

Elephantine Laparoscopy

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Designing a medical device to remove bullets from
live elephants



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by

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Background Elephants that wander onto the fields of farmers in Myanmar are being shot with makeshift guns. By doing this, the farmers are able to make these animals leave the area without killing them. This results in elephants walking around with bullets inside their body and wounds that need to be looked after. Traditional methods for bullet removal are not allowed in Myanmar as the government does not allow surgery on these government-owned animals.

Method A set of requirements was determined based on a case research provided by a veterinarian. It was determined that a gripper needed to be designed that is able to reach down a 1 m deep fistula with a diameter of 8 mm. The gripper has to be able to provide visual assistance and rinse the fistula during the procedure. The focus of this research was placed on the gripper head, as there are already flexible and steerable shafts designed. The best gripper was to be determined by a pulling test where the maximum pulling force was measured. Another important requirement was the versatility of the gripper. The shape and size are not 100% certain so the gripper must be able to grasp multiple bullet shapes.

Results The important requirements were met in the final design. For the test phase, multiple prototypes were made with slight alterations in the design. Force measurements determined a higher pulling force on an 8 mm spherical bullet with 4 arms (Median= 16.59 N, IQR= 4.7) than with 3 arms (Median= 13.07 N, IQR= 2.3). The pulling force on that bullet was highest with a tip length of 3 mm (Median= 17.49 N, IQR= 2.9). The final design was used in a gelatin 'phantom' to show its usefulness in a more realistic setting. The gripper was able to remove the bullet five out of five times.

Conclusion The 4 armed 3 mm tipped gripper is able to travel through the bullet wound without creating new holes and able to grasp and retract from the wound with the dexterity of a veterinarian.

Preface

This research was written from a deep passion for prototyping and a love for animals. The ability to make a difference that helps take the load of the shoulders of the caregivers is also a very nice addition to this. The problem with farmers shooting the elephants to scare them off is that it is not yet possible to trace the farmer that did this. Creating a solution that brings justice is a great way to end a Master in Biomedical Engineering. The addition that the medical device could be used in more situations than one is even more exciting.

The results that came out of this research would not have been possible without the great supervision of Dr. Gerwin Smit, Dr. Aimée Sakes, Dr. Willem Schaftenaar and prof. Paul Breedveld. Special thanks also go out to Remi van Starkenburg for his great help with creating the prototype. Jos van Driel is thanked for his help with the test setup. Finally the author would like to thank friends and family that provided support during the writing process.

*T.M. Jamin
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Contents

1	Introduction	1
1.1	Elephant Poaching	1
1.1.1	Scaring off elephants	1
1.1.2	Ivory poaching	1
1.2	Reasons for bullet removal.	2
1.2.1	Saving elephants from infection	2
1.2.2	Elephantine forensics	2
1.3	Goal of this study	2
1.4	Layout of this study.	3
2	State-of-the-art	5
2.1	State-of-the-Art in Elephant Gun Mechanics	5
2.1.1	Common bullet sizes	5
2.1.2	Bullet types	6
2.1.3	DIY Bullets	7
2.2	State of the art in bullet removal	8
2.3	Other state of the art removal procedures.	9
3	Design requirements	11
3.1	Case study: Hnin	11
3.2	Case Study: Assumptions	11
3.3	Design requirements	12
3.4	Design wishes	13
3.5	Setting.	13
4	Bullet removal process	15
4.1	Intended Bullet Removal Procedure.	15
4.2	Reaching the bullet.	15
4.2.1	Categorization	15
4.2.2	Leaving the connective tissue intact.	16
4.2.3	Pushing the fistula wall out of the bullet's way	16
4.2.4	Removing the fistula wall tissue	16
4.2.5	Removing the bullet prior to removing the fistula wall tissue	17
4.2.6	Decision making: cutting	17
4.3	Bullet removal	17
4.3.1	Morphological overview	17
4.3.2	Grabbing options	17
4.3.3	Going around the bullet and gripping it from the front	19
4.3.4	Gripping the bullet from the side.	19
4.3.5	Gripping the bullet from the rear.	19
4.4	Design directions	20
4.5	Bullet removal concept development	20
4.5.1	Going around the bullet and gripping it from the front	20
4.5.2	Gripping the bullet from the side.	22
4.5.3	Gripping the bullet from the rear.	24
4.6	Harris Profile	25
4.6.1	Decision making: grasping.	26

5	Final conceptual design	29
5.1	Gripper design	29
5.1.1	Leaving the fistula intact	29
5.1.2	Gripper Design	29
5.1.3	Minimizing friction	30
5.1.4	Fabrication	30
5.2	Design dimensions	31
5.2.1	Calculations on the gripper arm	31
5.2.2	Not removing the fistula wall	31
5.2.3	Simplicity	32
5.3	The Prototype.	32
6	Experimental phase	35
6.1	Experimental protocol	35
6.1.1	Experimental Goals	35
6.1.2	Experimental Variables.	35
6.1.3	Experimental Set-up	36
6.1.4	Data Analysis.	38
6.2	Results	39
6.2.1	Pulling.	39
6.2.2	Pushing	39
6.2.3	Boxplots.	40
6.2.4	Damage to the bullets	40
6.2.5	Proof of concept	41
7	Discussion	43
7.1	Main findings	43
7.2	Limitations	43
7.3	Recommendations	44
7.4	Future vision	44
8	Conclusion	47
A	Fistula cutting options	51
A.1	Tissue removal concept development.	51
A.1.1	Pushing the fistula wall out of the bullet's way	51
A.1.2	Cutting by pushing	51
A.1.3	Cutting by pulling	52
A.1.4	Cutting tangential.	53
B	One device with two functions	57
B.1	Combining concepts	57
B.1.1	Stent devices	57
B.1.2	Spinning razor blade devices	57
B.1.3	The umbrella scraper device.	58
B.1.4	Apple corer devices	59
B.1.5	Grater devices	59
B.1.6	Milling cutter devices	59
C	Rejected designs	61
C.1	Rejected designs	61
C.1.1	Rejected concepts due to practicalities	61
C.1.2	Selected designs	61
C.1.3	The closing tube mill	62
C.1.4	The wedge gripper mill	62
C.1.5	The three point gripper razor blade	65
C.2	Design selection	67

D	Transmission for the cutting device	69
D.1	Rotation of the device in low resource setting.	69
D.1.1	The distal end.	69
D.1.2	Clamping	70
E	Code used in Matlab	71

Introduction

1.1. Elephant Poaching

1.1.1. Scaring off elephants

Elephants in Myanmar can sometimes wander onto the property of farmers. This is mostly because these elephants are attracted by the crops that the farmers are growing. These dangerous creatures then go onto the farms and feast on the crops that are the livelihood of the farmer. The farmers then shoot these elephants to try and protect the crops. The guns that are used by these farmers are no factory made weapons. The guns are mostly makeshift guns held together by some wires and straps wound around the barrel. Figure 1.1 shows these guns on a picture taken by a veterinarian that helps with the elephants. The goal of the farmers is not to kill the elephant but to scare or hurt it enough that it wanders off the property. This way the crops will not (all) be trampled or eaten by the elephant.



Figure 1.1: Makeshift guns used to shoot elephants, next to some unknown objects.

1.1.2. Ivory poaching

Next to removing bullets from live elephants, this research could prove useful in postmortem research on elephants that were killed for their tusks. Ivory poaching has become a large problem in Africa. This is due to a number of factors. China has a large demand for ivory to use in luxury jewelry. There is a small amount of ivory that is legally supplied but this is (apparently) not enough. Another problem is the customs inspection in the port of Hong Kong, where less than 1% is inspected before it is allowed into the country. Corruption is another big factor that contributes to the ongoing trade in illegal ivory. In addition to that, the poachers have large networks of criminals and corrupt law enforcers behind them [1].

The gross of ivory poaching takes place in Africa and up to 70% of it ends up in China. 25,000 elephants were poached in Africa in 2012. That is more than 68 elephants per day. The African elephant has an IUCN (International Union for Conservation of Nature) status of vulnerable, which means that the status will be moving to endangered if the circumstances do not improve [1]. Ivory is also used medicinally, especially in China. Ivory powder, or 象牙 (Xiang Ya) in Chinese, is believed to "Clear heat and relieve convulsions, remove toxicity and promote tissue regeneration." There are mentions of the treatment of ulcers, osteoporosis and sore throats with ivory powder[2].

Ivory poaching does not only apply to elephants. Rhinos are often poached for their horn. Ed Hern, a Lion and Rhino reserve owner in South-Africa came up with the initiative to poison the rhino horns that are known to be consumed in Asia. The intention was to "kill or seriously harm anyone who consumes rhino horn". This method was harmless to the rhino as there is no connection to the bloodstream in the horn. Unfortunately, it was deemed inhumane by many and turned out to be less effective as the toxin did not spread throughout the horn. This method seems promising and could be very effective when a toxin can be made that does spread through the horn without harming the rhino. [3]

1.2. Reasons for bullet removal

1.2.1. Saving elephants from infection

Once there is a bullet inside the soft tissue, a so-called Foreign Body Response (FBR) starts. FBR's can also happen with implants or other materials that enter the body (e.g. a splinter). Foreign body response is best described as a chronic inflammation. In the event of a non-sterile object (such as a bullet) the inflammation is complicated by an infection. The inflammation does not occur because of the bacteria on the foreign object, but as a healing response. A response of the body is to send macrophages to phagocytize the bullet. This fails, since the bullet is too large and not biodegradable. The body then forms connective tissue around the foreign object [4]. This has also happened in the case of this study: elephant Hnin. Hnin was shot twice over 11 years ago. The entry wounds are now approximately 8 mm diameter holes that run 50 and 80 cm deep, respectively. The bullet has traveled downwards due to gravity, resulting in a curve in the wound. This makes it impossible to use a simple rigid mechanism to remove the bullet. On top of that, a layer of connective tissue has grown on the inside of the wound, possibly rendering the wound narrower than the bullet. In order to remove the bullet it might be useful that this layer of connective tissue is removed prior to the removal of the bullet. Through personal connections with Dr. Willem Schaftenaar, it has become apparent that the thickness of the connective tissue is in the order of millimeters.

1.2.2. Elephantine forensics

The Dutch forensic institute is currently working on a method to link the corpse of a shot elephant to the poacher that shot it. Using this technique, it is believed to be possible to track down poachers and reduce the amount of poached elephants in these areas. The objective here is to investigate the scratch patterns on the bullet and the material of the bullet. This will allow the forensic team to at least determine the type of gun used and tie multiple poached elephants to the same poacher using their bullets. In order to properly investigate the scratch patterns, it is imperative to keep the bullet intact and damage it as little as possible.

1.3. Goal of this study

The goal of this study is to design, fabricate and test a functioning prototype that is able to remove a bullet from an elephant in Myanmar. The focus lies on the case Hnin in Myanmar, but the designed gripper will be tested on other bullets. The main issue for Hnin is that there is no solution to remove the bullet. The elephants are property of the government and they do not allow surgery on the animals. This means that elephants have to walk around with bullet wounds and the bullet remains inside their body. This requires caretakers to clean the bullet wound daily in order to prevent it from clogging up with pus. This is a tedious process for the caregivers. The bullet needs to be taken out before the wound can be allowed to fully heal by itself.

1.4. Layout of this study

In the next chapter, background information on bullets, state of the art technology and other methods to remove foreign objects is given. The Method is discussed in Chapter 3, where the design requirements and wishes are given. Chapter 4 gives concepts for removing bullets. Chapter 5 discusses the final gripper design and prototype. Chapter 6 gives the Experimental setup to validate the design and the results of these experiments. The Conclusion and Discussion are given in Chapters 7 and 8, respectively. The Appendices show the code used to get the results from the raw data and some other design options that were rejected

2

State-of-the-art

2.1. State-of-the-Art in Elephant Gun Mechanics

2.1.1. Common bullet sizes

In order to create a device that can remove bullets from wounds it is important to know what will be removed. Since there is a vast range of bullet types and sizes, it is useful to have an overview. Other cases of elephants being shot in the same area have reported 'DIY-bullets', described in section 2.1.3. Knowledge on standard bullet sizes could benefit this research to be more versatile. The a size comparison of different standard bullets is shown in Figure 2.1 and the bullets are discussed below.

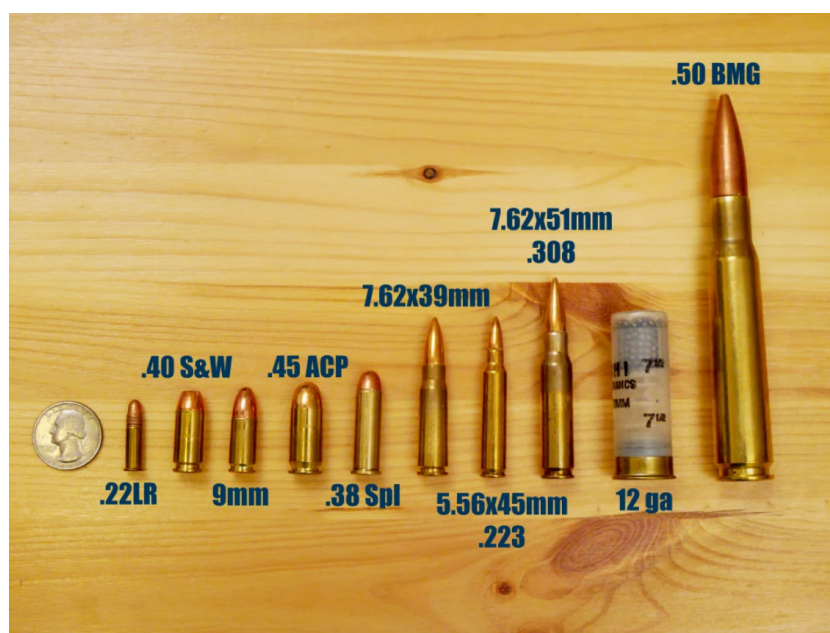


Figure 2.1: Common bullet types, taken from [5]. A united states quarter coin is used to indicate the sizes, which is the same size as a 50 cents euro coin.

The twenty-two Long-Rifle (.22 LR) is a small calibre bullet with a bullet diameter of 5.7 mm [6]. The small bullet is used to hunt rodents, snakes and birds [5]. Next to the .22 LR (in Figure 2.1) lies the .40 (inch) Smith Wesson (.40 S&W) bullet. The .40 S&W has a diameter of 10.2 mm. It was developed to be used by the FBI in their handguns [7, 5]. The 9x19 Parabellum is commonly known as the 9mm (diameter) bullet. It is commonly used by police forces in their handguns and likely the most well known bullet in this overview[8]. The .45 Automatic Colt Pistol (ACP) has a diameter of 11.4 mm. It was created by Browning in the same year as his Colt model 1911, to be used in said gun. It is also used in Tommy guns (drum magazine machine guns) [9]. The thirty-eight special (.38 Spl) has a diameter of

9.65. The bullet is still commonly used in revolvers and dates back to 1880 [7]. Moving to the right in Figure 2.1 we move from handgun ammunition to machine gun ammunition. The 7.62x39mm Soviet is used in the AK-47 (the Avtomat Kalashnikova). It was designed in 1943 in the Soviet Union. At the end of the twentieth century, over 100 million Avtomat Kalashnikovs were produced, setting the record for most produced firearm in history [10]. The 5.56x45 mm NATO round and the .223 Remington bullets have almost the exact same dimensions, with the .223 being 0.1 mm larger in diameter. The 5.56 has more firepower in the cartridge (the part with the gunpowder), making it possible to use .223 bullets in 5.56 rifles. Using 5.56 bullets in rifles designed for .223 bullets is not advised, as these rifles were designed for lower pressure build up. It is used in the (popular) M16, M4 and AR-15 rifles [5]. The 7.62x51 mm NATO bullet is also roughly the same size as the .308 Winchester bullet, with the .308 being 0.2 mm larger in diameter. These bullets are used in (automatic) assault rifles, machine guns and sharp shooting (sniper) rifles [11, 5]. Shotgun shells come in multiple types: birdshot, buckshot and slug. Birdshot shells contain multiple small round pellets, up to 4.5 mm in diameter, that are used to hunt birds or clay pigeons. Since there is no spread of multiple entry wounds it is unlikely that Hnin was shot with a birdshot 12 ga shell. buckshot shells have larger pellets, up to 9 mm in diameter, that are used to hunt animals like deer. Slugs are shotgun shells filled with one single pellet. This slug has a diameter of 20 mm [5]. The .50 BMG or .50 cal (from caliber) was developed to fit the 1921 Browning machine gun. These 13 mm diameter rounds were found to be useful in long distance sharp shooting rifles. In fact, the record for furthest confirmed kill, recently set by a Canadian sharpshooter in Iraq in 2017. The special forces sniper used a McMillan TAC-50 rifle to shoot a .50 BMG 3540 meters. The shot took around ten seconds to reach its target from being fired and the shooter had to calculate the Coriolis force into his aim [12].

2.1.2. Bullet types

Apart from the different size of the bullet, there are a few bullet types that have different properties and effects. Listed below are some common bullet types:

Full Metal Jacket

Full Metal Jacket (FMJ) bullets are regular (normal) bullets, they consist of a soft metal core (usually lead) that is covered by a harder metal (such as copper). The bottom of the bullet is sometimes not covered by the jacket. The tip can be different shapes, depending on the desired application. FMJ keep their shape after being fired and are shown in Figure 2.2 [5].



Figure 2.2: The bottom of the FMJ, taken from [13].

Hollow point

Hollow point (HP) bullets expand on impact, this is done to do more damage to the internal organs of the target. HP bullets do not penetrate the target as deep as FMJ bullets, but are more likely to fatally wound a target. HP bullets are commonly used by law enforcement in the United States. Because of

their shape, these bullets are less aerodynamic and less accurate. Figure 2.3 shows HP bullets before and after firing[5, 14].



Figure 2.3: HP bullets, before and after firing. Taken from [14].

Open Tip Match

Open Tip Match (OTM) bullets are similar to FMJ bullets. The difference is that the full metal jacket is covered from the top to the bottom, sometimes leaving the bottom uncovered, showing the soft metal inside. OTM are covered from the bottom to the top, leaving a small opening at the tip of the bullet (this is the reason for the small opening in the front). This opening does not expand the bullet on impact, as it is designed to be small enough not to. OTM bullets are designed to be more accurate than a FMJ as the bullet base is more uniform and the centre of gravity is further back. Figure 2.4 shows a cross section of two OTM bullets [5, 15].



Figure 2.4: OTM bullets, taken from [15].

Ballistic Tip

In order to use the aerodynamics and accuracy of the FMJ whilst keeping the destructiveness of the HP, the Ballistic Tip (BT) was designed. The BT is basically a HP with a plastic tip on it. This way, the bullet is more aerodynamic and precise whilst being as destructive as a hollow point. The cross section of a BT bullet is shown in Figure 2.5, before and after firing [5, 16].

2.1.3. DIY Bullets

Instead of using factory made bullets that have the gunpowder in a cartridge, it is also possible to use small metal pellets and loose gunpowder (similar to the musket, a front loading weapon). In those cases



Figure 2.5: BT bullet cross section both before and after firing, taken from [16].

the gun consists of a long pipe with a hole for the fuse. To load the gun, the gunpowder is poured into the barrel of the gun. The bullet is then dropped into the barrel on top of the gunpowder. In order to fire, a fuse is inserted and lit. These pellets can be any metal. These pellets can be made by melting the metal into a mold.

2.2. State of the art in bullet removal

Human healthcare has already developed methods to remove bullets from patients. In advanced hospitals, it is possible to make a Computed Tomography (CT) scan and locate the bullet inside the victim. After this, a surgeon can use laparoscopic instruments to remove the bullet through a small hole. This is done by creating two small incisions on the abdomen, inflating it with gas and inserting the endoscope and the gripper into the abdominal cavity. The gripper can then be operated through the handle to grasp the bullet and retract it from the pelvic cavity through the incision made for the surgery. The device used consists of a simple serrated gripper that ensures a firm grip on the bullet [17, 18]. Figure 2.6 shows the laparoscopic gripper holding a bullet inside the pelvic cavity along with a drawing of the device.

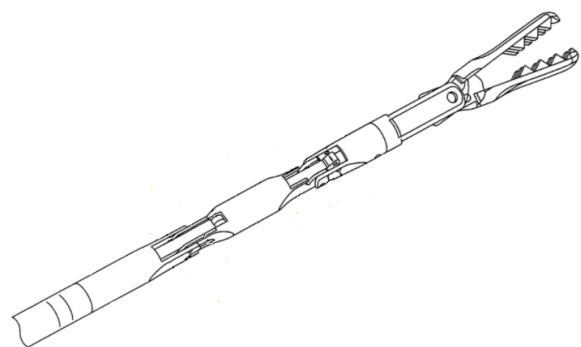


Figure 2.6: The laparoscopic gripper used to remove the bullet from the pelvic cavity (left), taken from [17]. The patent drawing of the gripper is given on the right, adapted from [18]

The removal surgery is performed after the CT scan that is used to locate the bullet [19]. A CT scan is made by a CT-scanner, a rotating x-ray device that spins around the subject, taking multiple x-rays

at different angles. These x-rays are then converted into a higher resolution image. Since there is no CT scanning device available in Myanmar or in the African plains, it is hard to determine the location of the bullet from the outside. A CT scan of the lower abdomen with a metal bullet clearly visible inside is given in Figure 2.7.



Figure 2.7: A CT scan showing the location of the bullet in the abdominal cavity, taken from [20].

Not all bullets require multiple holes to be removed from the body. With a case study showing a bullet lodged in the middle cranial fossa (the floor of the cranial cavity), one hole was made inside the nasal cavity. Through this one hole, the surgery to remove the bullet took place. A florescein was drained into the cerebrospinal fluid, this allowed the flow of the fluid to be traced. The bullet was located at the source of the fluid leak [21]. This bullet was near the subjects brain and could have caused serious damage upon entry, but also during removal as removing the bullet does not go without risk, especially if the bullet resides near the Central Nervous System (CNS). The bullet can be expected to move during the removal surgery, making neurological deficits a possible complication. In non-laparoscopic surgery, or when the bullet is lodged in a superficial position, regular surgical clamps can be used to remove the bullet.

