Elephant bullet removal device

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June 2019

Abstract

The goal of this bachelor thesis is to design a device that enables the operator to remove a bullet from a wounded elephant. By using the ACRREx method [1], three gripper concepts are designed and prototypes are created and tested. Looking at functionality, fabrication, maintenance, invasiveness, and convenience, the so-called Wedged Capsule comes out as the best possible concept for a bullet removal device in this research. The working principle of this concept is based on enclosing the bullet with six gripper arms. The final design has to be 3D printed in a titanium alloy in order to create the stiffness needed for the device.

1 Introduction

Indian elephants in Myanmar are often the victim of shootings by farmers determined to protect their crops. Although these elephants are heavily injured, they are not killed. The infection that follows, however, might be fatal. Currently there are no techniques to remove the bullets due to the depth of the bullet and lack of resources. Myanmar facilitates shelters that harbour these wounded elephants and prevent the infection by cleansing the wound daily. Due to the military dictatorship and the resistance to modern technology, the Myanmarese do not have tools to save these threatened animals according to Dr. Schaftenaar (personal communication, March 19^{th} 2019). Therefore the technology, medical knowledge and treatment methods are not sufficient to fully treat these elephants.

The goal of this thesis is to design a device that can remove a bullet from an elephant.

1.1 Background shot and wound

The following information in this chapter is obtained at a personal communication with Dr. Schaftenaar, retired veterinarian at Rotterdam Zoo, on the 19^{th} of March 2019.
The guns and bullets that the farmers use to shoot the elephants are very primitive and often hand-made by the culprit. These bullets act similarly to bullets with a copper jacket and lead core, also called full metal jacket bullets (FMJ). The solidity of these bullets prevents them from severely deforming [2]. They can have a diameter up to 10 millimetres and can penetrate up to one meter deep into the body of the elephant. This bullet leaves an open canal behind with a path of scar tissue.

1.2 Problem

As stated before, Myanmar facilitates shelters where the wounded elephants are treated on a daily basis to prevent an abscess or infection from forming. This procedure is performed by inserting an elastic tube, with a diameter of 8mm, into the canal until it reaches the full depth. Next, closing off the tube on one side results in a vacuum, after which the tube is pulled out of the wound taking the puss out with it. This process is repeated multiple times after which the wound is cleansed with water. The bullet remains in the elephant's body for years and sometimes even sinks deeper into the tissue. If the current treatment plan does not change, these elephants will become extremely dependent on humans for their survival.

1.3 Focus case research

Throughout this research paper, the focus will lie on one specific case. This elephant, located in Green Hill Valley in Myanmar [3], has two bullet wounds: one of approximately 52 cm deep at the right elbow and one of approximately 80 cm deep at the left shoulder (Appendix A). The wound canal has a diameter of 8.5mm and is made of scar tissue. Since, the specific features of the bullet are unknown, a few assumptions were made. The bullet is assumed to most likely be larger than the canal. So, the bullets have an diameter within the range of 8-10mm and are made of lead, copper or bronze. The bullet is encapsulated by tissue and puss. However, it will not be lodged too tightly due to the relative stiffness and adhesive capabilities of scar tissue, according to Dr. Schaftenaar. To have a good vision of the operation an endoscope will be used. The device will operate in a corrosive environment, due to the puss and blood of the wound. Therefore it is necessary that the device is waterproof and corrosion resistant to enlarge its durability. The tube connected to the device must be hollow so the rinsing water and actuation have enough space to function properly. The situation is visualised in Figure 1.

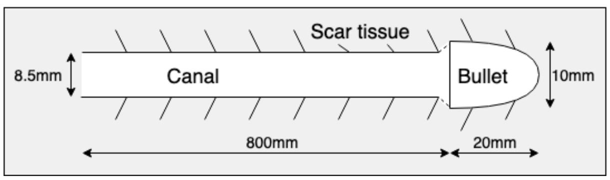

Figure 1: Situation sketch

1.4 Objective

The goal of this research is to design a functioning bullet removal device that can be applied in this and similar cases, without harming the animal.

1.5 Structure of this report

All the assumptions, requirements and preferences will be stated in the Chapter 2 Method. Chapter 3 Design presents the design process and introduces three prototypes. In Chapter 4 Tests & Results the prototypes will be tested and the results will be exhibited. Chapter 5 Discussion will revise the results. Chapter 6 Conclusion will summarise the outcomes of the project and Chapter 7 Recommendations will reflect on the research and give final recommendations.

2 Method

2.1 Assumptions

Throughout this thesis, some assumptions are made to describe the problem. The assumptions are based on case specific data.

- The bullets are solid, made of lead, bronze or copper and have a diameter of 8-10mm. This uncertainty in the properties is a result of the strong belief the guns and bullets used, are handmade from scrap materials.
- The bullet is covered by tissue and puss, because the body of a mammal naturally reacts in this manner.
- The bullet is not lodged firmly, the scar tissue can endure approximately 3 times less yield strength than normal tissue [4]. This value will be roughly 9 MPa [5].
- The bullet is not deformed by the impact and therefore keeps its cylindrical form, due to the low impact strength of tissue.
- The wound is purposely held open, therefore leaving space to insert the device.
- The wound can easily be cleansed with a hose as is currently done.
- The elephant tissue is not rigid. Therefore the canal can be stretched due to the combination of the geometry and the material properties of the internal tissues.
- The canal has a smaller diameter than the bullet, because the scar tissue partially closed the canal.
- The canal has a minimum diameter of 8.5mm.

2.2 Design specific demands

Also, a number of design specific demands are drafted in order to improve the final functionality of the device. The realised design must

- function for bullets with a diameter from 8mm to 10mm;
- function whilst supporting an endoscope with a maximum diameter of 2mm;
- be water and corrosion resistant;
- function at a maximum wound depth of 1.0m;
- have a maximum outer diameter of 13mm;
- not obstruct the endoscope's view;
- be attachable to a hollow tube.

2.3 Preferences for the design

Apart from the design specific requirements, five preferences are drafted. It is desired that the device is portable, simple and robust. Also, in order to make the realised design affordable, an end recommendation of max €2500,- is made. Finally, it is desirable that the instrument has a maximum outer diameter of 11mm to minimise the stretching of the canal. This diameter was chosen because the maximum bullet diameter is 10mm, therefore the device can grab it with a 1mm play.

2.4 Design methodology and protocol

To make design choices the ACRREx method will be used. This is to be certain all options are explored

[1]. The feasible concepts will be further elaborated and tested: modelling and design will be done in Solidworks® and finite element analyses will be executed in COMSOL®. After this the selected prototypes will be tested in an experimental setup for further improvements. Finally the choice will be made regarding the set up criteria and test results.

3 Design

3.1 Choice of grip orientation

The gripping contact area can be subdivided into three categories: proximal, lateral and distal, as is shown in Figure 2.

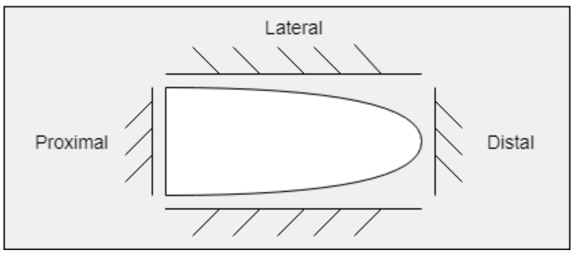

Figure 2: Gripping contact area

To consider which option is the most viable, a linear grading system has been used regarding safety, reliability and gripping potential (table 1). The purpose of this table more indicative than decisive concerning the grip orientation. Proximal gripping might theoretically require the least amount of space. This is because a discrete solution can be found that takes up less cross sectional area than the bullet. Therefore, it is less invasive as the canal does not have to be stretched beyond the bullet's shape. Due to the small surface area the mechanism that applies adhesive force to bind itself to the bullet is more complex. Moreover, because this mechanism binds itself proximally, the bullet is still lodged in the tissue. As shown in Figure 17 in Appendix B the shape of the bullet and the amount of contact area between the bullet and the canal generates high friction. As a result more force is necessary to remove bullet compared to lateral and distal, which decreases the reliability of the device. In other words, there is a lower chance of succeeding in removing the bullet because a higher force is required.

For lateral and distal gripping, more contact area will be available compared to proximal gripping. Lateral gripping will require more shear force because this principle uses a friction-locked connection whereas distal gripping uses a shape-locked connection. In Figure 18 and Figure 19 in Appendix B a force analysis is shown for lateral and distal gripping respectively.

Lateral gripping is dependent on the friction coefficient between the device and the bullet. The normal force exerted on the bullet will always be larger than the effective pulling force. The friction force of tissue on the bullet will be small as there is less surface area that can create friction. For distal gripping, there will be little to no friction as the bullet is shape locked. Therefore the entire normal force will be translated into pulling force. This means distal gripping leaves the least risk of slip or loss of grip entirely. Distal gripping, however, might be more tedious during the operation. This is the case because the device must work its way past the entire length of the bullet by stretching the canal or cutting through it.

Gripping	Safety (x1)	Reliability (x2)	Grip (x3)	Total
Proximal	2	1	1	7
Lateral	2	3	2	14
Distal	1	3	3	16

Table 1: Gripping location and their scores (ranging from one for little importance to three for high importance) on different aspects.

