with 3D printers.

Ⅲ. Fabrication/Development Process

a. Materials

The decision was made to use 3D Printable Titanium (Ti64A14V) due to the fact that the structure of the final design has a smaller surface area making it more prone to failure. A stronger material was needed to ensure that the product would not fail. Titanium is used in almost all dental implants; various studies show that failure rates over considerable time periods are extremely low, at least 89% and typically 97–99% of titanium implants survive for over 10 years [16]. Specifically Ti64A14V is a 3D-printer powder and has an elastic modulus of 113.8 GPa and a yield strength of 830 MPa [17]. Ti64 powder costs around $20 per gram and takes around 3-4 weeks to be 3D printed [18]. Titanium (Ti) is an element from transition metal with lustrous silver color, high strength, and low density. Ti has high resistance to corrosion under different circumstances, and Ti has biocompatible and nontoxicity properties in humans [19]. The final design was 3D printed through Materialise. Materialise prints Ti6Al4V with a tolerance of 0.5 mm which is in accordance with the dimensional casting tolerance grades (DCTG) [20].

b. Methods

To create the SolidWorks STL file, a simplistic set of two ellipsed rings connected by a curved support bridge was assembled. In order to make this design easily adjustable, the file was made so each of the variables referenced each other and would not cause overlapping of parts when measurements were changed. An incline plane was then added that referenced the ring and the support bridge measurements, which allowed for changes to any of the measurements to cause the others to adapt and form a final patient-specific model.

With the SolidWorks STL file, the client measures the four required variables of the ring design: the upper length of the maxillary canine and upper width of the maxillary canine (Figure 9), the distance between the insides of the maxillary canines (Figure 10), and the degree of tilt of the incline plane (Figure 11). The client uses the measurements in the SolidWorks Design Workflow to create a patient-specific model (see Appendix B). This model is then 3D printed in PLA in order to check the fit on the patient. If the fit is correct, the product is 3D printed in titanium (Ti64) and placed into the patient's mouth using dental cement.

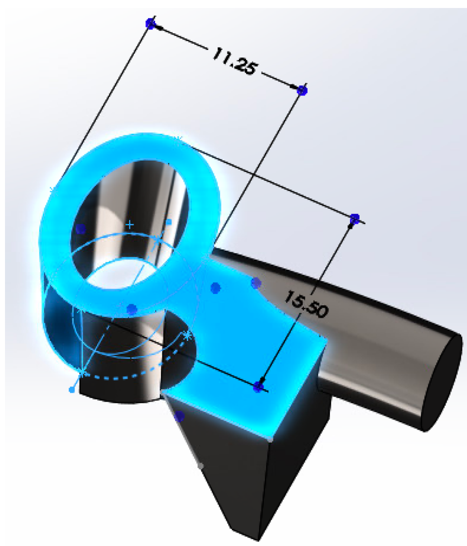

Figure 9: *Patient-specific length and width dimensions of the maxillary canines in millimeters.*

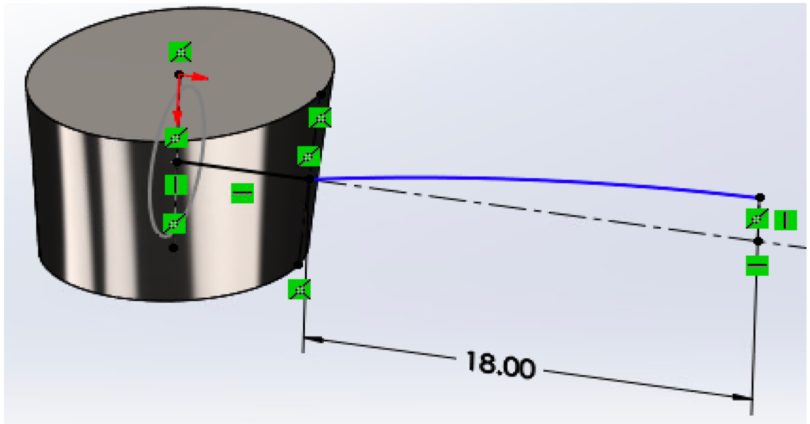

Figure 10: *Patient-specific distance between the maxillary canine/ support bridge length input in millimeters.*

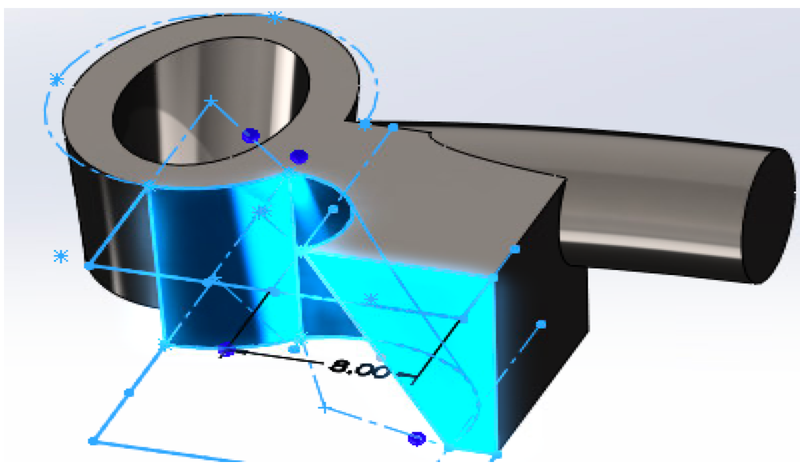

Figure 11: *Patient-specific degree of tilt of the incline plane input in millimeters.*

c. Final Prototype

The final design is inspired by an expired patent, US5151027A [15]. The design features two ellipsed rings with a support bridge attaching both of them and an incline plane on the end where the ring and support bridge meet (Figure 12). The rings will be secured to the upper maxillary canines of the patient with dental cement. The incline plane will be used to tilt the lower mandibular canines into place. The goal of this design is to offer the most optimized design while also simplifying the workflow. The final design has four main variables that the client will have the ability to manipulate, are four main variables in this design, being the upper and lower diameter of the elliptical rings, the length of the supporting bridge, and the angle of tilt of the incline planes (Figure 13). These variables are all patient-specific, and therefore will need to be measured and altered for each patient. The simplification of the design eliminates the need for costly CT scans and allows the client to simply take measurements in the patient's mouth, alter a base 3D model of the design following our workflow, and 3D print the device. The final design was 3D printed in titanium (Ti64) and underwent compression testing.

