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VETMED: 3D PRINTED, PATIENT SPECIFIC INCLINE PLANE FOR MANAGEMENT OF CLASS 2 MALOCCLUSION – IMPROVEMENT IN DESIGN AND WORKFLOW

FINAL REPORT

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Abstract

Class II malocclusions in dogs are often treated with orthodontic brace devices, called incline planes. Incline planes adjust the angle of the maloccluded teeth by applying consistent pressure over time. A common way of producing incline planes is applying composite resin directly to the dog's maxillae and drilling the guiding slope into the material. Another design is made of cast metal and has a telescoping bridge to allow for growth of the patient's jaw. A 3D printable incline plane can be constructed using scans of the patient's jaw. Despite the safety and efficiency benefits of 3D printing for orthodontics, several problems exist with the current design and workflow of the 3D printed incline plane. The process requires many prototypes and the help of a software engineer to produce a device that will be used on a patient. The client has also requested a more adjustable, flexible design that can fit patients of different sizes and allow for growth over time. To improve the design of the incline plane, the team first devised three potential alternative designs and evaluated them. The chosen design consists of two 3D printed pieces on each side of the mouth, allowing for growth of the maxillae, and decreasing risk of palatitis by reducing contact with soft tissue. The team also evaluated different softwares that can be used to produce the 3D printable model of the incline plane. The use of Blender for Dental and MeshMixer allowed the team to manipulate and visualize the model as well as convert different file types.

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I. Introduction

Problem Statement

To correct Class II Malocclusions in canine patients, client Dr. Graham Thatcher produced a 3D printed patient-specific incline plane brace to be used on patients. The current process of creating a 3D printed incline plane starts with taking a CT scan of the patient's jaw. The data from the DICOM file is then used to produce the printable incline plane with the aid of a software engineer. The prototype incline plane would be placed and tested on a model of the patient's jaw then adjusted for the next prototype with the software engineer's help. This process is time-consuming and complex. In addition, the design of the current 3D printed incline plane does not allow for flexibility between different patients, being designed for the individual dog only, and is not able to adjust to growth of the dog's jaw.

Dr Graham Thatcher has asked the team to design a software workflow that will save time and eliminate complications in the current workflow, as well as improve on the current design so that it may be more adjustable and versatile for a wider range of patients.

Current Methods & Devices

Several other methods for creating incline planes exist. One method is to apply self-curing bis acryl composite material directly to the teeth in the dog's mouth, then shaped with filing tools to form the hole by which the tooth will be guided by [4]. This method may lead to some complications; if the material is applied to and contacts the mucosa, inflammation can occur [12]. If the orthodontic appliances are not handled properly, the material used for the incline plane can generate too much heat and burn the dog's mouth [13].

Another design is the Mann incline plane, which is a fixed incline plane made of cast metal [10]. The Mann design is telescoping so that the size of the incline plane changes with growth of the patient's maxillae. Another advantage to cast metal incline planes is that they contact only with hard tissue, thus avoiding inflammation of soft tissue [11]. However, construction of this kind of incline plane requires models of the patient's teeth to be made. This increases costs and complicates the process. Due to the metal material, it is not easy to make adjustments as well. The fixed metal device is difficult to remove from the mouth.

Yet another method involves the use of telescoping metal rods combined with composite resin [14]. This device is built intraorally during one anesthesia procedure. The design allows for growth of the maxillae due to the telescoping aspect, but can also result in gingivitis and other complications associated with direct composite resin incline planes.

Motivation

Malocclusions are heritable traits that can cause issues for dogs and cats if not treated. The treatment process for malocclusions with incline planes involves visits for adjustments in addition to applying and removing the orthodontic treatment device, and these procedures require anesthesia. The creation process of the 3D printed incline planes is currently inefficient, although the adoption of a smooth 3D printing workflow in veterinary orthodontics may improve the efficiency of procedures and open other possibilities for 3D printed orthodontic devices. The use of 3D printing also alleviates safety complications associated with alternative treatment processes, such as risk of burns. Treatment using inclined planes involves many possible complications, as adjustments may be needed throughout the process, and gingivitis is a very common side effect to treatment. This project's goals are to not only improve treatment for the patients but streamline the process for veterinarians and veterinary orthodontists alike.

II. Background

A. <u>Physiology and Biology</u>

Class II Malocclusion

Just like humans, many canines have orthodontic problems that affect their ability to live and especially eat. Types of these orthodontic problems range similarly to those of humans. There is one specific orthodontic issue called Class II Malocclusion that is directly specific to the misalignment of three teeth within a canine's mouth. These three teeth involve the maxillary canine, the maxillary 3rd incisor, and the mandibular canine. In normal occlusion of the upper and lower jaws, the mandibular (lower) canine sits within a diastema between the upper canine and the upper third incisor, as shown in *Figure 1.* However, in Class II Malocclusion, the occlusion of the dog's jaws is distorted with an emphasis on the location of the lower canine. As shown in *Figure 2*, the lower canine will sit more distal (towards the middle of the mouth) rather than the normal position up against the diastema [1].

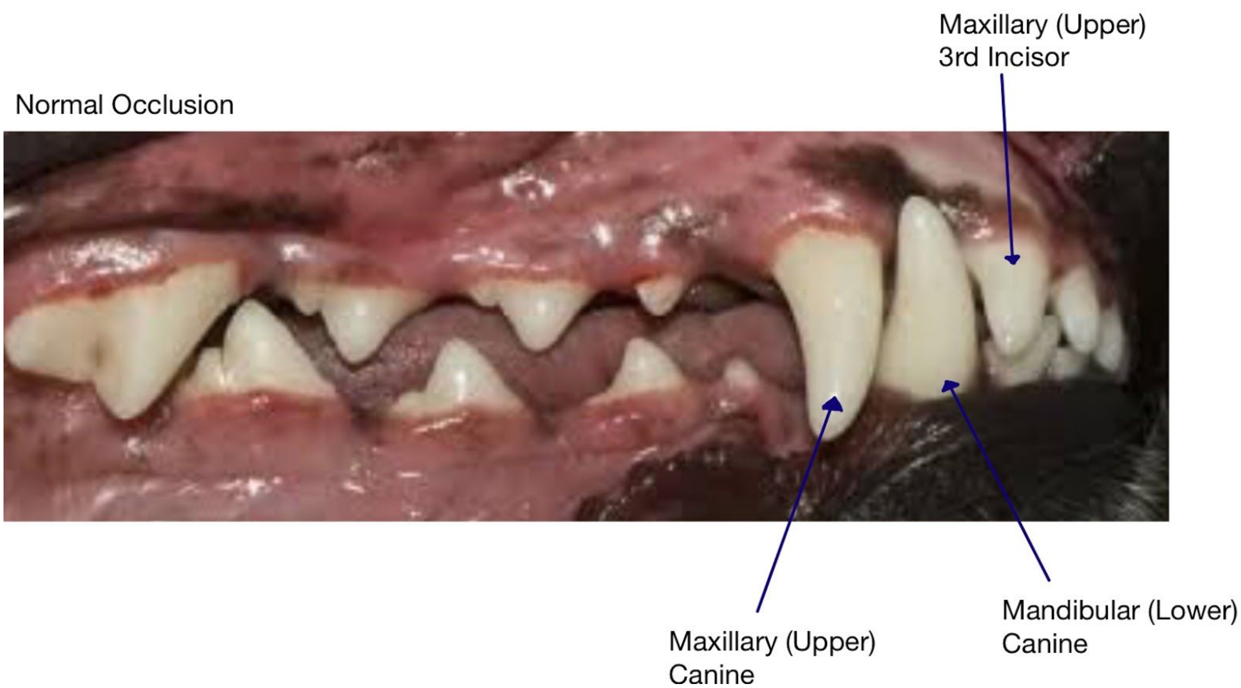


Figure 1: Normal Occlusion in a Canine. This figure shows a side view of a canine mouth with normal occlusion between the maxillary and mandibular jaws. The mandibular canine sits within the diastema (gap) between the maxillary canine and maxillary third incisor.

Class II Malocclusion is generally defined as "mandibular distoclusion" which is commonly referred to as an overbite [1]. The lower jaw sits entirely too far distal in the mouth causing the mandibular canines to not sit correctly in relation to the upper teeth. The reason this type of alignment is problematic for canines is due to the damage it can cause. A misaligned canine can cause irritation and damage to surrounding tissue and teeth. In addition, the misalignment can cause conditions such as dental attrition, periodontal diseases, and oronasal fistula [4]. As well, dogs use their canines to both puncture, tear, and hold items so they are a crucial part of their lives and daily tasks [2]. Thus, there is a high importance to ensuring they are in the correct position and alignment.

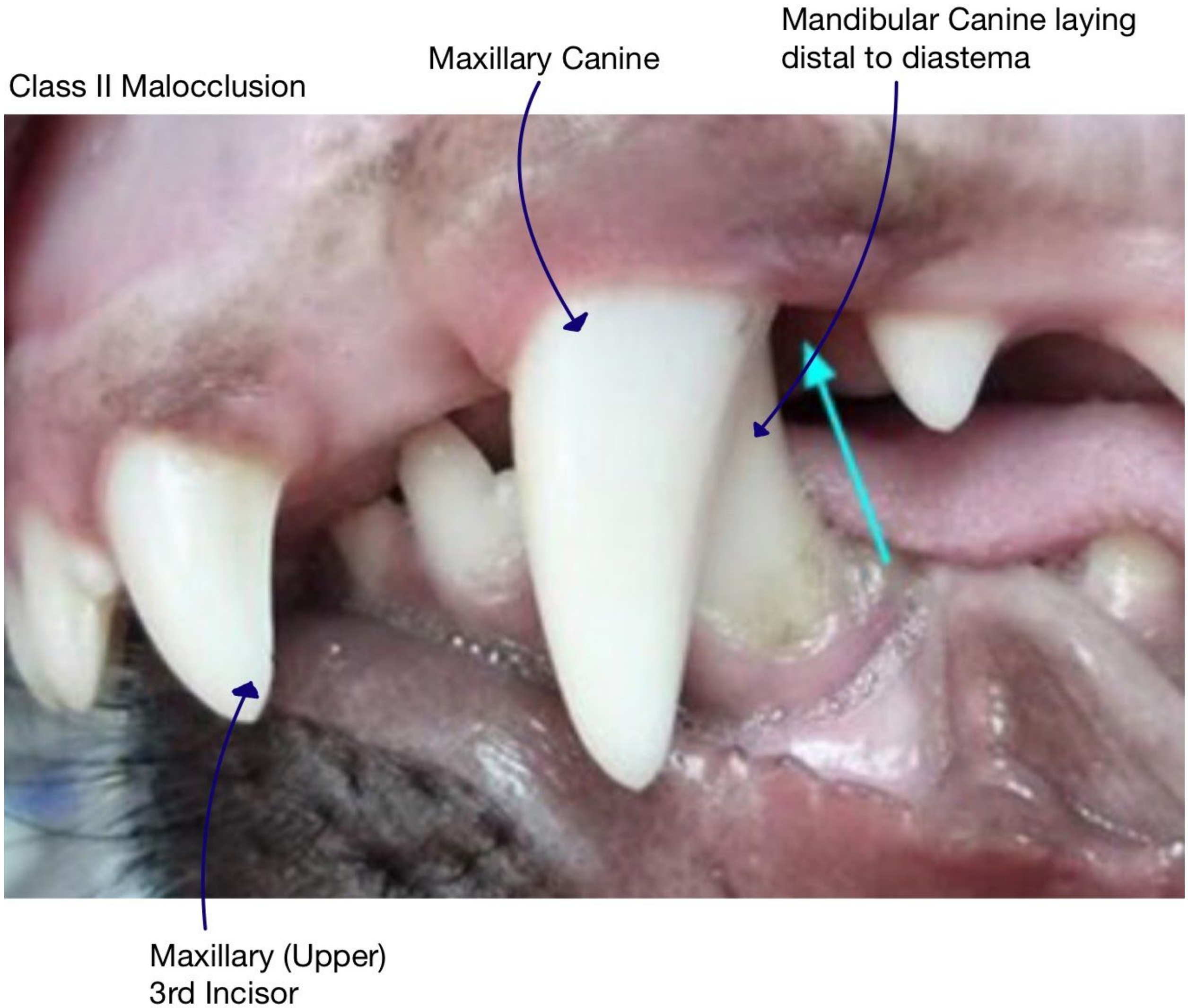


Figure 2: Class II Malocclusion. A side view of a canine mouth with class II malocclusion. The mandibular canine sits distal to its normal position within the diastema.