3.1.1 Table explanation and evaluation

In table 1, safety means minimal invasiveness or risk for the elephant. Grip refers to the amount of axial force that the gripper can exert on the bullet. Reliability measures to what extent the device is expected to function the way it is designed to.

This evaluation indicates distal gripping is the best option. When the bullet is gripped distally it is completely enveloped. Once the bullet is gripped properly, risk of escape is minimal in comparison to lateral and proximal gripping. An important sidenote to be made is that one could state that in all three of these categories there is a chance that the device pushes the bullet further into the tissue instead of encapsulating or grabbing the bullet. However, an endoscope will be used in the device to visualise both the path of the bullet and the bullet itself. The operator will therefore notice if he is pushing the bullet further into the tissue and anticipate this possible mistake.

3.2 ACRREx

The ACRREx tree (Figure 21 in Appendix C) of the bullet removal device has two main branches: direct contact or no/indirect contact. Choosing these two options as main characteristics for possible solutions makes sure that no solution is left out of the solution space. Also, direct and no/indirect contact are fundamentally different approaches in finding a solution for a bullet removal device. When considering direct contact the device touches the bullet to bind it, with indirect or no contact, the binding process starts before the contact is made.

When looking at the options for indirect contact, three branches come to mind. The chemical option carries too many health and safety risks when combined with toxic lead. A magnetic solution is improbable because lead does not have ferromagnetic properties, which implies that magnetic material has to be added in the design for it to function. The relatively small dimensions would cause the magnets to constantly lock and make mechanical operations hard. Lastly fluid pressure is a possibility, but this is unreliable and unpredictable in its behaviour due to the turbulent flow and the geometrical shape of the canal, leaving a risk of it sucking itself vacuum. This eliminates the entire no/indirect contact branch. For this reason the focus was put on the contact branch.

For the plastic deformation, a few options are difficult to apply on this scale without compromising the safety of the animal: welding, soldering and abrasion. Drilling was eliminated because one drill would make the bullet spin axially whereas two drills and the double actuation would create difficulties in spacing. Furthermore, by plastically deforming the bullet it is no longer possible to trace the bullet back to the culprit. For the elastic deformation there are three options: chemical, fluid pressure and physical contact. The chemical option is dangerous due to the hazardous properties of lead particles and the irreversible characteristics of chemical compounds like glue. Fluid pressure is a feasible option, a balloon dilation for example could be a quick efficient method. However, this can be quite unreliable if the object that must be retrieved is larger than the canal out of which it must be retrieved. This is because positioning the balloon is a difficult process. Also, when the balloon is dilated too early it can push the bullet further sideways into the tissue. The final option is physical contact. This is the most promising option as the premises of the situation are quite uncertain.

Making physical contact through a grabbing mechanism is the least complex way of grabbing the entire bullet distally. There are two possible ways to do so: locking the bullet to the device or guiding it through the device. Locking the bullet shows good prospects since the bullet can be completely encased and then retrieved as one whole with the entire system. Guiding the bullet through the entire system is impractical. By getting the bullet in the guiding position, the bullet has already been locked. Thus guiding leads to unnecessary complexity, especially because the entire instrument has to leave the wound anyway.

Four possible ways to lock the bullet that are considered feasible in this thesis are: Wires, Axially alternating guide beams, Jaws/Fingers and Biopsy. When considering these options more carefully the following conclusions were drawn. Using wires to lasso or catch the bullet is too complex: the bullet has the same or a greater width than the canal. On top of that the circumstances in which the bullet will be found, especially the orientation and the state of the encapsulating tissue, are too uncertain. The axially alternating guide beams have a complex actuation and are very shape sensitive. The jaws and biopsy ideas are promising. As it is unclear to what extent the bullet will be attached to the surrounding tissue, hooked tips have preference over straight tips. Three main designs emerged out of this process to be further analysed and improved (Figure 20). The three designs that will be tested to make the final decision are the Sliding Joint Gripper, the Wedged Capsule and the Bullet Pince. All of these designs will have space available to insert the 2mm endoscope and can facilitate a water flow.

3.2.1 Sliding Joint Gripper

This gripper (Figure 3) consists of two jaws (part 1 and 2) connected to a base (part 3) with either a rotating (positions 4) or compliant joint. The jaws both have a slanted slot (5) (rotated roughly 30 degrees with respect to the axial direction of the gripper/wound canal). These slots are interconnected by a steel pin (6) that pushes the jaws outward when the pin is pulled along the axial direction of the gripper by pulling a Bowden cable (away from the bullet (8). Part 7 is the axial slider that transfers the force from this Bowden cable (9) to the pin. The tips of the jaws are shaped like fish-hooks to trap the bullet. The jaws are slightly flexible throughout the thin section between the bulk and the tip. This allows the hooked tips to tightly wrap around the bullet.

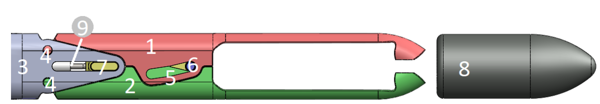

Figure 3: Sliding Joint Gripper Closed

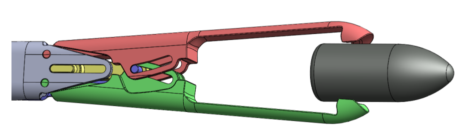

Figure 4: Sliding Joint Gripper Open

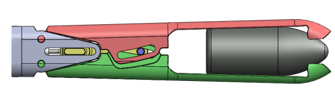

Figure 5: Sliding Joint Gripper Clamping the Bullet

3.2.2 Wedged Capsule

The Wedged Capsule works as follows: the equilibrium position allows the entire system to enter the canal with minimal skin deflection, because it has the same diameter as the canal (8.5mm). When the bullet is reached, a wedge in the shape of a truncated cone (part 2) is pulled down by a Bowden cable (part 3) causing the 6 arms to deflect outwards (Figure 6 and Figure 8). The maximum deflection is larger than the 10mm diameter of the bullet. The system then slides over the bullet, thus encapsulating it. As shown in Figure 6, the tops of the hooks are sharp in order to cut through and push away parts of the tissue enclosing the bullet. The hooks function both as a cutting tool for the tissue covering the top of the bullet and as a locking mechanism. When the bullet is completely surrounded, the tension on the wedge is relieved by pushing back the Bowden cable. This results in the arms returning to equilibrium position and causing the bullet to be fully surrounded and locked in by the hooks.

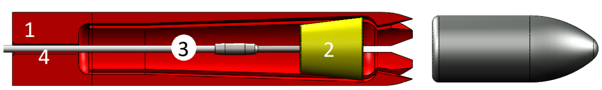

Figure 6: Wedged Capsule Closed

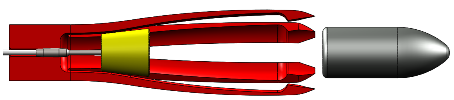

Figure 7: Wedged Capsule Open

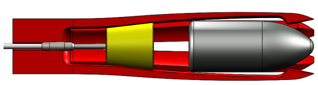

Figure 8: Wedged Capsule clamping Bullet

3.2.3 Bullet Pince

The Bullet Pince consists of three main parts: a outer cannula (part 1), an inner cannula (part 2), and a closing mechanism (part 3). The outer cannula is used as a knife to cut the tissue around the bullet (part 4, Figure 9). The inner cannula guides the knife through the bullet canal more efficiently. It stretches the canal gradually, reducing friction and makes sure that it does not cut into the tissue before it reaches the bullet. The closing mechanism is a leaf spring that closes the inner cannula with the bullet inside. Part 6 is meant fot the Bowden cables an part 5 attaches the outer cannula to the inner cannula.

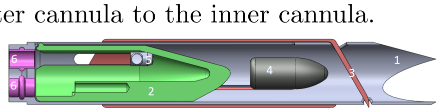

Figure 9: Bullet Pince

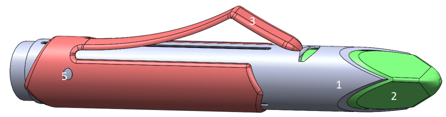

Figure 10: Bullet Pince Side Section

3.3 Load Calculations

Before a selection of materials can be made and design dimensions can be specified, a few load cases need to be considered. The goal is to use a number of approximations and assumptions to get an indication of the load cases in order to guide the design process further.