2.3. Other state of the art removal procedures

There are also other medical procedures where something is removed from the body. Unfortunately, these often include reducing the size of the object to be significantly smaller than the hole they have to go through. An example is the 'atherectomy' where the plaque in arteries is cut into small bits to increase the blood flow [22]. Another example of this is the biopsy of bowels, where a small tissue sample is taken from the bowels to examine [23]. Another example from the bowels is the removal of polyps, where a larger chunk of cells is cut from the bowel wall. This is done by introducing a steerable device that cuts the polyps at the base [24].

A better example is the nasal foreign body in children. When a child has stuffed something up their nose and it does not come out, a pediatrician removes it with a few different methods: with tweezers, pressure, suction, glue and a balloon catheter. Tweezers are used to grasp the object and pull it back. Pressure is applied to the other nostril in the hope that the pressure build up behind the foreign object is sufficient to blow the foreign object out. When using suction, the pediatrician uses a catheter to suck the object out. Glue is used to stick the foreign object to a small stick in order to pull it out. Balloon catheters are the last resort before the pediatrician has to refer the patient to the hospital for surgery. A catheter is inserted past the foreign object. A small balloon at the tip of the catheter is filled with water behind the foreign object. By retracting the catheter, the object should come out [25].

Design requirements

3.1. Case study: Hnin

The case study for this research is Hnin the elephant in Myanmar. Hnin has two deep fistulae: one near the distal end of the right humerus and the other near the left scapula. The locations of the fistulae have been given in Figure 3.1. Hnin fell victim to a farmer protecting their crops approximately a decade ago. She can still move around on her own but the fistulae have to be rinsed daily to prevent the wound from closing with the bullets still inside.



(a) The fistula near the humerus



(b) The fistula near the scapula

Figure 3.1: Hnin and her two fistulae

A small tube connected to a hand driven water pump is used to clean the wound daily. Using this tube it is possible to determine the depth and the curve of the fistula. The fistula near the humerus is more curved than the one near the scapula. The fistula near the humerus is also shorter than the fistula near the scapula, measuring 50 and 80 cm deep respectively. Two closeup pictures of the fistula and the tube inserted in the fistula are given in Figure 3.2.

3.2. Case Study: Assumptions

The assumptions that were made in this research relate mostly to the fistula. The most important assumption is that the fistula has a diameter of 8 mm throughout the length of the fistula. It is also assumed that the bullet diameter is allowed to be bigger than the diameter of the fistula with a maximum of 13 mm. The estimated diameter of the bullet is 8 mm. Standard research on foreign body responses show that connective tissue forms on the fistula wall, it is assumed this also happened in this case. For the device to work it is important that the elephant will stay in place during the operation. There was no information available on the bullet material meaning that the magnetic properties are unknown. The bullet should be at a maximum of 100 cm deep in the fistula and the fistula is not straight. Using power drills and hand operated pumps is allowed as these are assumed to be on site. Rinsing the fistula with water during the removal of the connective tissue should be sufficient to flush the cut tissue out of the

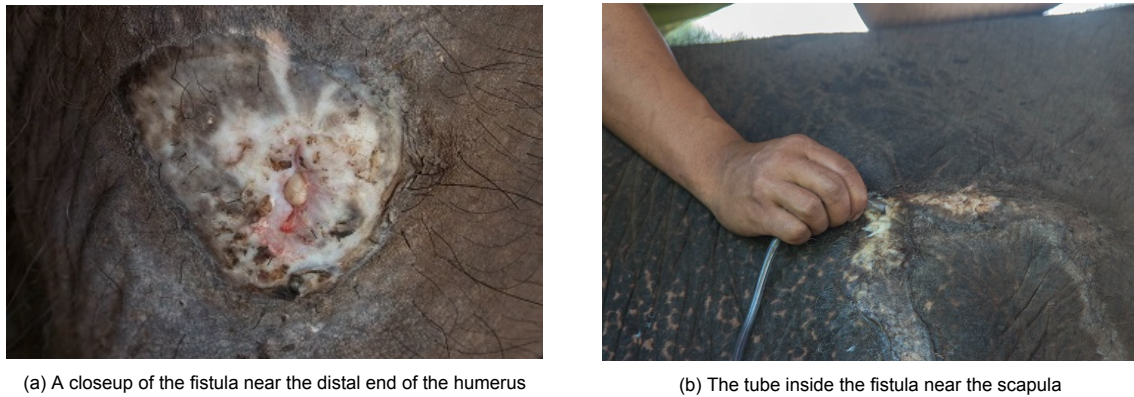


Figure 3.2: Two closeup pictures of the fistulae

fistula and the connective tissue can be stretched fairly easily [26]. A sketch of the inside of the fistula is given in Figure 3.3, showing the dimensions used for this case study.

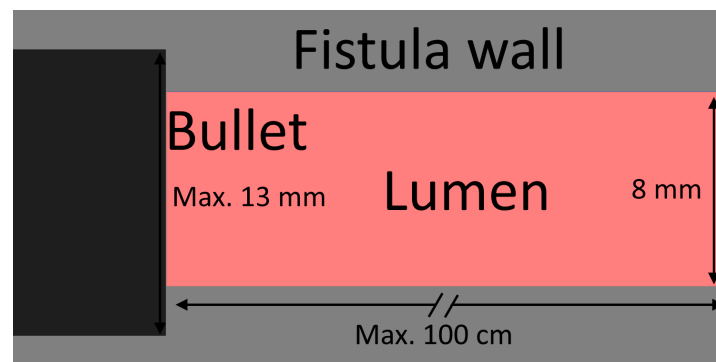


Figure 3.3: A 2D sketch of the bullet inside the fistula

3.3. Design requirements

In order to judge the prototype on functionality, it is important to separate the requirements from the wishes (i.e. distinguishing between what the device must do and what would be convenient). The requirements for the device are determined by the case study (i.e. the dimensions must be suited for the procedure on Hnin and the device must work in a low resource country).

Because surgery on the elephants is not allowed by the state, the device must be able to reach the bullet without cutting the skin. This means that the device must enter through the (8mm diameter) bullet wound. The bullet wound is curved because the bullet started 'traveling' downward due to gravity. The device must be able to follow the curve of the entry wound. The inside of the wound is moist, in order to prevent fast degradation of the device, the device must be corrosion resistant. An experienced veterinarian with their surgical dexterity should be able to operate the device without extensive training. This veterinarian must be able to see what they are doing. The procedure should be visualised (i.e. images of the inside of the wound should be displayed outside the elephant in real-time). The visualization is necessary to check whether the bullet is actually grasped and to steer the device to the bullet at the end of the fistula. The portion of the fistula where the bullet resides is most likely larger in diameter and filled with pus. As mentioned before, the setting is a low resource country, so the device must be hand operated or battery powered (maximum 18V, as this is used in regular power tools), as there is no guarantee of a power outlet. If the bullet gets damaged, metal shavings could be left inside the fistula, which keep the foreign body reaction going. The bullet must be removed with minimal damage to the bullet and the elephant. The device must work on bullets that are spherical and 8 mm in diameter. As these are estimated to be the ones used on Hnin.

It is not allowed to create a new hole in the skin of the elephant. Should the design for the bullet

retrieval device be too large to fit through the fistula, it is possible to create a second device to cut away the fistula wall tissue in order to make the bullet removal device fit. Bleeding will occur during the removal of fistula wall tissue, which can clog up the fistula and block the view. The device must be attached to a hollow tube in order to allow for rinsing during the operation. The device must be able to remove enough connective tissue in order to let the bullet and the bullet removal device easily pass through the fistula on their way out. This is set to be a maximum of 7 mm as the connective tissue was estimated to be "a few millimeters thick" by Dr. Willem Schaftenaar.

3.4. Design wishes

The design wishes are written down to add features in the event that all requirements are met. These features are desirable to have but are not essential to the functionality. In order to properly clean the device, the devices have to be easily assembled and taken apart. In order to easily operate the device (and transport it), the devices must be lightweight (under 5 kg) this way it is also light enough that it does not cause trouble when checking in a suitcase on the flight to Myanmar. The device should not be single-use. The devices must be able to remove at least 15 bullets before breaking. This is mostly because a device designed for single use might break during the surgery when a slightly higher force is applied. The connective tissue removal device must not cut away more than 3 mm of tissue at a time in order to leave the healthy tissue underneath (mostly) intact. The cost of production for one set of devices must remain under €1000 as the procedure will be performed pro bono. Once the surgery is performed, there is less need for check-ups resulting in a lower cost for flights to and from Myanmar, which is why €1000 is reasonable. In order to increase the versatility, the bullet retrieval device must also work on bullets in other shapes and sizes, as mentioned in section 2.1.1.

3.5. Setting

The device will be designed by first doing a round of concept generation, cherry picking the most promising concept and then performing tests to determine the final parameters of the design. This is done by measuring the amount of pulling force the gripper can perform and using the best design to perform a final proof-of-concept test, where a gelatin phantom will be used to mimic the fistula.

Bullet removal process

4.1. Intended Bullet Removal Procedure

In order to properly remove the bullet with minimal damage a few steps need to be taken to properly remove the bullet from Hnin. The steps are visualized in Figure 4.1.

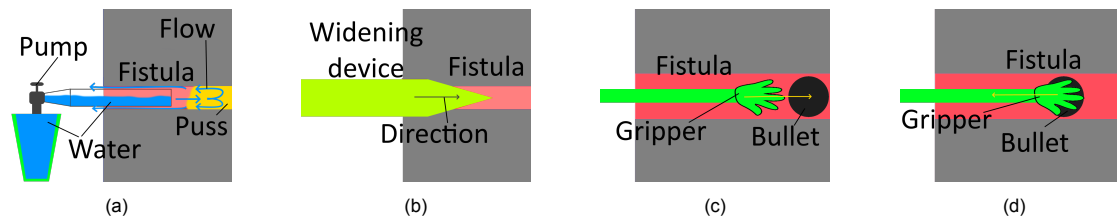


Figure 4.1: A cartoon visualizing the steps to remove a bullet. (a) Shows the fistula being cleaned. (b) Shows the optional step of widening the fistula. (c) Shows the gripper grabbing the bullet. (d) Shows the gripper with the bullet being retracted from the fistula

1. Cleaning the fistula: By using simple tubes and a hand powered pump, water is pumped into the bullet hole in order to clean the pus from the fistula.

Optional: Widening the fistula: The connective tissue that has grown is an obstacle that prevents the bullet from going back through the fistula. Using local anaesthesia, the layer of connective tissue can be removed from the inside of the fistula. The fistula must be thoroughly rinsed during this, as the blood and cut off tissue will obstruct the view. This is done by pumping water through the tube that is attached to the scraping device.

2. The bullet must be grabbed using a device that minimises damage to both the elephant and the bullet.
3. The bullet must be retracted through the entry wound fully intact, following the curve mentioned above.

After this, the fistula can fully close and the need for daily rinsing will decrease. This must all be doable in the time span of the local anaesthetic through an 8 mm hole. This is assumed to be no longer than one hour.

4.2. Reaching the bullet

4.2.1. Categorization

The fistula wall is lined with bacteria, inflamed tissue and white blood cells, which is a few mm thick. Therefore, it might be impossible to fit the bullet removal device through the wound. There are three options regarding the fistula wall, visualized in Figure 4.2.

- Leaving the fistula tissue intact
- Pushing the fistula wall out of the bullet's way
- Removing the connective tissue

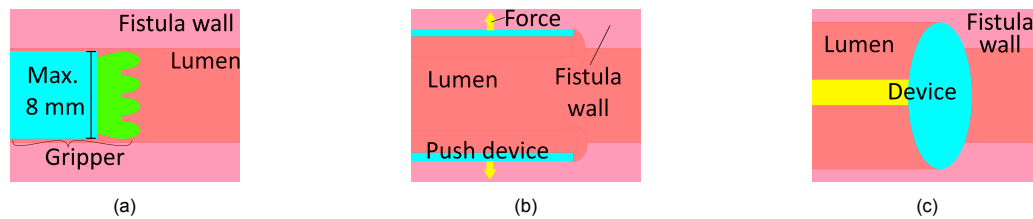


Figure 4.2: A schematic representation of the options for the fistula wall. (a) Shows the option to leave the fistula as it is, (b) shows the option to push the fistula out of the way and (c) shows the option to remove the fistula wall.

Removing the connective tissue can be done by cutting tangential or lengthwise. Lengthwise cutting can be done by either cutting by pushing the device into the fistula or by introducing the device into the fistula and cutting during retraction. This is, of course, only necessary for the elephants that have been scared off by farmers and left alive because dead elephants do not form connective tissue. Nonetheless the bullet needs to carefully be removed from the corpse, as drilling a new hole to reach the bullet most likely damages the bullet, rendering it useless for forensic research. In Appendix A concepts are discussed for these options. The required cutting force for elephant fistulae could not be found in literature. An estimation for this force is based on a research into the relation between cutting speed and cutting force on soft tissue. The tissue used in this experiment was non-preconditioned pig liver, resulting in the estimation of cutting forces for elephantine fistulae being inaccurate. One of the characteristics of the cutting force measured was that the force on the scalpel blade increases when the blade is not cutting and rapidly decreases during cutting. The maximum cutting force given in the research was around 4.5 N to cut soft tissue with a standard scalpel. It is assumed that the cutting force for elephantine fistulae is less than 5 times this upper limit for pig liver. This means that a maximum cutting force of 22.5 N is estimated [27]. This means that when cutting by pushing, a maximum pushing force of 22.5 N has to be exerted if the cutting mechanism matches the geometry of a standard scalpel. When cutting by pushing, a pushing force of 22.5 N should be exerted. For reference, a 1 mm Bowden inner cable can withstand 780 N [28]. When cutting tangential, a minimum arm length of 4 mm is given (because of the 8 mm diameter). Combining the force and arm length, a torque of $(22.5 \cdot 0.004 =) 0.09$ Nm is required to drive the cutting shaft.

4.2.2. Leaving the connective tissue intact

One of the requirements is minimal damage to the elephant. Since removing the fistula wall is damaging the elephant, a point can be made that leaving the fistula wall intact is the better solution. The downside of this is that the connective tissue might prevent the fistula from healing optimally. Cutting the connective tissue away and therewith removing the bacteria instead of rinsing the wound daily allows the fistula to properly heal, preventing infections in the long run.

4.2.3. Pushing the fistula wall out of the bullet's way

By creating a second device that permanently moves the connective tissue it should be possible to make the bullet removal device slightly bigger. This could be beneficial in the prototyping step. The downside of this solution is that the fistula remains open even after the procedure. This could be prevented by using materials that are biodegradable in a short period of time. This does limit the options, unfortunately. Another option is to design the device to only temporarily push the fistula wall out of the way. This means that only a small portion of the device can be made bigger than 8 mm in diameter, or the friction could cause difficulty inserting the device.

4.2.4. Removing the fistula wall tissue

Concepts for these categories can be found in Appendix A. These concepts were moved to the Appendix as the final design is a combination between leaving the fistula wall intact and pushing it aside locally.

Cutting by pushing

Since the cutting device has to be inserted into the fistula, it is intuitive to cut the tissue during insertion. This is also found outside the medical field in numerous ways, e.g. grating, cutting with a knife or chiseling. The benefit of this is that these devices do not require rotation (like tangential cutting does). The downside of this method is that the device might not as easily follow the fistula path.

Cutting by pulling

Since pulling something flexible out of the fistula is a lot easier than pushing something flexible in, it is wise to explore the options that involve pulling. An example from outside the medical field is when electricians have to add electrical wiring to a house they use a draw wire. This device can be pushed through a small pipe and can thereafter be used to pull the wires through. This is done because it is easier than pushing the wires through directly. Another benefit of a mechanism that cuts by pulling is that the device follows the fistula. The downside would be that inserting the device could be troublesome.

Cutting tangential

Tangential cutting is an interesting solution to removing the fistula wall tissue. A non-medical example of this is found in milling. This method could prove to be more precise (as the devices are self-centering, if they are symmetrical). The downside of this method is the need for a rotating motion.

4.2.5. Removing the bullet prior to removing the fistula wall tissue

Another option would be to remove the tissue after removing the bullet. This method is safer in the sense that the fistula wall is only removed if the bullet removal was successful. Unnecessary pain and stress is caused on the elephant when the fistula wall is removed before a failed bullet extraction. When the bullet is removed prior to the fistula wall tissue there is less need for the combination of devices. In the event that the bullet has already been removed from the fistula it is possible to remove the fistula wall without rinsing the fistula, as visuals are not necessary anymore. Since the biggest reason for the fistula wall removal was the gripper being able to fit through the fistula, it is advised to not remove the fistula wall after bullet extraction, as this has a risk of damaging more than it solves.

4.2.6. Decision making: cutting

Cutting the fistula wall comes with risks of infection due to the inability to sterilize the equipment on site. Pushing the fistula wall aside can either be a permanent widening of the fistula (when something is left inside the fistula to hold it open) or temporary (when the device to grab the bullet pushes the fistula out of the way). In this research, a combination between temporary pushing the fistula out of the way and leaving the fistula wall intact was picked. The device proposed in this research has a maximum diameter of 8 mm when it is collapsed. In the collapsed state it will be navigated through the fistula, where it should smoothly glide through. In order to grasp the bullet, the arms of the gripper need to extend past the 8 mm diameter that was given. Extending past this 8 mm means that the fistula wall is pushed aside temporarily. This is considered the best option as there is little risk of infection and keeping the design simple reduces the risk of breaking parts. The cutting option was also viable, as this allowed for larger grasping designs. The setting of the surgery being far from sterile was the most important factor to not use a cutting design. A stent device was ruled out because of the duration of the procedure: placing 100 cm worth of stents would require the elephant to stay put for too long. It was assumed the elephant would not be able to stand still for so long without getting bored and walking off.

4.3. Bullet removal**4.3.1. Morphological overview**

A morphological overview was created to generate concepts. From this morphological overview, one solution per category is picked to create a concept design. The morphological overview is given in Table I. The best combinations from this morphological chart have been presented in section 4.5, The concepts are combined with the concepts from Appendix A in Appendix B.

4.3.2. Grabbing options

Once the fistula is wide enough for the bullet to go through, another device must enter the fistula to grab onto the bullet firmly enough to remove the bullet. Since using magnets to grab a hold of the

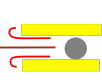
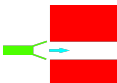
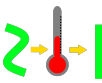
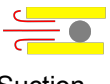
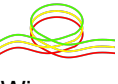
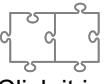
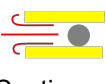
Grabbing site				
	Front	Side	Back	
How to keep the bullet from falling out				
	Form closed gripper	Clamping	Suction	Adhesives
				
	Pushing	Wires	Magnets	
Open the gripper				
	Wedge	Push it against the bullet	Wires	Pretension it as open
				
	Insert it as open	Shape memory alloys	Magnets	Springs
				
Suction				
Close the gripper				
	Wedge	Wires	Pretension it as closed	Shape memory alloys
				
	Magnets	Push it against the back of the fistula	Inflate an air pocket	Springs
				
	Click it in place	Suction		

Table I: A morphological overview of the gripper

bullet is not possible due to the unknown metals used in the bullet, another connection must be made. Chemical bonds would damage the bullet and could be harmful for the elephant. Altering the bullet in any way is also not possible (e.g. drilling holes/sawing into the bullet, melting part of the bullet, welding a rod onto the bullet, crushing the bullet or denting/scratching the bullet). The concepts are divided into three subgroups:

- **Going around the bullet and gripping it from the front:** This method allows for facile pulling of the bullet, but going around the bullet in order to connect the device could prove arduous. Given in Figure 4.3a.
- **Firmly grasping the bullet from the sides:** This method negates the need to go around the bullet in order to connect the device. The strenuous part of this method would be to grasp the sides of the bullet hard enough to allow the bullet to be taken out with ease. Given in Figure 4.3b.
- **Gripping only the backside of the bullet:** Methods can be explored to grab the bullet from the rear, this is the most facile way of gripping the bullet, but pulling the bullet out could prove difficult. Given in Figure 4.3c.

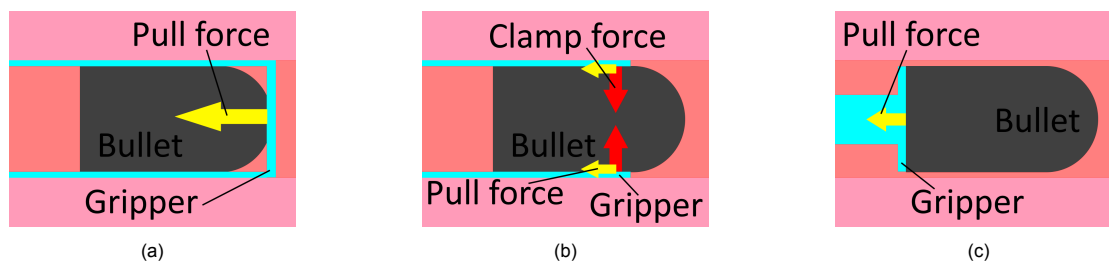


Figure 4.3: The three methods of pulling the bullet out of the fistula. (a) shows pulling from the front. (b) shows pulling from the sides. (c) shows pulling from the rear.

4.3.3. Going around the bullet and gripping it from the front

There are multiple designs possible to grab the bullet from the front. The benefit of grabbing the bullet from the front is the ease of removal once the bullet has been grasped. If the material does not break under the pulling force, the chances of the bullet falling out of the gripper are relatively small. This design is best suited for deep fistulae because the extra effort of going around the bullet to grab it outweighs the effort of having to grab the bullet each time it comes loose. The fistula wall can be used as an advantage in these designs due to the normal force from the fistula helping to keep the gripper closed.

4.3.4. Gripping the bullet from the side

Gripping the bullet from the side negates the need to bring something behind the bullet where it is difficult to see what is happening. A firm clamping grip is needed in order to ensure that the bullet stays in the device. This mechanism also uses the fistula wall as an advantage, like in the previous option. Gripping the bullet from the sides does not grant a form-fitting solution, so the closing force of the gripper must be higher than in gripping from the front. The pulling force is the friction force generated by the clamping force.

4.3.5. Gripping the bullet from the rear

Gripping the bullet from the rear can be done in a few ways that do not damage the scratch marks on the bullet. The benefit of this is that a device can be made that does not require the fistula to be stretched any further than it has to stretch for the bullet. The fistula is not used to an advantage in this situation and causes high friction forces on the bullet. In the previous options, the bullet was (partially) shielded from this friction force by the gripper. Since the gripper does not go over the bullet, there is no shielding the bullet from the friction force. This means that the gripper has to exert higher forces on the bullet than in the previous options.