B. Existing Treatments/Device

Extraction:

One treatment type is to simply remove the misaligned canine. This may get rid of the misalignment, but, removing the teeth will bring up more lifestyle problems for the dog. This is due to the fact that dogs need their canines to eat food and hold things in their mouth. Thus, this is not a preferred method.

Shortening:

Another treatment type is to shorten the tooth so the canine does not cause irritation to the palette. While this will cause some temporary relief, again, the canine is distorted and not being able to function normally for the dog.

Incline Plane:

The last type of treatment was designed by client Dr. Graham Thatcher and involves dental orthodistry treatment for the dog. The incline plane is a 3D printed device made of FDA approved dental material. The device acts as a retainer for the dog and is attached to the mandibular jaw through hole attachments. As shown in Figure 3, the incline plane attaches to the mandibular jaw through holes that are placed on the mandibular canines and molars.

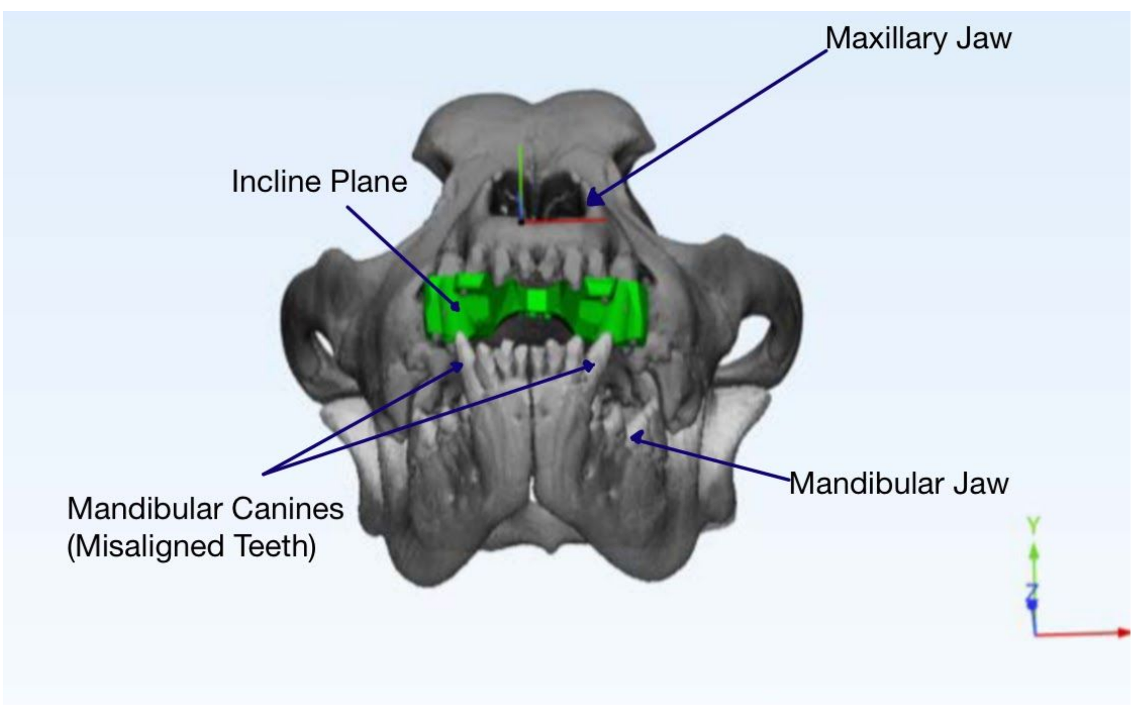
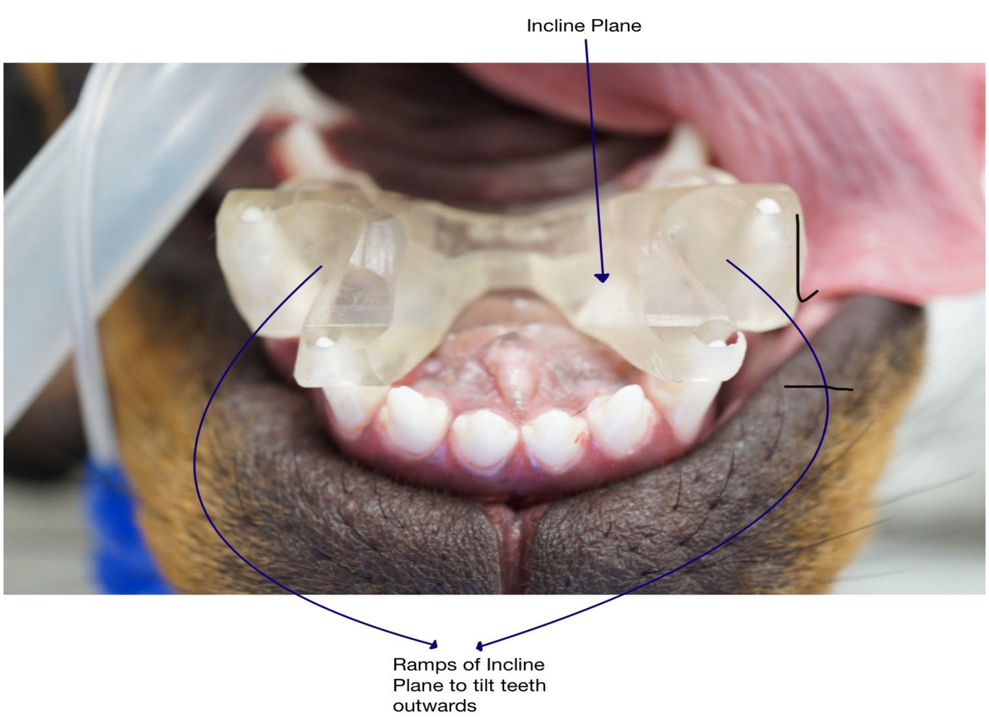
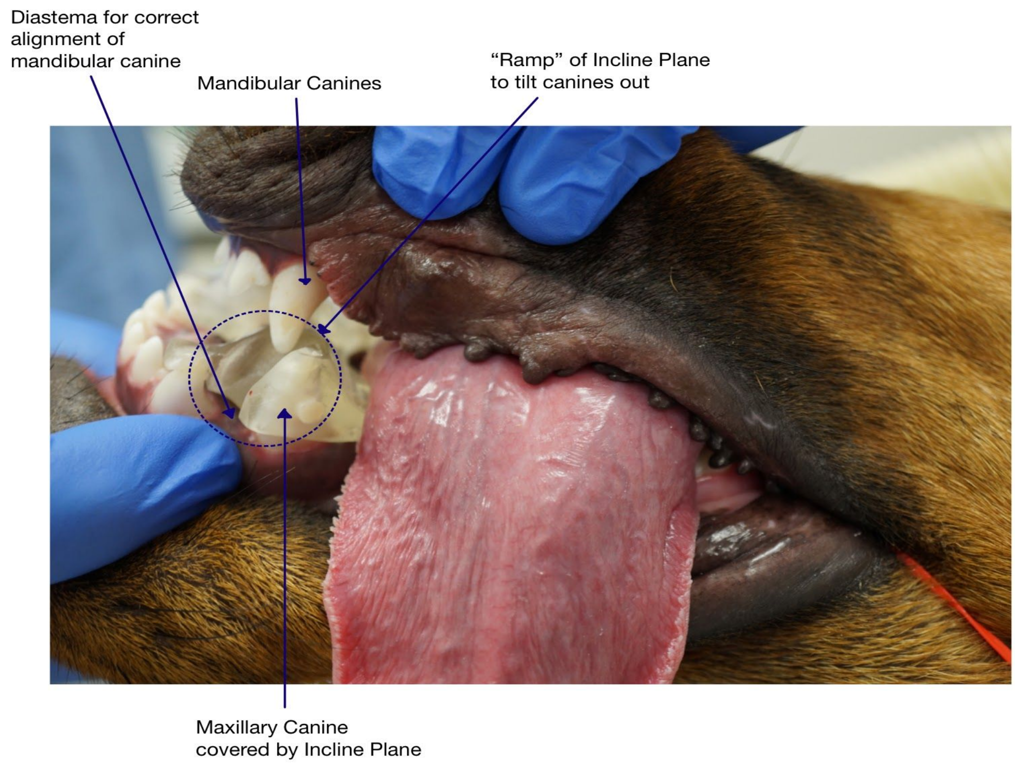


Figure 3 Incline Plane in stl file: *This figure shows a CT scan of the dog's skull with the green portion indicating the incline plane device used to tilt the mandibular canines out.*

The plane is essentially a combination of two ramps that are aligned to direct the mandibular canines into the correct position. Canine teeth, in dogs, are easily tilted without the need of major pressure so the use of the ramps within the inclined plane work effectively. As shown in Figures 4 and 5, the inclined plane is designed so that the mandibular canines, when the dog closes their mouth, tilt outwards towards the correct position in the diastema.





Figures 4 (Top) and 5 (Bottom) Client 1**:** *Inclined plane attached to Dr. Thatcher's first client and how the ramps work to push the teeth outward.*

Over time, the incline plane will shift the permanent position of the mandibular canines so they are set into their correct alignment. In addition, when the canine is moved into its correct position, no further retainer is needed due to the maxillary incisor and canine naturally holding the tooth into place. Although the incline plane designed by Dr. Thatcher was successful in the first client, it poses many inefficiencies that are associated with negative consequences of the plane as well as the development of the plane itself.

C. Existing Development Process of Incline Plane.

While Dr. Thatcher has succeeded in creating an incline plane, his process for doing so is very inefficient and complicated. His process involves first taking a CT scan of a dog's mouth. He then 3D prints the skull of the mouth and uses a dental material to arbitrarily mold a potential design for the plane onto the skull model. Once he is satisfied with the design, he sends the CT scan (DICOM files) and the model to a software engineer who takes all the information and builds an stl file of the incline plane in an engineering software. Dr. Thatcher and the engineer then work back and forth to perfect the design through adjustments, printing prototype designs, and trials. Ultimately, this process isn't efficient nor timely for widespread practice. Resultantly, the second half of the team's project involves the development of an interface and software program that expedites and simplifies the process of designing the incline plane.

D. <u>Client Information</u>

Dr. Graham Thatcher is a veterinary dental surgeon working at the University of Wisconsin-Madison Veterinary Hospital and the School of Veterinary Medicine. He is responsible for the management of dentoalveolar and orofacial diseases and trauma as well as is an educator to current veterinary students [5]. Dr. Thatcher is currently working on this project and has solicited this team's help to refine and better his current designs.

E. <u>Design Specifications</u>

Incline Plane:

The new incline plane has several specifications that must be met. Firstly, the product must be able to withstand constant pressure of up to 400 lbs over the course of 3-8 weeks of treatment due to the dog's natural eating and lifestyle habits. In addition, the incline plane must be able to adjust the angle of the mandibular canines by about 30 degrees of tilt. This angle will vary by each dog's unique anatomy.

Software/Interface:

When designing the software program, many specifications must be considered when choosing the right pathway. For one, the process must be simple enough where a veterinary orthodontist can easily utilize the software without the help from a software engineer. The software must also be compatible with common computers found in veterinary hospitals and offices. Lastly, the main specification is that the software must be able to manipulate multiple cross sections of a DICOM file so the veterinary orthodontist can move the mandibular canines to the right position within the program.

Preliminary Designs

I. Incline Plane:

Design 1: Adjustable Bridge

The team's first design consists of manipulating the portion of the original prototype that connects the ramps on the incline plane of both sides of the mouth. In the original prototype, this "bridge" was made of the same dental material as the ramps and created one continuous device. That continuity resulted in palatitis in the dog's mouth due to the dental material causing irritation. It also resulted in a lack of adaptability and adjustability for the incline plane to be used for other dogs and for intra-treatment changes. In this design, the team seeks to solve both these solutions by replacing the bridge with a metal adjustable bridge. Inspiration was taken from a human orthodontic expander [6]. The metal bridge would consist of a centric mechanical element that can be used to adjust the width of the incline plane. Just as an expander is adjusted to widen, and to thus widen the maxillary jaw, the same would apply here but with a purpose to help the incline plane be adaptable to other dogs. The rest of the design would be similar to that of the original prototype with the ramps serving the same function and being made of the same material.