3.3.1 Elastic Energy of the Canal

The canal will be modelled as a stack of infinitesimal length hollow cylinders (sections) along the x-direction with initial inner radius a. The outer radius will be approached as being infinite for the sake of simplification as the actual wound canal is sufficiently small compared to the bulk of surrounding tissue. The load will be modelled as a local, uniform pressure $p_i(x)$. These sections will deform independently of each other, neglecting shear stress, as their bulk is expected to deform similarly to their neighbouring sections. Let $w(x)$ be the elongation of the local radius. The tissue around the canal is assumed to have isotropic material properties with Young's Modulus E_{canal} and Poisson ratio ν. Then the strain can be obtained in polar coordinates using Hooke's Law in Equation 1:

$$\varepsilon_\phi(r, x) = \frac{1}{E_{canal}}(\sigma_\phi(x) + \nu\sigma_r(x)), \tag{1}$$

with r in the radial direction and ϕ the circumferential direction. According to S. Timoshenko in 'Theory of Elasticity' [6], radial and circumferential stress, σ_r and σ_ϕ, can be obtained from Equations 2 and 3:

$$\sigma_r(x) = \frac{a^2 p_i(x)}{b^2 - a^2}\left(1 - \frac{b^2}{r^2}\right) \tag{2}$$

$$\sigma_\phi(x) = \frac{a^2 p_i(x)}{b^2 - a^2}\left(1 + \frac{b^2}{r^2}\right) \tag{3}$$

Here, b is the outer radius of the cylinder of which the limit to infinity will be taken as stated at the beginning of this paragraph. Next, $\varepsilon_\phi(a, x)$ can be derived from $p_i(x)$ and related to $w(x)$. Let $w(x)$ have positive values for $x \; \epsilon \; [0, L]$ and zero elsewhere. The elastic energy stored in the canal U_{canal} can be obtained through the relation $dU_{canal} = p_i(x)dV$, with the change in volume dV defined as $2\pi a dw dx$, resulting in Equation 15:

$$U_{canal} = \frac{\pi E_{canal}}{1-\nu}\int_0^L w'(x)^2 dw' \quad (4)$$

3.3.2 Required Force for opening a Gripper Jaw

The jaw of a gripper can be modelled as a flexible beam using Classical Beam Theory. In order to avoid fourth order non-linear differential equations, the shape of the beam will be approximated with a concave parabola to simulate the anticipated counterpressure from the canal (Figure 11). The base of the beam can rotate freely about the joint (O) with angle θ where it will be actuated with torque T. The tip of the beam at $x = L$ will remain tangent to the line $y(\theta)$.

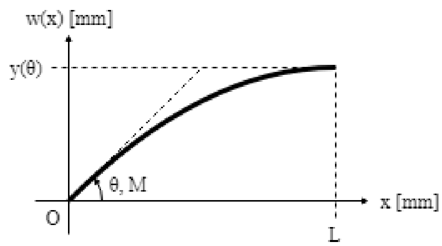

Figure 11: Deflection profile of the gripper jaw modelled as a simple beam.

Applying the mentioned constraints, the deflection of the beam follows the profile of Equation 5:

$$w(x) = -\frac{y}{L^2}x^2 + \frac{2y}{L}x, \quad y = \frac{1}{2}L\theta \quad (5)$$

Using the area moment of inertia (I) and the Young's Modulus for the material of the device (E_B), the elastic energy stored within the jaw can be derived from Equation 5. This results in the relationship in Equation 6:

$$U_B = \int_0^L \frac{M(x)^2}{2E_B I} = \frac{2E_B I y(\theta)^2}{L^3}, \quad (6)$$

where $M(x) = E_B I \frac{\partial^2}{\partial x^2}w(x)$. Given N identical jaws are pushing the canal outward where the deflection $w(x)$ of each jaw equals the increase in radius of the canal, the total energy of the system U_{total} equals $U_{canal} + NU_B$. Now the torque required per jaw can be calculated by using $T(\theta) = \frac{1}{N}\frac{\partial U_{total}}{\partial \theta}$. Expressing θ in terms of y, the torque per jaw can be calculated as a function of y (Equation7):

$$T(y) = \frac{2y}{L^2}\left(\frac{4\pi E_{canal} L^4}{15(1-\nu)N} + E_B I\right) \quad (7)$$

To get some actual figures, the wedged capsule will be used as an example, leading to the following parameters: $N = 6$, $E_{canal} = 18.51$ kPa (moderate hardness for muscle tissue, [7]), $\nu = 1/2$ (exact value for incompressible materials as tissue is mostly made up of water and fatty acids), $E_B = 1.2GPa$ (the available material at DEMO lab for their 3D printer [8]), $I = 0.333 \cdot 10^{-12}$ mm^4 (rectangular section of 4mm wide and 1mm thick) and $y = 5mm$ in order to extend the jaws far enough to grab a 10mm wide bullet. Additionally, the required torque has been converted to a force, applied 20mm away from the rotating joint. The results of the calculations are listed in table 2:

L (mm)	40	50	60	80	100	120
T (Nmm)	85.2	130	187	331	517	745
F (N)	0.43	0.65	0.94	1.66	2.59	3.72

Table 2: Required force per jaw of length L to open six jaws 5mm. The force is applied 20mm away from the rotating joints of the jaws.

Upon inspecting equation 7 more thoroughly, it can be seen that the torque scales linearly with y and independently of initial radius a, meaning the results from table 2 can be converted to fit scaled prototypes. Additionally, setting $E_B = 0$ (which would be true in the ideal case) reveals that most energy is used to stretch the canal. When all spacial dimensions are scaled up, the required force scales. For a detailed derivation of Equations 1 to 7, see Appendix D. It can be concluded that necessary torque (see table 2) that must be generated to stretch the canal is dependent on the geometry of the arm. Keeping this in mind, the geometry must be chosen so that the maximum stress does not cause fractures.

3.4 Choice of Materials

To create a functioning mechanism, certain material properties are necessary, serving as a basis for the material choice. The device will operate in a wet and corrosive environment so it must be corrosion-resistant. Furthermore the material must be stiff enough to be able to push away the tissue and stretch the canal. However, it must not be too brittle that it cracks under stress. It also cannot excrete toxins that are harmful to the animal. The material should be relatively cheap and easy to manufacture. Ideally it is a bio compatible material to limit the possible harm it can do to the elephant. Considering these factors there are two plausible options: stainless steel or titanium. Both are applied in the medical field but titanium is preferred as it has better bio compatibility than stainless steel and is more corrosion resistant in biological media [9]. Titanium is non-ferrous, which entails that the sterilisation and the cleansing of the wound should not form any issues. Moreover, titanium is light weight (40 % lighter than stainless steel [10]) with a density of 4430 kg/m^3 [11] and can bear high tensile stresses (958 MPa [12]). With heat treatments the stiffness and brittleness can be optimised. The surface properties of titanium instruments can also be modified easily during the manufacturing phase and specific local properties can be incorporated with great detail. Also, it is non-magnetic and non reflective when anodised. Therefore the endoscope's sight is not impaired and there is no risk of interference of other magnetic appliances. On top of this it is very durable, which is lucrative taking into account both the budget and the working principle: the instrument must remain sharp and reusable [10]. Finally, all three concepts rest on a principle where two parts slide over each other. Titanium sliding over titanium has a friction coefficient of 0.45 to 0.49, which is the lowest metal on metal value found thus far [13].

3.5 COMSOL Multiphysics® Modeling Software

The corresponding figures in this paragraph are listed in Appendix E. The mechanical properties used in the finite element analysis are based on the titanium alloy, Ti-6Al-4V. The compressive yield strength of this material is 970 MPa [14]. The tensile strength of this material is 15 times higher than the tensile strength of the photo polymer. Stress within the acceptable range entails the COMSOL analysis shows no red critical areas.

3.5.1 Sliding Joint Gripper

The bending at the end of the Sliding Joint Gripper in Figure 3 is caused by the outside pressure of the tissue (Figure 22). This outside pressure will be used to improve the grip on the bullet. The stresses on the Sliding Joint Gripper are within acceptable region, with a clear maximum at the start of the arms.

3.5.2 Wedged Capsule

The actuation mechanism of this cylindrical device forces the arms to move outward. As the sides move outward, the inward force rises which results in an equilibrium with a stress distribution that always remains within an acceptable range (Figure 24). The sharp edges are now pushed further around the bullet and closed, which results in the corresponding stress distribution. In this case the stress always remains in the acceptable range as well.

3.5.3 Bullet Pince

The Bullet Pince naturally has a strong cylindrical shape. A small bending at the sharp endpoints is caused by the pressure of the tissue around (Figure 26). However, as stated in Chapter 3.2.3, during movement in major part of the canal the inner cannula is located within the outer cannula (Figure 10), which stops latter from bending at the endpoints. Figure 26 also shows that the highest stresses arise in between the endpoints.

3.5.4 Manufacturing

The device has to be small in size, very precise and strong. The best material to meet these demands is titanium. It is not possible to manufacture these prototypes by hand in the workplace, because of the small size. The device has to be developed using a 3D printer. The best result can be obtained using the LASERTEC 30 SLM 2^{nd} Gen, a powder bed printer. The working principle of this machine is based on the usage of powder and a laser. The laser shapes the material by melting this powder. This printer has the capacity to be precise with a focus diameter of 70 μm - 200 μm and a layer thickness of 20 μm and 100 μm [15]. This precision is required for the fine and small elements of the device.