4.4. Design directions

The designs will be generated in a few rounds. The subcategories mentioned above will be used to generate a number of concepts that fall within these categories. The cutting and grabbing concepts are then combined to explore the option of using a single device rather than two separate devices. From these concepts, the most promising designs are cherry picked and optimized. These designs are then put in a Harris profile to determine the best possible device that both cuts and grabs, given in Appendix C. These design were moved to the appendix as the final design is not a combined design.

4.5. Bullet removal concept development

4.5.1. Going around the bullet and gripping it from the front

The wedged capsule:

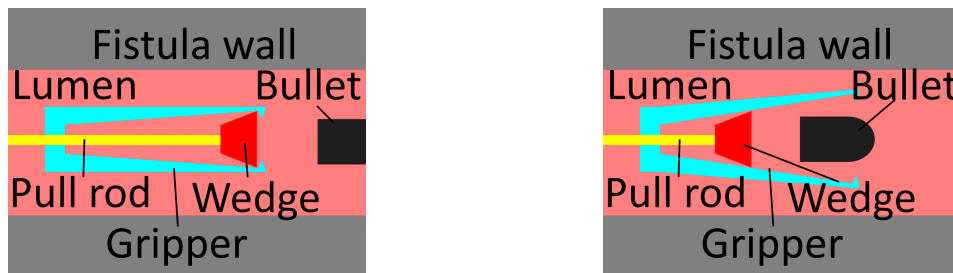
This design was made by a group of Bachelor students as a precursor to this research. The group decided to test only designs that grip the bullet from the front. Their final design was a capsule with 6 arms that could go around the bullet and grab it from the front. A sketch of this design is given in Figure 4.4. The benefit of this design is the low amount of moving parts, making it a sturdy design.

This design keeps the bullet from falling out by using a form closed gripper, the gripper is opened by a wedge and closes because it is pretensioned as closed. Taken from the morphological chart in Table I.

In this design, the force is exerted on the bullet by the bent tips of the gripper. These tips are approximately 2 mm long, 2 mm wide and 0.5 mm thick (in order to be able to still move around the bullet). The maximum allowed moment in these tips can be calculated using Equation A.5. The moment of inertia is different in this design, due to the different design and dimensions of the tips. The moment of inertia of a beam is calculated by using the following formula:

$$I = \frac{b * h^3}{12} \quad (4.1)$$

Where I is the moment of inertia (in m^4), b is the width of the beam (in m) and h the height of the beam (in m). The beam in this design has a width of 2 mm and a height of 0.5 mm. Using these values in Equation 4.1 results in a moment of inertia of $2.083 * 10^{-14} m^4$. By using the yield strength of stainless steel (520 MPa) and including the value of d (0.25 mm) it is possible to calculate the maximum allowed moment in these beams using Equation A.5. This results in a moment of 0.043 Nm, knowing that the tips are 2 mm long, this is a force of 21.6 N on the tip of the beam, per beam. Using four tips would result in a pulling force of over 80 N.



(a) A 2D sketch of the wedged capsule (2 arms instead of 6 given for simplicity)

(b) The wedged capsule with the bullet inside the gripper (2 arms instead of 6 given for simplicity)

Figure 4.4: A schematic representation of the wedged capsule with only 2 arms given for simplicity.

The mechanical finger:

This concept is based on a human hand. The working principle is a set of straight rods that can bend behind the bullet and pull it out of the fistula. This does not fully encapsulate the bullet but uses the walls of the fistula to keep the bullet within the grasp of the 'finger'. Figure 4.5 shows two sketches of this concept. The wire is pulled to bend the 'finger' around the bullet.

The benefit of this design is that the finger bends around the bullet and also works on different shapes and orientations of the bullet. The rods have a small piece of material that goes over the hinge. This

is both to protect the hinge from scraping over the fistula wall and to prevent the 'finger' from bending the wrong way.

This design keeps the bullet from falling out by pushing from behind, the gripper is open because it is inserted as open and closes with wires. Taken from the morphological chart in Table I.

The force on the bullet exerted by the finger can be calculated by first calculating the moment exerted around the hinge by the wire. Equation A.1 was used in Section A.1.3 to determine a pulling force of 200 N using a 0.7 mm wire. 200 N would be a high force on the wire that could damage the fistula where the fistula is curved while the wire is pulled straight. Therefore this value is used as the maximum pulling force on the wire. A realistic thickness for the mechanical finger is 2 mm. This means that the central axis lies 1mm from the surface of the finger. The wire was designed to be 0.7 mm, so the central axis lies 0.35 mm from the surface of the wire. This means that the length of the 'arm' is 1.35 mm in the calculation of the moment generated by the wire. The moment generated by the wire becomes $200N * 0.00135m = 0.27Nm$. If the finger tip has a length of 5 mm, this results in a force of 54 N on the bullet. This does require the wire to be covered inside the fistula, lest it cuts the fistula wall.

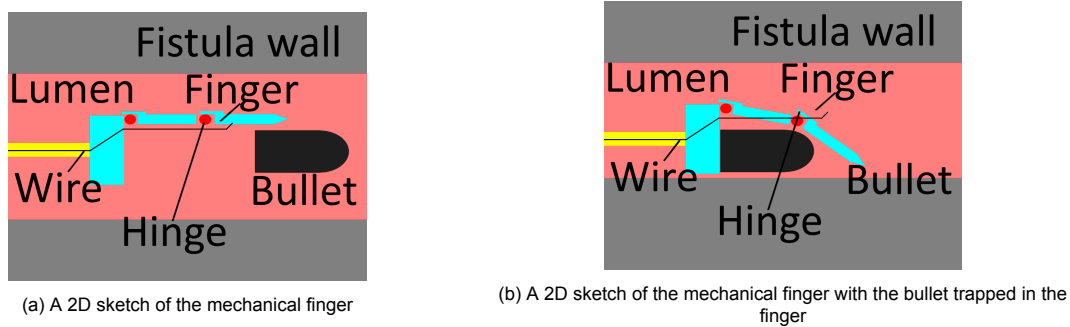


Figure 4.5: The mechanical finger concept with the 'finger' trapping the bullet between the fistula wall and the device

The fishing net:

This concept requires a lot of dexterity. The working principle of this concept is to bring a ring behind the bullet and hook some needles with a bent tip onto it to create a fishnet like structure. Figure 4.6 gives a 2D sketch of this concept. The benefit of this concept is that it requires very little space around the bullet. This can therefore be applied to bigger bullets with smaller fistulae. Extra stability could be added by using more hooks. The risk of this design is that the wires could all move to one side of the bullet. This would result in the bullet staying in place while the device is pulled back.

This design keeps the bullet from falling out by using wires, the gripper is open because it is inserted as open and closes by clicking it in place. Taken from the morphological chart in Table I.

Using the 0.7 mm wire from Section A.1.3 for all three rings and the ring, it would theoretically be possible to pull the bullet with a force of 800 N. This is most likely impossible due to the fistula wall being sliced by the wires. The hooks might also bend out of shape. The hook can be designed as a square U-shape rather than a circle to allow for simple calculations. By designing the hook as a 3x3 mm square (with an opening at the top) and wire thickness of 0.7 mm it is possible to calculate the angle of deflection in the bottom corner of the hook. The Maximum angle of deflection is set at 10 degrees (0.175 rad). The formula for maximum slope in a beam with the force exerted in the middle is:

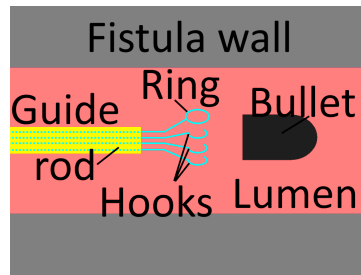
$$\theta_{max} = \frac{-P * L^2}{8 * E * I} \quad (4.2)$$

Where θ_{max} is the slope (in radians), P is the force (in N), L is the length of the beam (in m), E is the Young's modulus (in Pa) and I is the moment of inertia (in m^4) Equation 4.3 can be rewritten as a function of the force P:

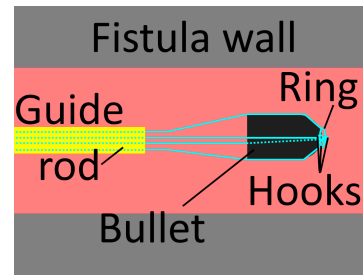
$$P = -\frac{\theta_{max} * 8 * E * I}{L^2} \quad (4.3)$$

Where θ_{max} is the slope (in radians), P is the force (in N), L is the length of the beam (in m), E is the Young's modulus (in Pa) and I is the moment of inertia (in m^4). The minus indicates the direction of the force being in the negative y-direction. Using Equation A.4 (with the inner diameter being 0) to

calculate the moment of inertia for a 0.7 mm wire it gives $I = 1.18 * 10^{-14} m^4$. The Young's modulus of 302 AISI steel is 193 GPa. Including these numbers in Equation 4.3 with a maximum angle of 0.175 rad it gives a maximum force of 353 N which is higher than the 200 N pulling force. The bending of the hooks should not be a problem.



(a) A 2D sketch of the fishnet concept



(b) A 2D sketch of the fishnet concept with the bullet trapped in the wires

Figure 4.6: The fishnet concept with the hooks hooked into the ring, trapping the bullet inside the device

The closing tube:

This concept requires the tissue in the fistula to be stretched all the way down to the bullet. A short tube is pushed through the fistula (slightly wider than the diameter of the bullet). Once the tube is fully over the bullet, the opening of the tube will close, trapping the bullet inside. Figure 4.7 shows a schematic representation of this concept. The flippers allow for the bullet to go into the tube and keep it trapped inside. The benefit of this concept is the low chance of the bullet being released from the device, as it creates a chamber for the bullet to lie in instead of gripping the bullet. This also results in lower damages to the bullet.

This design keeps the bullet from falling out by using a form closed gripper, the gripper is opened by pushing it against the bullet and closes because it is pretensioned as closed. Taken from the morphological chart in Table I.

For this design to work, it is important that the wall thickness of the tube is thin enough (0.5 mm) that it can go around the bullet inside the fistula while withstanding the pressure from the fistula wall. The stress in the wall of cylindrical vessels is calculated using:

$$\sigma = \frac{p * r}{t} \quad (4.4)$$

Where σ is the stress in the vessel wall (in Pa), while calculating the maximum pressure, this is the yield strength of the material (302 AISI steel). p is the pressure on the wall (in Pa), r is the radius of the vessel (in m) and t is the wall thickness (in m). Rewriting Equation 4.4 as a function of p gives:

$$p = \frac{\sigma * t}{r} \quad (4.5)$$

Where σ is the stress in the vessel wall (in Pa), p is the pressure on the wall (in Pa), r is the radius of the vessel (in m) and t is the wall thickness (in m). The yield strength of 302 stainless steel is 520 MPa, t was set at 0.5 mm and r is the radius of the tube (6.5 mm). Running these numbers in Equation 4.5 gives a maximum allowed pressure of 40 MPa. This is rather high but decreasing the wall thickness makes production difficult.

4.5.2. Gripping the bullet from the side

The tightened three-point gripper:

This concept is basically a gripper with three 'fingers' that grab a hold of the bullet from the side. The addition to this design is a piece of string that goes around the three grippers and can be pulled to firmly tighten the grip. Figure 4.8 shows sketches of the gripper grabbing the bullet. The pads on the gripper can be made of a rubber in order to enhance grip. The benefit of this design is the small space needed around the bullet when pulling the bullet out of the fistula. The gripper house can be sealed with a thin membrane to prevent the gripper house from clogging up. Since there are three arms, the gripper can be used for both cylindrical and spherical bullets.

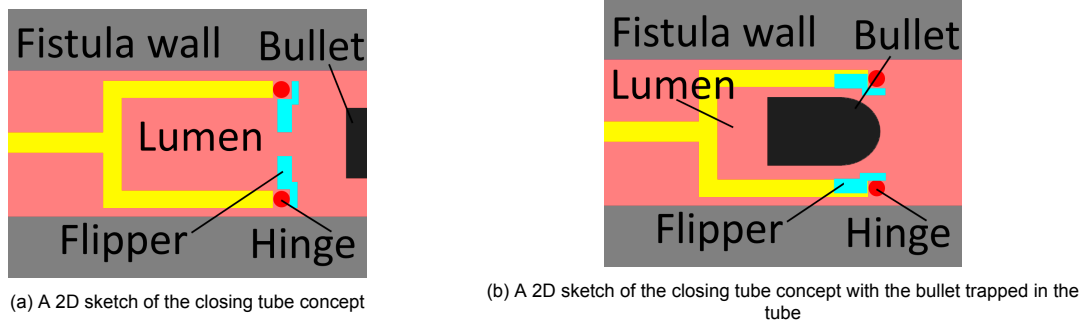


Figure 4.7: The closing tube concept with the flippers keeping the bullet inside.

This design keeps the bullet from falling out by clamping, the gripper is opened because it is pre-tensioned as open and closes because of a wedge. Taken from the morphological chart in Table I.

Instead of shielding the bullet from the friction forces generated by the fistula, this design uses the normal forces from the fistula as an advantage to help clamp the bullet in place. Since the material of the bullet is unknown, there is little to be said about the friction coefficient. On top of the normal forces pushing the tips towards the bullet, the string will pull them together. The tips will have the same cross section as the tips of the wedged capsule, meaning that the moment of inertia for the tips is the same as in Section 4.5.1: $I = 2.083 \times 10^{-14} m^4$. The length is far longer than the tips of the wedged capsule, being approximately 40 mm. The maximum deflection of these tips is given by:

$$\delta = \frac{P * L^3}{3 * E * I} \quad (4.6)$$

Where δ is the deflection (in m), P is the force (in N), L is the length of the beam (in m), E is the Young's modulus (in Pa) and I is the moment of inertia (in m^4). The Young's modulus of 302 AISI steel is 193 GPa. $I = 2.083 \times 10^{-14} m^4$ as explained in the previous section. P is 400 N (the wire pulls in both directions). Running these numbers in Equation 4.6 gives a deflection of 2 m. This is not possible, but does prove that the device is able to close the tips with the wire.

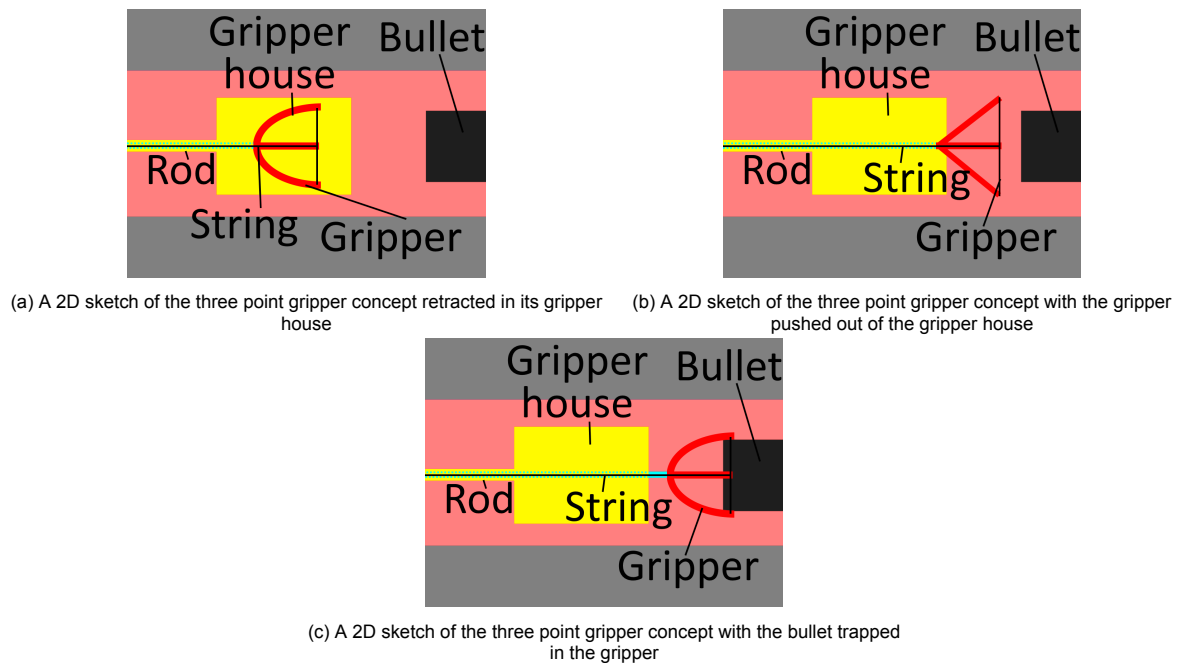


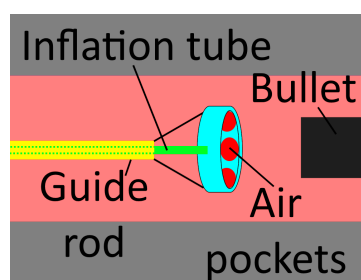
Figure 4.8: The three point gripper concept showing all three steps of the bullet trapping

The inflated ring:

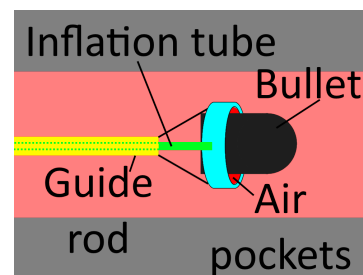
This device brings a metal ring loosely around the bullet. On the inside of the ring are small inflatable rubber air pockets that are inflated to grab a hold of the bullet. Figure 4.9 is a 2D sketch of this concept. The benefit of this design is the gentle and firm grip. The bullet is grabbed firmly enough to ensure that it can be pulled out. The rubber air pockets take the shape of the bullet and are made of a soft material, hence not scratching the bullet. The inflation tube is protected by the guide rod to keep it from buckling and getting punctured. Inflation can be done by using a simple bulb pump.

This design keeps the bullet from falling out by clamping, the gripper is inserted as open and closes by inflating an air pocket. Taken from the morphological chart in Table I.

A realistic width for the inflating ring is approximately 10 mm. Assuming that the ring contains air pockets that cover 80% of the circumference of the 13 mm bullet it is possible to calculate the contact area: $10 * 0.8 * 13 * \pi = 327 \text{ mm}^2 = 0.000327 \text{ m}^2$. The necessary pressure in the air pockets can be calculated by dividing the force over the area. If a force of 10 Newton is necessary, a pressure of 30.6 kPa is needed inside the air pockets (if the friction factor between the air pockets and the bullet is 1.0). Considering that this friction factor will most likely be lower, the pressure in the air pockets has to be higher.



(a) A 2D sketch of the inflated ring concept



(b) A 2D sketch of the inflatable ring concept with the bullet trapped in the ring by the air pockets

Figure 4.9: The inflatable ring concept concept with the air pockets inflated to trap the bullet inside the ring.

The heat shrinking ring:

Nitinol, the shape memory alloy, can be made in such a way that it curls up when heat is applied. This heat can be applied by running a current through the material. By doing so, a ring of Nitinol can be made to curl into a smaller sized ring, trapping the bullet inside. Figure 4.10 shows this concept. The benefit of this concept is that it allows for multiple bullet shapes and orientations to be grabbed. Insulation must be applied to the Nitinol ring (and the electrical wires) in order to keep the charge from going through the bullet.

This design keeps the bullet from falling out by using clamping, the gripper is inserted as open and closes because of shape memory alloys. Taken from the morphological chart in Table I.

Going from a 14 mm diameter circle to a 7 mm circle would require the Nitinol wire to zig-zag with angles of 60deg (that way the way length is doubled). The circumference of a 14 mm diameter circle is approximately 44 mm. By making the length between the angles 2 mm, there are 22 straight beams connected via 60deg corners. Because of the bullet, these corners will be stretched out. The stiffness of the Nitinol creates a resistance in the form of the gripping strength.

4.5.3. Gripping the bullet from the rear

Using an adhesive:

By using a small drop of non-toxic glue it can be possible to glue the bullet onto a small platform. This platform is already connected to the guide rod and should be replaced for every procedure. This should not be a problem if the disposable part is cheap or unchallenging to make. The bullet must be cleaned more thoroughly for this concept to work, as the glue will not stick otherwise. Figure 4.11 shows this concept. The push rod is used to keep the glue droplet safely inside a small hole in the platform. Once the device is in front of the bullet, the push rod is pushed, forcing the glue onto the bullet. The push rod is then retracted and the platform is gently pushed against the bullet. Once the glue has dried up,

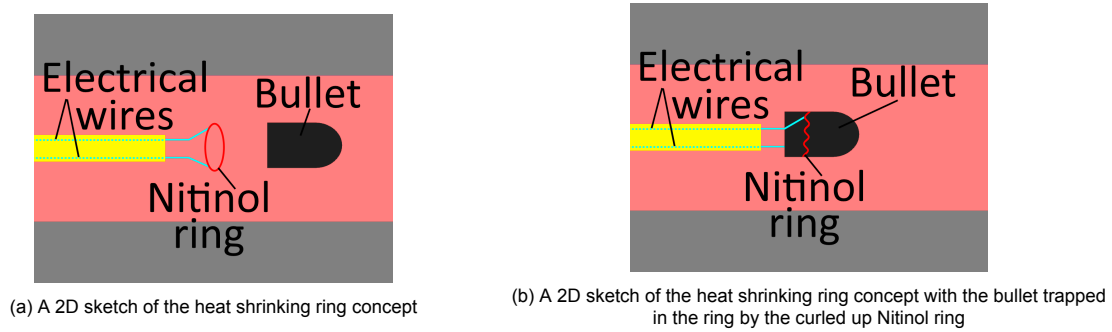


Figure 4.10: The heat shrinking ring concept with the Nitinol ring in the open position (cold) and in the curled up closed position (hot)

the pull rod can be pulled, taking the bullet with it. The benefit of this design is that very little dexterity or training is needed.

This design keeps the bullet from falling out by using adhesives, the gripper is inserted as open and 'closes' by pushing the bullet against the back of the fistula. Taken from the morphological chart in Table I.

The smallest bullet that is considered is the .22 LR with a diameter of 5.7 mm. This means that the bullet has an area of $\pi * 0.00285^2 = 0.0000255m^2$. A metal epoxy glue (Kombi metaal) made by BISON claims to have a force of $220 kg/cm^2$, or $21.5 MN$ per square meter. This would result in a maximum pulling force of $21.5 * 10^6 * 0.0000255 = 550N$.