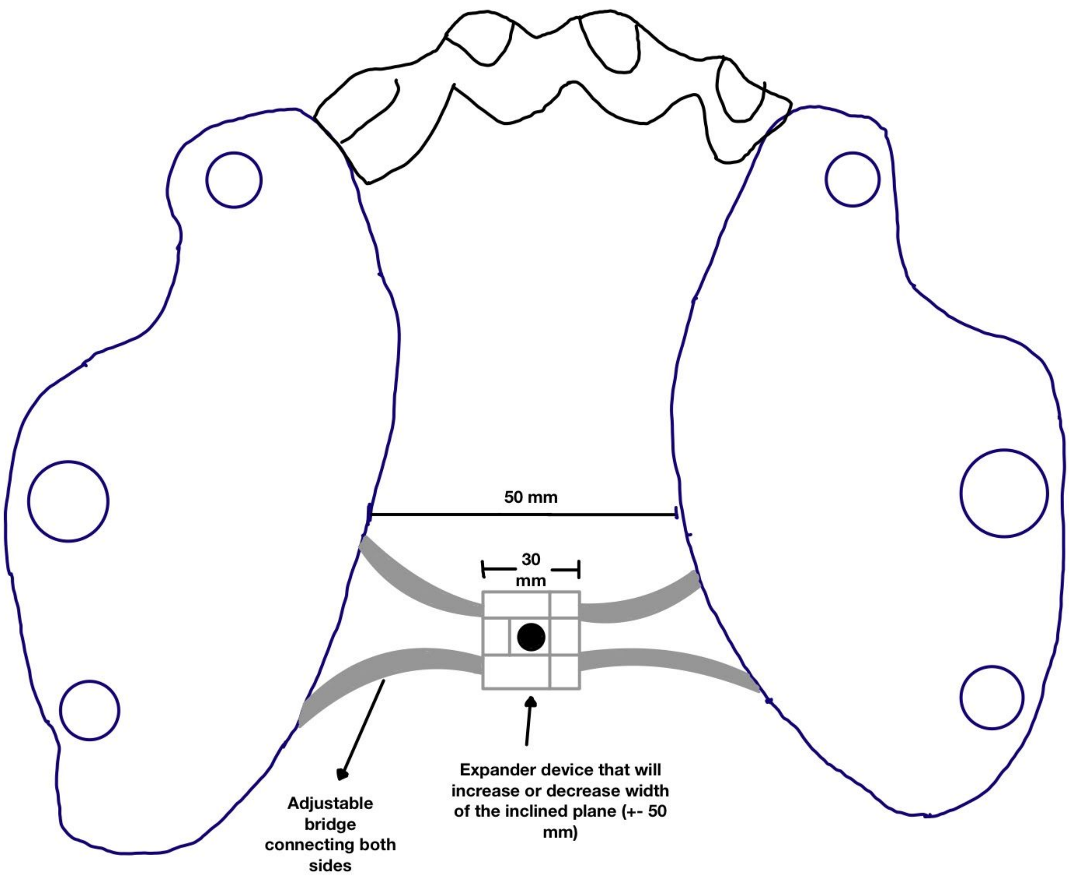


Figure 6 Adjustable Bridge. *The adjustable bridge design consists of an expander device that can shorten or lengthen the width of the entire incline plane. This helps increase adaptability and adjustability.*

Design 2: Separate

The second design also is aimed to address the issue of palatitis and adaptability by separating the incline plane into two pieces. This eliminates the bridge component, which was shown in the first trial of the device to cause irritation on the palate due to constant contact between the device and the soft tissue. The separate design consists of two pieces for the correction of each mandibular canine individually. The design aims to separate the malocclusion of each canine into its own unique situation to create a specially designed ramp for each canine on both sides of the mouth. The diameters of the respective holes for the mandibular teeth are shown in *Figure 7.* Again, while separate, the ramps will be of the same dental material and have the same task to tilt the lower canines outwards.

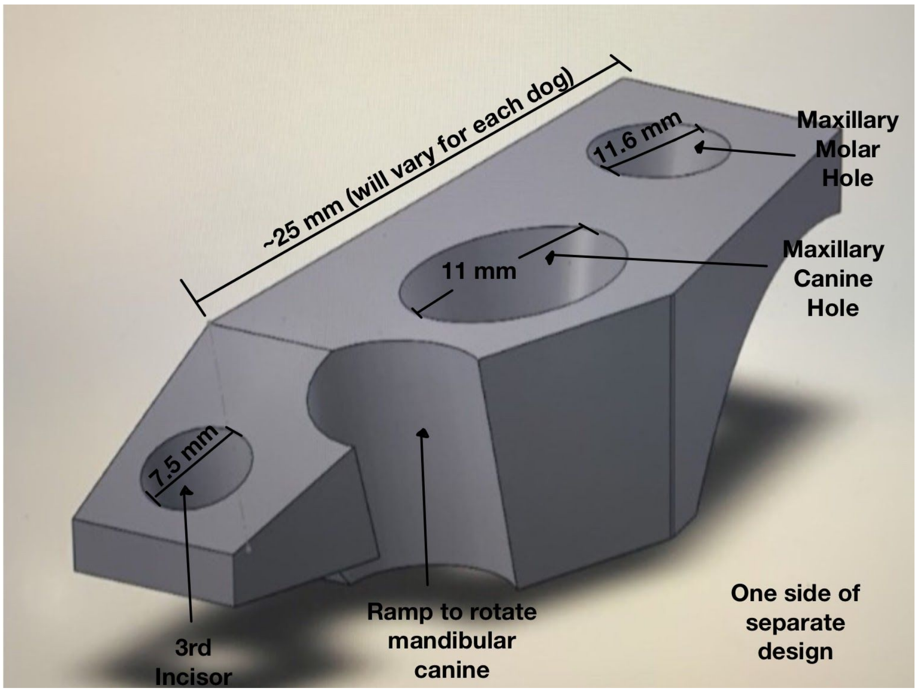


Figure 7 Separate Design: *One piece of the separate design. The holes are the locations for the respective maxillary teeth and each of their approximate diameters are shown. The ramp is used as normal to tilt the mandibular canines outwards.*

Design 3: Rubber incline Plane

The third and final incline plane design is a model that is very similar in size and shape to Dr. Thatcher's incline plane, but instead of being made of plastic, it will be made of a rubber material. This material will allow the device to be stretched and manipulated to various different orientations, which in turn will be able to fit a variety of dog mouths'. The main goal of this design is to increase the adaptability of the device, and overall declutter the current process of generating and creating the incline plane. This design will also provide the dog with a more comfortable fit due to the softer rubber material.

II. Software

Design 1: 3D Slicer

The first design interface to help with the process of designing the incline plane is the program called 3D slicer. This program has functions that work best with processing and viewing DICOM files from CT Scans. It is based on the purpose to easily view medical images and be able to draw conclusions and conduct research from those images. It allows the user to isolate different levels of tissue from a CT scan and to also see individual frames of it as seen in *Figure 8*. However, it lacks the feasibility and ease of manipulating cross-sections of images and overall is a very complicated software.

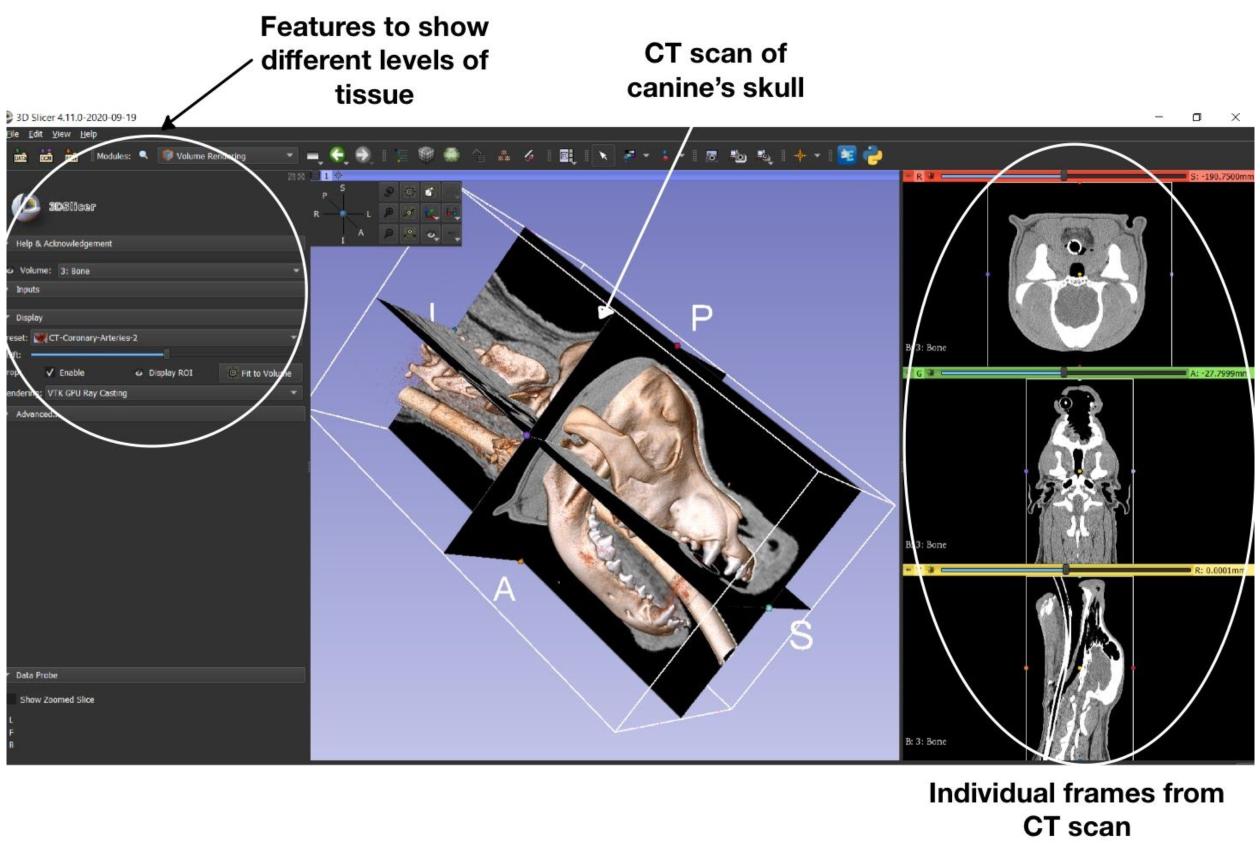


Figure 9 3D Slicer: *The 3D Slicer interface shows it's ability to better view CT scans and to see* *cross-sections of tissue levels.*

Design 2: Osiris X

Osiris X was the next software the team sought to utilize to help with the production process. This is a very mathematical based software that works with vectors and directions. It is helpful in manipulating cross sections and is specific to being able to view DICOM files well. The software was designed for medical imaging so it is very useful in simply analyzing scans.