3.6 Experimental Set Up

The entire set up was scaled up by factor two so that the fundamental working principles could be tested. To simulate the animal muscle tissue, a gelatin substance was made (10.7m% gelatin-to-water). This was then poured into the test setup (a box with dimensions 10x10x30cm (Figure 38)) and left to harden. The canal is simulated by embedding a garden hose with a diameter of 17mm into the gelatin with a bullet placed at the end. This hose deflects in the same way as the actual canal could. After the gelatin has hardened the hose is removed to complete the canal simulation. The prototypes are now guided through the canal until they reach the bullet. Then the mechanical properties and functionality of the different prototypes can be tested. These tests will mainly function as a proof of concept. After some improvements the devices will be printed to scale and tested in PVA [16]. PVA is a hydrophilic material that is comparable to human tissue. The particular PVA has a 6.6 m% PVA-to-water, simulating the stiffness of the tissue of an elephant. The percentage is based on the values used in liver tissue simulations in the research done by J. de Jong et al. (2017)[17].

3.7 Final Designs

In theory the three designs work. To further eliminate these options, tests will have to be performed. The tests will be practical. First the test will be performed with scaled up plastic printed prototypes. Secondly the refined models will be tested at 1:1 scale. Finally, based on the preferences and the functioning, a decision will be made on which design is best.

4 Tests & Results

4.1 Printed prototypes

The first 3D printed prototypes (Appendix F) were printed scaled up by factor two by the UltiMaker in polylactic acid (PLA)[18] to see if the concepts work. Since this 3D-printer is filament based (about 0.4mm resolution in this case), the orientation of the printed object relative to the printing direction influences the mechanical properties. As seen in Figure 23 and Figure 24 in Appendix E, stress is mainly localised in the bending points. Therefore the prints were made in longitudinal direction to minimise failure due to bending (Figure 29). This prototype was tested in a simulated situation and provided a proof of concept for the wedged capsule (Figure 27).

The Form 2 -3D Printer 'Grey Pro' prints a photopolymer with a resolution of 25-300microns [19] (Figure 31). The Sliding Joint Gripper concept was printed and scaled up twice, allowing a proof of concept (Figure 30).

Providing a proof of concept for the Bullet Pince is more difficult, since the dimensions require high precision manufacturing methods that only very accurate 3D-printers can obtain. However, this concept is already being used to perform biopsies on human tissue so therefore there is proof of concept at a model that is scaled down bij a factor nine [20]. With proper and advanced fabrication methods this idea could be produced and tested.

The EnvisionTEC Perfactory P4K [21], a high resolution (50-100microns) 3D-printer, was employed to print the prototypes to scale. It prints using a photopolymer which is a substance on methacrylate-/ acrylate-basis called R5 [8]. After printing, the prototypes were treated with UV radiation to harden them. To improve the mechanism for the wedged capsule the UV treatment was applied in two stages. In the first stage the entire device was treated and in the second stage the tips of the device were additionally hardened. This was done to ensure the bending points are placed properly and the tips of the arms have a higher stiffness. Also, to prevent the arms from bending in the wrong direction under the pressure of the tissue. The prototypes are visualised in Appendix F: Sliding Joint Gripper (Figure 28), Wedged Capsule (Figure 27) and the Bullet Pince (Figure 36).

4.2 Tests

The goal of the following experiments is to test the functionality of the devices and their critical points. The test setup will be as described in paragraph 3.6. Multiple tests will be performed with the printed prototypes. The controlled variables will be the bullet size (8mm diameter and 10mm diameter), the medium in which the test will be performed (gelatin, PVA 2 freeze cycles, PVA 3 freeze cycles) and the material from which the prototypes are printed (PLA, Grey Pro, R5). The device will be inserted into the canal by hand with a velocity of approximately 5mm/s. Due to the absence of an endoscope, the operator has to feel when the device has reached the bullet. The grabbing mechanism shall then be triggered. The device will be removed at a velocity of approximately 3mm/s after encapsulating the bullet to ensure there is no rupture in the test setup. The tests will give a qualitative result rather than a quantitative result. It should provide a proof of concept to justify the further development of the tool and a clear indication which concept has the most merit.

4.2.1 The Sliding Joint Gripper

Whilst testing the sliding joint gripper (Figure 30 in Appendix F), some complications emerged which led to improvements of the design. The first prototype of PLA the resolution was too low and as result the parts did not fit. In Grey Pro, when triggering the grabbing mechnism, it turned out that the pressure of the gelatin on the arms was too high. The resulting width of the spread arms was smaller than expected. Therefore, the Sliding Joint Gripper was not able to reach behind the bullet. After this test the following improvement was made: in order to increase the stiffness of the arms, it was made in a geometrically stronger shape. When printed to scale in R5 (Figure 32) the stiffness was still not sufficient to stretch the PVA two freeze cycles. This is due to the material properties of R5.

4.2.2 Wedged Capsule

The force exerted on the arms of the Wedged Capsule by the truncated cone turned out to be high enough to widen the gelatin around both a large and a small bullet. This resulted in a working bullet removal device. Despite the fact that this is a positive result, two points of improvement were implemented. First of all, the arms of the Wedged Capsule turned out to be sensitive to fatigue in the pivot points. Another problem is that the geometric shape of these pivot points is too weak. The arms broke at this exact same point two times, so the design was altered so that the bending points were more flexible and more material was added in the critical points. The Wedged Capsule in R5 (Figure 33 and Figure 34) can broaden its six arms wide enough in the tissue and can secure the large and small bullet inside, see Figure 39. After three freeze cycles of the PVA the Wedged Capsule could no longer create enough force to get around the bullets.

4.2.3 Bullet Pince

The Bullet Pince is made of three main parts that have to fit perfectly. The PLA printer was not accurate enough to reach this result. In Grey Pro the parts of the prototype did not slide over each other easily but there was a proof of concept. To improve this in the R5 prototype the fit was amended to be less tight to ensure the working principle would function (Figure 36). The knives of the Bullet Pince in R5 are quite sharp due to the accurate printing. However, the device the locking mechanism that should have enough prestress to cut through the tissue, this was not the case in R5. When testing the R5-prototype Bullet Pince on PVA (two freeze cycles and three freeze cycles), it did cut through the tissue partially but did not enclosed the bullet. Operating the device was not easy.

5 Discussion

5.1 Comparison

Based on the test results, the design and assembly, the considerations and evaluation in Table 3 are drafted.

	Max Score	Sliding Joint Gripper	Wedged Capsule	Bullet Pince
Functionality	10	5	8	7
Maintenance	7	3	6	5
Fabrication	5	3	4	4
Invasiveness	5	4	3	2
Convenience	4	3	3	2
Total	31	18	24	20

Table 3: Quantitative analyses of prototype test results and design.

The functionality of the prototypes is of great importance since the goal can only be achieved if the tool functions. The required maintenance should be low since resources in Myanmar are scarce. Fabrication includes both how difficult and how expensive it is to fabricate. This factor is less important but should definitely be taken into account. Invasiveness also should be considered, but factored in less heavily than functionality and maintenance. The device will operate in scar tissue, which is less sensitive than normal tissue and the healing process is improved by removing this tissue therefore the procedure can be a little invasive. Convenience entails convenience in usage. This mainly desirable for the operator but also ensures more safety, as an easy protocol leaves less things that can go wrong.

5.1.1 Functionality

Functionality is a combination of the efficiency and success of retrieving a bullet. The Sliding Joint Gripper has more difficulty in successfully retrieving a bullet in comparison with the other designs. This is because it does not completely enclose the bullet, which makes it more vulnerable to forces in the canal. The Wedged Capsule uses the inward pressure of the canal to keep the bullet locked inside and works quite efficiently. The challenge regarding the functionality of the Bullet Pince lies in the locking mechanism that needs enough pretension to cut through a few millimetres of tissue in order to fully enclose the bullet.

5.1.2 Maintenance

The maintenance takes multiple things into account; reshaping and repolishing the material and part replacement. The vulnerable parts of which the Sliding Joint Gripper consists, make it the prototype that is most likely to need frequent maintenance to replace parts (due to fractures and wear). The Wedged Capsule and the Bullet Pince both require frequent repolishing in order to keep the tips sufficiently sharp. Especially the Bullet Pince has very thin and sharp tips that get blunt and deflected during impact with the bullet.

5.1.3 Fabrication

The difficulties in fabrication mainly lie with manufacturing errors and post-processing such as polishing and heat treatments. The dimensions of the parts, out of which the Sliding Joint Gripper is built, are a very small, especially the joints which have a thickness of about 1mm. These joints have forces acting on them, which make them susceptible to failure due to fractures, also during manufacturing. The first times the prototypes where created, the material often failed during assembly or during the printing phase. The main difficulty with fabricating the Wedged Capsule and the Bullet Pince is polishing afterwards in order to decrease the surface roughness. This must be done to make cutting through the tissue more efficient. This way, polishing is especially important for the Bullet Pince since sharp edges are an absolute must for the design to work. The main difference between the three prototypes is the amount of parts, difficulties during assembly and post-processing of the material.

5.1.4 Invasiveness

None of the prototypes seriously compromise the health of the organism during surgery. They are, however, not equally invasive. Particularly, the Bullet Pince is invasive because it cuts through tissue both the most and the deepest. Moreover the device has a diameter of 13mm which means that the canal is constantly stretched to 1.5 times its own size which is also considered invasive. The Wedged Capsule is less invasive but there is a possibility that it pokes into the tissue when in its deflected state. The Sliding Joint Gripper is the least invasive since it only has two arms that can inflict damage to the tissue. This concept also rests on the principle that it stretches the canal longitudinally therefore only changing the shape of the canal, not the circumference.