Figure 12: *Front view of final prototype in Ti-64. This is the configuration for which it will be placed in the patient's mouth.*

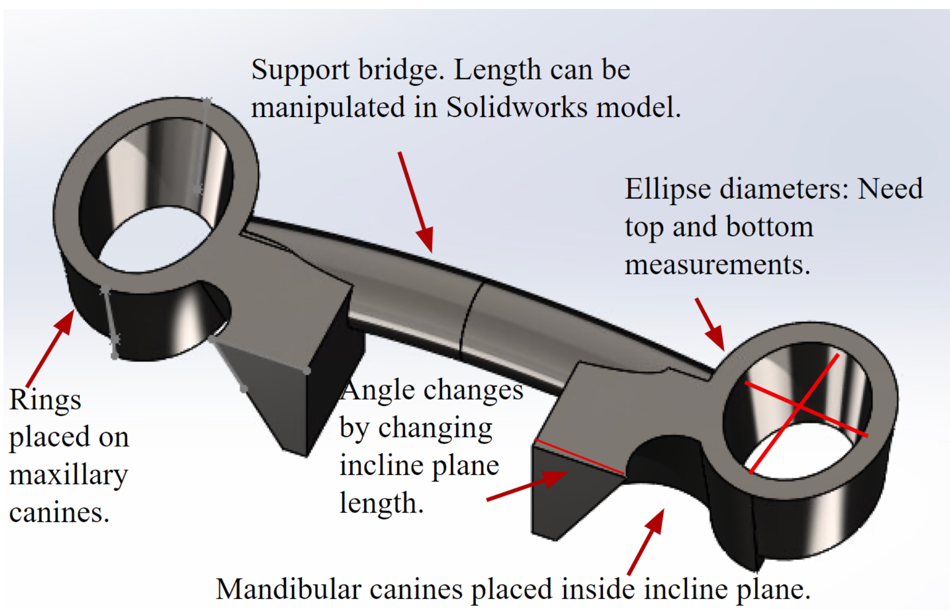

Figure 13: *SolidWorks design of final prototype showing workflow changes.*

d. Final Workflow

The final workflow was designed so that individuals without SolidWorks knowledge would be able to create a patient-specific incline plane by following a step by step instruction manual (Appendix B). The first step in the workflow explains the measurements that are needed and where they should be taken from. In order to create the rings that are designed to fit the canines, 4 measurements need to be taken. It is important that the user knows the difference between the minor and major axis measurements taken on the tooth because these measurements are situated in different planes. These four measurements are shown in figure 14, there is a 3D coordinate plane showing the axes that the measurements are taken from. The axes are color coded with respect to the plane they are referenced on. Additionally, the upper and lower measurements are shown on each of the faces of the tooth. It is important to note that the upper and lower measurements are taken 8mm apart from each other, this is the dimensioned length of the ring in the SolidWorks file. The next measurement the veterinary orthodontist needs to take is the length from one canine to the other, this will be the length of the bridge. The final measurement is the desired angle of the incline plane, this is completely up to the veterinary orthodontist to determine based on the severity of malocclusion.

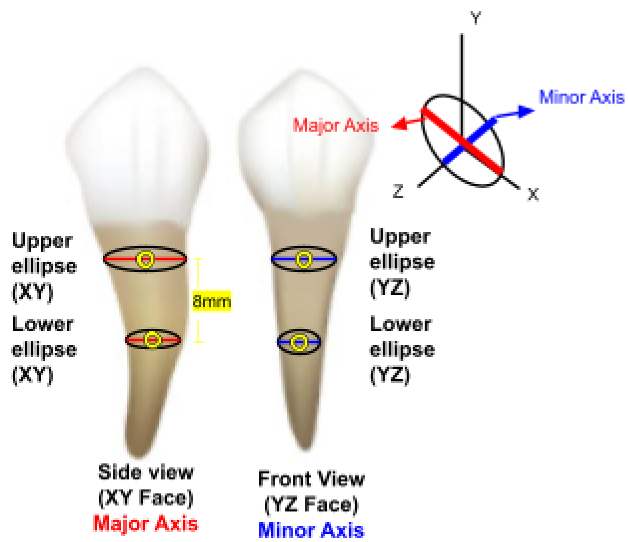

Figure 14: *Diagram of the measurements taken for the ellipse dimensions*.

Due to the way the SolidWorks design was constrained and mirrored, the measurements must be altered in order to ensure the design will fit into the patient's mouth. A spreadsheet is linked in the manual to ensure that the user does not need to do any manual conversions. All the user must do is copy and paste the measurements into the spreadsheet and the converted measurements will be outputted. This saves the user time and reduces any human error. Equation 1 describes the conversions applied to the upper and lower tooth's major and minor axes; 4 mm is added to take the thickness of the rings (2mm on each side) and 1 mm is added as a tolerance. Equation 2 describes the conversions applied to the support bridge measurement; 4 mm is subtracted from the length to take into account the thickness of the rings and then divided by 2 because the part is mirrored. Equation 3 computes the length of the incline plane that will adjust the angle; the angle used in the equation is the desired angle determined by the veterinarian. The measurements calculated by these equations in the spreadsheet are the measurements that will be inputted into the SolidWorks file.

Equation 1: $(Original\ axis\ measurement)\ +\ 4\,mm\ +\ 1\,mm$

Equation 2: $\frac{((Original\ bridge\ measurement) - 4\,mm)}{2}$

Equation 3: $(\frac{10}{tan(\theta)})\ +\ 2\,mm$

The second step in the instruction manual is to go into the solidworks file and edit the dimensions that are found in the feature tree. The manual gives step by step directions with pictures of the screen to guide the user. Once step two is completed, the user will have ½ of a patient-specific incline plane. The third step is to then mirror the part. Similar to step two, the manual gives step by step directions with pictures of the screen to guide the user in mirroring the part. Once the part is mirrored, the user will have two sides of the incline plane. To connect these incline planes together, the user will create an assembly of the two pieces. Step four of the manual gives step by step directions with pictures of the screen to guide the users to create an assembly and save the file as a whole piece. Step four is the final step, once the file is saved, it can be 3D printed.

e. Testing

After simulated testing using Solidworks SimulationXpress (see Appendix D), the team conducted compression testing of the incline plane device on an MTS machine. Using an aluminum plate with two 1/4 inch-20 fastening the titanium incline plane in place (Figure 15) and an aluminum plate with two 1/4 inch-20 bolts acting as the mandibular canines (Figure 16), two platens were fabricated to use as the upper and lower platens for the MTS machine. The platens were then calibrated into place and up to 989.5 N of force was applied to the incline plane (Figure 17), mimicking the environment of a dog’s bite that the incline plane would experience in a patient. The test was run for 3 cycles, at a strain rate of 0.001 s^{-1}.The goal of the test was to ensure the titanium incline plane could withstand the 926N maximum bite force of a canine tooth.