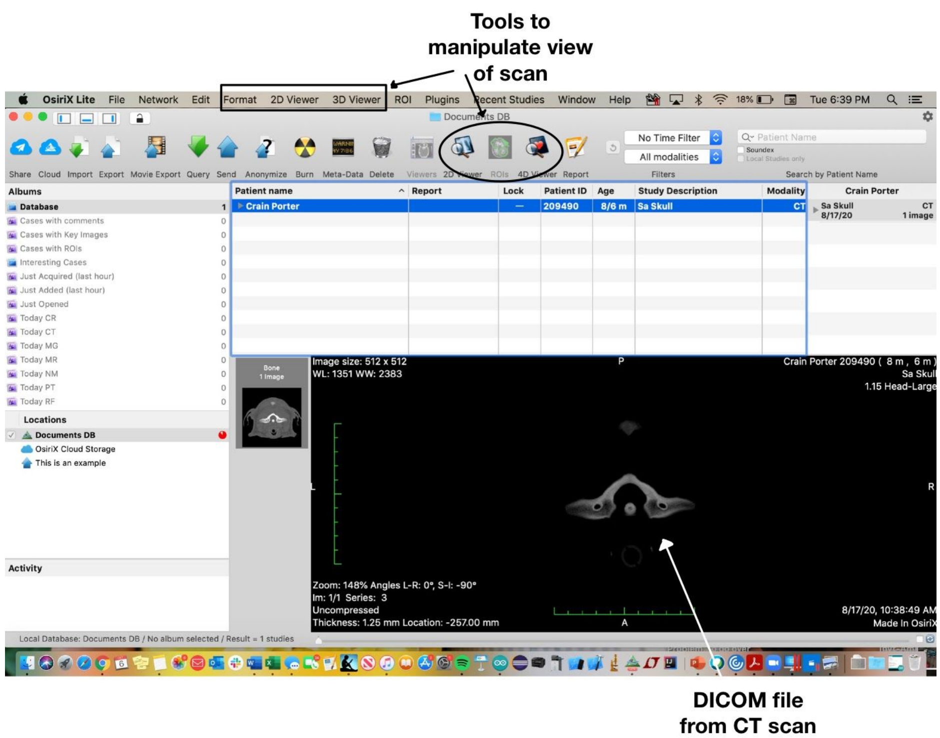


Figure 10 OsirisX. *There are many tools within this program to better view and understand the CT scan*

Design 3: GeoMagic

Lastly, GeoMagic is a software that works within SolidWorks which is a CAD software used by engineers to create 3D products. GeoMagic is able to process large data sets including DICOM files and can be used to generate stl files for 3D printing as well. Due to this program being embedded into CAD software, the feasibility of use is greatly simplified and allows for matriculate adjustments.

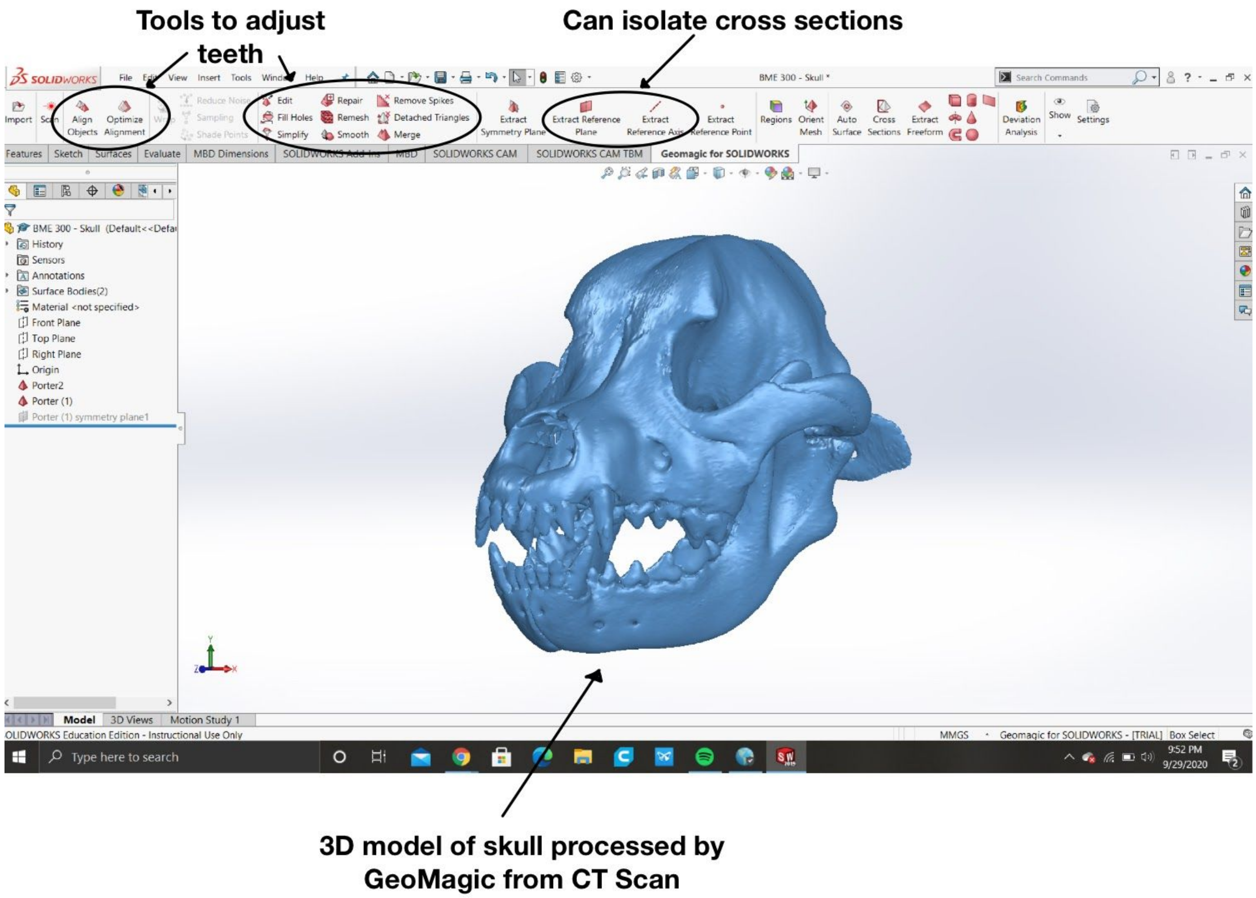


Figure 11: *GeoMagic within SolidWorks. This interface demonstrates an ability for the program to manipulate teeth, process CT scans, and create additional devices and parts with the model.*

Protocol for Geomagic software- Repeated in Appendix A

Below is the list of processes that would be used to design and edit the stl files:

1. Open Geomagic for Solidworks
2. Load in DICOM file in the Solidworks interface
3. Remesh structure to 15 mm for accurate dimensions
4. Use window feature to window out upper jaw
5. Load in stl file of brace design
6. Using assembly, mate the brace to the upper canines
7. Make any design adjustments necessary for fit
8. Using the simulation feature on Solidworks, change the material to match dental LT resin
9. Perform mechanical testing on brace
10. Change any aspects of design based on fit and testing

Preliminary Design Evaluation

Design Matrix: Incline Planes

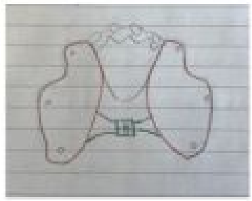
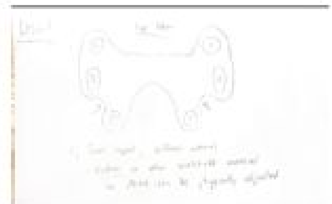
Design Criteria	Design One: Adjustable Bridge 	Design Two: Separate 	Design Three: Rubber Inclined Plane 
Effectiveness (30)	25	20	25
Adaptability (20)	15	20	15
Ease of Manufacturing (15)	5	15	10
Durability (15)	10	15	5
Safety (10)	5	5	10
Cost (10)	10	10	10
Total(100)	70	85	75

Figure 12: *Incline Plane Design Matrix. The separate pieces design was chosen based on the team's assessment of various criteria.*

As far as choosing the criteria went, the team chose what were believed to be the 6 most important aspects that applied to all 3 incline plane designs. The team ranked these criteria based on importance to this specific project, assigning each of the 3 designs with a score based on how accurately they represent each criteria. Effectiveness was defined as how well the design functions, and was ranked the highest, at 30. This is because effectiveness is the main priority of the project; if the device doesn't execute its job properly, it is a failed project. Designs 1 and 3 received the highest score in this criteria, just because they are both single-piece devices that model Dr. Thatcher's successful incline plane, meaning that the worry of how a dog will react to multiple pieces in its mouth is nonexistent. After effectiveness is adaptability, which the team defined to be how easily the device can be adjusted to different dogs. The team ranked this aspect at 20, simply because adaptability was one of the main reasons this project was assigned, and the goal is to improve the overall process of creating the incline plane for different dogs. They then gave design 2 the highest score in this category because it eliminates the problem of differing sizes of the dog's palate. Next is ease of manufacturing, which the team ranked at 15 and defined as how long it takes to create each of the designs. This criteria is ranked where it is because not only will ease of manufacturing make the overall process much more efficient, but it will also allow veterinarians to produce and print these designs without the help of an engineer. The team ranked design 2 the highest in this criteria because Dr. Thatcher has already proven that printing the incline plane with this material is possible, and in fact, relatively easy. Following ease of manufacturing is durability, which is defined as how long the device will last. Then, the team decided to also rank this criteria at 15 because in order for the device to properly adjust the dog's teeth, it must be able to last the correct amount of time in the mouth of the dog. Design 2 received the highest score in this criteria, again due to the fact that this material has been proven to last for the specified amount of time in the dog's mouth. Next is safety, which the team defined as how user friendly the device is to the veterinarian, the owner, and the dog. The rubber incline plane was ranked safety as 10 because although safety is a very important aspect of all designs, the team believes that none of the 3 incline plane designs pose a significant safety threat to the dog. The team gave design 3 the highest score in this category because it is made out of rubber, which is a much more giving material than hard plastic. The final criteria for the incline plane designs is cost, which is a self-explanatory criteria, and is ranked at 10. The team ranked all the designs the same for this criteria because it anticipated all 3 designs to cost roughly the same, with all of the costs being within the specified budget. After careful consideration and construction of the design matrix, the team has decided that <u>design 2</u> will be the proposed incline plane design, receiving an overall score of 85 out of 100.

<u>Design Matrix: Software</u>

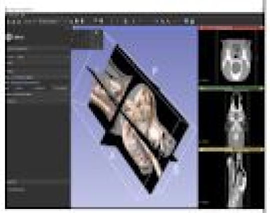
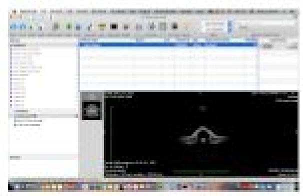
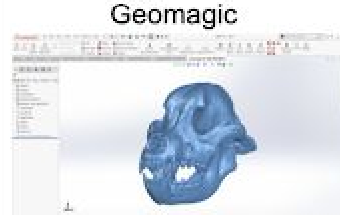
Design Criteria	Design One: 3D Slicer 	Design Two: Osirix 	Design Three: Geomagic 
Effectiveness (30)	15	20	25
Adaptability (20)	0	10	18
Ease of Use (15)	15	10	10
Cost (10)	0	0	5
Total(75)	30	40	58

Figure 13: *Software Design Matrix.*

The team chose the criteria for the software design matrix in a similar fashion to the incline plane design matrix, choosing what the team thought were the most important aspects of the software programs. However, the team excluded ease of manufacturing from this design matrix because the 3 software programs that the team chose do not require any manufacturing in terms of coding the program.

The team also did not include safety, because this does not apply to online softwares. Effectiveness was once again ranked highest at 30, for the same reason as above; a design that is ineffective is considered a failure. However, with the software in mind, the team defined effectiveness as how efficiently the software functions. Design 3, Geomagic, received the highest score in this category because after working with the software, the team determined that Geomagic was able to process a CT scan and convert it into an stl file, of which can be manipulated within SolidWorks. The next criteria is adaptability which the team ranked at 15, and defined as how well each of the software programs can convert between different types of files. This criteria received the ranking that it did because being able to convert various types of files into an stl file is crucial in this project, because it removes the step of having to send the CT scan to a software engineer. Once again, Geomagic received the highest score in this criteria because it is the most versatile software. The third criteria, ease of use, was defined as how user-friendly the software is. Ease of use is an important criteria, especially in software programs, simply because the more easily the software is used, the more likely that the user will be able to generate what they are looking for. Design 1, Slicer, received the highest score in this criteria because it allows the user to view CT scans in a variety of ways, giving them different viewpoints and overall a better understanding of the scan. The final criteria is cost, and Geomagic received the highest score in this aspect simply because it is a free program to use. With this being said, the team had originally decided for the proposed final software design to be Geomagic, due to the fact that it is most representative of what the team is trying to accomplish. However, after future research and advice from the team's advisor, they settled on an entirely new software called Blender which will be explained in further detail.

Proposed Final Design

Software: Blender

As mentioned, the team evaluated many forms of software before deciding to work with Blender as the main form of visualizing how well (or not well) the piece fit in the mouth and effectively (or ineffectively) allowed for the correct future orientation of the teeth. Blender is a 3D modeling and animation software that allows the user to import and create models for design. The base Blender software is free but the Team discovered a purchasable add-on for Blender, known as Blender for Dental. This add-on gives the user a wider variety of options that the normal Blender software does not give you, such as tooth separation commands, tooth bracket simulations, and a larger variety of cutting and editing tools.