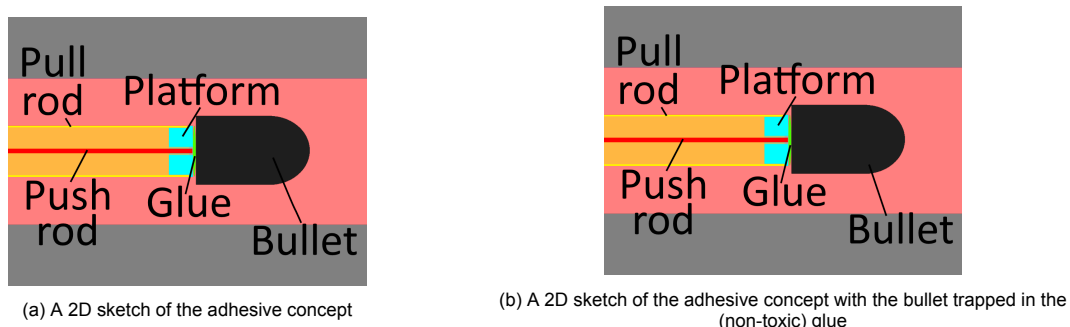


Figure 4.11: The adhesive concept with a push rod to push the glue droplet out when the device arrives at the destination. Preventing the glue from sticking to the fistula wall.

Using suction:

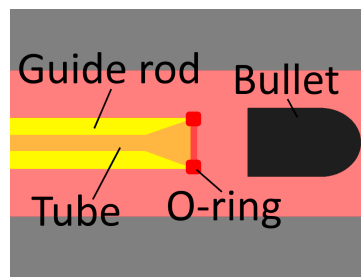
This method also requires thorough cleaning of the bullet. By using a thick rubber O-ring and an airtight tube it could be possible to create a vacuum strong enough to pull the bullet out of the fistula by air pressure alone. The problem with this concept is that one tiny puncture in the tube renders the whole device worthless. Figure 4.12 shows this concept in both positions. The benefit of this concept is that it does not require the use of adhesives and disposable parts, with the benefits of the adhesive concept. In the event that the device loses its grip, it can be easily reattached.

This design keeps the bullet from falling out by using suction, the gripper is inserted as open and 'closes' because it is pushed against the back of the fistula. Taken from the morphological chart in Table I.

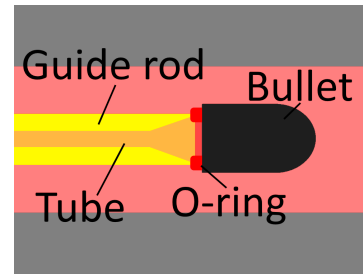
A perfect vacuum would result in a pressure difference of around 100 kPa. Using the area calculated in Section 4.5.3, this would result in a maximum pulling force of $100.000 * 0.00002551758 = 2.5N$

4.6. Harris Profile

In order to decide which concept is the most promising, a Harris profile was made to aid in the decision making process. A Harris profile is a suitable tool that uses ranked criteria to estimate the value of a concept. The criteria are listed on the right in Figure 4.13. The top criterion is considered the most



(a) A 2D sketch of the suction concept



(b) A 2D sketch of the suction concept with the bullet trapped in the O-ring by pumping the air out of the tube

Figure 4.12: The suction concept before and after pumping the air out of the tube.

important criterion. The concepts are awarded a -2, -1, +1 or +2, based on how well they perform on a certain criterion. The concept that 'topples to the right side the most' is considered the most promising concept. The criterion 'Friction during insertion' was graded on the diameter needed for the concept to work, the smaller the diameter, the higher the score. The 'clamping force/input force' criterion meant the amount of force that was used as input divided by the output force on the bullet. The lower the input force and the higher the output force, the higher the score. 'Applicable to different bullets' means just that, the score is higher when differently shaped and sized bullets work on the concept. The criterion 'Shielding the bullet from friction' was valued on how much force from the fistula was dragging on the bullet during retraction. The higher the drag, the lower the score. The 'ease of operation' was a criterion that weighed the dexterity necessary to operate the device. If a high dexterity is needed, a low score was awarded. The final criterion 'ease of re-gripping' was based on easy it would be to re-grip the bullet if it falls out of the gripper. This was considered the least important criterion as a device that is perfectly capable to grab the bullet and completely shield it from the drag could score bad at ease of re-gripping but re-gripping could never be necessary. The Harris profile shows only one concept that scores only +1 or +2: The 3-point gripper. This concept is further developed into a prototype in the continuation of this research.

	Wedged capsule				Mechanical finger				Fishing net			
	-2	-1	+1	+2	-2	-1	+1	+2	-2	-1	+1	+2
Friction during insertion												
Clamping force/input force												
Applicable to different bullets												
Shielding the bullet from friction												
Ease of operation												
Ease of re-gripping												

	Closing tube				3-Point gripper				Inflated ring			
	-2	-1	+1	+2	-2	-1	+1	+2	-2	-1	+1	+2
Friction during insertion												
Clamping force/input force												
Applicable to different bullets												
Shielding the bullet from friction												
Ease of operation												
Ease of re-gripping												

	Heat shrinking ring				Adhesive				Suction			
	-2	-1	+1	+2	-2	-1	+1	+2	-2	-1	+1	+2
Friction during insertion												
Clamping force/input force												
Applicable to different bullets												
Shielding the bullet from friction												
Ease of operation												
Ease of re-gripping												

Figure 4.13: A Harris profile showing the different concepts from this chapter.

4.6.1. Decision making: grasping

The final design for this research leaves the fistula wall intact. This is because the diameter of the final design is 8 mm, allowing it to fit through the fistula with ease. Another benefit of not removing the

fistula wall is that the risk of infection is reduced. The operating site does not allow for sterilizing the device, making cutting in tissue a great risk. There is also no unnecessary harm done to the elephant if the bullet grabbing procedure fails. If the fistula wall is all cut open and the bullet is too stuck or the surgeon is unable to grab the bullet, the situation is made worse.

The gripping method used in the final design is gripping the bullet from the side. This is because the normal force of the fistula wall provides a great benefit with this method. Gripping the bullet from the rear was not advisable due to the low pulling force with suction and the toxicity of the glue. The wedged gripper and the closing tube required larger diameters of the device in order to work. Calculations showed that the inflated ring and mechanical finger would require too high input forces. The fishing net requires more dexterity than can be expected from a surgeon and does not provide visual aids for hooking the hooks into the ring behind the bullet. The Nitinol ring was too unpredictable and requires electricity and heat inside the wound which is not desired.

The proposed design is a variation on the three point gripper. In this version, the gripper house is replaced by a ring that pushed the gripper arms together. By using a ring instead of a gripper house, the diameter is kept at 8 mm. This means that there is no need to remove fistula wall tissue. In order to have the gripper arms grip the bullet, there is a need to open the arms to go around the bullet. This requires the gripper to open up to 10 mm in diameter. This is considered not problematic as this is a small expansion of the lumen.

Final conceptual design

5.1. Gripper design

5.1.1. Leaving the fistula intact

Designs that were created to remove the fistula with the same device as grabbing the bullet can be found in Appendix B, how these were to be operated can be found in Appendix D. After careful consideration these were not used in this research based on the reasons listed in that appendix. Not removing the fistula wall is a great option if the design of the gripper does not exceed 8 mm in diameter. This is due to the friction given by the fistula during insertion. If the design is smaller than the hole it has to go through, there is no need to widen the hole. Appendix C shows designs of the most promising combined concepts.

The cutting of the fistula wall presents the benefit of a wider opening, but it has its downsides: The inability to properly clean the instrument before inserting it into the fistula could introduce bacteria into the open wound. It could be possible that the bullet can not be grabbed due to unforeseen circumstances, this would mean that the fistula would already be cut whilst the bullet remains inside the elephant. Cutting the fistula wall also lengthens the operation substantially, which could mean that the elephant grows impatient and walks off.

A separate gripper that is able to grab the bullet without cutting the fistula wall could be more beneficial. This is also partially because there are multiple unknown factors about the fistula wall, which cannot be measured due to the elephant being in Myanmar. The gripper has to be able to grab a hold of multiple shapes, sizes and orientations of bullets, without knowing the material of the bullet. While removing the bullet without removing the fistula wall it is even more important to have a firm grip on the bullet.

5.1.2. Gripper Design

The gripper as proposed in Figure C.5b shows a gripper designed specifically for the .50 BMG. Other bullets could fit in this design but the long arms could prove a nuisance when the bullet is already difficult to grab. By slightly altering the design, a gripper can be designed that is able to grab a hold of multiple bullets without the nuisance of the long arms. This does however require the working principle to be different. Section A.1 showed three options for gripping the bullet: front, side or back grabbing. The design proposed in Figure C.5b comes down to gripping from the front of the bullet. The proposed design for the universal bullet gripper is based on gripping the bullet from the side. The reason this method was picked over gripping from the side was that gripping the bullet from the side could result in slipping and even in releasing the bullet when the fistula introduces a normal force (and therewith a friction force) on the bullet. This is negated when the bullet is pulled inside a tube (as proposed in Figure C.5).

A new design was created to fulfill these needs. The basis for this design was the three point gripper. This design adds a bullet cover to this design that works based on the frictional forces of the fistula wall. The design is rather simple, but involves few moving pieces and can be easily operated. The design is given in Figure 5.1. A cartoon showing this design is given in Table II.

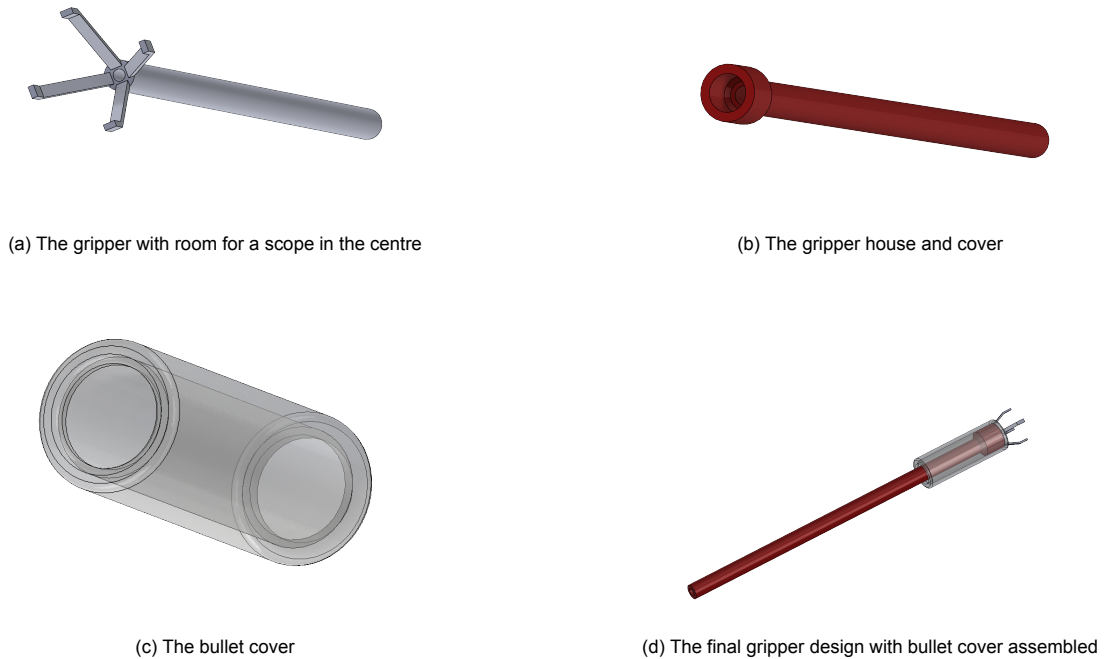
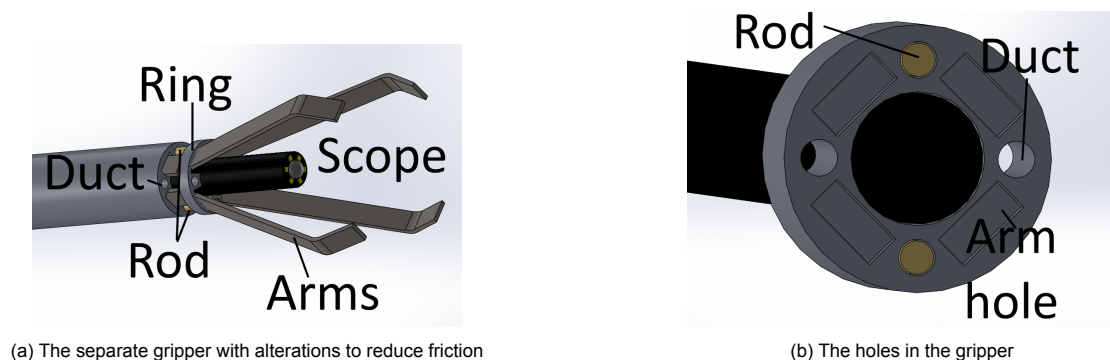


Figure 5.1: The gripper design, showing the bullet cover in transparent gray to show the inside of the device.

5.1.3. Minimizing friction

The bullet cover presented in Figure 5.1 (c) results in greater friction during the insertion of the device. The reason this cover was included in the design was to shield the bullet from frictional forces while retracting the device. After careful consideration the cover was removed from the design in order to ensure smooth insertion. The gripper house was also redesigned to reduce frictional forces. The gripper house's function was taken over by a ring with the same diameter as the rest of the device that is pushed over the gripper arms to allow them to close. The final design is given in Figure 5.2. The flexible axis that is connected to the end of the device is a 3D printable design by PhD candidate Fabian Trauzettel from the Delft University of Technology. This design is simple, requires no sharpening and is easier to fabricate than the other designs proposed. The width of the gripper arms was also limited by the wound diameter.



(a) The separate gripper with alterations to reduce friction

(b) The holes in the gripper

Figure 5.2: The gripper design, showing the ring to push the arms together

5.1.4. Fabrication

The design for the separate gripper has more upsides than just being small, easy to operate and applicable to different bullet types. The gripper is, out of the designs proposed, the easiest to fabricate. This is a great benefit as the cost of production rises with the difficulty of production. Calculations were made to ensure the optimal design for the gripper arms. The design is cylindrical, as the fistula is also

round. The scope is placed in the centre with the gripper arms around it to have the best visibility on the grabbing process and the holes for the rinsing are on both sides of the device to ensure the rinsing process goes well. The device is not made hollow, so the puss and rinsing water would have to flow around the device.

5.2. Design dimensions

5.2.1. Calculations on the gripper arm

In order to determine the right dimensions for the gripper arms, calculations were performed. The set values in these calculations are a Young's modulus of 1.2 GPa, the diameter of the bullet (8 mm) and the thickness of the spring steel (0.5 mm). The spring steel thickness was set to 0.5 mm as the options for spring steel were limited. The width, length and angle of the spring steel were determined through iterative calculations. The spring steel was set to be beam shaped to facilitate in the fabrication process and to allow the gripper arms to slide around the bullet in the wound with ease. The thickness of the spring steel could not be varied over the length of the arm. The moment of inertia of the gripper arm was calculated through Equation C.5. The bending of the arm where the ring presses onto the arm was calculated using Equation C.4. The angle of the arm where the ring presses against the arm was calculated using:

$$\theta = \frac{F * L^2}{2 * E * I} \quad (5.1)$$

In Equation 5.1 the angle of deflection (θ) in radians is calculated from the force (F) in N, the length (L) in m, the Young's modulus (E) in Pa and the moment of inertia (I) in m^4 . The rest of the arm is not affected by the ring and therefore continues straightforward under the angle caused by the deflection. The variables were fine tuned by changing them in a calculation tool in order to plot the arm, its bending and the bullet. The optimal values were reached with a width of the arm of 2.5 mm, an opening angle of 20 degrees and a closing angle of 40 degrees. These angles were balanced in such a way that the gripper can slide over the bullet with relative ease while still having the angle of the pulling force pointed from the front of the bullet to the rear, resulting in a higher pulling force. The dimensions are given in Figure 5.3. The 5 mm section on the left side of the figure is added to attach the gripper arm to the rest of the device. The tip of the gripper has been given a length X , this is because the tip length is determined by performing an experiment in the next chapter. A tail of 5 mm was added to attach the gripper arms to the body of the gripper. This sinks into a hole that is 3 mm deep. The ring that pushes the arms together is 2 mm thick, resulting in the 5 mm tail length.

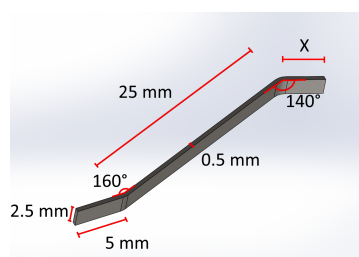


Figure 5.3: The dimensions of the gripper arm

5.2.2. Not removing the fistula wall

The chosen design does not remove the fistula wall. The main reason to remove the fistula wall was to fit the gripper through the hole and to remove the lining of white blood cells. The proposed design does fit through the fistula without cutting the fistula, removing the need for a wider hole. The only reason to cut the fistula would then be to remove unwanted fistula wall tissue. The risk of infection due to the operating site not being sterile in the slightest makes the risk higher than the reward. The operating site is a simple hut created by putting a thatch roof on a few poles in the woods. This site also lacks the equipment to sterilize the device. Another benefit of not cutting the fistula is that if the bullet removal fails, there is no harm done to the elephant, whereas the cutting of the fistula wall would be in vain when the bullet grabbing is without success.

5.2.3. Simplicity

The design is simple, but effective. The other designs proposed, both in the concept generation and in the final conceptual design, were more complex. The strength of this design comes from its simplicity. There are few moving parts, all bending is elastic, there is no rotation required, there is room for an endoscope, the clamping force is higher because of the normal forces used, the design is fabricable and there is less risk of infection.

"Nature is pleased with simplicity. And nature is no dummy."

Isaac Newton[29]

5.3. The Prototype

The prototype body was made by 3D printing aluminium. This was done to decrease production time, increase the precision of the prototype and to have a stiff product that does not deform as much as plastics do. The final design is given in Figure 5.4.

The gripper arms were created out of spring steel, because of its stiffness and formability, a .5 mm thick spring steel plate was cut into rectangles of 2.5 mm by 31 mm, 33 mm and 35 mm. These were then bent into the desired shape by hand and fitted onto a 1:1 2D model of the arms in order to ensure proper shape and size.

As discussed in the test protocol, the first tests were performed with the 5mm tips in the 4 arm and 3 arm configuration. The results should show a difference in the force between pulling with 3 or 4 arms. Theoretically, it would be expected that this force is 33.33% higher. This is because the force in the gripper comes from the normal force between the bullet and the gripper arms. Adding another arm to the gripper results in an increase in the (total) normal force on the bullet with 4/3. By equally distributing the arms over the gripper, the sum of all normal forces remains zero. Since the friction force is a percentage of the normal force, the resulting friction between the bullet and the gripper arms increases. Adding a fifth arm was not possible due to the size restrictions. Reducing the size of the arms would result in a lower friction force due to the lower stiffness in the gripper arm. Reducing the size of the arms and adding more arms would therefore not be advised. In addition to that, smaller parts are more prone to plastic deforming and breaking during use or transport. It is therefore concluded that the 4 arm setup is the optimal choice.

The ring that pushes the gripper arms together was also 3D printed with aluminum. This was also done because of the high precision needed for this part. The holes made in the ring for the rods to push it upwards are 1 mm in diameter and need to be perfectly aligned with the holes in the body of the device to ensure smooth operation of the ring.

The rods that push the ring upwards are 1 mm diameter brass rods. This material was picked to ensure a small friction coefficient and a high enough stiffness to push the ring up and down.

The endoscope used in the test was a no-brand 4 mm endoscope. Upon arrival the actual diameter of the scope head was 4.1 mm. This was solved by filing the head casing down to 4 mm. The endoscope was still fully functional after filing it down.

Operating the prototype can be done using a steerable shaft such as the one designed by F. Trauzettel (PhD candidate, Delft UoT). By running a Bowden cable of 1 mm through the shaft [28], it is possible to operate the ring that pushes the arms together. The gripper body is designed to be 30 mm in length for the current prototype. This is done to ensure less buckling of the rods that push the ring upwards and to create a proper surface to hold the gripper in place during the experimental phase. The eventual gripper head can be designed at 10 mm in length because the Bowden cable running through the shaft will be less likely to buckle than the free hanging ones in the experimental phase and the gripper will be held in place by the shaft. A picture of the gripper on a bendable shaft is given in Figure 5.4a

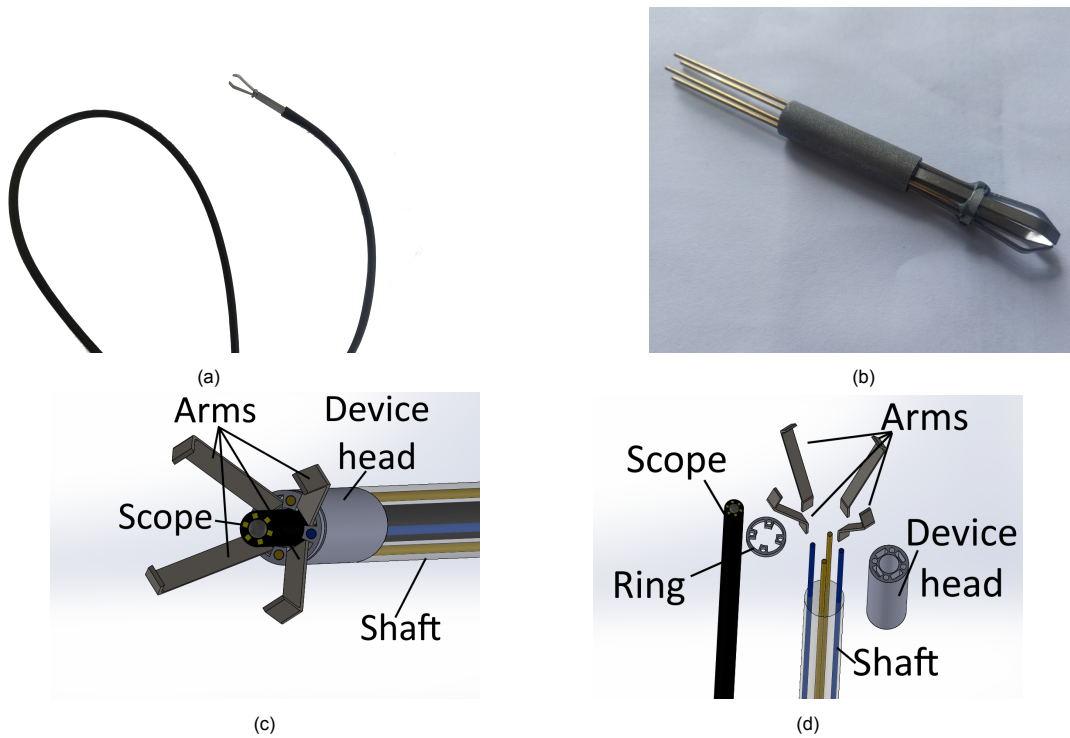


Figure 5.4: Visualizations of the final design. The 'shaft' is steerable and has the wires of the scope, the bowden cables to operate the ring and the rinsing channels inside of it. The scope is given in black, the bowden cables are given in yellow and the rinsing channels are given in blue. (a) And (b) show pictures of the final prototype: (a) shows the gripper on a flexible shaft and (b) shows the gripper as it was used in the experimental phase. (c) And (d) show 3D sketches of the design. (c) Shows an assembly and (d) shows an exploded view.