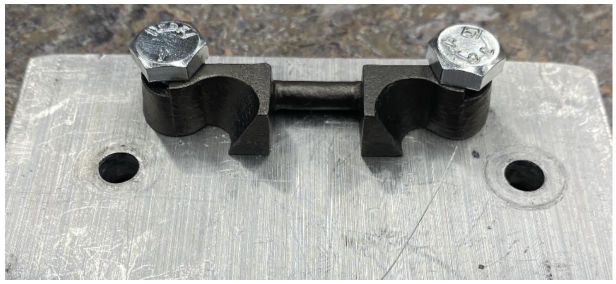

Figure 15: *Lower platen used in MTS compression testing featuring the incline plane fastened in place by two 1/4 inch-20 bolts.*

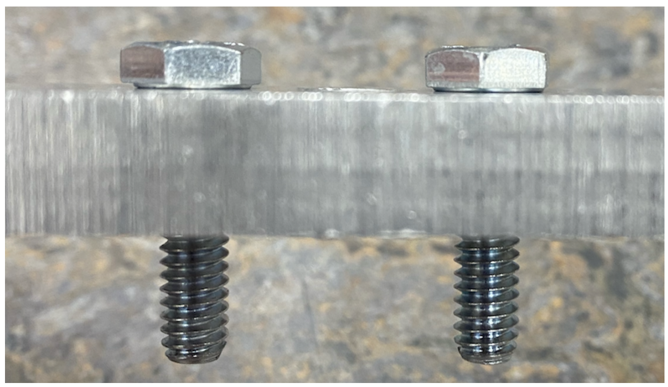

Figure 16: *Upper platen used in MTS compression testing featuring two 1/4 inch-20 bolts mimicking mandibular canines.*

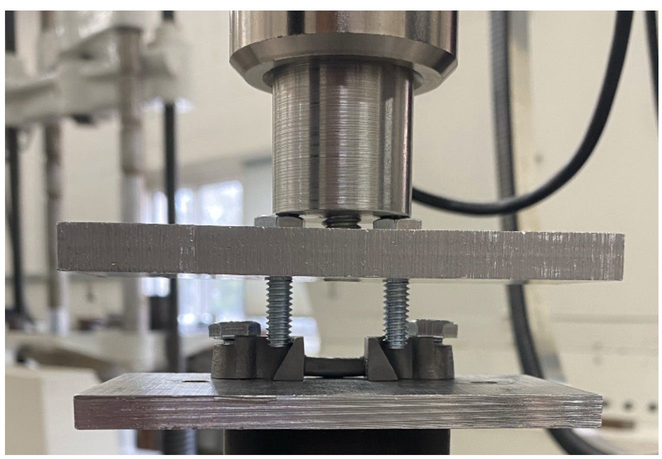

Figure 17: *Configuration of upper and lower platen in the MTS machine.*

The team also conducted testing on the effectiveness of the Solidworks workflow. After gathering peer feedback during the semester show and tell session, the team made improvements to the existing workflow, and made it easier to navigate and manipulate the Solidworks file. Once the document was optimized, three UW Madison students with varying expertise in Solidworks ranging from beginner to proficient were given the Solidworks file and workflow document and timed on how quickly they could accurately create a new file given dimensions from the team.

Ⅳ. Results

The results from the compression testing conducted by an MTS machine showed that the Ti-64 incline plane can withstand the max biting force from a canine's mandibular teeth. After three cyclic trials, no deformation was recorded on the part and a force displacement curve was obtained, showing the extension of the upper platen versus the load being applied to the incline plane (figure 18). The initial distance from each point of contact between the bolts and the incline plane was 23.76 mm before testing and 23.76 mm after, proving the part did not enter into plastic deformation range. There were also no visible scratches or marks on the incline plane after testing. This test, along with supporting literature, prove that the Ti-64 incline plane would not fracture under the conditions of a canine’s mandibular max bite force as the fatigue limit of the material Ti-64 is 410 MPa [21].

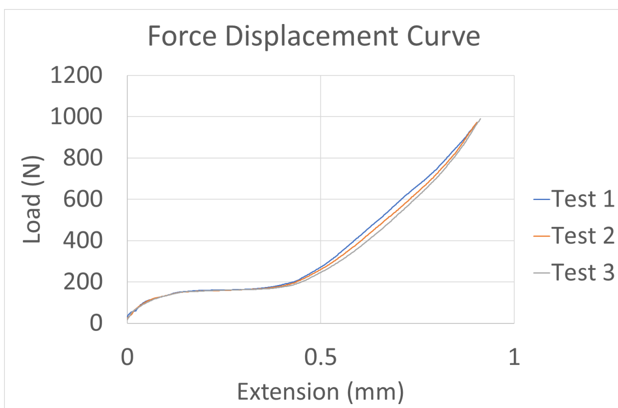

Figure 18: *Force displacement curves for the three compression tests conducted on the incline plane.*

The results from the student testing of the Solidworks workflow concluded an average time of completion of 15 minutes and 49 seconds for taking measurements and 17 minutes and 31 seconds to convert the measurements and implement them into the Solidworks design. This is lower than the time of 1 hour total specified in the product design specifications and proves the workflow to be easily followed by a user with little to no Solidworks experience.

Ⅴ. Discussion

The goal of this project is to help the client optimize the workflow and improve the design to aid in the treatment of class II malocclusions. The final design first does this by significantly decreasing the workflow for the client. The process to create a patient-specific model has been reduced from having to take a CT scan of the patient's mouth, print out a 3D model of the patient’s skull, make a carved mold of an incline plane on the skull model, and then send the mold to a software engineer to make and print a 3D model to only having to adjust the four required variables of the Solidworks STL file of the final design and then 3D print. The original process took two to three weeks before the final product was ready to be printed whereas the improved process allows for the client to have the patient-specific final product ready to print in under an hour. Additionally, this process eliminates the cost of CT scans and the cost to outsource work to a software engineer, which reduces the total cost of the product from $2,500-$3,000 to $300. In addition, the final design has been improved to be a more simplistic incline plane, which allows for only four variables needing to be changed to make it patient-specific. With the design being more simplistic, structural integrity was compromised which is why the decision was made to 3D print in titanium (Ti64). Throughout the MTS machine testing, the results showed that the design made out of Ti64 would be able to withstand about 975 N which is more than the max bite force of canine teeth on a large dog [9]. This result was further confirmed through SolidWorks SimulationXpress testing (see Appendix D). Throughout the design process, it was also important to consider morals and ethics in the design and testing process. Patients will be treated as if they are human, using non-toxic materials and ethical test standards. The procedure and product of the design do follow the standard, “ISO 13504” Dentistry requirements and related accessories used in dental implant placement and treatment along with implant and implant materials following “ISO 13504” Dentistry requirements as the material used, Ti64, is a biocompatible material and the standard procedure to implant the incline plane by the client is similar to how braces are implanted in a human's mouth [13]. Also, the initial veterinary examination done by the client does follow the AAHA-AVMA canine preventive healthcare guidelines [3]. Any sources of error from the design process would have taken place during testing.

Ⅵ. Conclusions

The goal is to create a streamlined, efficient process for correcting class II malocclusions in dogs, in a safe and harmless manner. Class II malocclusions stem from the misalignment of the mandibular, or the lower canine tooth, causing puncture wounds and issues in the upper gums of the patient. Currently, the process for fixing the malocclusions with an incline plane is crude and inefficient. The other processes that are currently used include removal or crown reduction of the mandibular canine which can lead to future conflicts in the patient. The design and process created last year also fell short in efficiency and durability. This semester, the goal is to finalize the SolidWorks STL file and workflow document in order to 3D print a patient-specific incline plane in Ti64 and confirm its durability with mechanical testing.