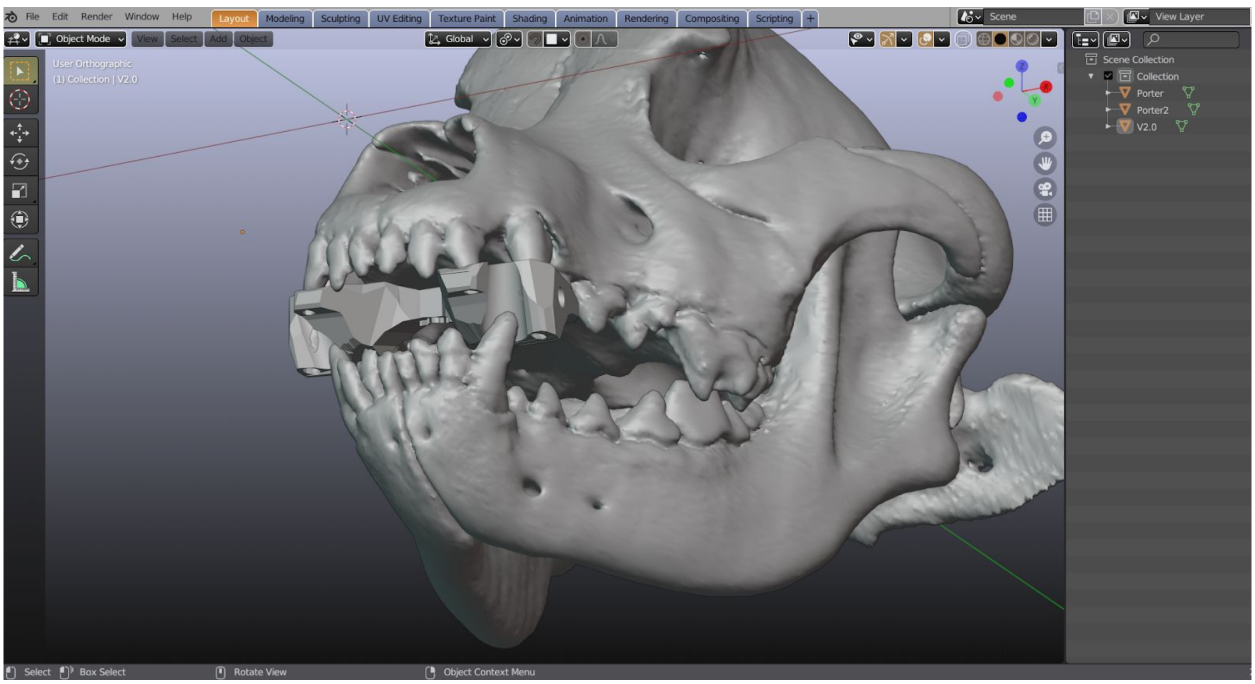


Figure 14: *All three stl files of the lower jaw, upper jaw and initial brace loaded into the Blender interface.*

Specifically, Blender allowed for the team to visualize these pieces well with the animation tool – a tool that allowed for the team to see the progressive change of the teeth into the correct orientation at the correct angle. Therefore, the team was able to see if this change in angle would be possible with axial force that would be applied upon implementation of the specific incline plane. To understand the process of animation in Blender, see Appendix D.

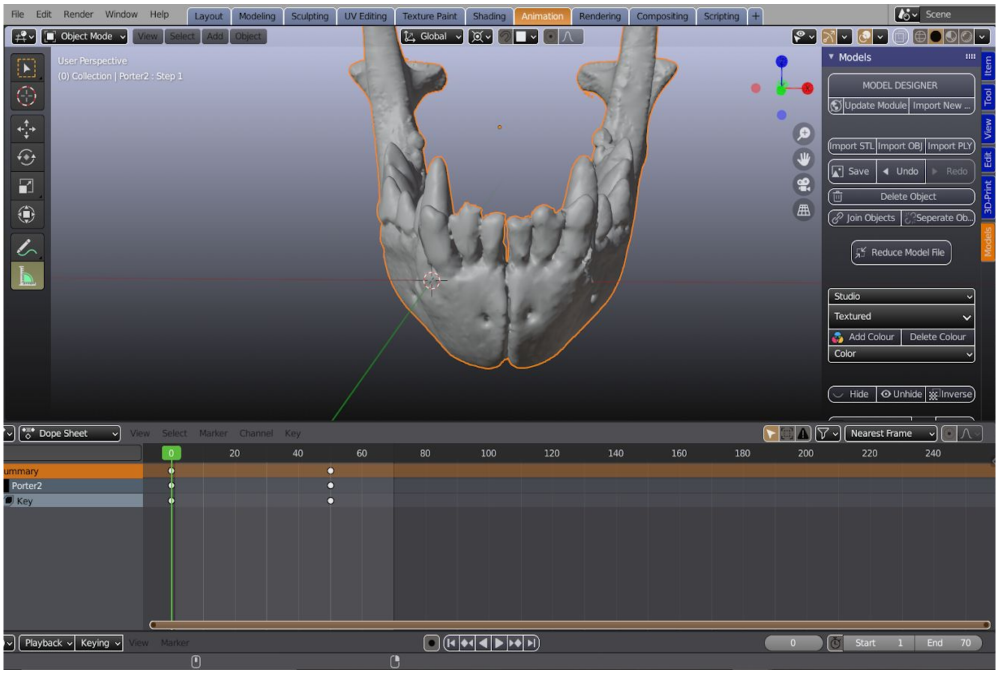


Figure 15: *Lower canines in a class II malocclusion*

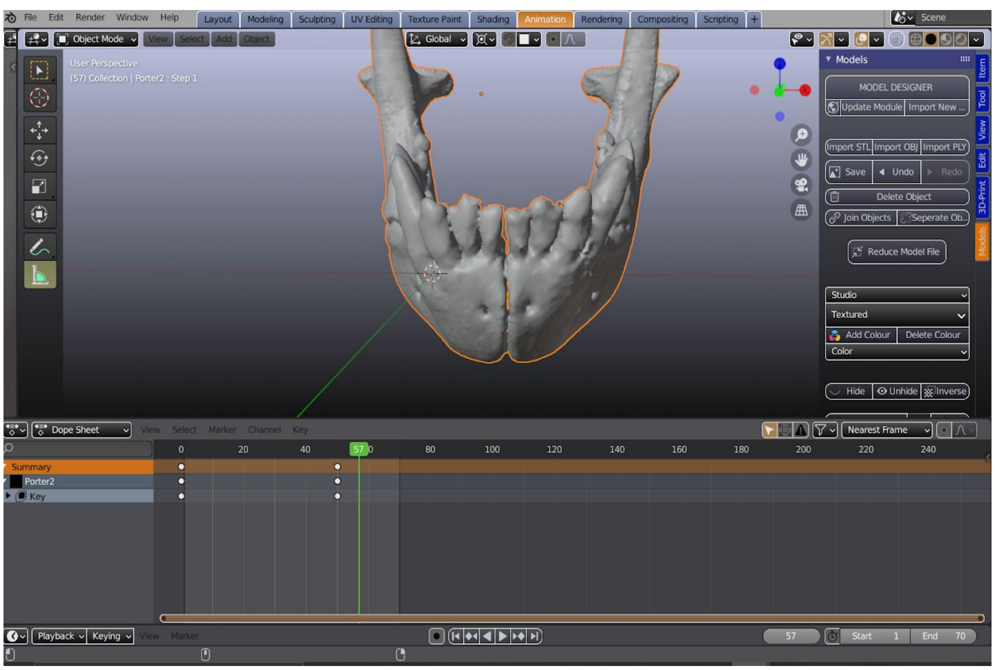


Figure 16: *Using animation techniques, the lower canines have moved to a normal occlusion angle of around 30 degrees to the vertical plane*

Both the technique of animation and 3D visualization were important aspects of Blender that made the team switch from Geomagic for Solidworks. Both softwares are effective in their own rights, but Blender is a free software that can be easily downloaded and shared while Geomagic for Solidworks brings with it a large learning curve and a higher price for use. While Blender was successful for these tasks, much of Blender's cutting and splicing tools are used for geometrically simple shapes, not complex stl and DICOM files. For editing the final design, a program called MeshMixer was used.

Software: MeshMixer

As mentioned, the team used MeshMixer to slice the incline place into two separate pieces – a design evaluated early in the project to minimize variables for the orthodontist. The .stl file given by the client was unable to be edited in SolidWorks because the piece was made of only surface bodies, a hollow mesh. Therefore, MeshMixer was needed in order to manipulate the mesh to our new design and convert the mesh to a 3D solid that could be tested in Solidworks. MeshMixer has capabilities of sculpting, editing, and cutting mesh bodies, as well as converting mesh to 3D solid bodies. In order to make the cut, the team utilized the 'plane cut' feature of Meshmixer. This tool allowed the team to specifically locate where the two cuts would be on the original inclined plane that would remove the middle bridge piece. The team defined the two planes and made the two cuts, retaining both sides of the device and thus creating a new .stl file with the two pieces. The dimensions of each of these pieces will vary for each canine and the file can be scaled using both Blender and MeshMixer. However, general approximations for the starting size of the stl file include ~17.5 mm in width, ~36 mm in length, and ~15 mm for the diameter of the ramp for each piece. Ultimately, using MeshMixer, the team was able to edit the incline plane and export it as an .stl solid body for 3D printing.

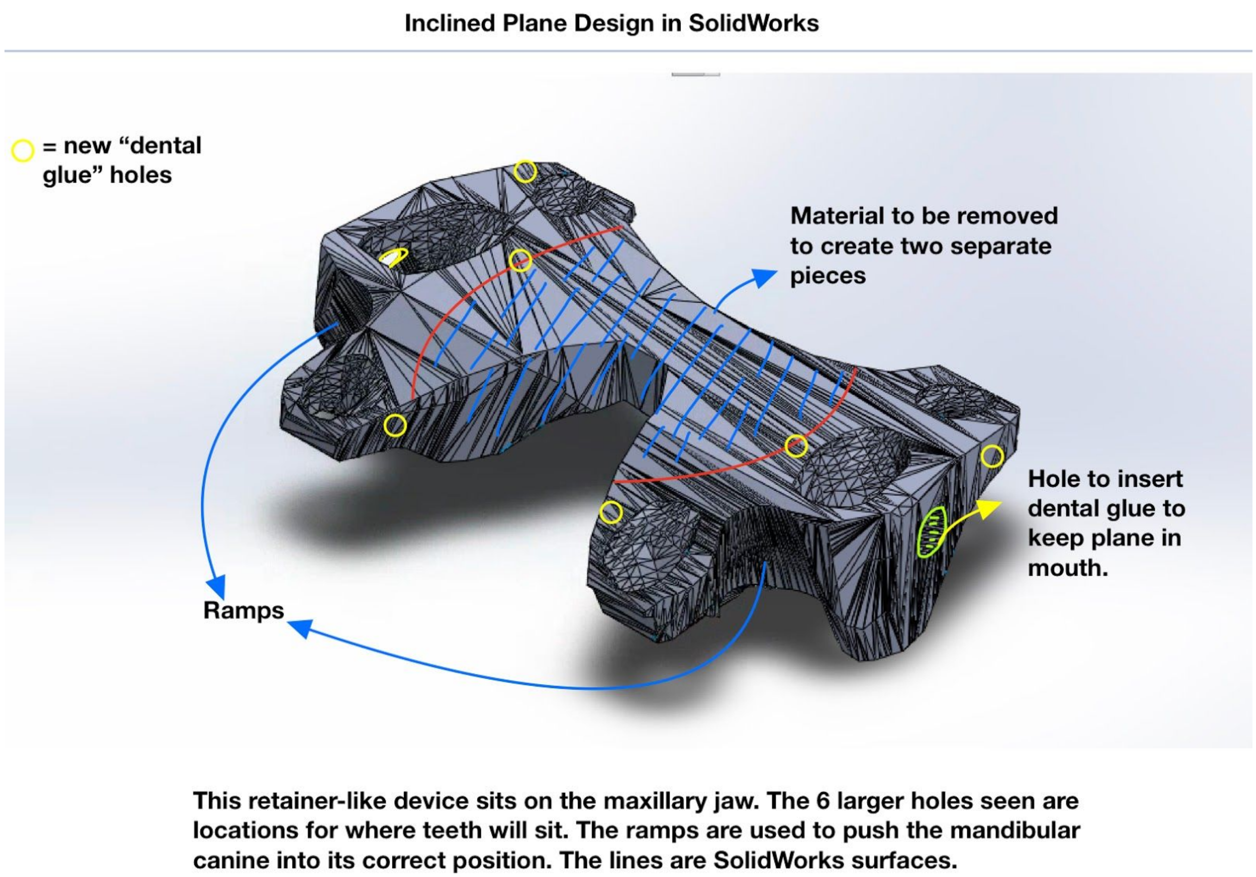


Figure 17: *.stl file in Solidworks. Edits to initial designare shown for final proposed design.*

Final Fabricated Design

The final design was two separate pieces that still encompassed three holes for the upper maxillary, canine, and incisor teeth of the dog, as well as a ramp to push the lower canine teeth into the correct position of the mouth.The team chose this design because it eliminated two problems that the client is facing: (1) altering the width of the device to fit various size dogs and (2) dog experiencing irritation in the upper palate due to the presence of the bridge. In addition, having a two piece device separates each side of the malocclusion into its own unique situation/problem that the client can work with/tackle. In other words, the isolation allows for greater individual manipulation of each of the two lower canine teeth. In the end, the team was able to 3D print the device using Dental LT Resin (a material

FDA approved and used in the first device).