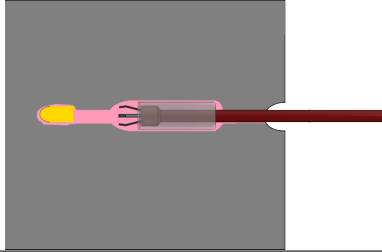
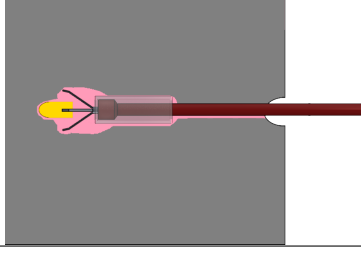
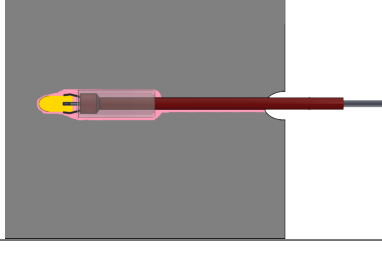
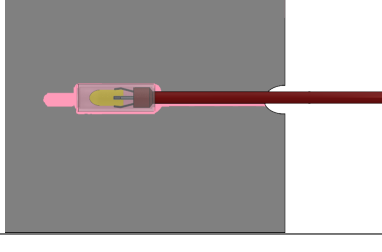
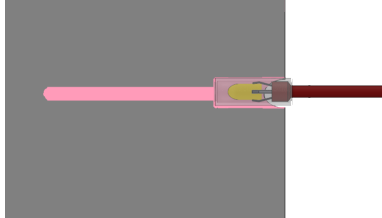
	The gripper design, showing the gripper (gray), the gripper house and cover (red) and the bullet cover (transparent grey)
	By pulling the end of the gripper (gray), the gripper is pulled into the gripper house, bringing the gripper arms to a closed position.
	The device is then inserted into the fistula by pushing the gripper cover (red) forward. The bullet cover (transparent grey) is pushed forward by the gripper house (red)
	The gripper (grey) is pushed forward out of the gripper house (red) once it reaches the bullet. The arms now reach over the bullet.
	The gripper house (red) is then pushed forward, bringing the gripper arms to a closed position around the bullet.
	The gripper (grey) with the bullet and gripper house (red) are then retracted out of the fistula. Due to the frictional forces of the fistula, the bullet cover (transparent grey) remains in position, covering the bullet.
	The device is retracted out of the fistula.

Table II: A cartoon showing the working principle of the gripper

6

Experimental phase

6.1. Experimental protocol

6.1.1. Experimental Goals

In order to test the value of the device in the real life setting, it is imperative to ensure the device is capable of performing a few tasks. The device will need to:

1. Grip the bullet tightly
2. Prevent the bullet from slipping out of the gripper during retraction
3. Not damage the bullet in such a way that debris is left inside the fistula

This must all eventually be done by using only the visual aid given by the scope that was included in the design.

6.1.2. Experimental Variables

In the first experiment, a few variables are present. Some of them dependent (test values) and others independent (set values).

Dependent Variables

The dependent variables are:

- Maximum pulling force: measured in Newton with a LSB201 Junior S-beam load cell, manufactured by Futek advanced sensor technology Inc. The signal from the loadcell is conditioned by a Analog signal conditioner: The CPJ analog transmitter manufactured by Scaime. This analog signal is then digitized by an Multifunction I/O Device: The NI USB-6008 manufactured by National Instruments. The Multifunction I/O Device is connected to the USB port of a computer that runs the software Labview 2018 by National Instruments. This software then connects the signal to a force and saves it in a .txt file. The setup is given in Figure 6.3
- Maximum pushing force: measured by the same setup as the pushing force
- Diameter and shape of the bullet: varied over the bullets to resemble the given bullets. 5 Bullets are used: a .45 ACP, a .22 LR, a 7.62x51 mm, an 8 mm sphere and a 10 mm sphere. The bullets are custom made to be able to fit on the force sensor (a piece of M3 thread is placed at the tip).
- The length of the gripper tips: 1 mm, 3 mm and 5 mm, visualized in Figure 6.1
- The amount of gripper arms: 3 or 4, Visualized in Figure 6.2.

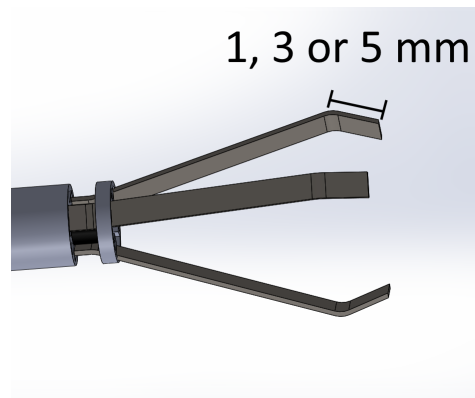


Figure 6.1: The tip length of the gripper that is varied over the experiment

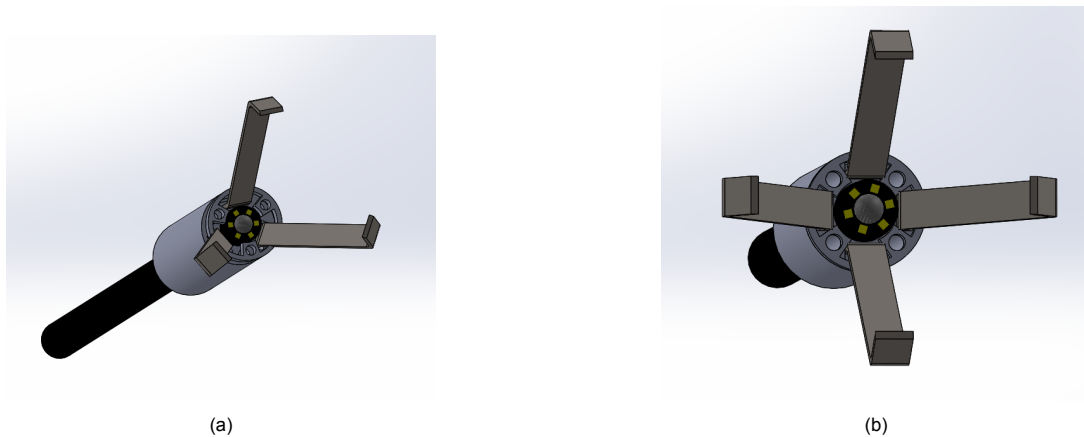


Figure 6.2: The gripper designs for the experimental phase. (a) Shows a gripper design with 3 arms and (b) shows a gripper design with 4 arms.

Independent Variables

The independent variables are:

- Room temperature: 293 K
- The Young's modulus of the gripper arms: $E=1200$ MPa (spring steel)
- The other dimensions of the device: As visualized in Figure 5.3.

6.1.3. Experimental Set-up

Force gripping: experimental protocol

The device is placed on a aluminium rail that guides the device and keeps it perpendicular to the force sensor as shown in Figure 6.4. A camera from a smartphone is used to film the test. The participant uses the prototype to grab the bullet slowly. Once the bullet is grasped, the participant retracts the device slowly until the bullet snaps out of the gripper or 60 Newtons in force is reached (as to not damage the sensor). This is done twenty times for all testing parameters. Results are saved in a .txt file and processed. Testing goes as follows:

1. The five bullets are tested with the gripper tips at 5 mm for the 3 arm and 4 arm configuration to determine the best suited setup. If the maximum pulling force lies at least 25% higher with the 4 armed version, that version is determined to be the better option.
2. The five bullets are tested with the gripper in the setup with the optimal amount of arms (determined in the previous test). This time with 1 mm tips. If the maximum pulling force with this design

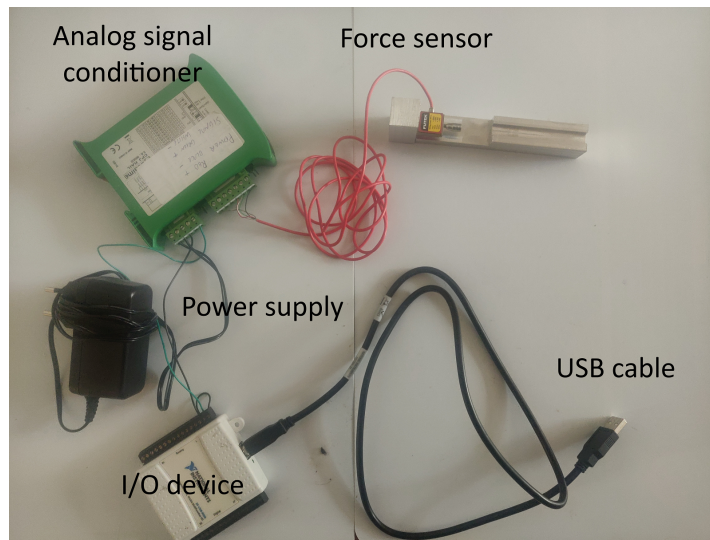


Figure 6.3: The devices used to measure the force

is not significantly lower than the 5 mm tips (10%), the 1 mm tips are picked as the optimal length. If the force is significantly lower another test is performed:

3. The five bullets are tested with the gripper in the setup with the optimal amount of arms (determined in the first test). This time with 3 mm tips. The results are compared to the 5 mm variant and if the results differ significantly (more than 10%) then the version with the highest pulling force is considered the best option.
4. After testing the pulling force, the pushing force is measured. This is the amount of force needed to get the gripper around the bullet inside the fistula. This is performed by closing the gripper enough that the maximum diameter of the arms is 9 mm (assuming a 1 mm stretch in the fistula wall due to the force of the gripper arms). The gripper is then pushed against the bullet until the arms are gripping the bullet. The lowest pushing force is considered best. If the pushing force exceeds 10 N, the setup is considered unsuited and removed from consideration, in that case, the next best option is picked. If no option is picked due to the insignificant differences in the results, the lowest pushing force decides the best option.

The 5 bullets are used to broaden this research, the focus lies on the spherical bullets

Force gripping: experimental facility

The devices used in this experiment are visualized in Figure 6.3. The devices in the figure are plugged into a laptop using the usb cable. The laptop is able to save the force values through the Labview 2018 software. A separate .txt file is created for each individual test in order to make data analysis simple.

Proof of concept: experimental protocol

For the proof of concept it is necessary to test the gripper in a more lifelike situation. A phantom was used to simulate the fistula of the elephant. Using only the scope to navigate, five separate tests were performed to show the usefulness of the design. Five separate phantoms were created to significantly prove the working principle of the most optimal gripper.

Proof of concept: experimental facility

A final proof of concept will be done after determining the best option to ensure the grippers usefulness. Gelatin with a bloom factor of 250 is used to encase 8 mm metal balls. An 8 mm rod is used to create a 'fistula' leading to the bullet. The bullet is then grasped and retracted to show the capabilities of the gripper. Figure 6.5 shows the phantom with the rod still in the gelatin. The phantom was created as follows:

1. Create liquid gelatin as described on packaging.

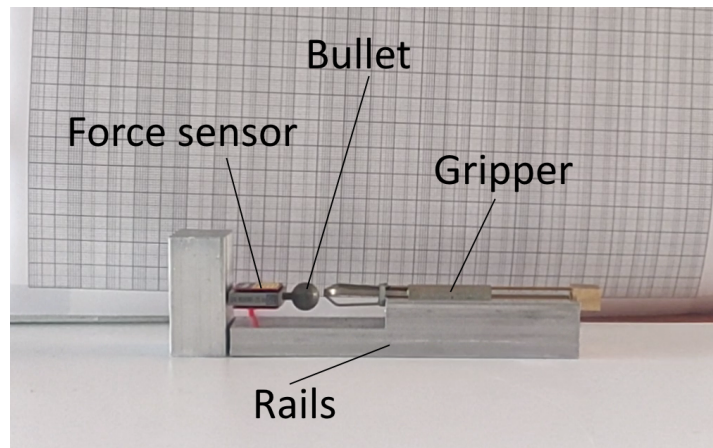


Figure 6.4: The experimental set-up

2. Fill a container up to 3 cm from the brim.
3. Let it solidify by cooling it for a few hours.
4. Place a bullet on top of the solid gelatin.
5. Pour new liquid gelatin over the bullet, fill the container up.
6. cover the 8 mm rod in cooking oil to ensure easy removal.
7. Place the 8 mm rod on top of the bullet and secure it in place.
8. Let the gelatin solidify by cooling it for a few hours.
9. Gently take the rod out of the phantom.

The gripper is then inserted in the phantom and the bullet is grasped by freehand operation of the gripper. The results are binary for this test, it either works, or does not work. This test is performed on five different phantoms to ensure the significance of the result. In order to show the concept of the scope, the scope is used to navigate into the phantom and grasp the bullet. The scope is connected to a laptop where the live footage from the scope is displayed on the laptop screen.



Figure 6.5: The 'phantom' used to test the gripper in, with clothespins to secure the rod in place.

6.1.4. Data Analysis

The force needed to remove the bullet is noted in a .txt file to analyse the data. A boxplot is created with this data to show the significance of the tests.

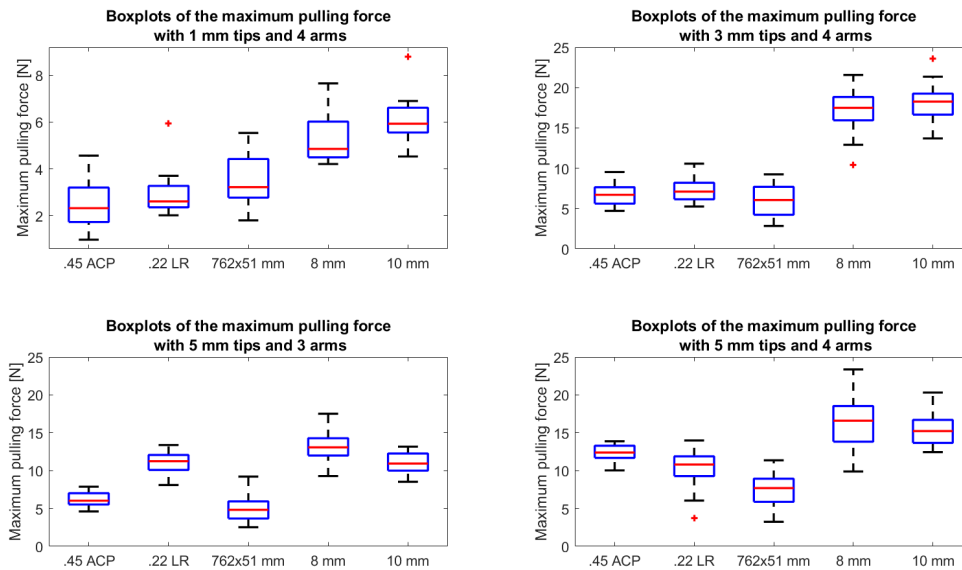


Figure 6.6: A boxplot of the maximum pushing force on the bullet during grabbing, showing the median and the interquartile range. Note: the upper left y-axis has a different scale, in order to be able to read the graph properly.

6.2. Results

6.2.1. Pulling

In this section, the results of the experiments to determine the maximum pulling force are discussed. The code used to graph the results and extract them from the raw data is placed in Appendix E. Table III shows the median and Inter Quartile Range (IQR) for the maximum pulling force (of the 20 experiments) for the different grippers and bullets.

Bullet	1 mm tip 4 arms		3 mm tip 4 arms		5 mm tip 3 arms		5 mm tip 4 arms	
	Median	IQR	Median	IQR	Median	IQR	Median	IQR
.45 ACP	2.32	1.5	6.70	2.0	6.03	1.5	12.38	1.6
.22 LR	2.61	0.9	7.10	2.1	11.24	2.0	10.80	2.6
7.62x51 mm	3.22	1.7	6.06	3.5	4.82	2.3	7.69	3.1
8 mm sphere	4.85	1.5	17.49	2.9	13.07	2.3	16.59	4.7
10 mm sphere	5.93	1.1	18.26	2.6	10.93	2.3	15.22	3.0

Table III: The Medians and Inter Quartile Range (IQR) of the maximum pulling force in Newtons

The maximum pulling force from each experiment was used to create boxplots that show the spread in the data (and outliers). The boxplots for the maximum pulling force are given in Figure 6.6.

6.2.2. Pushing

Table IV shows the medians and IQR's for the maximum pushing force (of the 20 experiments) for the different grippers and bullets. The maximum pushing force from each experiment was used to create

Bullet	3 mm tip 4 arms		5 mm tip 4 arms	
	Median	IQR	Median	IQR
.22 LR	1.26	0.9	x	x
8 mm sphere	4.73	0.6	9.01	1.7
10 mm sphere	7.10	2.5	13.13	1.3

Table IV: The Medians and Inter Quartile Range (IQR) of the maximum pushing force in Newtons

boxplots that show the spread in the data (and outliers). The boxplots for the maximum pushing force are given in Figure 6.7.

6.2.3. Boxplots

Boxplots are used to visually show the distribution of the data. In this research, each experiment was performed 20 times. The median in this research is the mean of the tenth and eleventh value when sorted from low to high. The code used to create these boxplots in Matlab (Mathworks, 2018) is given in Appendix E

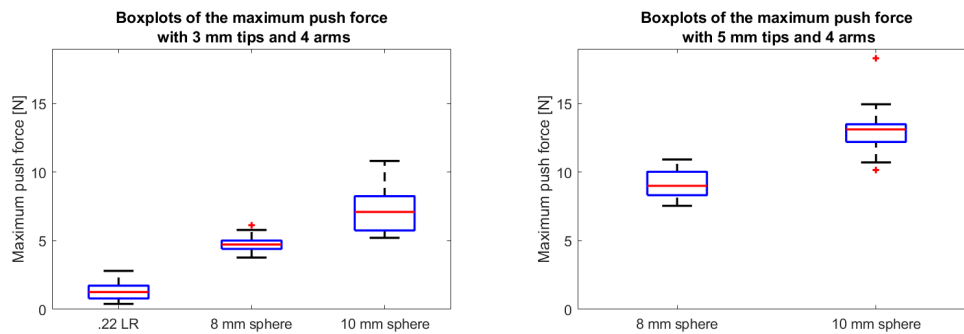


Figure 6.7: A boxplot of the maximum pulling force on the bullet during retraction, showing the median and the interquartile range

6.2.4. Damage to the bullets

One of the experimental goals was to *not damage the bullet in such a way that debris is left inside the fistula*. This was validated through visual examination of the bullets after the testing was performed. Only scratch marks from the gripper were found on the bullets. There were no signs of pieces being torn off the bullet. The scratch marks are visualized in Figure 6.8

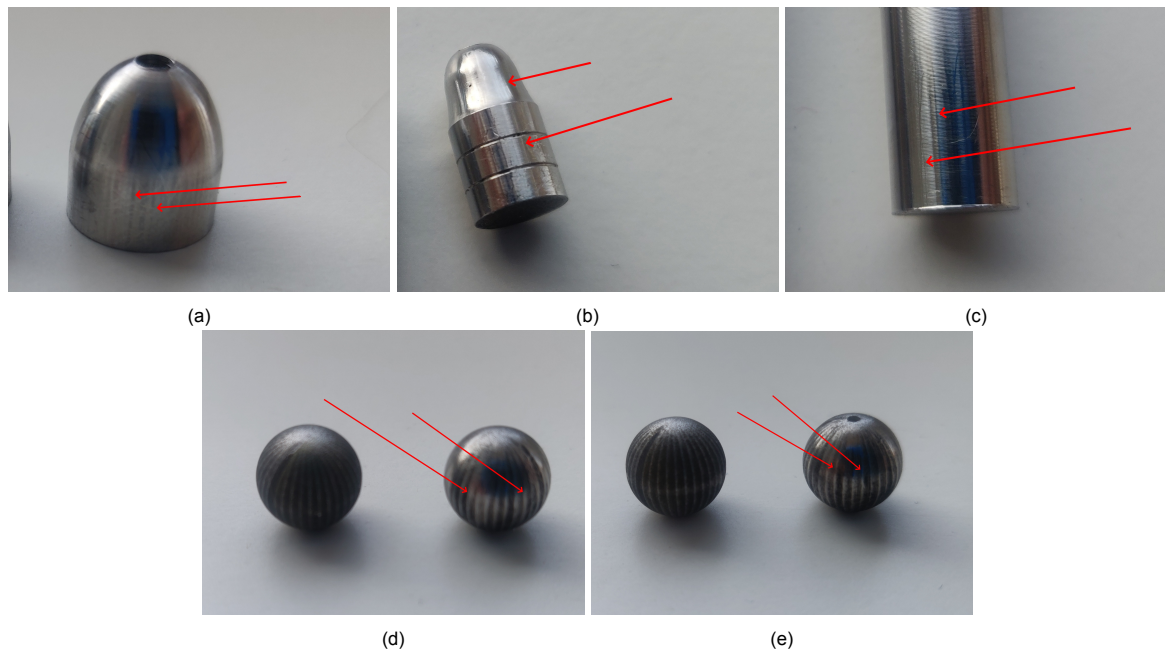


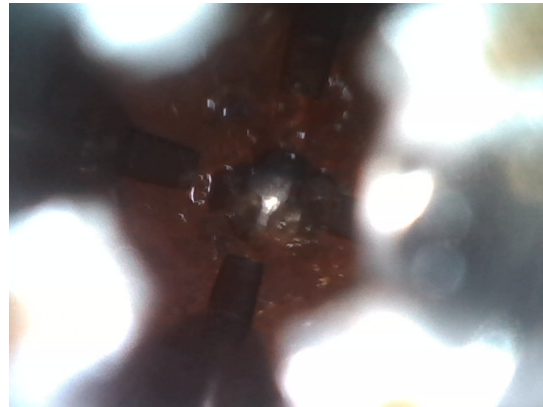
Figure 6.8: Scratch marks left on the bullets after testing, the red arrows indicate straight scratch marks from the pulling test. (a) shows the .45 ACP bullet, (b) shows the .22 LR bullet, (c) shows the 7.62x51 mm bullet, (d) shows a side by side comparison of the 8 mm sphere before (left) and after testing (right), (e) shows a side by side comparison of the 8 mm sphere before (left) and after testing (right).