The final design involves a ring around each of the maxillary or upper canines connected by a support bridge that offsets the force of the incline plane. An incline plane is connected to the bottom of these rings and used to gradually reposition the mandibular canines. Due to the small nature of the design, 3D printable titanium (Ti64) is used to ensure the stability of the product. The simplicity of the design also meant that a computerized tomography (CT) scan was not necessary to determine the variables of the patient-specific product, and instead, a caliper can be used to measure the variables [22]. Dental glue is also used to fix any small errors around the circumference of the canines. This workflow saves a substantial amount of money and simplifies the process.

In the future, the plan is to further optimize the final design. The inside of the rings and the incline plane will be fileted to ensure a sleek, compact, and safe design. The workflow will be tested by additional users with no SolidWorks experience to find any points which need further clarification and continuously update the document. Additionally, a veterinarian will use the workflow to create a model for an actual patient and test its ability to treat a class 2 malocclusion. This could be done with our client as Dr. Thatcher would collect specific measurements of a patient and apply them to the workflow document, as shown in Appendix B, followed by 3D printing the modified patient-specific Solidworks part in Ti64. Dr. Thatcher would then apply the incline plane in the patient's mouth using dental cement for a 6-8 week treatment. The success of the incline plane device will be determined by tracking the amount of correctness of the class II malocclusion in the patient. Finally, the team will continue working with WARF to pursue a patent for this workflow. A company could also be started (called "Canines Corrected") to act as an intermediary for veterinarians. These steps will help the 4 million dogs in the United States which have class II malocclusions each year [23].

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Ⅷ. Appendix

a. PDS

Team Members:
Benjamin Smith, *Team Leader*

Lily Gallagher, *BWIG*

Giovanni Militello, *Communicator*

Madeleine Kredell, *BPAG*

Abigail Stertz, *BSAC*

Client:
Dr. Graham Thatcher

Advisor:
Dr. John Puccinelli

Function:

Class II malocclusion is a common genetic skeletal deformity among a variety of animal breeds [1]. Specifically in canines, this type of mandibular distoclusion refers to the misalignment of the teeth; the canines lower jaw is shorter than the upper jaw[1]. This condition leads to destruction of the palate and gum tissue of the upper jaw. This negatively affects the canine's quality of life by inhibiting necessary instincts, such as eating and defense. The current design scope of our project is to further develop the current design, Dr. Thatcher's incline plane, by creating a design that is easier to manufacture and is more adaptable for each specific patient. In addition, to design a more efficient workflow by creating a general SolidWorks file that can be easily altered to create a patient-specific 3D printable model of the device.

Client Requirements:

- Incline plane device
- Device can be modified based on each patient-specific canine measurements
- Device must be easy to create from canine measurements using Solidworks
- Device must be placed in the patient's mouth
- Simplified Software Workflow
- Withstand 6-8 weeks of use
- Reduce the 1 week fabrication timeline (using a software engineer)

- Eliminate the need to intubate in the case of the device breaking (cost $90 to $200)
- Eliminate the need to take CT Scans ($100-$500) for each patient.

Design Requirements:

Physical and Operational Characteristics:

A. Performance requirements:

The goal of the incline plane is to slowly, over time guide the mandibular (lower) canines into the correct positioning. The incline plane will be positioned comfortably using dental glue on the maxillary palate (upper jaw) in the canine's mouth. It will need to withstand a bite force of the canine teeth ranging from 147-926 N [2]. In addition, the device will be easily manipulated in SolidWorks to be patient-specific, using measurements taken with calipers.

B. Safety:

The incline plane should not impede the canine's wellbeing. The device should adjust to the mouth without causing sores and pain. The device also must be made of a non-toxic material, it must follow the standard, "ISO 13504" Dentistry requirements and related accessories used in dental implant placement and treatment [3]. The device should be strong enough to withstand the force of the dog's bite, for 6-8 weeks without breakage. The initial veterinary examination should follow the AAHA-AVMA canine preventive healthcare guidelines [4]. In addition, the following implant and implant materials should follow, "ISO 13504."

C. Accuracy and Reliability:

The device will be patient-specific in order to minimize error. To get an accurate, personalized fit, a canine measurement using calipers is required to input into the SolidWorks file. The SolidWorks files will be used to 3D print a model that fits around the patient's teeth. In human orthodontics dimensional errors for the incline plane must be under 300-500 micrometers to be considered acceptable for treatment use [3].

D. Life in Service:

The inclined plane should last 6-8 weeks, depending on the circumstances of the malocclusion [1]. The device will be placed on the maxillary arches, and therefore will need to last in the mouth of the patient for the stated amount of time.

E. Shelf Life:

The plane needs to have a shelf life of up to 10 weeks to consider the time between manufacturing the device and putting the device into the mouth of the patient. After the correction cycle is complete, the device will not need to operate anymore as it is specific to one patient and it is then removed and disposed of.

F. Operating Environment:

The inclined plane will be worn 24 hours a day- 7 days a week and so the patient's day-to-day environment will be its operating conditions because the device will be attached to the patient's mouth, which is a moist environment and so the device needs to withstand the bacteria that is present in the mouth. For temperatures the device will need to be able to withstand a range of -32℃ to 50℃ to accommodate extreme weather conditions the patient may encounter. The device will need to withstand bite forces of a dog bite that ranges from 147-926 N [2] so the device is not loosened from the mouth or is not cracked or fractured. The device should not interfere with the patient's food consumption, so it should not have food stick to it or cause the device to peel off. The device should also withstand normal interactions with toys and other other objects. The software used should be accessible to the veterinary orthodontist to use. The software should also be easy to follow and can be used on most computers.

G. Ergonomics:

The plane will be placed on the mandibular canines of the patient. When the patient closes their mouth, force from the mandibular canines will be applied to the inclined plane. Over time, this repeating motion combined with the angle of the inclined plane will slowly guide the canines into the desired position. The device should be non-intrusive to the rest of the patient's mouth with a height and size that is patient-specific. The angle of the incline plane will be patient-specific; it will be determined by the degree of distoclusion, size of teeth, and time needed for correction, which typically falls into a range of 45-60 degrees.

H. Size:

The size of the inclined plane will vary from patient to patient and therefore should be size adjustable to accommodate for each patient and the varying Class II Malocclusions. Typical canine width to consider in the design is a 11 mm width of crown as percentage compared with widest crown [5].

I. Weight:

The inclined plane should weigh 170 grams or less. This will ensure that the patient does not notice the device and is able to use it comfortably for 6-8 weeks. The optimum weight would be around 85-113 grams, depending on the size of the patient.

J. Material:

The device will be 3D printed with Ti64 using a Lens MR7 printer. 3D printable resins such as Formlabs Dental LT Resin should not be used due to weaker mechanical properties.

K. Aesthetics:

Color is relatively unimportant for the functionality of the inclined plane, and therefore this aspect of aesthetics is not the focus of the design. The shape of the inclined plane will be that of the maxillary arches of the patient [2]. The design will have two rings for the maxillary canines. As for texture the devices should be smooth to negate any lacerations and to maximize comfort for the patient.