5.1.5 Convenience

Convenience is the combination of prior knowledge needed to operate the device and complexity of effectively operating the device. All of the devices are actuated by Bowden cables. The current design of the Bullet Pince, however, uses two cables which makes it more difficult to operate, especially because its design requires more caution whilst using it. During the tests with a prototype, this device was difficult to manage. The Sliding Joint Gripper, that is actuated by one cable, has the highest risk of losing contact with the bullet whilst pulling the cable out of the canal. Compared to the others, the Wedged Capsule is easiest to use.

5.2 Implications of test results

The evaluation factors in the previous paragraph can be used to discuss implications of the test results. The Wedged Capsule concept proves to be the best bullet removal device, according to Table 3. The best design specific aspect of this concept is the fact that is is able to grab bullets of different sizes with considerable force by using six points of contact. However, an important statement has to be made. In Chapter 3.5.4 it is stated that the final design would be made using the titanium alloy printing LASERTEC 30 SLM 2^{nd} Gen. As a result of high demand on using this printer, it was not possible to use it in the scope of this thesis. Therefore, other materials such as PLA, ABS and R5 (paragraph 4.1) were used to fabricate the prototypes. Due to the lower stiffness of these materials, the Sliding Joint Gripper was not able to widen the tissue enough to reach beside the bullet in every test scenario.

6 Conclusion

The goal of this thesis is to design a device that can remove a bullet from an elephant. In the design process of this thesis, the ACRREx method was used to achieve three possible device concepts. As discussed in Chapter 5, the Wedged Capsule was selected as best concept using the evaluation in Table 3. As stated in paragraph 5.2, the prototypes in this thesis were made out of PLA, Grey Pro and R5. The stiffness of the prototypes made of Grey PRo was not sufficient to widen the canal of the wound enough to enclose the bullet. It was not possible to print the PLA prototype to scale so it can be concluded that the final gripper prototype has to be made out of R5. However, as is stated in paragraph 5.2, one could reach a significantly higher stiffness and thus higher chance of succeeding if the device would be printed in a titanium alloy (paragraph 3.5.4).

7 Recommendations

In order to get a functioning and reliable device, we strongly recommend further development and research of the Wedged Capsule, using a high-resolution 3D-printer because of the necessity of precision. The preferred material is titanium-alloy due to its high wear-resistance, bio-compatibility, stiffness and strength. To test the design, the use of PVA is recommended because it best mimics the mechanical properties of mammalian tissue. One extra improvement that could be investigated is adding a break system for the push back of the truncated cone. During the test phase there was no endoscope available yet. Therefore, one could push the truncated cone back too far, which resulted in knocking the bullet out of the device. A break system could prevent this from happening and make the handling easier for the operator.

The Bullet Pince shows some prospects, therefore we recommend that further research should be conducted with varying bullet orientation because the device may have an advantage over the Wedged Capsule in cases where the bullet is not optimally oriented. In the case of redesigning it is recommended to use a locking principle that shape-locks the bullet to minimise risk of loosing contact with the bullet.

The Sliding Joint Gripper could also be promising if applied in lateral gripping instead of distal as it can then exert more force to stretch the canal. This could also be an interesting research.

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Appendices

A Case study

Figure 12: Shoulder wound

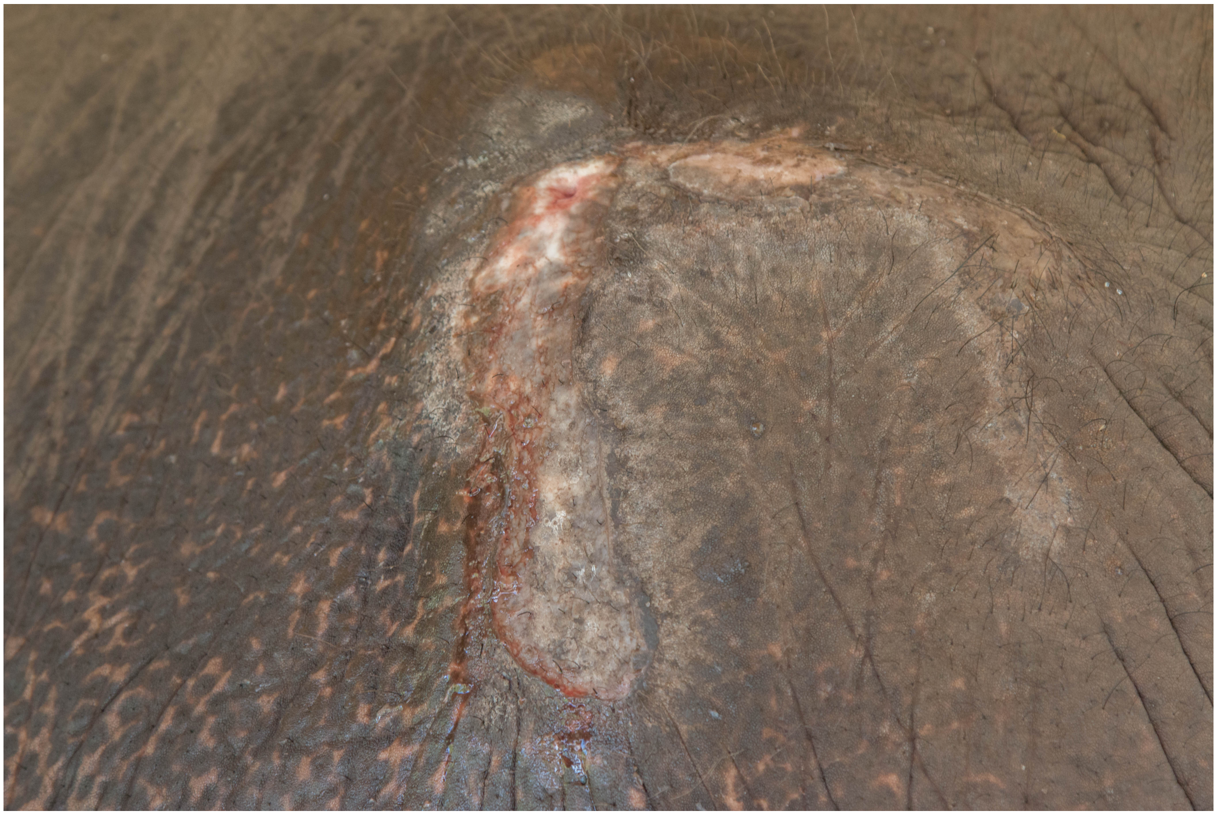

Figure 13: Shoulder wound close up

Figure 14: Leg wound

Figure 15: Close up elephant wound leg

Figure 16: Cleansed wound

B Force Analysis For Gripping Methods

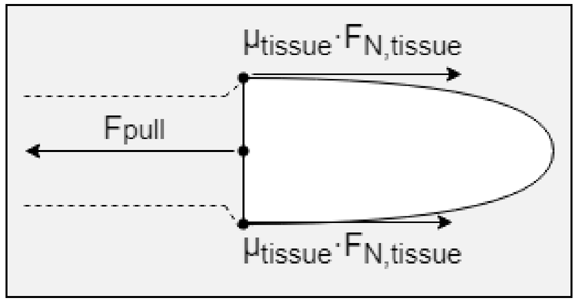

Figure 17: General force analysis for proximal gripping.

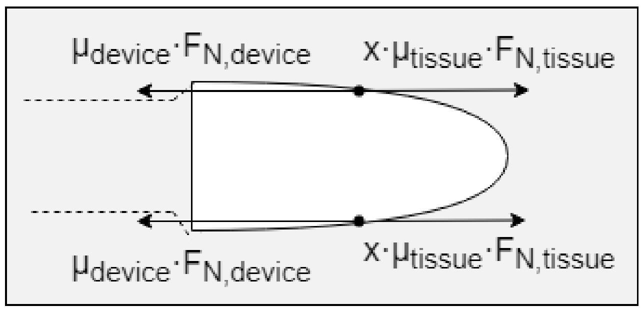

Figure 18: General force analysis for lateral gripping. Factor x depends on the horizontal point of engagement of the device.

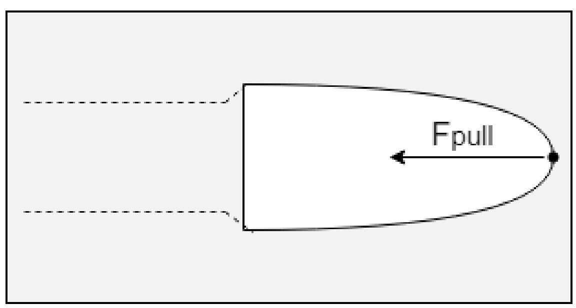

Figure 19: General force analysis for distal gripping.