6.2.5. Proof of concept

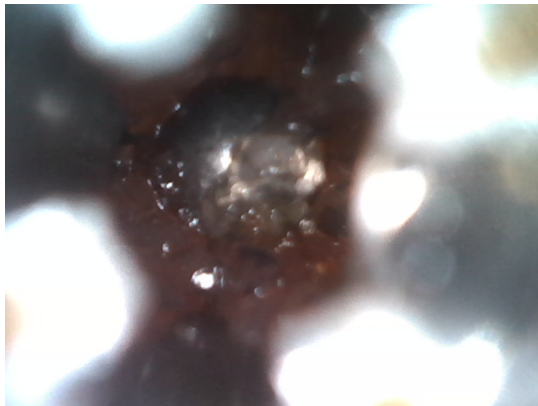
The proof of concept test was performed five times and the bullet was grasped and retracted five out of five times. A photo collage of removing the bullet from the gelatin is given in Figure 6.9. These pictures were taken with a 4 mm endoscope, which was inserted in the gripper. Operating the device through the endoscope was possible, but resulted in steering in the wrong direction a few times. The pictures give a good indication of the visual aid presented by the scope. The video provided by the scope was in real time (no serious delays) and had LED's to illuminate the phantom in order to properly see the bullet. The gripper arms are visible through the scope and the gap between them is also clearly visible. This helps with the closing of the gripper, as it is visible whether or not the bullet is inside the gripper and if the bullet fits inside the gripper.



(a) Inserting the gripper into the gelatin



(b) Reaching the bullet inside the gelatin



(c) The gripper with the gripper arms around the bullet



(d) The gripper is closed with the bullet firmly grasped

Figure 6.9: Four pictures showing the process of grabbing the bullet from gelatin

Discussion

7.1. Main findings

After careful consideration of all the options mentioned in this research, it was decided that the gripper that should be tested was the normal force gripper. This gripper was considered safest for Hnin (as it does not remove the fistula wall inducing the risk of infection), able to provide enough force to actually retract the gripper without the bullet falling out (unlike the suction concept) and can be used on a flexible steerable shaft. The design also has few moving parts, which reduces the failure modes. The design was tested and it was determined that the 4 arm configuration resulted in a significantly higher pulling force. On the 8 mm sphere the median pulling force was 16.6 N for the 4 arm configuration and 13.1 N for the 3 arm configuration. The tip length was set to 3 mm as this resulted in pulling force similar to the 5 mm tips and a pushing force that was significantly lower than the 5 mm tips. The median pulling force on the 8 mm sphere was 17.5 N for the 3 mm tip and 13.1 for the 5 mm tip versions. The median pushing force on the 8 mm sphere was around two times higher for the 5 mm tips than it was for the 3mm tips, with median pushing forces of 9.0 N and 4.7 N, respectively.

The gripper arm was determined to have a thickness of 0.5 mm to keep fabrication possible and to keep the forces needed to close the gripper at a reasonable level. The stiffness required to grip the bullet tightly with the closing system as it was designed determined the width and length of the gripper arm. This also determined that the options for the amount of gripper arms were limited. The gripper arms, rinsing holes, endoscope and the Bowden cables that control the closing mechanism need to fit on the top of the gripper head. The options were 1, 2, 3 or 4 arm(s). 1 arm would result in dragging the bullet along the fistula wall, which is not optimal. 2 arms result in an unstable system. The arms would need to be perfectly in line with each other to prevent the (round) bullet from slipping out. This resulted in either 3 or 4 arms.

From the experiments performed in this research it is apparent that the normal force gripper with 4 arms and 3 mm tips is best suited to remove the bullets from elephant Hnin. Next to that this research has shown its ability to pull other bullets from bullet wounds. The pulling force reached by the gripper on an 8 mm sphere was slightly more than 17 N. For comparison: the gravitational force on an 8 mm steel sphere is 100 times smaller (using a density of 8.05 grams per cubic centimeter). The pushing force exerted on the bullet while grabbing is slightly more than 4.7 N. For comparison: this is slightly less than the gravitational force of a 0.5L bottle of water.

Another benefit of the 4 arms configuration is that a larger percentage of the gripper is shielding the bullet from dragging along the fistula wall, reducing the chances of the bullet slipping out of the gripper during retraction.

7.2. Limitations

This research was limited by some factors. The most important factor was the knowledge gaps: there was insufficient research done on fistulae in elephants. This meant that the removal of the fistula wall was not possible to research. Another factor was the patient being in Myanmar, often times it is inspirational and helpful to see the setting in person. The amount of tests that can be performed is limited, especially with a higher number of variables. It was determined that each set of variables was

tested 20 times. This resulted in 100 pull or push tests with each gripper configuration. Four different configurations were tested in the pulling test, giving a total of 400 pulling tests. The pushing test was performed on 3 different bullets and 2 different grippers, resulting in only 120 pushing tests. This was done because the largest bullets (the .45 ACP and the 7.62x51 mm) did not go into the gripper when pushed from the rear due to their large diameter. All these tests needed to be performed with care. The accuracy of the data given in the Results is determined by the low amount of repeats per test (in this case, twenty). A higher amount of repeats would benefit the accuracy of the data but also increases the total amount of tests to be performed.

The proposed gripper looks quite simple. The other designs proposed looked more complex and interesting. The limiting factor herein was the limited fabrication options and the limited facilities in Myanmar. The cutting of the fistula would have been a great option if the device could have been made sterile.

The spring steel gripper arms were bent by hand, which also results in inaccuracies. The bending was done with utmost care and checked for the angle, but due to the small size it is possible that the angles were off by a small percentage. Inaccuracies from the 3D metal printer are not considered to be a limitation, as all parts (3D printed, laser cut and off-the-shelf items) fit together perfectly. Therefore it is assumed that these inaccuracies were negligible. While filming the grasping of the bullet through the endoscope there was gelatin in front of the camera, making the picture lose focus and obstructing the view from the bullet. In the final design this is solved by rinsing the fistula with water during the process.

Even though this research included extensive brainstorming, it is possible that some concepts were not considered for this research. This could mean that a design exists that works even better.

The extensive list of restrictions also limited this research. The best option in Western Europe would be to use an x-ray to locate the bullet and simply make a new cut to surgically remove it. Due to the elephant being in Myanmar, it was not allowed to do this. Other interesting solutions that included heat, electricity or cutting the bullet would have been rather interesting to explore. These solutions could have rendered a higher pulling force, but were not allowed.

As this research was written in 2020-2021, the COVID-19 pandemic was also rather limiting. There were some delays due to illness, quarantine and other factors.

7.3. Recommendations

There are still some steps to be taken before the gripper can be used inside an actual elephant. The gripper, as designed in this research has room for a waterproof scope with a diameter of 4 mm. The gripper was designed to be used on an existing 3D printable modular steerable shaft. This would require the operating of the gripper (opening and closing) to be done via a Bowden cable or a similar system. A recommended shaft for this is the steerable shaft created by PhD candidate Fabian Trauzettel from the Delft University of Technology. This does result in the design becoming a single-use device, as 3D printed PLA is not suitable for sterilization. Another option would be to have an instrument maker create a steerable shaft, driving up the cost of the device significantly.

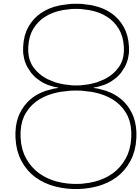
In order to fit everything inside the shaft, it is advised to modify the scope. By removing the scope head from the wiring it is possible to solder thin wires onto the scope head that are not covered by a thick layer of plastic. This does reduce the durability of the scope unfortunately. The scope used was a brandless endoscope that cost around €12,- so it is possible to bring multiple scopes when multiple extractions need to be performed.

Through the proof of concept test it was found that the gripper is operable with just the visual aid of the 4 mm endoscope. What could be useful is to color the gripper arms and have those colors represented on the handle of the device, in order to be able to easily steer inside the fistula. This is because the gripper has rotational symmetry and steering in the wrong direction could have severe consequences. Color-coding the gripper tips (which are visible through the endoscope) would reduce the chances of steering in the wrong direction.

7.4. Future vision

The setting of the surgery will be very different from the surgery settings in western hospitals. The only sterile objects are the ones that are sterilized before flying to Myanmar. This also means that per elephant at least one device is required. If multiple elephants are to be helped in a single trip, multiple

devices are needed. There are also no aluminium 3D printers available near the patients. This means that a backup is desirable as the whole trip is in vain if the device breaks either during transport or in surgery. A simple laptop will be used to show the endoscope images and local drinking water is used to rinse the wound (which is most likely not sterile, nor is the pumping equipment). Due to the simplicity of the design, it is not expected that many problems arise during the surgery caused by the device (e.g. there is no software to malfunction). Assumptions that were made can turn out to be inaccurate, resulting in a failed surgery (e.g. the fistula being only 3 mm in diameter after the first 20 cm, meaning that the device does not fit).



Conclusion

The design that was created is a normal force gripper with 4 arms with 3 mm tips. The thickness is 0.5 mm and the gripper is able to grasp multiple bullets (.22 LR and spherical bullets) by pressing against the back of the bullet. The gripper fulfills the criteria set: the dimensions, the visual aid and the rinsing are embedded into the device. The bullets are also not damaged in such a way that debris from the bullet (or the gripper) is left inside the fistula, only small scratch marks were to be seen on the bullets. The result is a simple but efficient gripper.

A test was performed to determine the amount of arms, the result was that 4 arms is the optimal amount (between 3 or 4 arms). After this test, the same testing protocol was used to test the pulling force with 1 mm tips and 3 mm tips respectively (in the 4 arm configuration). The 1 mm tips resulted in low grip forces. The gripper was deemed insufficient due to the low grip forces, as the test setup shows ideal conditions and the 1 mm tips gripper was not able to pull with more than 6 Newton on the 8 mm bullet.

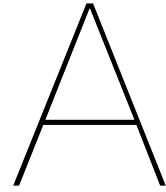
The 3 mm tips show a significant difference between the bullet types. The actual over-the-counter available bullets gave a lower pulling force than the spheres that this research is aimed at. The 3 mm tips and 5 mm tips are quite similar and due to the spread in the data it was not possible to rule one or the other out at this point. The pushing force was determined for the 5 mm tips and 3 mm tips grippers in the 4 arm configuration. The pushing force was determined as an indication as to how much the bullet would move while moving the gripper around the bullet. Most over-the-counter bullets were too large and too flat at the rear to grab this way. The spherical bullets that are the main focus in this research did give results. The push forces varied significantly between the 3 mm and 5 mm tips. Results show and increase with almost a factor 2 between these arms. Therefore the 3 mm tips gripper in 4 arm configuration was considered the best gripper in this research.

The Proof of Concept test shows the device is also capable of removing a bullet from a gelatin phantom by only using the endoscope to see the bullet.

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Fistula cutting options

A.1. Tissue removal concept development

A.1.1. Pushing the fistula wall out of the bullet's way

Stents are tubes usually used to widen a duct. The most known form is the coronary stent used in human coronary arteries, to widen the passage for blood to the heart in order to prevent a myocardial infarction. Stents are also used in the trachea of dogs when they have difficulty breathing. In this case research it would be used to push the connective tissue outwards to increase the diameter of the fistula. A great material for stents is Nitinol, a Nickel-Titanium alloy with "shape memory". This feature can be used to have the stents expand once they are in place in the fistula. A schematic representation of the stent concept is given in Figure A.1. Here it is made clear that the usage of stents widens the passage by compressing the connective tissue.

Stents can expand a little over four times in diameter. This means that in order to stretch the fistula to be 13 mm wide, stents need to be approximately 3.25 mm in diameter when collapsed. The materials used for stents vary, both metals and polymers are used[30]. A stent that is 10 mm in diameter uses wires of 0.14 mm in diameter[31]. This comes close to the desired 13 mm, so a wire thickness of 0.14 mm should be used, which would fit the design parameters.

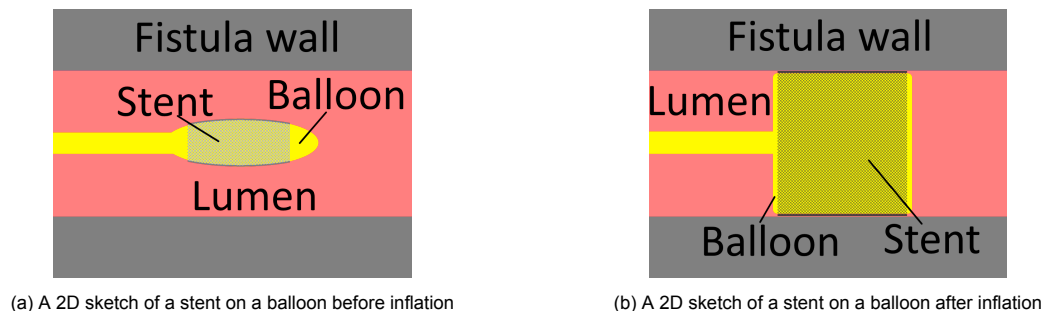


Figure A.1: A schematic representation of stenting, showing the increase in diameter of the fistula

A.1.2. Cutting by pushing

Using an apple corer:

By pushing a device similar to an apple corer inside the fistula it should be possible to remove tissue from the fistula wall. The advantage of the apple corer concept is the set diameter, which prevents unnecessary removal of healthy tissue. The downside, however, is that it is not prone to follow the prescribed path of the fistula. The apple corer concept will most likely 'drill' straight forward. Figure A.2 shows a sketch of this concept.

In order to not have the design undergo plastic deformation, it is necessary that the internal stress remains under the yield strength. In this case, the axial force would be responsible for most internal

stress. The stress is calculated through

$$\sigma = \frac{F}{A} \quad (\text{A.1})$$

with σ being the stress (in Pa), F the force (in N) and A the area (in m^2). The area is calculated through

$$\frac{\pi}{4} * (D_{out}^2 - D_{in}^2) \quad (\text{A.2})$$

with D_{out} being the outer diameter (in m) and D_{in} being the inner diameter (in m). A wall thickness of 0.5 mm and outer diameter of 13 mm would result in an axial force of over 8 kN without surpassing the yield strength of 414 MPa (aluminium 2014 T6). This is a rather high force that will not be reached in this design.

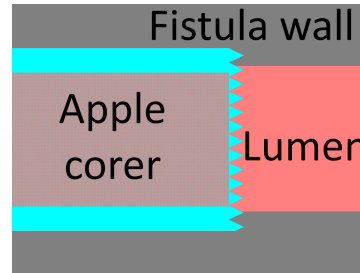


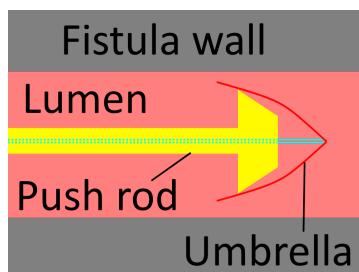
Figure A.2: The apple corer mechanism

A.1.3. Cutting by pulling

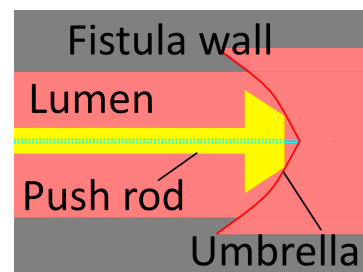
Using an umbrella scraper:

A promising solution where pulling is used is an umbrella scraper. Here, a folding structure (which resembles an umbrella) is inserted into the fistula in a closed position. Once inside the fistula, the structure is opened to have a diameter larger than the fistula. By using the sharp edges of the device, the connective tissue is cut off by pulling the device back. Rinsing is also necessary during this operation. Figure A.3 gives a sketch of this concept, showing the opening mechanism. This mechanism consists of an outer and an inner rod. The inner rod is inserted into the outer rod before it is inserted into the fistula. The outer rod has a wedge on the end that forces the 'umbrella' open. The umbrella is attached to the inner rod. In order to cut the tissue, the inner rod is pulled, ensuring the 'umbrella' stays open.

Using a stainless steel wire of 0.7 mm results in a pulling force of 200 N using the formulas given in Equations A.1 and A.2 and the yield stress of 520 MPa (Stainless steel AISI 302). Using Nylon would result in 13 N of pulling force ($\sigma = 35\text{MPa}$, lowest tensile strength of extruded Nylon6) up to 71 N ($\sigma = 186\text{MPa}$, highest tensile strength for extruded Nylon6), which are also relatively good pulling forces. Increasing the diameter would result in a quadratic increase in maximum pulling force.



(a) A 2D sketch of the umbrella scraper in the closed position



(b) A 2D sketch of the umbrella scraper in the open position

Figure A.3: A schematic representation of the umbrella scraper, in closed and open positions. By pulling the inner rod backwards, the umbrella scraper slides open over the trapezoidal end and scrapes the walls of the fistulae.

A.1.4. Cutting tangential

Using a rotating knife:

By rotating a bendable rod it can be possible to have a razor blade-like knife spin around inside the wound to scrape off the connective tissue. This method is precise in the way that it can be made to scrape of tenths of millimeters per rotation, by orienting the razor blade under a certain angle and offset. Rinsing during this operation is to prevent the device from clogging with tissue and blood. Figure A.4 gives a schematic representation of this concept. This sketch shows how the razor blade is pushed against the fistula wall by springs. This feature allows the veterinarian to keep cutting the tissue layer by layer instead of having to switch the device for another version of the device with a larger diameter.

The design presented in Figure A.4 uses a tube that is rotated with 2 small tubes attached to the spinning rod that hold the blades in place. The maximum cutting force is determined by the (bending) strength of the hollow tubes. a realistic design would be a 2 mm outer diameter and a 1 mm inner diameter (due to the size constraints). Stainless steel is a plausible material for this design. The maximum bending stress needs to be lower than the yield strength. The yield strength in this calculation is the same as in the previous calculation: 520 MPa (Stainless steel AISI 302). The maximum bending stress is given by the following formula:

$$\sigma_b = \frac{M * d}{I} \quad (A.3)$$

Where σ_b is the maximum bending moment in the tube (in Pa), M is the maximal moment on the tube (in Nm), d is the distance between the neutral axis and the outside of the tube (in m) and I is the moment of inertia (in m^4) The moment of inertia I is calculated with the following formula:

$$I = \frac{\pi}{64} * (D_{outer}^4 - D_{inner}^4) \quad (A.4)$$

In this equation, D_{outer} is the outer diameter of the tube and D_{inner} (in m) is the inner diameter of the tube (in m). Equation A.4 gives a moment of inertia of $7.363 * 10^{-13} m^4$. The length of the tube is approximately 2 mm. The neutral axis lies in the center of the tube, meaning that d in Equation A.3 is half the diameter: 1 mm. Rewriting Equation A.3 to have the moment isolated renders:

$$M = \frac{\sigma * I}{d} \quad (A.5)$$

Where σ_b is the maximum bending moment in the tube (in Pa), M is the maximal moment on the tube (in Nm), d is the distance between the neutral axis and the outside of the tube (in m) and I is the moment of inertia (in m^4) Using Equation A.5 to calculate the maximum allowable moment renders a moment of 0.383 Nm. The length of the tube was set at 2 mm, giving a maximum cutting force of 191 N.

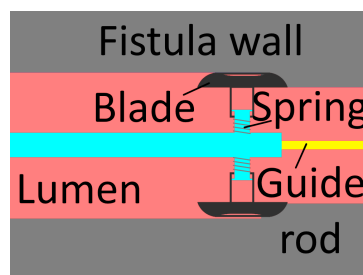


Figure A.4: The rotating knife mechanism

Using a milling cutter:

By using a guide rod that can be inserted in the fistula, a spinning milling cutter can be used to cut the connective tissue away. This milling cutter is basically a conical drill that also cuts on the sides and functions as such in this concept. Since the milling cutter is pointing deeper into the fistula it is important with this design to stop cutting a few centimeters away from the bullet. Cutting the last part must then be done at a very slow speed with high precision in order to not damage the bullet. Rinsing is needed for this operation as well. Figure A.5 shows a sketch of the concept and a picture of the

milling head. The added benefit of the conical milling head is the self-centering. This ensures that the connective tissue is cut over the whole fistula wall at an equal rate.

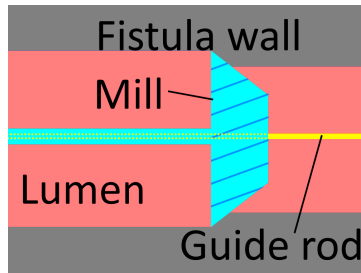
The milling cutter is rotated by a rotating rod that transfers the rotational force from outside the elephant. The weakest link in this (robust) design is the rotating rod. A steel rod would not work in this scenario as it is not flexible enough to follow the wound. Polypropylene is a widely used flexible plastic that would be more suited for the rotating rod. The torsional strength of this rod is the likely failure mode in this design. The maximum torsion to be transferred by the rotational rod is given by:

$$T = \frac{J_T}{r} * \tau \quad (\text{A.6})$$

Where T is the maximum torsion (in Nm), J_T is the polar moment of inertia (in m^4), r is the distance between the neutral axis and the outside of the rod and τ is the maximum shear stress at the outer surface (the shear modulus). The polar moment of inertia for a hollow tube is given by summing up the moment of inertia in x and y direction, since this is a tube, the moment of inertia for the x direction is the same as the moment of inertia in the y direction resulting in the polar moment of inertia being two times the moment of inertia I in Equation A.4:

$$J_T = \frac{\pi}{32} * (D_{outer}^4 - D_{inner}^4) \quad (\text{A.7})$$

In this equation, D_{outer} is the outer diameter of the tube and D_{inner} (in m) is the inner diameter of the tube (in m). Using an outer diameter of 4 and an inner diameter of 1 (to allow water to flow through for rinsing) Equation A.7 gives a polar moment of inertia of $2.50 * 10^{-11} m^4$. With an outer diameter of 4 mm, the value of r in Equation A.6 becomes 2 mm. The shear modulus of polypropylene is 400 MPa. Equation A.6 gives a maximum torsion of 5 Nm. Because the mill head had a maximum diameter of 13 mm, this results in a cutting force of 385 N.