Production Characteristics

A. Quantity:

Units are designed specifically for each individual patient, so quantity depends on the number of patients with Class II Malocclusions. One device is used per patient.

B. Target Product Cost:

The cost of production will be based on the specific material used for 3D printing the incline plane, which is around ~$100 [6], as well as the size of it as each incline plane will vary from each patient.

3. Miscellaneous

C. Standards and Specifications:

The incline plane would go under the category of Orthodontic appliance and accessories, in which the device is affixed on a tooth so that pressure can be exerted on teeth for orthodontic treatment, which is a Class 1 classification. This means the incline plane is low to moderate risk of injury [7].

D. Customer:

The client would like an incline plane that would be able to fit on any size canine with Class 2 Malocclusion. This would be achieved by having a general SolidWorks model that can be altered patient by patient through the use of calipers to take measurements of canines to create the patient-specific incline plane.

E. Patient-related concerns:

Before the device is placed in the mouth of the patient, the owner will be explained how the incline plane is supposed to work to fix the Class 2 Malocclusion. Each individual patient will be sedated so that measurements of the teeth and jaw structure can be taken. An incline plane will be created specifically for that patient, resulting in no need for sterilization between uses. Furthermore, the owner of the patient will be explained how the incline plane should be monitored when the patient eats or plays. If the device breaks, the owner of the patient needs to return to get another incline plane implanted.

F. Competition:

There exists a patent for an orthodontic fixture intended for use with animals to correct lingually displaced canine teeth [8]. This device uses non-toxic metal which can be costly and difficult to manufacture. This product can be improved by adding support, such as a thicker bridge and thicker crowns, to prevent this design from breaking upon usage.

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b. Solidworks Design Workflow

Step 1: Measurements

Tooth dimensions

- Four measurements are taken at two points on the maxillary canines to create the ellipse cone for the incline plane ring supports.
- The upper ellipse measurements need to be taken at the widest point of the tooth, the lower ellipse dimensions will be taken 8mm from that point.

➔ **Upper Ellipse Measurements**

1. Upper Ellipse (XY Face)- *Major Axis*

   _________ *mm*

2. Upper Ellipse (YZ Face)- *Minor Axis*

   _________ *mm*

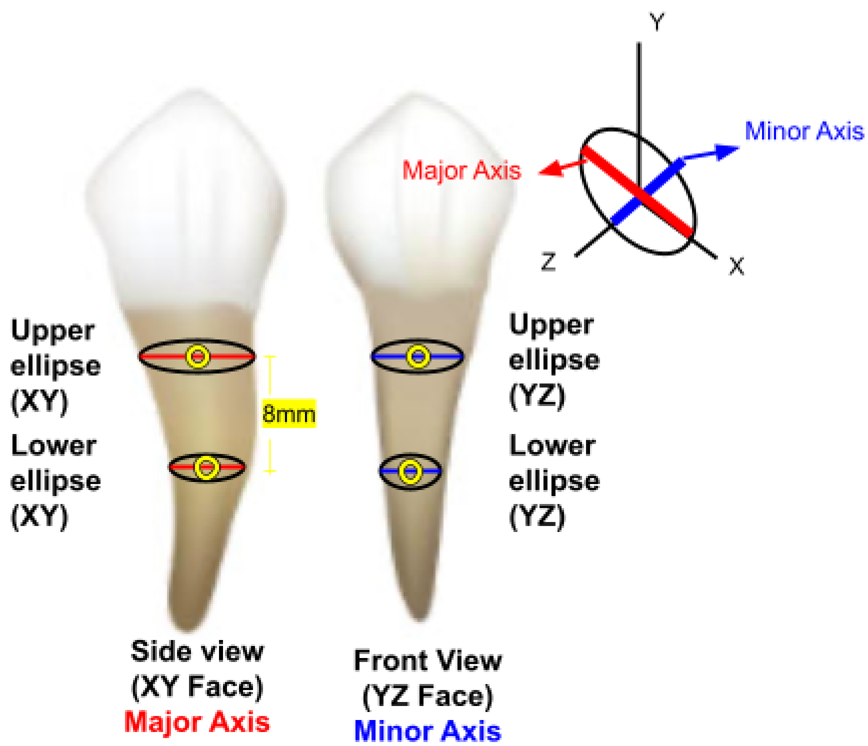
➔ **Lower Ellipse Measurements**

1. Lower Ellipse (XY Face)- *Major Axis*

   _________ *mm*

2. Lower Ellipse (YZ Face)- *Minor Axis*

   _________ *mm*

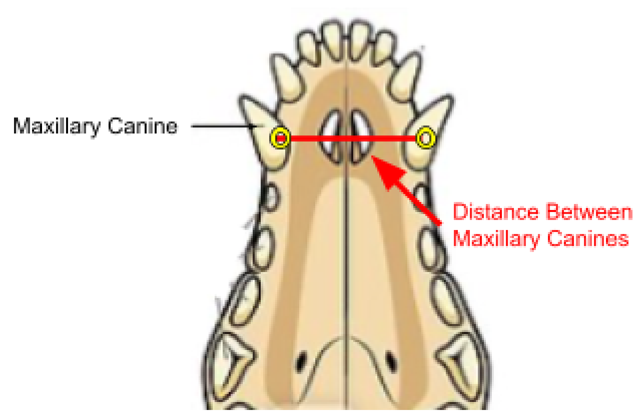


Support Bridge Measurements

- One measurement is needed to determine the length of the support bridge
- This measurement is taken at the point in between where the upper and lower ellipse dimensions were taken from.

➔ **Distance between the maxillary canine teeth**

   _________ *mm*



Angle Measurement

- The angle of the incline is determined by the orthodontist

Measurement Conversion

- Due to the solidworks constraints, these measurements need to be converted to take into account the thickness and duplication of the part.

➔ [Incline Plane Measurement Conversion]

  ◆ Input the measurements into this google document

  ◆ You will use these converted measurements to input into the solidworks file

★ **Converted Measurements from Google Sheets**

➔ **Upper and Lower Ellipse Measurements**

➔ **Support Bridge Measurement**

➔ **Desired angle**

_________ °

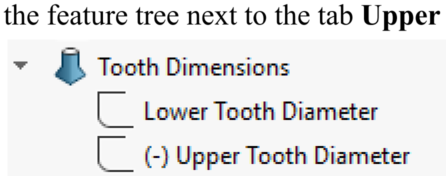
➔ **Dimension Output**

_________ *mm*

Step 2: Creation of Patient-Specific Part in SolidWorks

Insert Dimensions of Canines

1. Open up the **Final Design** document
   a. Double click on the **Tooth Dimension** tab. This is found by clicking the down arrow in the feature tree next to the tab **Upper Tooth Major axis**

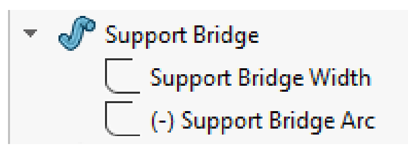


   b. Double click on the Major dimension and insert the number in millimeters of the converted upper ellipse major axis length