C ACRREx

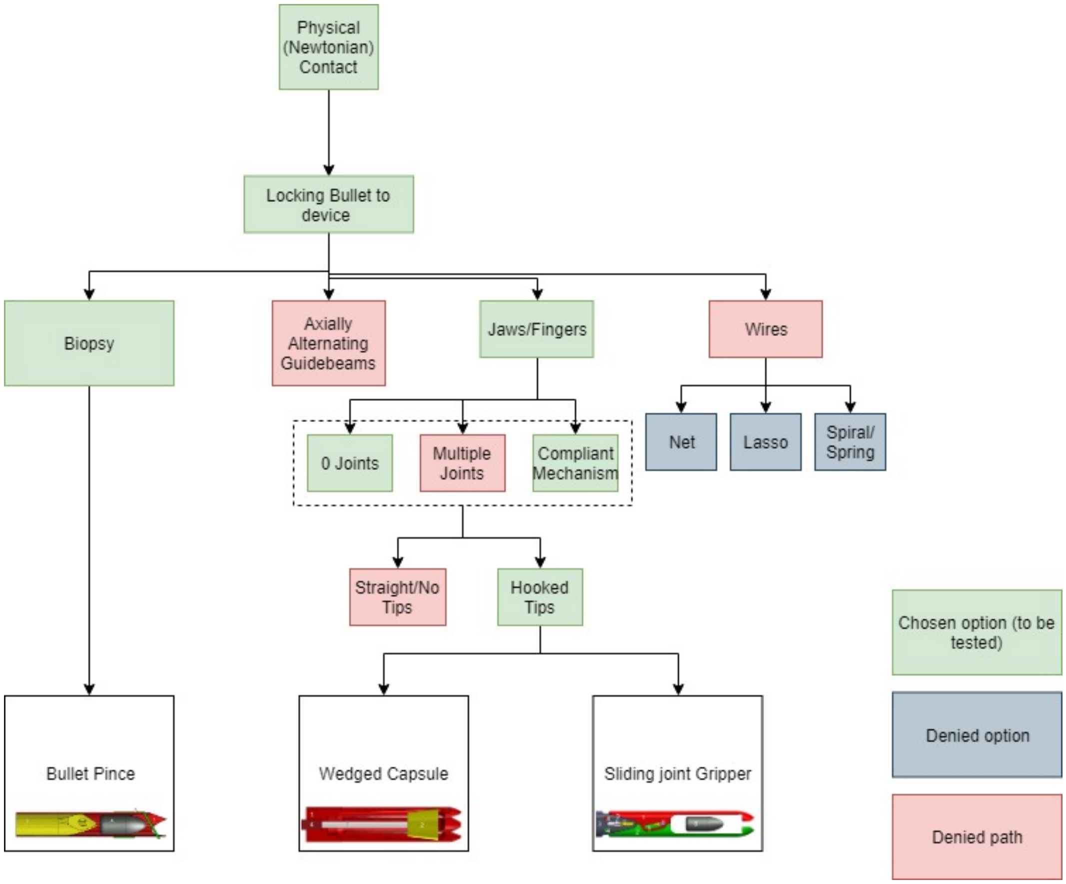

Figure 20: ACRREx tree concepts

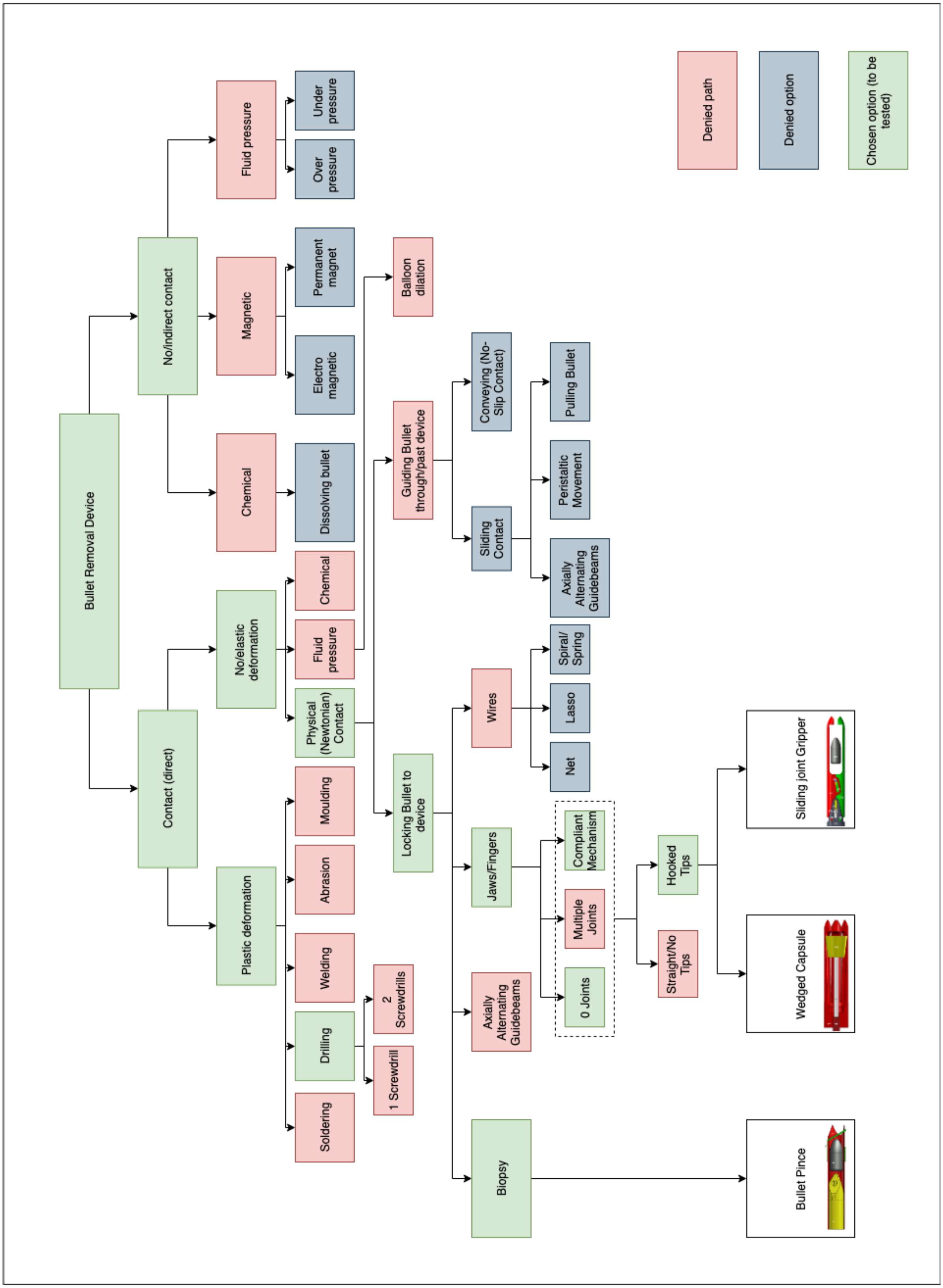

Figure 21: ACRREx tree

D Estimation of Required Torque

For an introduction to Equations 8 to 10, see section 3.3.1. $E_c = E_{canal}$:

$$\varepsilon_\phi(r) = \frac{1}{E_c}(\sigma_\phi(r) + \nu\sigma_r(r)) \tag{8}$$

$$\sigma_r(r) = \lim_{b\to\infty} \frac{a^2 p_i}{b^2 - a^2}(1 - \frac{b^2}{r^2}) = -\frac{a^2 p_i}{r^2} \tag{9}$$

$$\sigma_\phi(r) = \lim_{b\to\infty} \frac{a^2 p_i}{b^2 - a^2}(1 + \frac{b^2}{r^2}) = \frac{a^2 p_i}{r^2} \tag{10}$$

Substituting Equations 8 and 9 into Equation 10:

$$\varepsilon_\phi(r) = \frac{a^2 p_i}{E_c r^2}(1 - \nu) \tag{11}$$

Taking the circumferential strain at the inner surface of the canal section ($\varepsilon(a)$, Equation 11), defining $a_0 = a$ and l_0 as the radius and circumference respectively before straining the canal: Defining a_1 and l_1 as the radius and circumference after straining the canal: Defining $a_1 - a_0$ as w:

$$\varepsilon_\phi(a) = \frac{p_i}{E_c}(1 - \nu) = \frac{l_1 - l_0}{l_0} = \frac{2\pi(a_1 - a_0)}{2\pi a_0} = \frac{w}{a_0} \tag{12}$$

Rewriting Equation 12 to solve for p_i and introducing the dependency on x of p_i and w:

$$p_i(x) = \frac{w(x)E_c}{a(1 - \nu)} \tag{13}$$

Setting up the Differential Equation for the stored energy in a section of the canal:

$$dU_{canal}(x, w(x)) = p_i(x)dV = p_i(x) \cdot 2\pi a \cdot dwdx \tag{14}$$

Integrating Equation 14

$$\begin{aligned} U_{canal} &= \int_0^L \int_0^{w(x)} 2\pi a_0 p_i(x, w'(x))dw'dx \\ &= \int_0^L \left[2\pi a_0 \frac{w'(x)^2 E_c}{2a_0(1 - \nu)}\right]_0^{w(x)} dx \\ &= \int_0^L \frac{\pi E_c}{1 - \nu} w(x)^2 dx \end{aligned} \tag{15}$$