(a) A 2D sketch of the milling cutter



(b) The intended shape for the milling head, taken from [32]

Figure A.5: A schematic representation of the milling system with a picture of the intended milling head. By rotating the drive rod over the guide rod a rotation in the milling head will be brought about

Using a rasp/grater:

The concept of the surface-forming tool is centuries old, records show 'grate houses' in Amsterdam dating back as far as 1596 [33]. In modern times, the Surform (surface-forming tool) is used to grate wood. This device is capable of accurately removing a rather thin layer of wood in order to give the surface a smooth finish. Figure A.6 shows a sketch of this concept. The small holes are represented by the grid on the grater. The grate has to be hollow in order to discard grated tissue through the inside of the device.

The grater works similar to the mill head, with the difference of the shavings going through the inside of the device instead of the fistula. This requires a larger inner (and outer) diameter for the grater rotation rod than the mill rotation rod. By picking an outside diameter of 8 mm and keeping the cutting force (and the torsion) at the same value as the mill, it is possible to calculate the inner diameter of the grater rotation rod. The maximum torsion in the mill rod was calculated to be 5 Nm. The grater has a larger diameter on the rotation rod (8 mm instead of 4 mm), so r in Equation A.6 also increases (from 2 mm to 4 mm). Rewriting Equation A.6 gives:

$$J_T = \frac{T * r}{\tau} \quad (\text{A.8})$$

Where T is the maximum torsion (in Nm), J_T is the polar moment of inertia (in m^4), r is the distance between the neutral axis and the outside of the rod and τ is the maximum shear stress at the outer surface (the shear modulus). Entering the values in Equation A.8 gives a polar moment of inertia of $5 * 10^{-11} m^4$. Equation A.7 can be rewritten to give the inner diameter from the polar moment of inertia and the outer diameter:

$$D_{inner} = \sqrt[4]{D_{outer}^4 - \frac{J_T * 32}{\pi}} \quad (A.9)$$

In this equation, J_T is the polar moment of inertia (in m^4), D_{outer} is the outer diameter of the tube and D_{inner} (in m) is the inner diameter of the tube (in m). Using formula A.9 to calculate the inner diameter gives a value of 7.74 mm. This results in a rather small wall thickness, it is more practical to use a inner diameter of 7 mm.

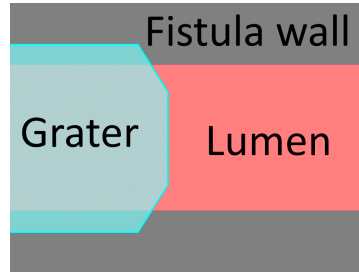
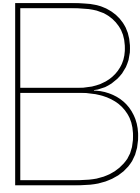


Figure A.6: The grater mechanism



One device with two functions

B.1. Combining concepts

By combining the two devices into one multi functional device, the total weight of the devices goes down. Combining the devices also nearly halves the amount of materials used. Another interesting reason to combine the cutting and grabbing in one device is the fact that everything is happening inside an elephant. The elephant (which is able to knock over a tree with relative ease) is stressed by the surgery that is happening. Caretakers have to keep the elephant comfortable to keep it from running off. Hnin has been rinsed thoroughly for years, so getting her to comply to the surgery should not prove all too difficult. The problem arises when the fistula removing device is removed. She has been trained to stay put during the rinsing of the wound, after the rinsing she is released and free to go. This could mean that Hnin tries to flee the scene after the device is removed. If the device does not need to be removed before the veterinarian is done with the entire surgery, chances are higher that the elephant will comply during the entire surgery. Fully sedating the elephant is not possible on site in Myanmar due to a lack of equipment. The downside of combining the devices is, however, the increasing complexity. Introducing more small parts will increase the amount of failure modes. This section shows the combination of (most) concepts. This is mostly beneficial for designs where the fistula wall is removed before the bullet. When the bullet is removed before the fistula it is not desirable to combine devices as the fistula wall could easily (unnecessarily) be damaged while removing the bullet.

B.1.1. Stent devices

By using a device that places stents, it is important to keep in mind that placing stents over a length of 100 cm is a tedious process. Every stent must be placed individually. This means that the device will be inserted and removed 50 times when using 2 cm wide stents. This means that the bullet gripping device, when combined to a stent placing device, will also go through this process 50 times. The sliding through the fistula may cause wear on the gripping device, decimating the amount of bullets that can be grabbed.

The wedged capsule combined with a stent negates the need for an inflatable balloon to place the stents. Since the gripper extends its diameter it takes over the role of the balloon. This shows the benefits of adding the devices together

B.1.2. Spinning razor blade devices

The devices that are combined with the spinning blade concept become larger in diameter. These devices, with the exception of the fishing net, inflated ring and heat shrinking ring, were all designed to have the maximum diameter after removal of the connective tissue. This means that the fistula must be made wider in order for the devices to pass through.

Another issue with these designs is that the retraction of the device has to be done in a spinning motion to not damage the spinning blades. Another issue with this is that the spinning motion introduces more wear and tear on the bullet removal device.

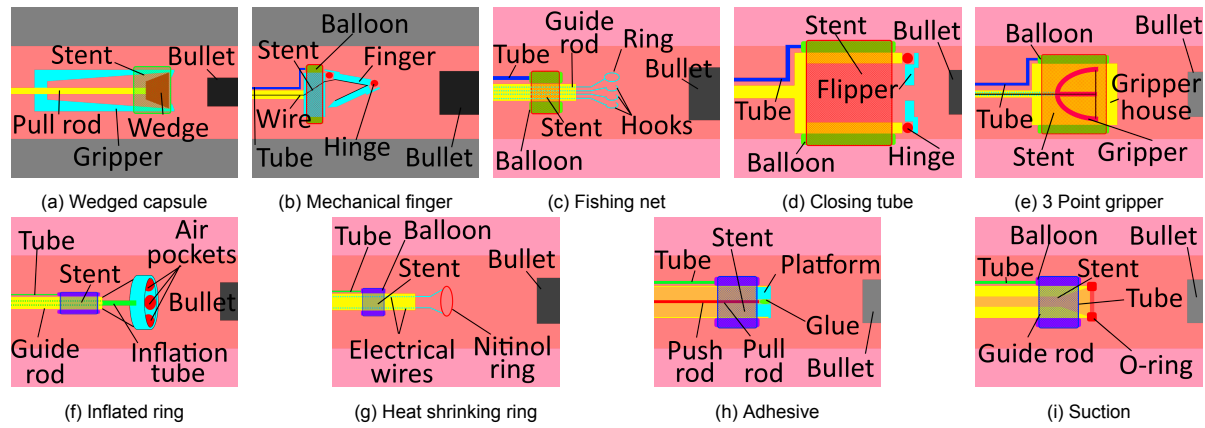


Figure B.1: All bullet grabbing designs combined with the stent concept

The 3 point gripper design does not have to be the same diameter as the bullet. If the gripper house can be made small enough to accommodate for the razor blade, this device could be a good combination of the two concepts. The gripper house prevents wear and tear on the gripper during the cutting and the spinning rotation could help dislodge the bullet.

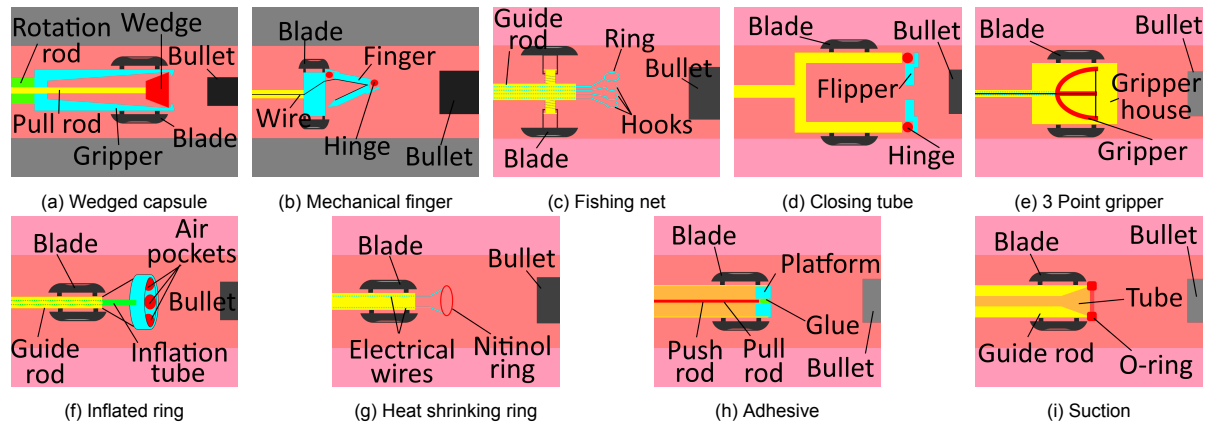


Figure B.2: All bullet grabbing designs combined with the blade concept

B.1.3. The umbrella scraper device

Since the umbrella scraper removes connective tissue with the proximal end of the device, it is important that the bullet removal device is small enough to fit through the tip of the 'umbrella' and is also not too long (because the connective tissue can not be removed behind the umbrella). This leaves only the fishing net concept as a viable option in combination with this concept.

The benefit of this design is that it removes the connective tissue without the need for rotations. This reduces wear on the gripping device.

The major downside is the fishing net concept, as this requires a lot of dexterity. Another downside is the large area of remaining connective tissue due to the shape of the umbrella.

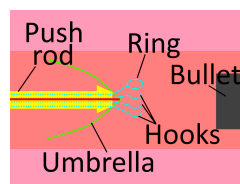


Figure B.3: The only design that allowed for the umbrella scraper to work is the Fishing net concept. Other designs are incompatible due to diameter or because the bullet gripper would be in the way of the umbrella scraper.

B.1.4. Apple corer devices

The downside of the apple corer is the inability to follow a prescribed path. This could result in a device that 'drills' straight forward therewith creating a second hole (not leading to the bullet).

The benefit of the apple corer design is the set diameter. This means that the hole left by the apple corer will be wide enough to fit the bullet. Once the apple corer has removed the fistula wall tissue, the remaining hole is the desired diameter, unlike e.g. the spinning blade design, where a variation in rotations results in a variation in hole diameter.

Another benefit could be the oscillating option of the apple corer. The design does not require full rotations like the spinning blade design. Full rotations could still be used to perform the cutting, make the device more versatile.

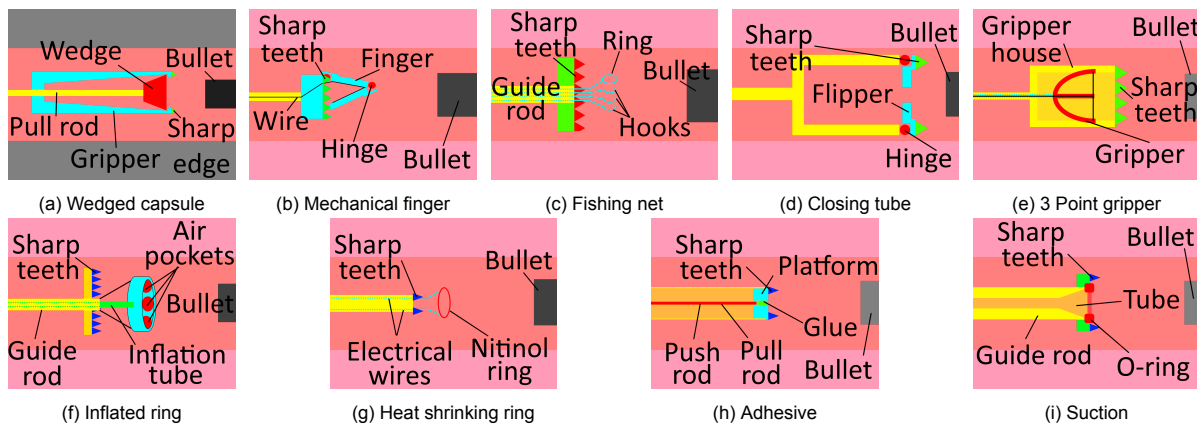


Figure B.4: All bullet grabbing designs combined with the apple concept

B.1.5. Grater devices

The grater has been around for centuries and is already being used to shape softer materials (e.g. wood, vegetables, cheese, etc.). The benefit of the design is the ability to remove small chunks of tissue, allowing for a very precise cutting.

The downside of the grater design is the clogging. The holes of the grater are prone to clogging up, rendering the device incapable of cutting the fistula wall tissue. This has to be solved by proper rinsing and a pressure acting inward.

Another benefit of the grater design is the small increase in diameter when combined with devices.

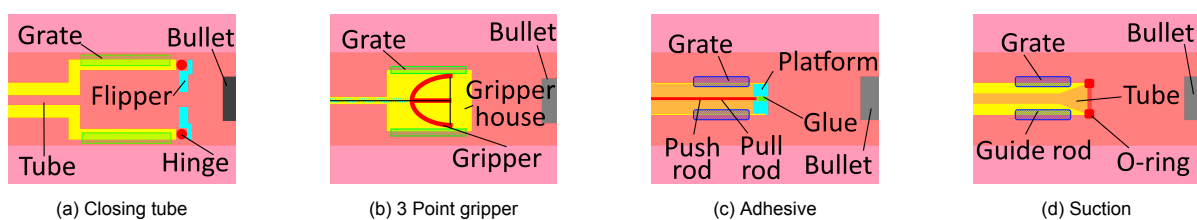


Figure B.5: All bullet grabbing designs combined with the grater concept. Not all combinations were possible due to the gripper device needing to expand in order to grab the bullet or the grater design counteracting the benefits of the cutting device.

B.1.6. Milling cutter devices

The milling cutter devices encounter roughly the same problems as the spinning blade devices. The benefit of this design over the spinning blade is that it can be retracted without the need to keep rotating. The downside is that there is a set diameter that is being cut away, so too much (or too little) connective tissue can be removed by this design.

Another benefit over the spinning blade mechanism is that the coarse removal of connective tissue requires less rotations per millimeter of connective tissue to be removed. This reduces the wear and tear of the bullet removal part.

A great combination is the closing tube with the milling cutter. Since all the connective tissue is removed all the way around the bullet and the bullet will reside inside the tube. A lock could be designed to lock the flippers in place while scraping the connective tissue to prevent clogging. The mechanical finger concept can be altered to have the sharp edges on the back side of the finger to improve the scraping ability of the design. This does require the finger to be larger in order to make it stiff enough to withstand the shear stress.

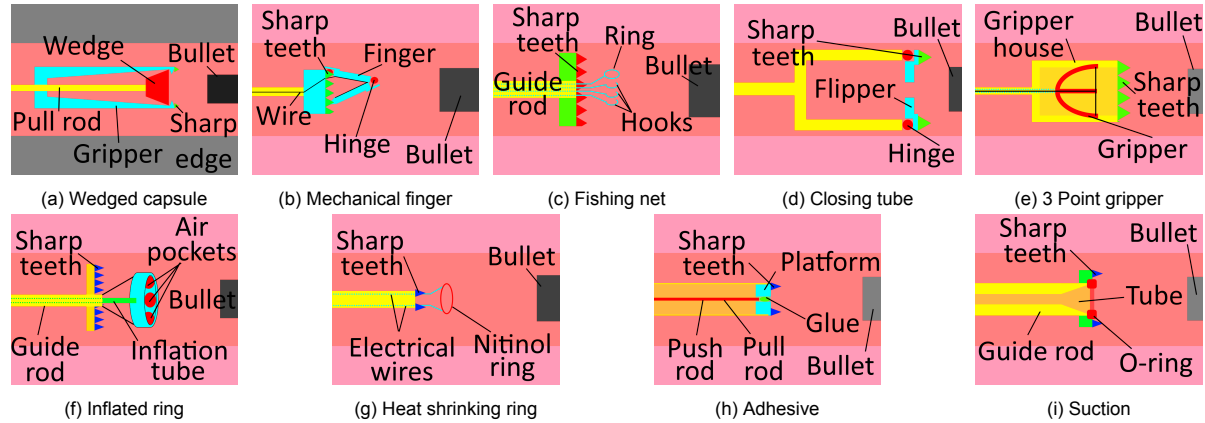
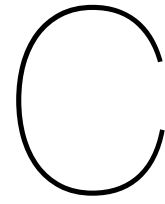


Figure B.6: All bullet grabbing designs combined with the apple corer concept



Rejected designs

C.1. Rejected designs

C.1.1. Rejected concepts due to practicalities

Most concepts generated in the previous chapter are viable but impractical, therefore a number of concepts were withdrawn from consideration. The devices that use stents to widen the fistula wall are the first to be withdrawn from consideration. Even with a system where it would be possible to feed the stents toward the from of the device it would take too long to stent the entire 100 centimeters of the fistula. The devices that were combined with the apple corer concept had the same benefits as the mill device had, with the downside of not following the fistula. These devices are also withdrawn from consideration. The umbrella scraper was only compatible with one gripper (the fishnet), or could be used as a standalone device. The spinning blade has more moving parts than other concepts. The design with the springs was taken from consideration and replaced by a design where the blades are at a set diameter, like the grater concept.

For the grippers, there was another selection withdrawn from consideration. The mechanical finger needed a rather high input force for a low pulling force. The fishing net gripper needs a high level of dexterity (higher than any other concept) without a visual aid. To prevent having to spend hours on end to get the hooks in the ring, the design was taken from consideration. The pressure inside the inflated ring needed to be too high for small pulling forces, therefore this concept was deemed less promising than others. The Nitinol ring was difficult to predict, requires heat and electricity inside the fistula and also requires more dexterity than other devices. The adhesive design was not allowed due adhesive being harmful for the elephant. The suction device was too weak to be able to pull the bullet out of the fistula (a perfect vacuum was used in the calculation, which is not possible)

C.1.2. Selected designs

Four concepts were picked to improve because of the promising concepts. The so called '3 point gripper' was picked as a standalone device with the umbrella scraper as a separate device for the fistula wall. This device was picked due to the fistula wall being used as an advantage to further close the gripper. Furthermore, this device does not require a rotating shaft.

The concept of the mill cutter in combination with the closing tube was picked to further elaborate on. This was done because the closing tube concept shields the bullet from friction from the fistula wall and the mill device helps to follow the fistula.

The mill cutter was also combined with the wedged capsule, similar to the aforementioned combination the mill cutter helps to center the wedged capsule inside the fistula. Another benefit of this design is the shielding from friction by the wedged capsule.

The final design that was picked to further elaborate on was the 3 point gripper in combination with the spinning razor blade (without the moving parts). The benefit of this design is that the gripper already has a hollow tube for the gripper to be retracted in, that can be used to flush out the cut pieces of fistula wall.

The designs mentioned above were designed as a 3D model using Solidworks [34]. This gave more insight in the dimensions, limitations and possibilities for the design. The 3D models can also be used

to create a 3D printed (scale) model of the devices to determine the usefulness.

C.1.3. The closing tube mill

Alterations in the design

Through personal communication with Dr. Schaftenaar it was brought to the attention of the author that the bullets can be partially lodged into bone. This could be caused by the bullet being shot into the bone on day one, or due to the bullet traveling downwards due to gravity and resting on the bone for a few years. The bullet being lodged in the bone causes issues with grabbing the bullet from the front. The benefit of gripping the bullet from the front is that the forces on the bullet are all Normal forces instead of Friction or Tensile forces. This meant that an adaption to the systems that were intended to grip the bullet from the front was necessary. The concept that was called the 'Closing tube' in the previous chapter was altered to feature the 'Suction' mechanism. This adaptation meant that the bullet could be gripped from the back (which is safest in regard to the bone tissue) and held in place before the tube slides over the bullet.

Another issue that was stressed by Dr. Schaftenaar was the rinsing of the fistula. Instead of just pumping water into the proximal end of the fistula it is necessary to pump the water through the device and therewith keep a continuous flow of water. This can be done in the new 'Closing tube with Suction' concept by having the water flow through the tube that is used to create a vacuum later on.

The design

By combining the benefits of two concepts it was possible to create a design that utilises the best parts of those designs. The benefit of the suction device was the ability to grip the bullet from the rear, therefore having no trouble with the tissue surrounding the bullet. The downside of this was the lack of support on the distal end of the bullet and the low pulling force. This could cause the bullet to be released from the device prematurely, meaning the device has to be reattached. The benefit of the closing tube concept was the very low chance of the bullet being released from the tube. The downside was that the surrounding tissue could become a problem in the event that the bullet was resting on bone tissue. Combining these designs negated these downsides of the designs. The resulting gripper allowed for integration with the spinning mill head. The suction tube doubles as a rinsing device and the cylindrical tube rotates to create the cutting effect of the spinning mill. A 3D model of the design is given in Figure C.1a A compliant (elastic) piece of material is used to keep the bullet inside the tube. This negates the need for fragile hinges, reducing the chances of failure. The mill is replaceable in this design to accommodate for other bullet sizes. The mill is placed on the tube by a simple push and turn mechanism. By placing the elastic compliant lid between the bottom of the mill and the bottom of the hole in the tube, it is possible to lock the components in place without glue. The mechanism is visualised in Figure C.1b. The system is guided by a guide rod, which houses the rinsing/suction tube and the scope. This is done in order to prevent these components from spinning with the mill head (and to save space). The guide rod is placed inside the fistula before the rest of the device is inserted. Once the end of the fistula is reached, the torsionally stiff rod is rotated over the guide rod, cutting of the tissue as it moves down the fistula. This is visualised in Figure C.1c

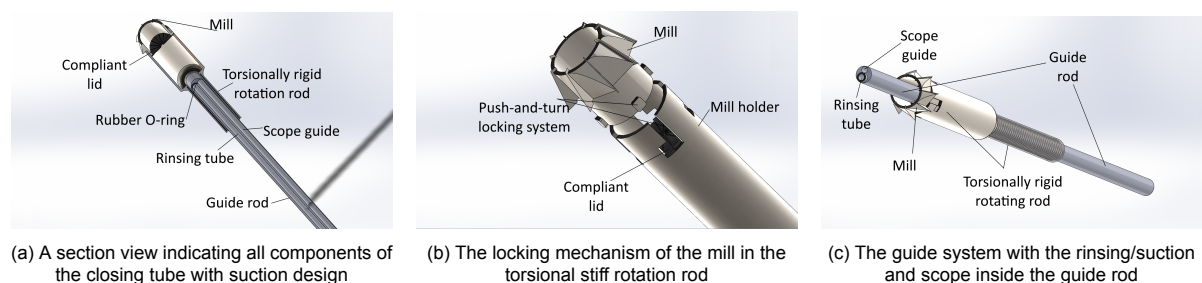


Figure C.1: The mill design

C.1.4. The wedge gripper mill

Alterations in the design

By giving the mill head a narrower hole in the middle and giving it more of a spherical nose, the issue of the mill head making its own path should be diminished. This means that the mill head will need to be redesigned to 'open' when it reaches the bullet. By partitioning the mill head into multiple parts radially, it is possible to have the mill head 'open' after reaching the bullet. This design was proposed in the concept 'wedged capsule'. By designing the device to have sharp edges between the mill parts it should be possible to cut through fibrous tissue that encapsulates the bullet. Rendering the device more versatile and suited for low resource countries.