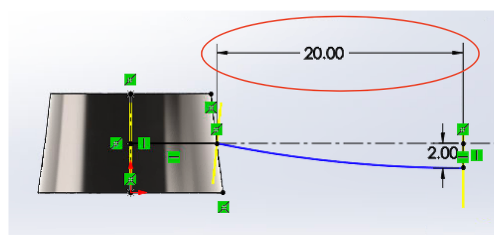
c. Double click on the Minor dimension and insert the number in millimeters of the converted upper ellipse minor axis length
d. Click exit sketch in top left corner of the screen
e. Double click on the **Lower Tooth Diameter** tab in the feature tree under the tab **Tooth dimension**
f. Double click on the Major dimension and insert the number in millimeters of the converted lower ellipse major axis length
g. Double click on the Minor dimension and insert the number in millimeters of the converted lower ellipse minor axis length
h. Click exit sketch in top left corner of the screen

2. At this point, the dimensions of the ring should be all set.

Edit the length of the support bridge.

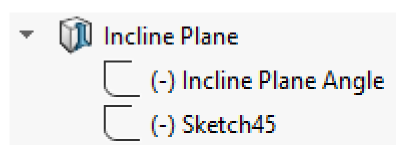


3. Click on the **Support Bridge** tab in the feature tree and double click on **Support Bridge Arc**. Again, click the down arrow next to the tab.

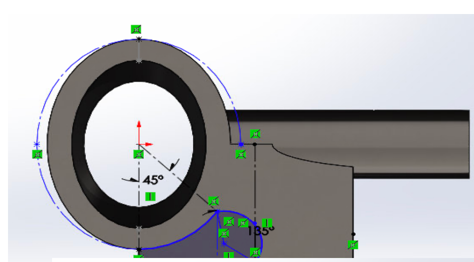


4. Double click on the dimension of the arc circled in red, and insert the converted value in millimeters.

Change the angle of the inclined plane.

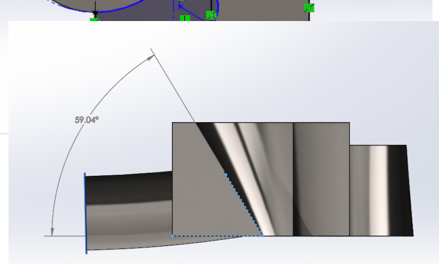


5. In the design tree, click on the **Incline Plane** tab and double click on the **Incline Plane Angle** tab

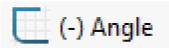


6. In this sketch, double click on the dimension circled in red below and insert the Desired Angle Output value (mm).

7. To verify the desired angle was obtained, exit this sketch, and click on the **Angle** tab in the design

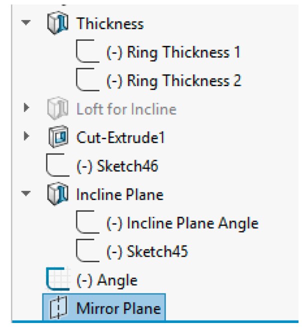


tree. In this sketch, the dimension shown is the angle of tilt for the incline plane. You may need to rotate the part.



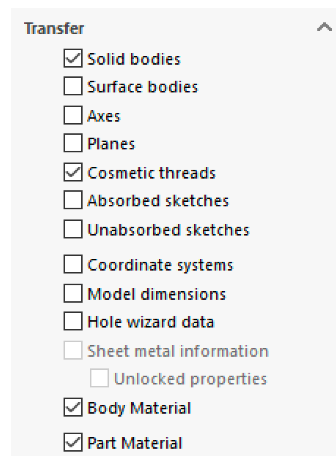
8. At this point, the part should be fully dimensioned and patient-specific. All that's left to do now is mirror the part, and create an assembly to make the piece.

Step 3: Creation of Mirrored Part

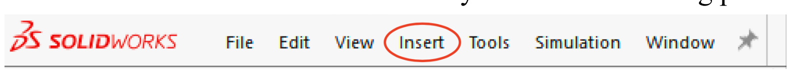


1. Now we want to mirror the part for the assembly.

2. Click on **Mirror Plane** at the very bottom of the feature tree

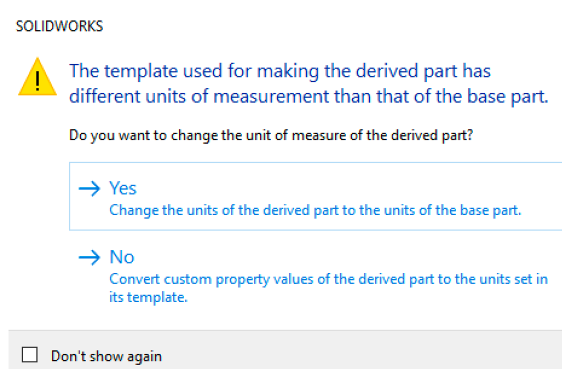


3. Next select **Insert → Mirror Part** found at the top of the screen, and make sure the boxes are checked as they are in the following picture



4. Click the green check mark above the box

5. If the following message appears, click **yes**

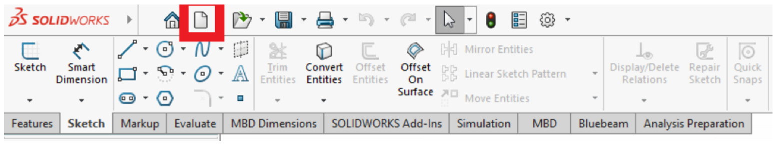


6. The mirrored part will appear, and you should now **Save As** a new part

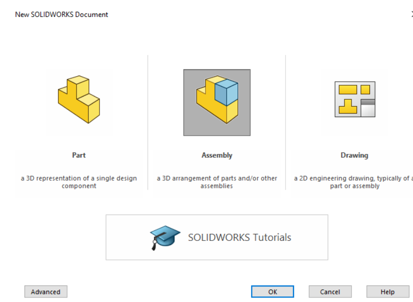
Step 4: Creation of Assembly

1. Open a new assembly in Solidworks

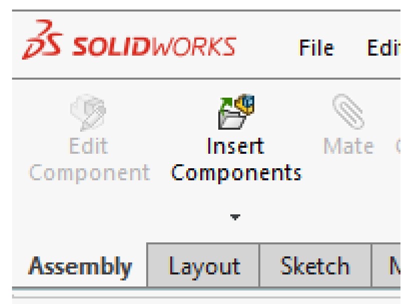
   a. Click the New button at the top of the screen



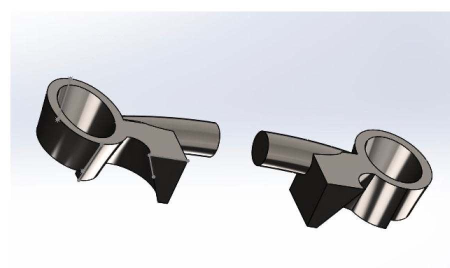
   b. Click Assembly the click OK



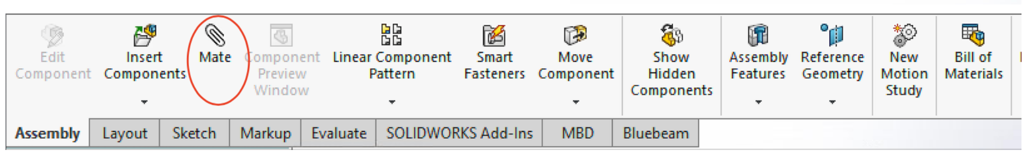
2. In the top left corner of the screen, click into the assembly tab and click insert components. Do this for both files you want to insert.