Fabrication/Development Process

Materials

Once the stl file of the final design of two separate pieces was created, the team used the 3D printers located in the UW Veterinary School to print off the desired pieces. The braces stayed uniform in terms of their material properties to limit the amount of variables that different materials will give the team. Dental LT was used as the material in Dr. Thatcher's initial brace design and was used again two print the two pieces off.. It is a clear resin used mainly for FormLabs 3D printers for biocompatible dental splints and guards. It is also FDA approved and is known to be resistant to the mechanical and chemical stresses that occur within the mouth of both humans and canines. Nylon and polycarbonate are also ideal candidates for the brace material as each has an extremely high abrasion and temperature resistance, which make them suitable for long term orthodontic use.

For the whole project, the team only utilized two main materials. The first material was the purchase of the Blender software for $79.00. This was the root of the team's project and provided them the tools necessary to fit the pieces to a CT scanned model of a canine jaw, as well as develop an interface for the development of more inclined planes. The second material was the Dental LT resin which was used to 3D print the two-piece device at the UW Veterinary School. The client had access to the printer and was able to print the device for $8 to the team. A table of the team's materials and budget is in Appendix [B].

Methods

As the team progressed through the process of creating materials, the team mostly used a combination of MeshMixer and Blender. These softwares allowed the team to make the incline-plane two piece (reasoning explained in the final fabrication section) and to visualize if the orientation of the plane would allow for proper movement of the team into correct alignment, respectively.

Blender Methods:

In order to do so, the team uploaded the DICOM and CT Files given by the client and, by placing them in-line with each other, was then able to check if the pieces fit properly or not. Although the team mostly used MeshMixer for complex cutting, the software does have splicing and editing capabilities, the team could change the dimensions of the incline-plane piece to better fit the model. Additionally, Blender has a scaling tool that allows the model or specified section (chosen by the software engineer) to either decrease or increase in size. Again, while these tools are helpful in some instances, the team turned to MeshMixer for editing dimensions.

MeshMixer Methods:

As the .stl file given to the team was a mesh surface body, and unable to be manipulated in SolidWorks, MeshMixer was used to clean up and edit the piece. The .stl file of the inclined plane piece was imported into MeshMixer. The given mesh was edited to remove holes and fix areas that were too thin. After cleanup, the mesh was converted into a solid body, which was cut into the two-piece design using plane cuts. The .stl file was then exported for 3D printing and stress testing [Appendix C].

Final Prototype

The final design incorporated two separate brace pieces that are similar to Dr. Thatcher's original design, but there is no bridge connecting the two to each other. In addition, the final software will be based in Blender. Creating a step-by-step process to design an inclined plane with this software was the main focus of this project.

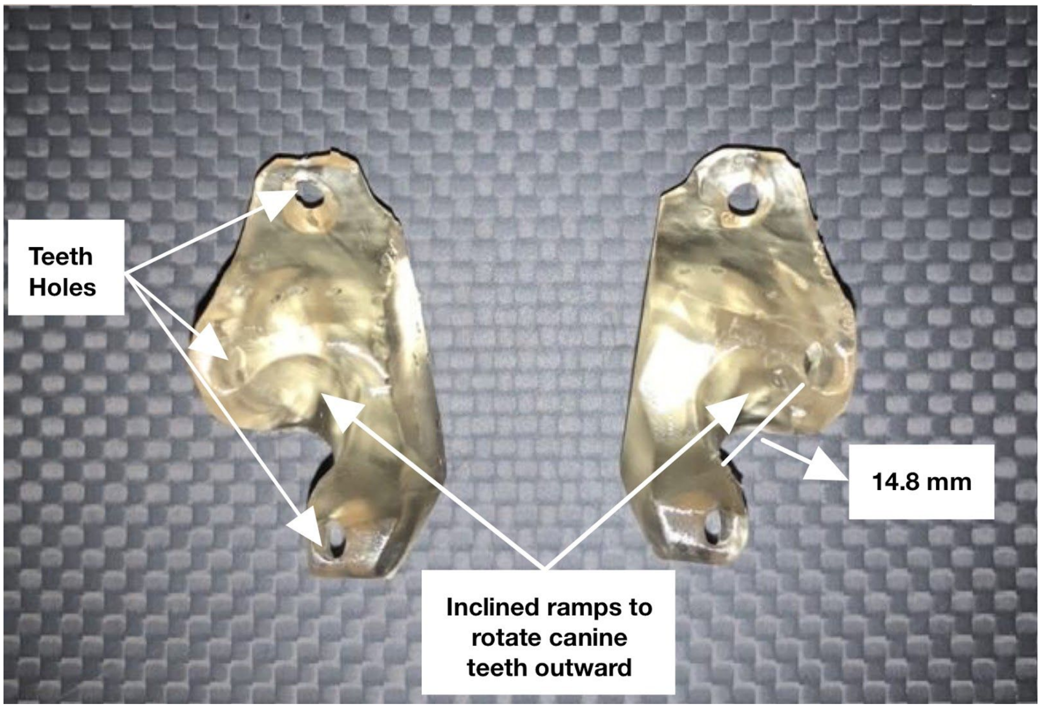


Figure 18: *Separate Inclined Planes from Mandibular Jaw Perspective*

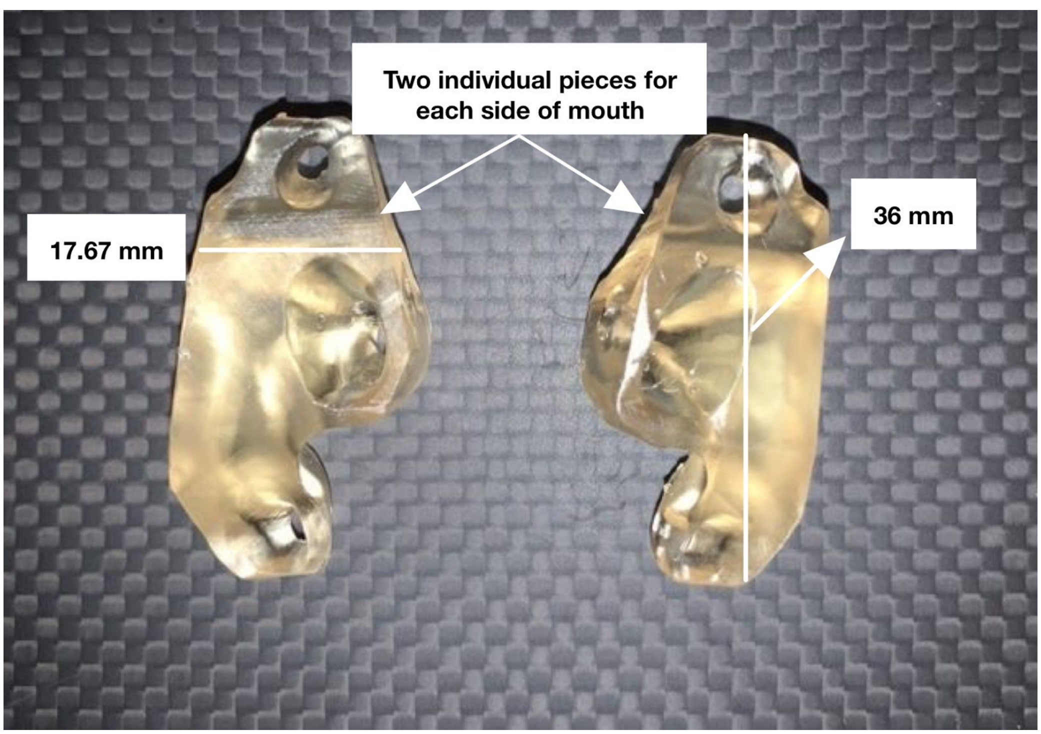


Figure 19: *Separate Inclined Planes from Maxillary Jaw Perspective*

Testing

Once the team had a set final design created in an stl format, testing and data acquisition began in Solidworks using the SimulationXpress wizard. This wizard gives the user an interface to apply specific forces to an stl file or design. Different materials can be implemented into the design to simulate how forces affect materials of varying mechanical properties. Since there is no material selection for Dental LT Resin in SimulationXpress, a material was customized to have the same mechanical properties as listed in the FormLabs material data sheet.[16] From this data sheet, Dental LT Resin has an ultimate strength of around 50 MPa and an elastic modulus of 1.3 GPa. Doing this type of mechanical test is important for both the client and the safety of the patient. It shows where the weak points of the device will be so further design changes can be made, and these changes will ensure that the patient receives quality care and effective results.

The first step to finding weak points and deformations in the design was choosing what quantity of force to apply. The client's first design was initially meant to fit the jaw of a rottweiler, which has a bite force of around 400 pounds [17]. Using simple calculations, it was found that this is equal to around 1350 newtons of force.

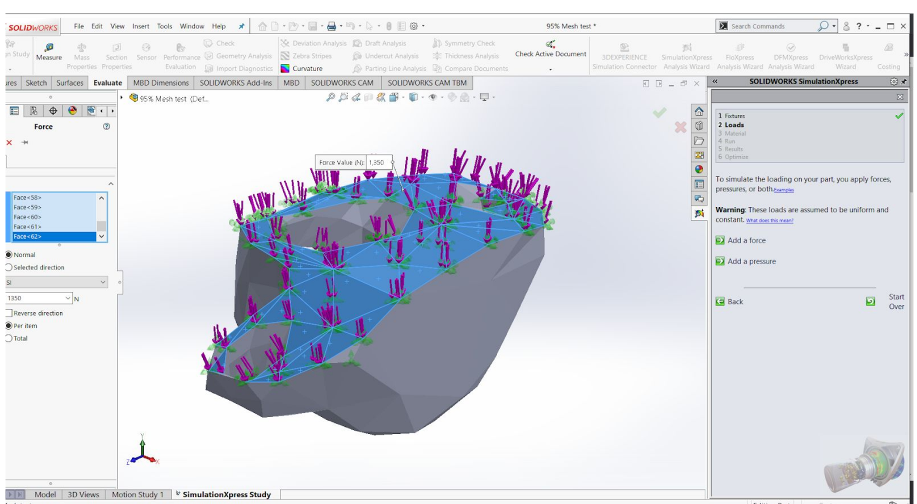


Figure 20: *One side of the device with force loads applied*

The stl file used in this experiment was too complex to apply loads with the processing power of the Solidworks program. To avoid this issue, the mesh of the stl file was altered using the program MeshMixer. The mesh percentage was decreased by about 95%, giving the model seen in figure XX. Another simplification made in this experiment was to only add force points to the top side of the design. Doing this enabled the team to see how force affected the widest and toughest aspect of the design, and it made the deformation data simpler to calculate for SimulationXpress. Once the top surface of the piece was selected, the material of Dental LT Resin needed to be chosen to accurately depict the stresses and deformations that would occur on the model. However, if given more time, the team was planning on performing clinical tests of the device and using MTS machines to gather more accurate stress-strain data.