Solving $w(x)$ according to the boundary conditions specified in section 3.3.2:

$$w(x) = Ax^2 + Bx + C \tag{16}$$

$$w(0) = 0 \to C = 0 \tag{17}$$

$$\frac{\partial w}{\partial x}(L) = 0 \to 2AL + B = 0 \to B = -2AL \tag{18}$$

$$w(L) = y \to AL^2 - 2AL^2 = y \to -AL^2 = y \to A = -\frac{y}{L^2} \tag{19}$$

$$B = \frac{2y}{L} \tag{20}$$

$$w(x) = -\frac{y}{L^2}x^2 + \frac{2y}{L}x \tag{21}$$

Obtaining the actuation angle of the beam θ as a function of y in Equation 22 and vice versa in Equation 23:

$$\theta \sim \frac{\partial w}{\partial x}(0) = B = \frac{2y}{L} \tag{22}$$

$$y = \frac{L\theta}{2} \tag{23}$$

Substituting Equation 21 into Equation 15 and soolving it:

$$\begin{aligned} U_c &= \int_0^L \frac{\pi E_c}{1-\nu}(\frac{y^2}{L^4}x^4 - \frac{4y^2}{L^3}x^3 + \frac{4y^2}{L^2}x^2)dx \\ &= \left[\frac{\pi E_c}{1-\nu}(\frac{y^2}{5L^4}x^5 - \frac{y^2}{L^3}x^4 + \frac{4y^2}{3L^2}x^3)\right]_0^L \\ &= \frac{\pi E_c}{1-\nu}(\frac{1}{5} - 1 + \frac{4}{3})y^2 L \\ &= \frac{8\pi E_c y^2 L}{15(1-\nu)} \end{aligned} \tag{24}$$

Using Classical Beam Theory to obtain the elastically stored energy U_B inside of the beam:

$$\begin{aligned} U_B &= \int_0^L \frac{M(x)^2}{2E_B I}dx \\ &= \int_0^L \frac{(\frac{d^2}{dx^2}E_B I w(x))^2}{2E_B I}dx \\ &= E_B I \int_0^L \frac{(2A)^2}{2}dx \\ &= E_B I \left[2A^2 x\right]_0^L \\ &= 2A^2 E_B I L \\ &= \frac{2E_B I y^2}{L^3} \end{aligned} \tag{25}$$

Adding up Equations 25 + 24 to obtain the total energy needed to stretch the canal radius up to the profile of $w(x)$:

$$\begin{aligned} U_t &= U_c + U_B \\ &= \left(\frac{4\pi E_c L^4}{15(1-\nu)} + E_B I\right) \cdot \frac{2y^2}{L^3} \end{aligned} \tag{26}$$

Obtaining the required torque applied at the joint of the beam by differentiating U_t with respect to $/theta$.

$$\begin{aligned} T(\theta) &= \frac{\partial U_t}{\partial \theta} \\ &= \frac{\partial}{\partial \theta}\left[\frac{2(\frac{1}{4}L^2\theta^2)}{L^3}\right] \cdot (\frac{4\pi E_c L^4}{15(1-\nu)} + E_B I) \\ &= \frac{\theta}{L} \cdot (\frac{4\pi E_c L^4}{15(1-\nu)} + E_B I) \end{aligned} \tag{27}$$

$$T(y) = \frac{2y}{L^2} \cdot (\frac{4\pi E_c L^4}{15(1-\nu)} + E_B I) \tag{28}$$