3. Insert both the initial part and the mirrored part in a similar configuration as shown below.

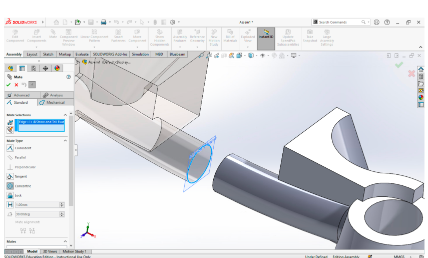


4. In the toolbar, select **Mate**

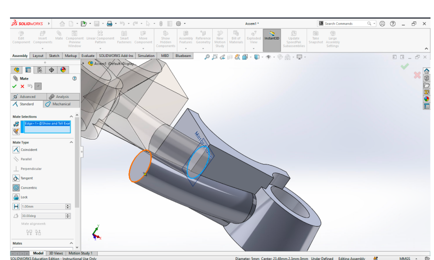


5. In the **Mate** tool, click on the edges of the two faces at the end of each support bar as shown below

Click on mate in



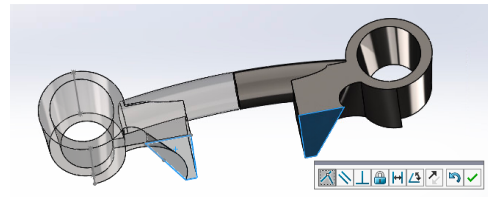
the



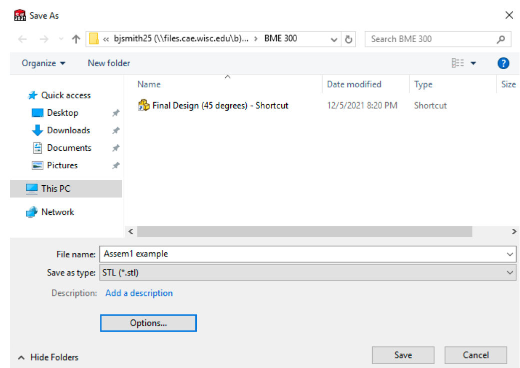
concentric sidebar once

these two edges are selected.

6. Click on **Mate** one more time, and this time, click on the two faces shown in the image below.

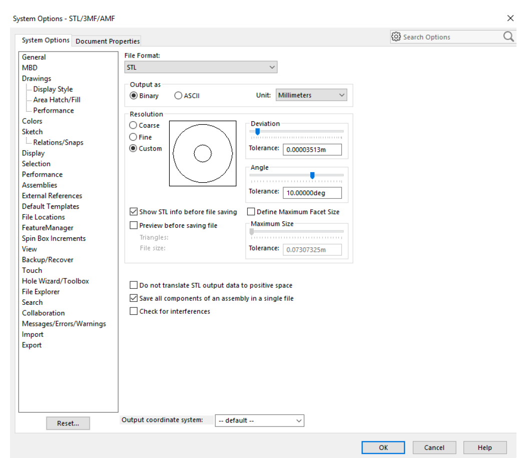


7. At this point, the piece is fully configured and ready to be printed.



8. Save the file as a .stl file
   a. Click options

   b. Check **Save all components of an assembly in a single file**



c. Expense Spreadsheet

Item	Description	Manufacturer	Part Number	Date	QTY	Cost Each	Total	Link
Category 1								
Makerspace Fee	Fee to utilize Makerspace	Makerspace		2/21/2022	1	$50	$50	
3D- Print	Printing of the Lower Jaw of 3D Model	Makerspace		2/21/2022	1	$6.96	$6.96	
3D- Print	Printing of the Upper Jaw of 3D Model	Makerspace		2/21/2022	1	$25.04	$25.04	
3D- Print	Printing of a prototype incline plane in PLA	Makerspace		3/4/2022	1	$0.24	$0.24	
3D- Print	Printing in incline plane in Ti-64	Materialise		3/12/2022			$121.77	
						TOTAL:	**$204.01**	

d. Previous Solidworks Testing and Results

Testing

Once the final design was created and assembled in Solidworks, Solidworks SimulationXpress Analysis Wizard was used to test if the design would be able to withstand a max force of 1400 N. The SimulationXpress feature allows the user to apply forces to particular portions of a design and determine where deformation and von Mises stresses would occur. In the SimulationXpress, the user is also allowed to choose a material to simulate how the material would perform under the forces applied based on its mechanical properties. Titanium alloy Ti64 was an option to select in the SimulationXpress and was used as the material for the final design for testing. During the process of testing, the support bridge was chosen to be fixed together as when the final design is 3D printed, the part is printed as one piece rather than two separate pieces (Figure 1). The forces were applied directly onto the incline plane as that is where the mandibular canines of a patient would come in contact with the device (Figure 1). Expected outcomes from the Solidworks SimulationXpress testing were that the design would experience little to no deformation as well low values for von Mises stresses.

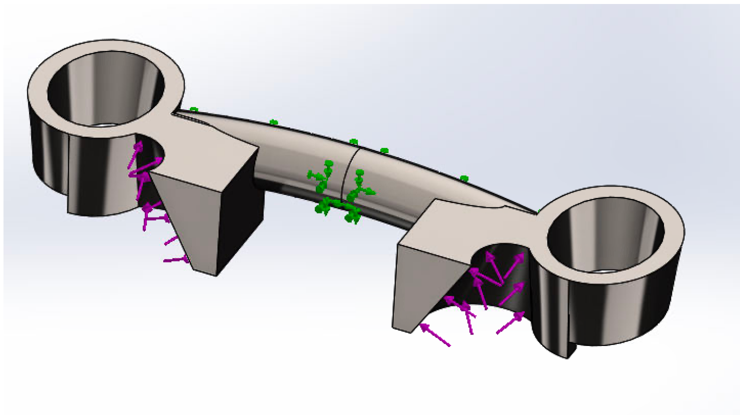


Figure 1: *Final design in Solidworks SimulationXpress with the support bridge fixed together and 1400 N force applied to the incline plane. The green arrows show where the device is fixed, and the pink arrows show where the force is applied.*

Results

Results shown from the Solidworks SimulationXpress test were as expected. Little to no deformation of the design occurred as a result of the 1400 N force applied. Maximum deformation occurred on the smaller edges of the incline plane, seen in the red regions, with the largest deformation being 7.12 µm. Deformation decreased significantly closer to the rings and support bridge as there is more material located in that portion of the design, with values of 0.71 µm in the blue regions (Figure 2). With little deformation being recorded, the assumption can be made that the design would not be distorted or change shape during clinical treatment. Von Mises stress values reported from the SimulationXpress test were relatively low. Maximum von Mises stress values were located on the corners of the incline plane attached to the support bridge, seen in the red regions, with the largest stress value being 88.6 MPa (Figure 3). Where the 1400 N force was applied on the incline plane, stress values ranged from 0.007 MPa, blue regions, to 44.3 MPa, green regions (Figure 4). With the yield strength of Ti64 being 830 MPa, the assumption can also be made that during clinical treatment, the design would not fracture at any location since under the 1400 N of force applied, the lowest factor of safety reported from the SimulationXpress test was 9.33. This will be tested and results will be obtained after compression testing is completed.