Results

The two figures below show the device after the 1350 N forces were applied. As expected, the weakest parts of the device were found to be near the incisor and molar holes which are the thinnest parts of the design. The red areas in figure XX show the areas of greatest deformation which came out to be .8103mm and experienced a von mises stress of 1.08e9N/m^2. This is compared to the blue areas of the design which experienced von mises stresses of 8.562e-2N/m^2 to 8.902e7N/m^2. This data shows that the device would do well under the condition of being inside of a rottweiler's mouth which experiences extreme biomechanical forces. It can withstand the max bite force of a rottweiler over much of the surface and do so using the Dental LT Resin recommended by the client, Dr. Thatcher. In terms of the overall safety of the device, the deformations did not pose any immediate issues for the team. These holes experienced slight breakage and damage during the initial clinical tests the client performed but the structure of the piece remained mostly intact. Since this design is fairly similar to the client's initial design, the team expects the same outcome; Structural integrity with little damage.

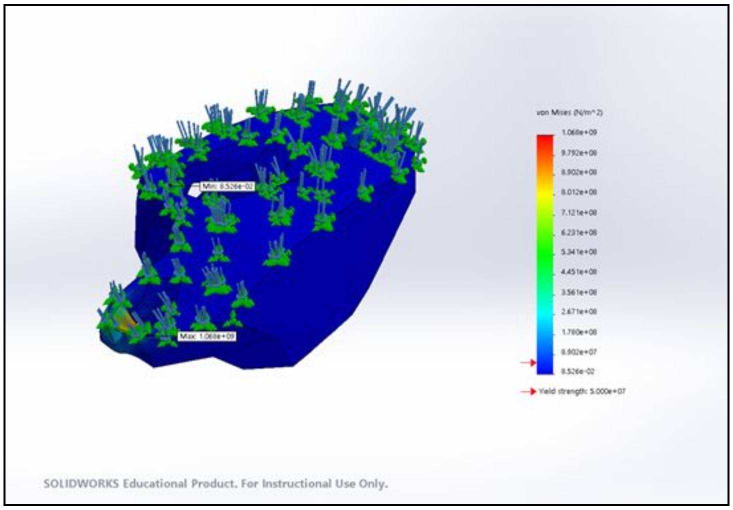


Figure 21: *Device after force loading. Bar on the right depicts Von Mises stress values and the color that matches the value.*

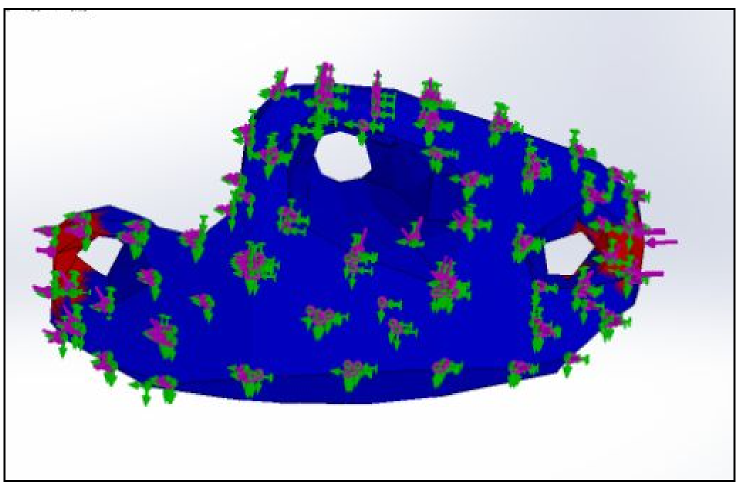


Figure 22: *Device after force loading. Blue areas show little to no deformation while red areas show areas of high stress and strain.*

Given the data above, a stress-strain curve was created to show the ultimate strength and yield stress of the device based on the values in the FormLabs data sheet. The elastic modulus of the was 2 GPa, ultimate strength of 167 MPa, and a yield stress of 50 MPa. The data from Solidworks does not give a fracture point but the ultimate strength of 167 is where the first signs of deformation begin to occur.

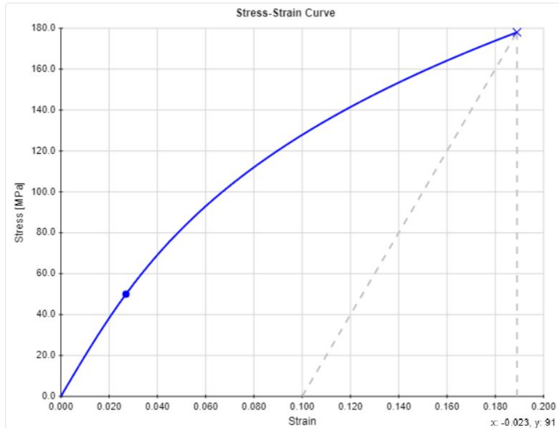


Figure 23: *Stress-strain curve for the orthodontic device*

Discussion

The results that the team gathered showed that the device had areas of success as well as areas for potential improvements to be made. The testing done in SolidWorks shows that there are weak spots in the design that could lead to the device breaking due to the force of the dog's bite over time. In the future, the device can be improved upon by reinforcing these areas in order to decrease the likelihood of the device breaking while in the dog's mouth. An issue with reinforcing areas of weakness is composing the fit of the device. Increasing the diameter of these holes could make the device too thick to fit around the upper incisors. While there is weakness in the device, the amount of strain the device undergoes does not warrant an increase in device width which would cause an improper fit. The client has experienced a device that has broken while attached to a dog's teeth and concluded that this does not cause any harm to the dog nor the procedure as long as the device stays in its position- which it succeeding in doing. The device shows that it will be successful in moving the teeth into the correct position. In addition, the team was able to eliminate the risk of palatatis by taking away the bridge. The design meets the ethical criteria because it is able to fix the Malocclusion without causing additional pain or infection. The device will allow for orthodontics and 3D printing to become more commonly used in correcting Class II Malocclusions in dogs and will decrease the need for extraction of the lower canines.

Conclusion

The team's goal was to increase the availability of veterinary orthodontics to treat class II malocclusions in dogs and decrease the need for alternative treatments such as extraction of major teeth. There is currently not an easy method for veterinary orthodontists to create a device specifically made for their patients. The team's goals are to streamline the workflow of creating a device that repairs malocclusions in dog's, specifically distal misalignment of the mandibular (lower) with the maxillary (upper) jaw. In addition the team also worked to improve the client's existing device. The team worked with both Blender for Dental and MeshMixer in order to develop the physical device. This will allow the orthodontist to be able to make adjustments to the implant (specific to the dog) on his own without the need for a software engineer.

The design that the team developed used Blender for Dental to isolate specific pieces of the mouth, particularly the teeth in question. The team was able to isolate the teeth in Blender for Dental to show the desired outcome after treatment. In addition the team was able to use this software to visualize the way in which the physical device would interact with the patient's jaw. The team used MeshMixer in order to split the original device into two separate pieces as well as fill in any unnecessary holes. By doing this the team was able create a device that effectively met the client's criteria.

In the future, the team hopes to test the device on an actual patient as well as allow for the device to be able to fit for many different types of dogs. The team hopes to be able to implement the streamlined workflow in new patients so that veterinary orthodontics become more common in treating class II malocclusions.

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Appendices

Appendix [A] - Protocol for Geomagic software

Below is the list of processes that will be used to design and edit the stl files:

1. Open Geomagic for Solidworks
2. Load in DICOM file in the Solidworks interface
3. Remesh structure to 15 mm for accurate dimensions
4. Use window feature to window out upper jaw
5. Load in stl file of brace design
6. Using assembly, mate the brace to the upper canines
7. Make any design adjustments necessary for fit
8. Using the simulation feature on Solidworks, change the material to match dental LT resin
9. Perform mechanical testing on brace
10. Change any aspects of design based on fit and testing

Appendix [B] - Product Design Specifications

Edited: 12/07//20

Function:
Veterinary canine patients often experience Class II Malocclusions; A movement of the upper jaw that causes the bottom canine teeth to puncture and injure the roof of the mouth. The goal of this project is develop a smooth workflow through software that will assist with the creation of a lower jaw device to move the lower canines into a suitable position within the lower jaw. Specifically, the team wants to utilize the software program Osirix to be able to view the DICOM file in 3D, section off pieces of the file/image, and alter the pieces in order to effectively streamline the process for the orthodontist.

Client requirements (itemize what you have learned from the client about his / her needs):
- Workflow must be simplified using software
- CT Scan must be configured into an stl file
- Device outcome should fit CT Scan

- Device needs to be moldable to other canine jaws based on CT Scan
- Device must be 3D printed
- Device must be held within canine jaw for 6-8 weeks
- Device must move canines lateral to upper jaw

Design requirements: This device description should be followed by a list of all relevant constraints, with the following list serving as a guideline. (Note: include only those relevant to your project):

1. Physical and Operational Characteristics

a. Performance requirements: The performance demanded or likely to be demanded should be fully defined. Examples of items to be considered include: how often the device will be used; likely loading patterns; etc.

The mechanical aspect of the device will be placed on the maxillary palate of a dog with Class II Malocclusion with a goal to, over-time, guide the mandibular canines into their correct positions within the diastema of the 3rd maxillary incisor and maxillary canine.

1. **The device will be designed to fit the canine's mouth through editing the DICOM file/stl file using 3D imaging and reduring tools (Geomagic)**
2. **The mechanical piece will be used for 3-8 weeks on a 24/7 basis as it is secured to the canine's palate with 'dental glue'**

b. Safety: Understand any safety aspects, safety standards, and legislation covering the product type. This includes the need for labeling, safety warnings, etc. Consider various safety aspects relating to mechanical, chemical, electrical, thermal, etc.

Material used should be nontoxic to dogs. The piece should effectively lock onto upper canine teeth in order to create the right forces to wing/push misaligned teeth outward. It should not move teeth that are in proper positions, or apply too much force to the moving teeth. The device should not break in the dog's mouth or cause breakage of the teeth.

c. Accuracy and Reliability: Establish limits for precision (repeatability) and accuracy (how close to the "true" value) and the range over which this is true of the device.

The device will need to be an exact fit for the patient's mouth. This will require a CT scan to get an accurate image of the jaw structure. In addition, the software will need to be able to create a model of the device that will fit perfectly around the patient's teeth. Specifically, the range over the true values are approximately 1cm, rather than a smaller value because the main goal is to correctly align teeth and not interrupt breath flow through the roof of the mouth tissue. In other words, the accuracy of dimensions pertaining to the exact DICOM file is less important than having the correct fit. As of now, the system is trial and error and the team hopes to limit the steps of trial and error through precision more than accuracy.

d. Life in Service: Establish service requirements, including how short, how long, and against what criteria? (i.e. hours, days of operation, distance traveled, no.of revolutions, no. of cycles, etc.)

The device will be attached to the patient's mouth for up to several weeks. The interval of weeks depends on the following:

a. **As long as the treatment needs; this is a new procedure, meaning trial and error**
b. **The age of the dog**
c. **How far the maloccluded teeth need to be moved outward (typically this value is ~30° but can be more or less pertaining to the patient**

e. <u>Shelf Life</u>: Establish environmental conditions while in storage, shelf-life of components such as batteries, etc.

The device will need to last at least 6-8 weeks while attached to the patient's mouth, but once removed the device will not need to be used again and will be discarded to ensure sanitation.

f. <u>Operating Environment</u>: Establish the conditions that the device could be exposed to during operation (or at any other time, such as storage or idle time), including temperature range, pressure range, humidity, shock loading, dirt or dust, corrosion from fluids, noise levels, insects, vibration, persons who will use or handle, any unforeseen hazards, etc.

Mechanical piece places to correct misalignment in teeth:
The device will be attached to the patient's (dog) mouth 24 hours a day- 7 days a week so its operating environment involves the conditions of a normal day-to-day environment. The device should be able to withstand temperatures ranging from -20°F to 120°F to account for any extreme conditions the patient may experience. The average force of a bite from a dog is approximately 320 pounds so the device should be able to withstand forces ranging up to 400 pounds without fracturing, loosening from mouth, or cracking. The device should also not interfere with food consumption nor should it be affected by it. Food should easily pass by the device and not stick nor peel the device's material.