E COMSOL Multiphysics® Modeling Software

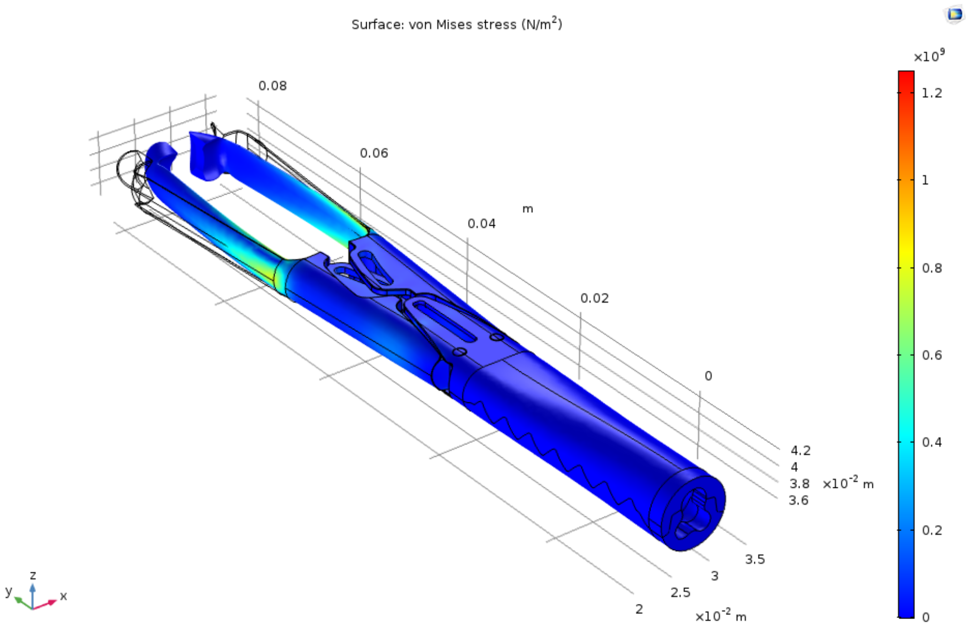

Figure 22: Stress Sliding Joint Gripper

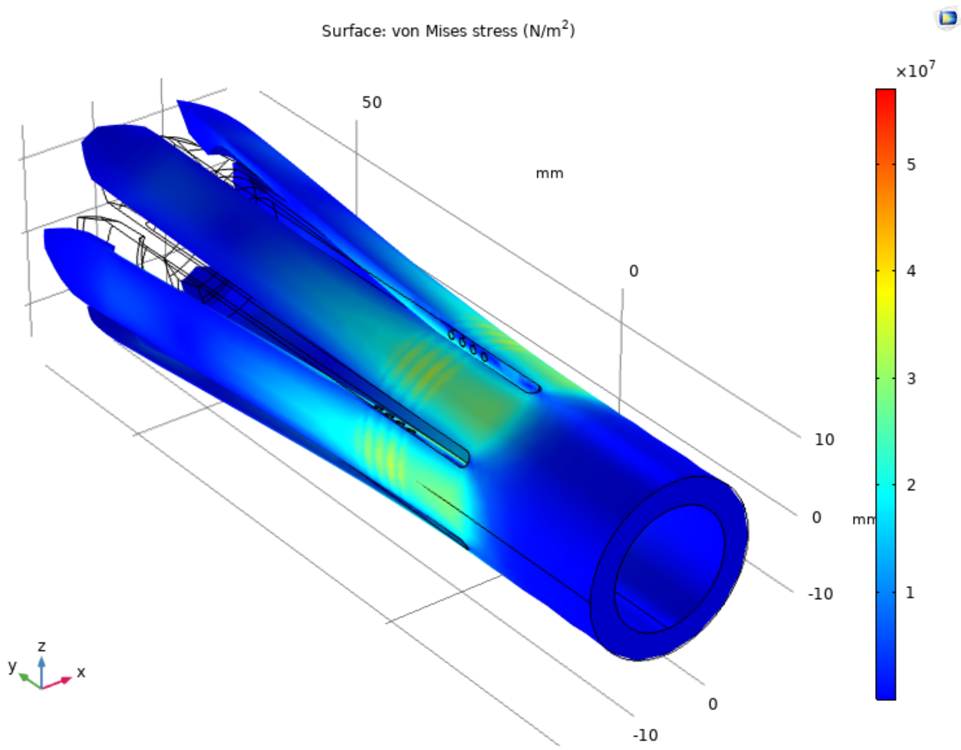

Figure 23: Stress Wedged Capsule

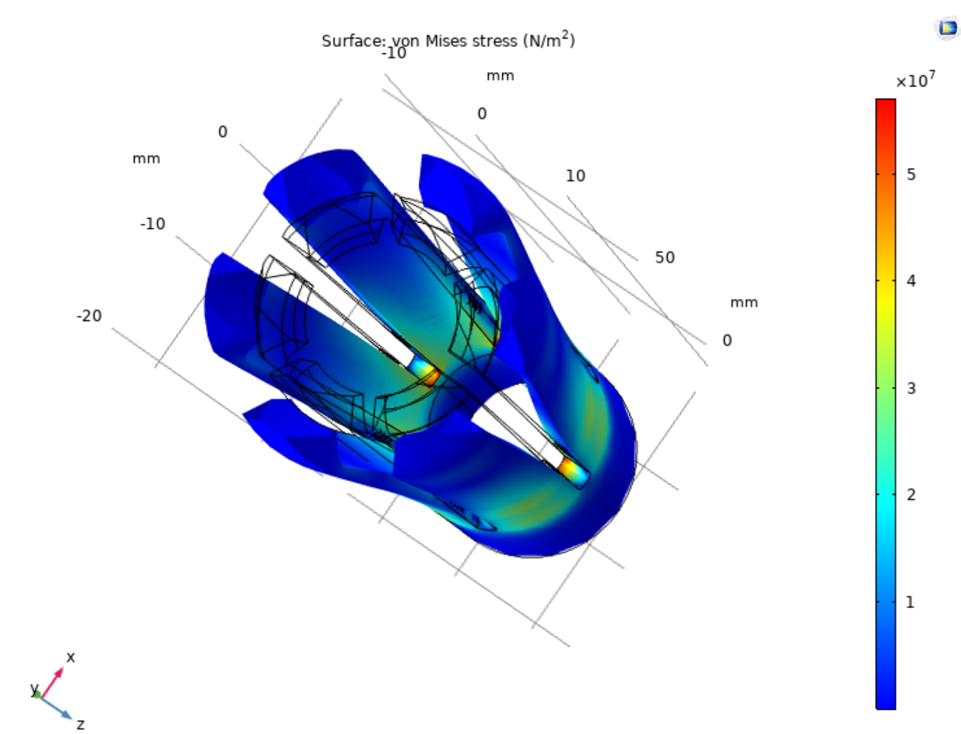

Figure 24: Stress Wedged Capsule

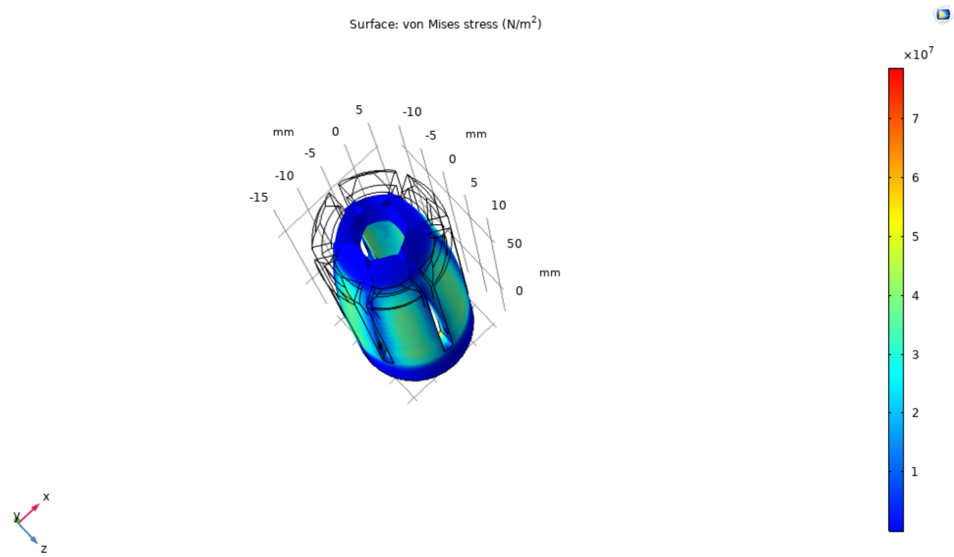

Figure 25: Stress Wedged Capsule

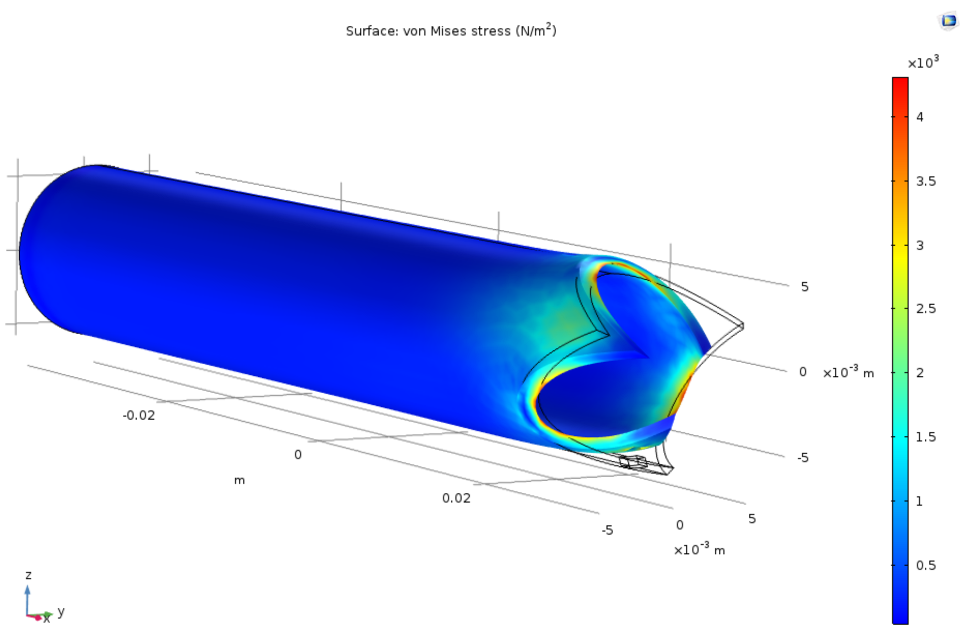

Figure 26: Stress Bullet Pince

F Prototypes

Figure 27: Prototype 1 Wedged Capsule

Figure 28: Prototype Sliding Joint Gripper

Figure 29: Prototype longitudinal printed Wedged Capsule

Figure 30: Working prototype Sliding Joint Gripper

	METRIC[1]		IMPERIAL[1]		METHOD
	Green[2]	Post-Cured[3]	Green[2]	Post-Cured[3]	
Tensile Properties					
Ultimate Tensile Strength	35 MPa	61 MPa	5076 psi	8876 psi	ASTM D 638-14
Tensile Modulus	1.4 GPa	2.6 GPa	203 ksi	377 ksi	ASTM D 638-14
Elongation	32.5 %	13 %	32.5 %	13 %	ASTM D 638-14
Flexural Properties					
Flexural Stress at 5% Strain	39 MPa	86 MPa	5598 psi	12400 psi	ASTM D 790-15
Flexural Modulus	0.94 GPa	2.2 GPa	136 ksi	319 ksi	ASTM D 790-15
Impact Properties					
Notched IZOD	not tested	18.7 J/m	not tested	0.351 ft-lbf/in	ASTM D256-10
Temperature Properties					
Head Deflection Temp. @ 1.8 MPa	not tested	62.4 C	not tested	144.3 °F	ASTM D 648-16
Heat Deflection Temp. @ 0.45 MPa	not tested	77.5 C	not tested	171.5 °F	ASTM D 648-16
Thermal Expansion (-30 to 30° C)	not tested	78.5 um/m/C	not tested	43.4 µin/in/°F	ASTM E 831-13

Figure 31: Mechnical Properties Photopolymer

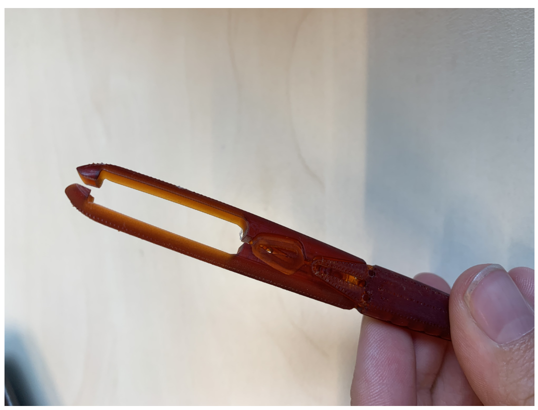

Figure 32: Sliding Joint Gripper

Figure 33: Wedged Capsule Closed

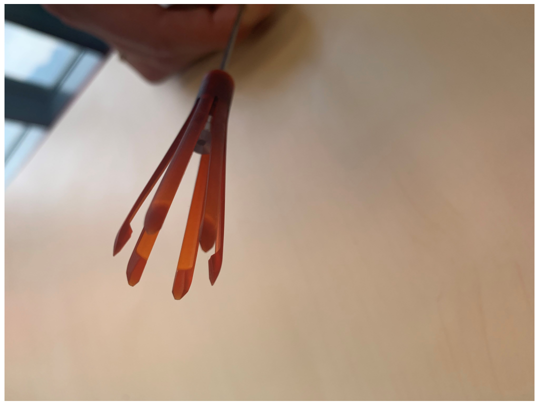

Figure 34: Wedged Capsule Open

Figure 35: Bullet Pince

Figure 36: Bullet Pince Knife

Figure 37: Set Up Gelatine

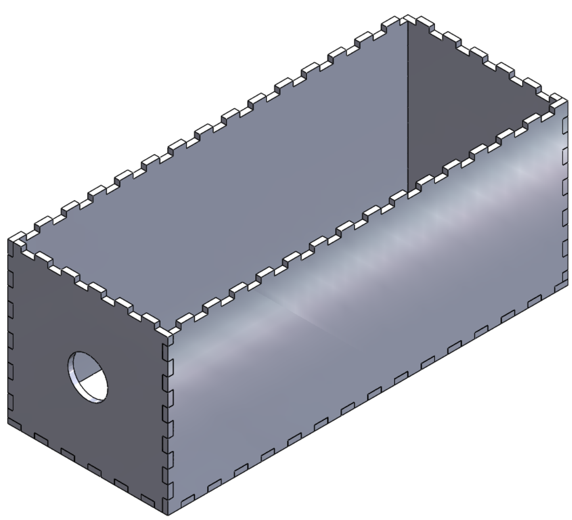

Figure 38: Housing Set Up

Figure 39: Wedged Capsule tested in PVA