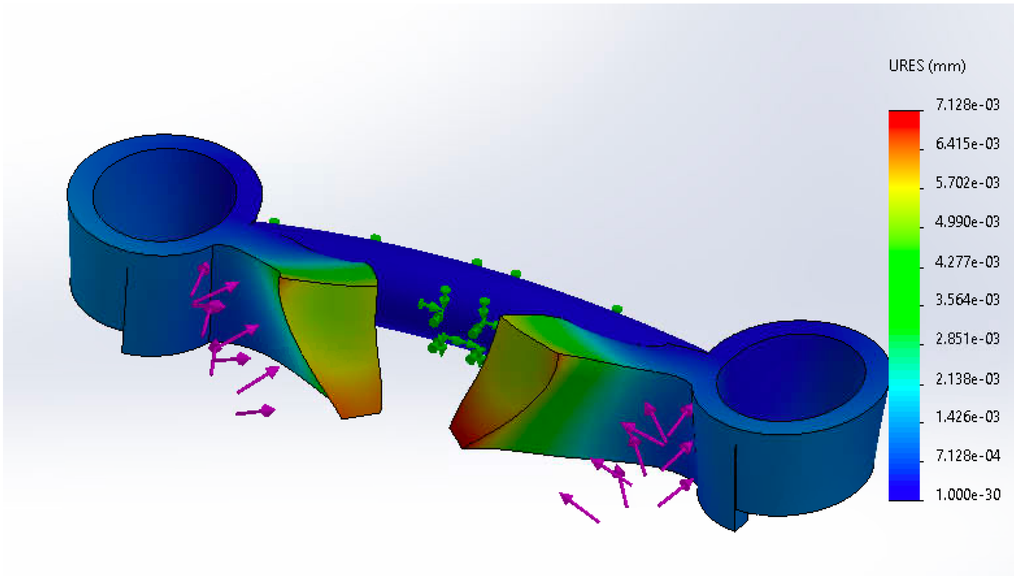


Figure 2: *Deformation (µm) of the device under 1400 N force applied on the incline plane. Max deformation occurring in the red regions at 7.12 µm. Towards the middle of the incline plane, deformation decreases to 3.56 µm, in the green regions. Near the ring and support bridge, lower deformation was recorded at 0.71 µm, in the blue regions.*

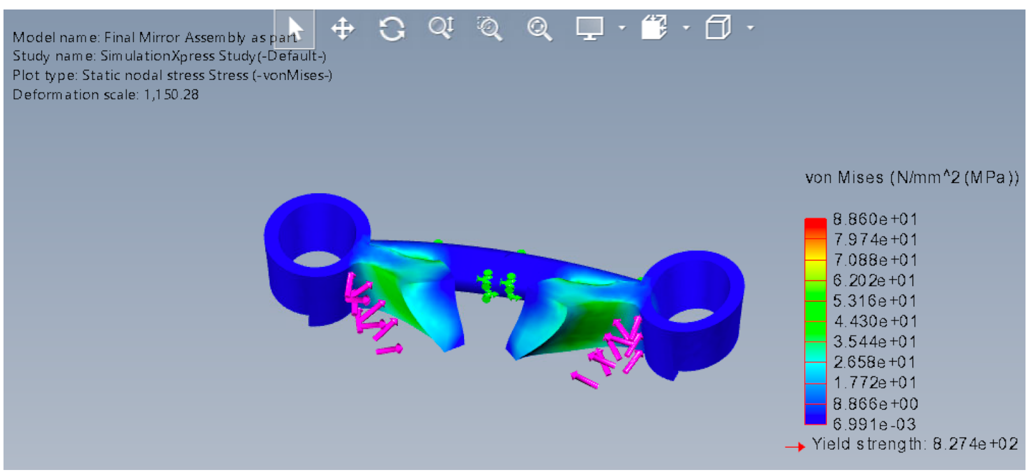


Figure 3: *Von Mises stress (MPa) of the device under 1400 N force applied on the incline plane. The incline plane underwent 44.3 MPa of stress, in the green regions, where the force was applied.*

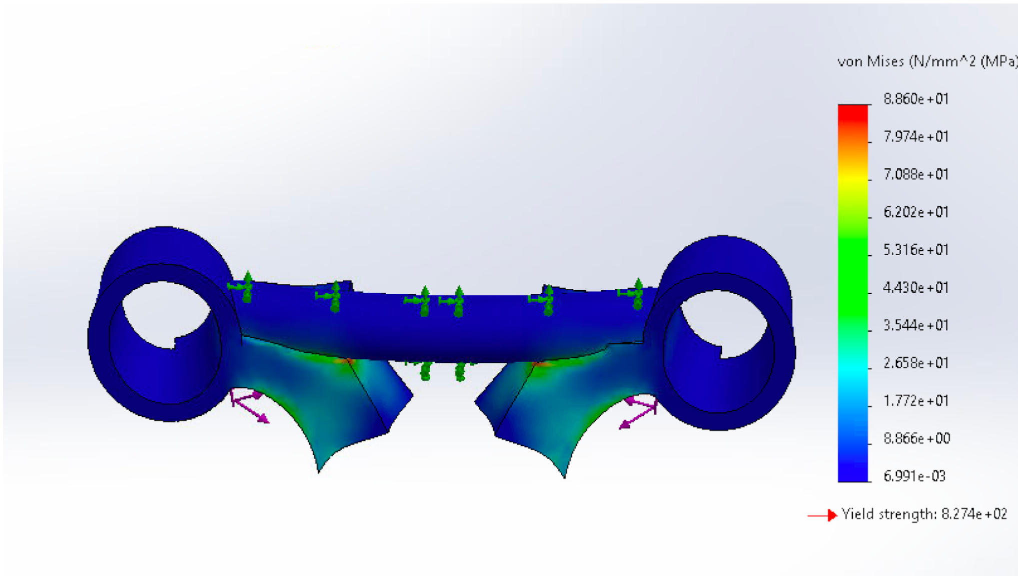


Figure 4: *Von Mises stress (MPa) of the device under 1400 N force applied on the incline plane. The corners of the incline plane connected to the support bridge underwent a max of 88.6 MPa of stress, in the red regions.*