Interface used for streamlining software engineering:
The software should be able to be utilized by a veterinary orthodontist. The interface should be compatible for most computers and easy to follow. The software should include 3D imaging of the DICOM file to give access to all images as well as the ability to convert to an stl file. Once the image is converted into an stl file, the user (without software engineering prior knowledge) should be able to section off desired piece of image and alter to the users discretion, knowing that these edits will be visible on the mechanical piece once printed.

g. <u>Ergonomics</u>: Establish restrictions on the interaction of the product with man (animal), including heights, reach, forces, acceptable operation torques, etc..

The ramping grooves (used for correcting the canines alignment during continuous bitting) of the device should be applied to the maxillary teeth. The device will come into contact with the

mandibular canines when the mouth closes and apply passive force to direct the teeth away from the palate. The device should avoid contact with the mucosa. The slope of the incline plane will be 45-60 degrees.

A torque needs to be applied from the brace to create an axial moment. This type of shear moment causes a sagittal rotation of the tooth that leads to a normal occlusion. [15]

h. Size: Establish restrictions on the size of the product, including maximum size, portability, space available, access for maintenance, etc.

The size of the product will be dependent on each patient and their mouth size and unique Class II Malocclusion. Maintenance could be a factor depending on the integrity of the incline place. Removal of the incline plane may need to take place but cannot be out for more than 72 hours to avoid any reversal of tooth movement.

i. Weight: Establish restrictions on maximum, minimum, and/or optimum weight; weight is important when it comes to handling the product by the user, by the distributor, handling on the shop floor, during installation, etc.

The device should weigh no more than a few ounces to ensure it sits correctly in the mouth and does not become misaligned due to weight adjusting the fit over time.

j. Materials: Establish restrictions if certain materials should be used and if certain materials should NOT be used (for example ferrous materials in MRI machines).

The device will be planted in a canine's mouth so the material used should not be toxic to the animal. The material also should erode or deteriorate over time due to water and food being passed by it.

k. Aesthetics, Appearance, and Finish: Color, shape, form, texture of finish should be specified where possible (get opinions from as many sources as possible).

Aesthetics will not be considered, but the incline plane of the device should be smooth enough to not apply excessive friction to the tooth. Rough edges should be taken away in imaging to ensure that the 3D piece is high quality and fits/operates correctly.

2. Production Characteristics

a. Quantity: number of units needed

Production will be on a customer-need basis. One device per patient with condition.

b. Target Product Cost: manufacturing costs; costs as compared to existing or like products

Currently the client has offered the team to use their 3D printer that prints with a specific material used for safety during orthodontic procedures. Therefore the team has not made purchases on materials. However, the team expects to use most of its budget towards software development tools, such as advanced Geomagic.

3. Miscellaneous

a. Standards and Specifications: international and /or national standards, etc. (e.g., Is FDA approval required?)

An orthodontic brace that has the ability to reposition teeth is known as a Class I device, meaning it has low to moderate risk of injury.

b. Customer: specific information on customer likes, dislikes, preferences, and prejudices should be understood and written down.

The client wants the software interface to be able to create a mechanical tool that works for any canine with these Class II malocclusions. The team should be using software to adjust a specific model of the ramping grooves to fit any sized lower jaw.

c. Patient-related concerns: If appropriate, consider issues which may be specific to patients or research subjects, such as: Will the device need to be sterilized between uses?; Is there any storage of patient data which must be safeguarded for confidentiality?

A new device will be created for each dog through a software developed by the team so sterilization will not be necessary. The patient (owner of the dog) should be given a rundown of what the device is and how it operates before being inserted into the mouth of the dog.

d. Competition: Are there similar items which exist

There exists a metal incline plane called a Mann incline plane.1,5. However, this method/device is very costly to the patient and intra treatment adjustments cannot be made to the device. In other words, there are seemingly no competitors in this exact field, as it is a new procedure that the team gets the chance to help streamline.

Table of Expenditures and Budgeting:

Item	Description	Manufacturer	Part Number	Date	QTY	Cost Each	Total	Link
Software								
Blender for Dental	Blender Add-on for Orthodontia	Blender for Dental	N/A	10/27/2020	1	$79.00	$79.00	https://www.blenderfordental.c
							$0.00	
Fabrication								
Final Design	3D print of the separated Final Design	UW-Vet School	N/A	12/2/2020	1	$8.00	$8.00	
							$0.00	
						TOTAL:	**$87.00**	

Appendix [C] - Final Prototype Methods/Pictures

MeshMixer: Method of Splitting Inclined Plane

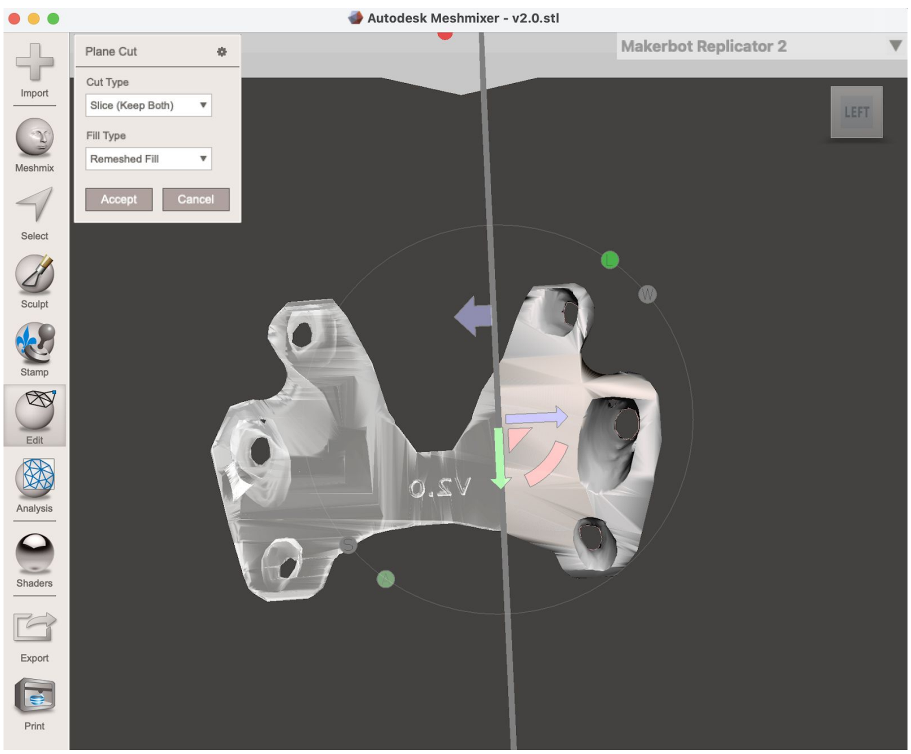

Figure XX: *Plane Cut feature used to make two cuts*

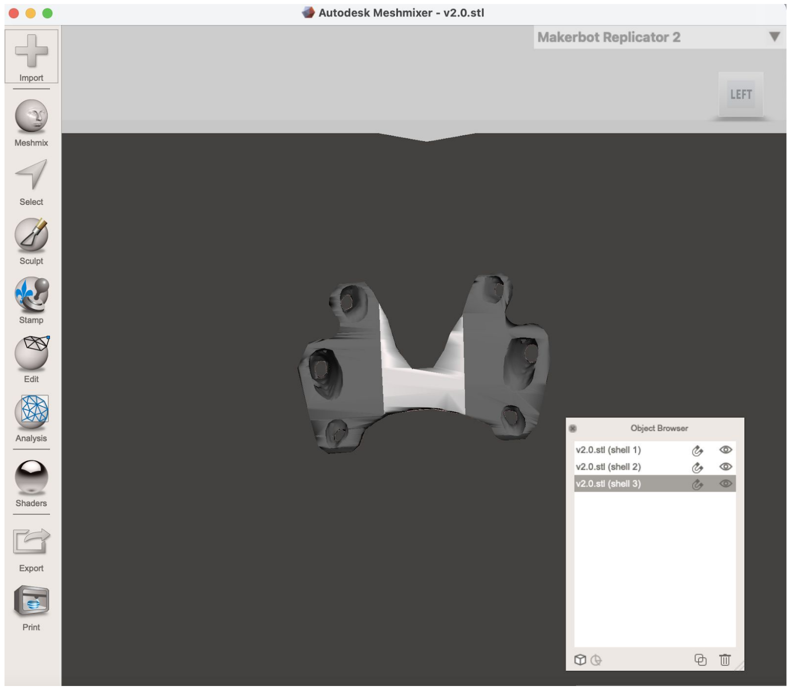

Figure XX: *Separate Shells feature to remove bridge piece (Before)*

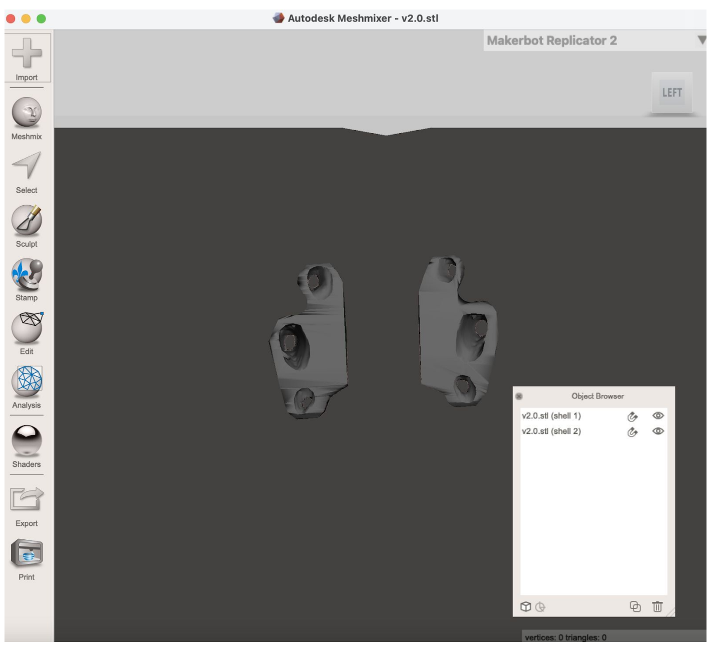

Figure XX: *Separate Shells feature to remove bridge piece (Before)*

Fabrication: 3D Printing Process

The stl file that the team received from our client was edited and cut appropriately in the program MeshMixer. From here, the stl file was uploaded into the slicing software Cura, where the device was rotated into correct printing orientation. Cura also enabled us to make proper support pieces in order to successfully print the device. The support pieces were set to minimum thickness and automatically generated within the software to create a flat base, of which the device could rest on when being printed. The stl file with the support pieces was uploaded to a flash drive and transferred to the 3D printer, which was a Creality Ender 3 Pro V2. The device and various support pieces were then able to print, lasting approximately an hour. The first printed device was printed with standard 1.75 mm PLA filament (polylactic acid), simply because that was the only material available at the time. However, we received another printed prototype from our client, which was printed on the correct material, being Dental LT Resin. Although the first printed piece was not an acceptable material to use within a dog's mouth, it still provided an accurate representation of how the device looks and functions.

Appendix [D] - Blender Animation for Teeth Movement

1. Load in jaw model into Blender Interface
2. Select the model and go into edit mode using *tab.*
3. By using the *C* key, select the two lower canines of the jaw, making sure to be careful not to bleed the selection onto other parts of the model.

4. Once the teeth are selected, hide the selection on one of the teeth using the select feature and add the selected tooth onto the *vertex groups* portion on the main menu. Do the same for the other tooth.
5. On the menu in the *Object Data Properties* window, find the *Shape Keys* column and add the current tooth selection using the plus symbol. Do the same for the other tooth.
6. Select the origin or set a point on where the tooth should be rotated around. Hit the *R* key to see the rotation about the fixed point.
7. Click the *Animate* tab. Move the teeth into the first desired position by selecting which tooth should be moved. Both will be moved but for simplicity, choose one at a time.
8. Once the *Animate* tab is chosen, a dope sheet will appear which will be used to select the frames for movement.
9. Making sure the green bar is at the 0 key frame, select *insert* at the top right corner of the viewing area. This will lock this tooth into place.
10. Move the tooth to the next desired position. Press the *insert* button again but make sure the slider is at around 50 frames on the dope sheet.
11. Repeat steps 9-10 for the other tooth, and press the play button to see the animation.