The design

As mentioned, this design is a combination of the wedged capsule and the mill concepts. In the initial combination of these concepts, the design was made with four sleek arms that had a gap in between them. The mill was designed as 'sharp edges' on these arms. By closing the wedged capsule design completely, it was possible to design a continuous mill. This makes the cutting process smoother and reduces the chances of breaking. The rotating rod was designed as a double helix that has the benefit of being torsionally stiff while still being flexible. The scope (not pictured) goes through the wedge to keep it from rotating with the device. A render of the design is given in Figure C.2.

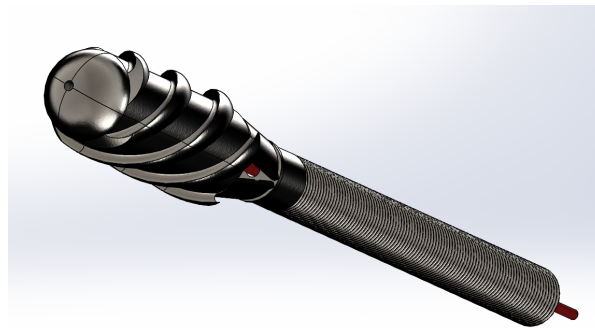


Figure C.2: A complete overview of the redesign

Validation through calculations

In order to validate this model, calculations were done to ensure the right strength of materials.

The amount of stress needed at the tip of the mill to cut through the tissue is 44 MPa [35]. The helix angle on the mill is set to 30° to maximize the force [36].

The first important calculation is to determine the amount of torque needed to cut the tissue. If this is insurmountable, the whole device will be rendered useless. The amount of torque is calculated through simple mechanics.

$$T = F * r * \sin(\theta) \quad (C.1)$$

In Equation C.1 T is the amount of torque in Nm, F is the required force, calculated by taking the product of the pressure (in Pa) and the area (in m^2), the force is in N. r is the shortest distance between the centre of rotation and the line of the applied force. θ is the angle between the force vector and the r vector. Since the angle is 90°, $\sin(\theta)$ is equal to 1.

The first 10 mm of the mill will do most of the cutting, so the area is calculated over the first 10 mm. Resulting in a Torque of 2.9 Nm per mill blade, calculated by Equation C.1. There are 4 mill blades, so the total desired torque is 11.6 Nm. A high end battery powered hand drill for home use can deliver a torque of 115 Nm (Makita DDF481 or DHP481, Makita Japan). This is considered to be more than enough to compensate for friction and other losses.

The torsionally stiff rod must also endure the torque given by the drill. The shear stress generated by this torque may not exceed the 888 MPa [37].

The inner diameter of the shaft is designed to be 0.0035 m, the wall thickness is 0.004 m. This results in an outer diameter of 0.0115 m. Calculating the moment of inertia and maximum shear stress through:

$$I = \frac{\pi}{32} * (D_{outer}^4 - D_{inner}^4) \quad (C.2)$$

In Equation C.2 the moment of inertia I is in m^4 , the D_{outer} and D_{inner} are the outer and inner diameters of the shaft respectively and in m.

$$\tau = \frac{T * r}{I} \quad (C.3)$$

Equation C.3 calculates the shear stress (τ) in Pa from the Torque (T) in Nm, Outer radius (r) in m and the moment of inertia (I) in m^4 . results in a shear stress of 388 MPa. This is less than half the maximum shear stress for spring steel. This is also calculated using the maximum torque of 115 Nm which will not be reached during normal use.

An important side note here is that even though this may seem over-dimensioned, it is designed this way to aid in the ease of manufacturing. Using half the wall thickness was an option, but would result in yield when the drill provides maximum torque while the tip of the device is e.g. stuck. To prevent this, the wall thickness of 4 mm was chosen. A close-up of this is given in Figure C.3a.

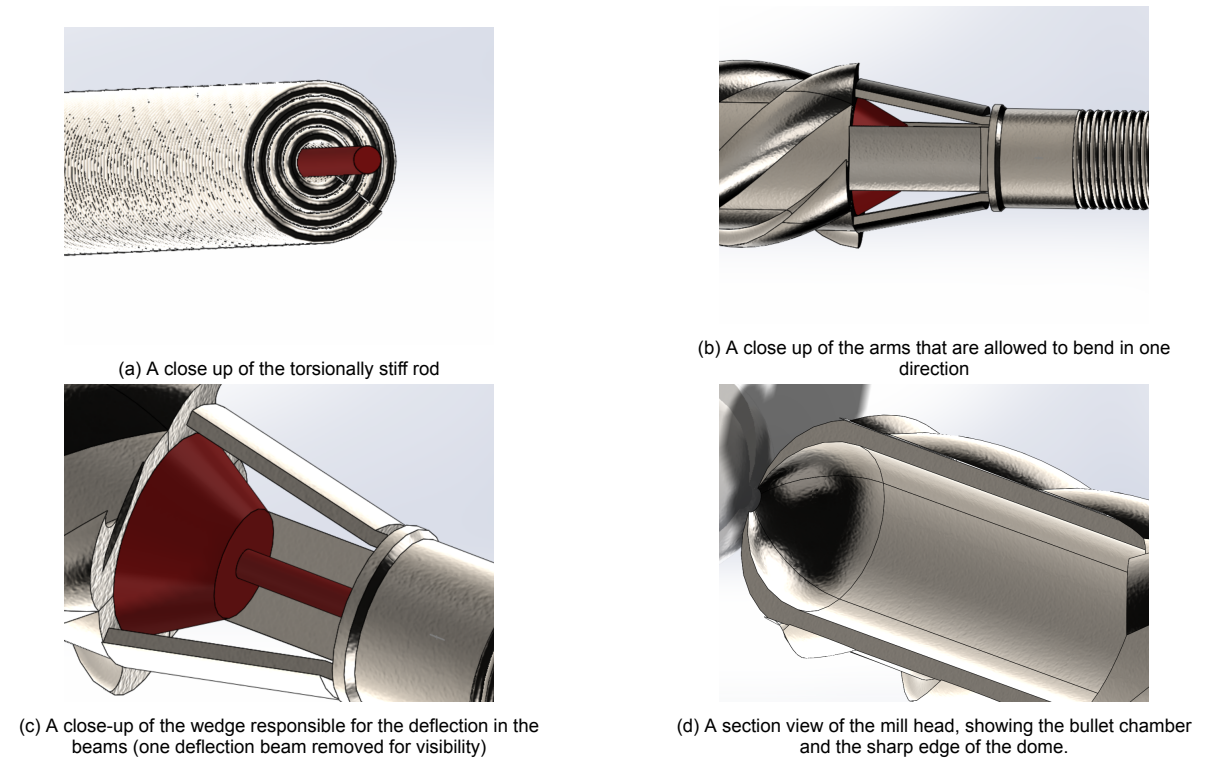


Figure C.3: Three close-ups of the enhanced mill device

Since the mill consists of four separate parts, it is imperative that these do not bend out of the formation. Through the formula for deflection in loaded beams it is possible to calculate the dimensions of the arms connecting the mill to the base:

$$\delta = \frac{F * l^3}{2 * E * I} \quad (C.4)$$

In Equation C.4 the deflection (δ) in m is calculated from the force (F) in N, the length (l) in m, the Young's modulus (E) in Pa and the moment of inertia (I) in m^4 . The maximum deflection (δ) was set to 0.0005 m. The length of the arm holding the mill is 0.00153 m. The moment of inertia is calculated through:

$$I = \frac{1}{12} * w * h^3 \quad (C.5)$$

Equation C.5 calculates the moment of inertia (I) in m^4 from the width (w) in m and the height (h) in m. Substituting the moment of inertia in Equation C.4 for the formula given in Equation C.5 and

rewriting the formula to be a function of the height gives:

$$h = \sqrt[3]{\frac{12 * F * l^3}{3 * E * \delta * w}} \quad (C.6)$$

Equation C.6 calculates the height (h) in m from the force (F) in N, the length (l) in m, the Young's modulus (E) in Pa, the deflection (δ) in m and the width (w) in m. Setting the width to 0.001 to keep the flexibility to bend outwards this results in a height of 0.0033 m. This is the minimum for the dimensions of the arm. The arm was designed to be 7.5 mm deep and 1 mm wide. This resulted in a deflection of less than a tenth of a millimeter. A close-up of these arms is given in Figure C.3b.

A wedge was placed between the arms that connect the mill to the rod. This was done to create a large opening force, next to the large closing force created by the outer shell. The wedge is connected to a cylindrical 2 millimeter thick wire. The material is a steel alloy, 28Cr2 steel, which has a yield strength of 550 MPa. This results in the wire being able to pull 1728 N before yielding. This means 176 kg can be held by the wire. This is more than necessary, but the diameter is already rather small, decreasing it further could result in discomfort during use. A close-up of the wedge is given in Figure C.3c

The mill head is hollow, similar to the closing tube concept. Since the mill head opens, there is no need for a compliant lid. The dome on top of the mill functions as a lid to keep the bullet inside, a cutting mechanism for encapsulated bullets and as a guide mechanism to guide the mill through the hole. A section view of the mill is given in Figure C.3d

C.1.5. The three point gripper razor blade

Alterations in the design

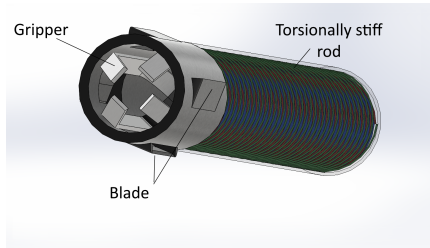
Just like the mill design, the device needs guiding to properly follow the path given by the fistula. The blade design had a disadvantage over the mill head in this case, as the mill is trapezoidal and self centering. A tip was added that can be retracted through the entire system to make room for the gripper. The tip is designed to be printed from thermoplastic polyurethane (PLU) which is rather flexible. The design of the tip has also been optimized to allow bending of the tip. When the device is forced against the wall due to a curve in the fistula a perpendicular force will be applied to the tip by the fistula wall. The tip (if printed at 100% infill to match the given Young's modulus) bends 3.3 mm over 15 mm, or about 23 degrees, when the perpendicular component is 50 N (5 kilograms). The force that is applied is dependent on the veterinarian. The force used to push the device forward goes up when the curve becomes sharper, making the tip bend more. Figure C.5a shows the bending tip. The hollow tube also allows for water to be pumped through.

The design

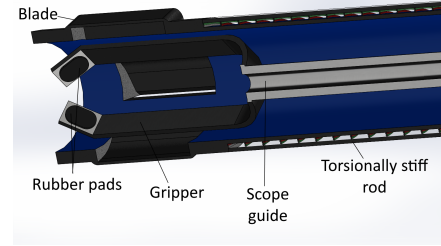
The design is a combination of the three point gripper and the razor blade concepts. The rotating rod from the previous design was used to provide the design with the needed torsion. The rod was altered to have the same inner diameter as the gripper house. The rod now consists of 2 layers of springs instead of four. Rubber pads were designed on the tips of the three point gripper. A good variable in the testing phase is the amount of arms, as the design made uses four arms, whereas the original concept had only three arms. The razor blade design was chosen in combination with the three point gripper because of its sturdy design. The three point gripper has no hinges or other such parts. The gripper arms are leaf springs that are tensioned inside the gripper house and push against the wall. Once the gripper is pushed out of the gripper house, the arms will expand outwards. The gripper arms are then placed around the bullet and the gripper house is pushed over the gripper, closing the gripper. The razor blade part of the design has been modified to contain no moving parts (apart from the entire design rotating). This was done in order to diminish failure modes in the design. This design is visualised in Figure C.4a. Rubber pads were placed on the arms of the gripper to enlarge the friction coefficient, therewith enlarging the frictional (gripping) forces on the bullet. The torsionally stiff rod is designed to be hollow, to allow for rinsing water to be pumped through the device without the need for extra tubes. This was visualised in Figure C.4.

Redesign of the blade

The design of the blade is less efficient than of a grater, since the design is designed to move forward and rotate at the same time. By using a grater instead of a blade, the cutting is performed more locally



(a) A 3D render of the three point gripper concept



(b) A section view of the three point gripper concept showing the scope guide and the rubber grip pads

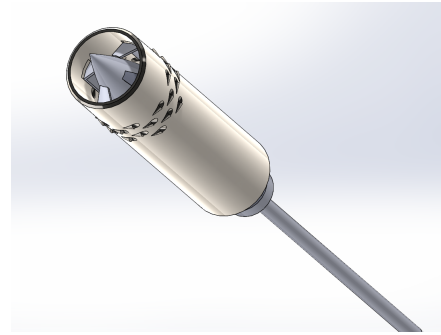
Figure C.4: The spinning blade design

and therefore done with more precision than a blade. The downside of this is the amount of edges that might need sharpening in the eventual device. This should be kept low enough to ensure manual sharpening of the grate holes is not too time consuming. Figure C.5 shows the grater design with 4 rows of 8 grate holes (32 holes in total).

Since rubber is not bio-compatible it is unwise to include this in the design. The friction that was deemed necessary for the design to work has been replaced by a closed shape design in the optimisation. This means that the gripper is designed to go all the way around the bullet and close tightly enough that the bullet can not fall out. Once the gripper is retracted into the gripper house, the entire device can be retracted, keeping the bullet and the gripper tightly inside the device.



(a) The flexible tip



(b) The bullet inside the device

Figure C.5: The grater design, showing the bending tip that guides the device through the fistula and the bullet inside the gripper

Validation through calculations

The bending of the tip can be calculated through simple mechanics of materials. The tip is designed to be hollow, with a tube in the centre that allows a scope to be pushed through. This means that the cross-section of the tip is basically two concentric circles. Since the bending axis goes through the centre of the circles, we can simply add the two moments of inertia to get the complex moment of inertia:

$$I = \frac{\pi}{32} * (D_{2outer}^4 - D_{2inner}^4) + \frac{\pi}{32} * (D_{1outer}^4 - D_{1inner}^4) \quad (C.7)$$

In Equation C.7 the complex moment of inertia (I) in m^4 is calculated by adding up the two separate moments of inertia. The moment of inertia of the outer wall (D_2) is calculated by subtracting the inner diameter (D_{2inner}) in m to the power of 4 from the outer diameter (D_{2outer}) in m to the power of 4. The same is done for the inner wall (D_1): the inner diameter (D_{1inner}) in m to the power of 4 from the outer diameter (D_{1outer}) in m to the power of 4. This moment of inertia is then used as an input in Equation C.4 to calculate the deflection. This results in a deflection of 3.3 mm with a tip length of 15 mm. This is equal to an angle of about 23° with an infill of 50% during printing with Polyflex filament. The dimensions of the holes are a good variable in testing. Based on other grate designs it was determined that the width of the hole is equal to 1.5 times the height.

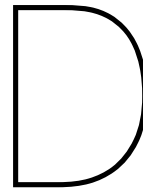
C.2. Design selection

A Harris profile was created to determine the most valuable design for the case study. The Harris profile works as follows: The criteria for the design are ranked in order of importance. The top criterion being the most important one. These criteria are then scored -2, -1, +1 or +2, based on how well the design performs on these criteria. The figure that comes from this process can be viewed as a toppling tower, the tower that topples to the right the most is considered the best option for these criteria. The Harris profile for this research is given in Figure C.6. This Figure shows that the Separate 3 point gripper concept should prove most useful for the case research. This design will be used in the testing phase in the next chapter.

	Wedge gripper mill				Closing tube mill			
	-2	-1	+1	+2	-2	-1	+1	+2
Friction during insertion								
Clamping force/input force								
Applicable to different bullets								
Shielding the bullet from friction								
Ease of operation								
Ease of re-gripping								

	3 point gripper grater				Separate gripper			
	-2	-1	+1	+2	-2	-1	+1	+2
Friction during insertion								
Clamping force/input force								
Applicable to different bullets								
Shielding the bullet from friction								
Ease of operation								
Ease of re-gripping								

Figure C.6: The Harris profile used to determine to most suitable design



Transmission for the cutting device

D.1. Rotation of the device in low resource setting

D.1.1. The distal end

Most designs have a hollow spinning tube where other tubes and scopes have to go through. This can prove to be rather difficult on the other end (outside the elephant). Regular drills have drill chucks that are only open on one side: the front. In order to properly use the scope and rinsing tube it is imperative to have a design that can rotate the shaft and is open in the front and the back. This does reach beyond the scope of this research, however it is useful to know the existing solutions discussed below.

Since the endoscope has to go through the hollow rotated tube to be attached to a screen (all while not rotating the scope), it is most important to have the end of the scope come out of the end of the hollow tube. This problem basically boils down to a problem that has existed in mechanical engineering for years: transmission of non-concentric rotation. Since the focus is put on developing countries it is important to keep the source of the energy input as simple as possible: i.e. an electric (battery powered) drill. The setup is visualized in Figure D.1. Using a battery powered drill also negates the need for a separate slip clutch, as this is already featured in the battery powered drill. Since that is kept as a boundary condition, the solution has to lie in the transmission of non-concentric rotation. In engineering, there are a few solutions to this:

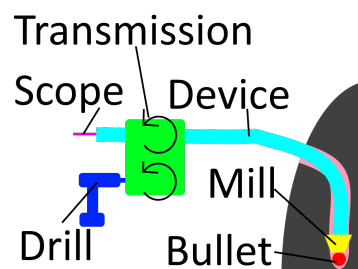


Figure D.1: The rotating of the device using a transmission

A belt drive

A belt drive is a rather simple concept: two pulleys, that are not necessarily the same size, are connected by a timing belt. The 'teeth' on the timing belt fit perfectly in the pulley, reducing slip. By rotating one pulley, the other pulley is rotated by the timing belt. By taking different sizes of pulleys it is possible to trade-in torque for rotational speed or vice versa. Timing belts are also capable of transferring high torque.

A drive chain

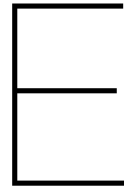
Drive chains are similar to belt drives. The difference is that a belt chain used sprockets instead of pulleys and a chain instead of a belt. Drive chains require more maintenance (lubrication and cleaning) than belt drives. Drive chains have less torque loss compared to belt drives.

Gears

Gears are a pretty straightforward solution to this problem. They are not as good at high speeds as belt or chain drives. Because the design will not make that many rpm, gears are still suitable to create a transmission. Another downside of gears is the short distance, which is not that much of a problem but the freedom in the design that belt and chain drives grant is preferred.

D.1.2. Clamping

In order to make setting up the device easier for the vet, it is preferred to have a design where the hollow tube can be detached from the gears, drive chain or belt drive. The clamping mechanism of a lathe is a great example of how this can be done. In these disk shaped clamps, three 'fingers' can be radially moved towards (or away from) the center by rotating one knob. This ensures proper centering of the clamped object. The clamps have a hole in the center of the disk that allows the clamped object to be extended through.



Code used in Matlab

This first piece of code was used to extract the results from the raw data. This file has been used to calculate the maximum pulling force in each test performed. This file was used 20 times (one for each bullet-gripper test) with different names in the title of the boxplot and different names for the variables stored at the end.

```
close all
clear all
clc

files = dir('*.txt'); %call all files in the folder
Nfiles = length(files) ; % make a vector with the length of the amount of
files
fid = fopen('maxofall.txt','w') ; %create/open a .txt file called maxofall
to write the maximum values to

for i = 1:Nfiles %This loop imports the data from all the files
and looks for the maximum values
    fname = files(i).name ;
    data = importdata(fname) ;
    iwant = max(data) ;
    fprintf(fid,'%f %f %f %f\n', iwant) ;
end
fclose(fid) ;
load maxofall.txt

for i=1:20
    Maxforce(i)=maxofall(3*i) %the maximum values of the timestamps and
the voltage measured by the sensor are also in the files, this loop removes
those values
end

boxplot(Maxforce) %create a boxplot for this test
title('4 arms 5mm gripper with 7.62x51mm')
ylabel('Force (N)')
Mean5mm4arm762=mean(Maxforce); %save the mean to a variable
STD5mm4arm762=std(Maxforce); %save the standard deviation to a variable
Force5mm4arm762=Maxforce; %save the maximum force values for all tests to a
variable
```

```
pathname = fileparts('C:\Data\');
matfile = fullfile(pathname, 'keep.mat');
save(matfile, 'Mean5mm4arm762', 'STD5mm4arm762', 'Force5mm4arm762', '-append')
```

```
%save the three variables to a separate file called keep.m
```

This file loads the aforementioned file keep.m to create boxplots of all results in one single file

```
close all
clear all
clc
```

```
load('keep.mat') %load the file
Total(:,1)=Force1mm4armACP'; %fill a vector with all the results
Total(:,2)=Force1mm4armLR';
Total(:,3)=Force1mm4arm762';
Total(:,4)=Force1mm4arm8';
Total(:,5)=Force1mm4arm10';
Total(:,6)=Force3mm4armACP';
Total(:,7)=Force3mm4armLR';
Total(:,8)=Force3mm4arm762';
Total(:,9)=Force3mm4arm8';
Total(:,10)=Force3mm4arm10';
Total(:,11)=Force5mm3armACP';
Total(:,12)=Force5mm3armLR';
Total(:,13)=Force5mm3arm762';
Total(:,14)=Force5mm3arm8';
Total(:,15)=Force5mm3arm10';
Total(:,16)=Force5mm4armACP';
Total(:,17)=Force5mm4armLR';
Total(:,18)=Force5mm4arm762';
Total(:,19)=Force5mm4arm8';
Total(:,20)=Force5mm4arm10';
```

```
figure %create a subplot containing the results for different grippers
subplot(2,2,1)
boxplot(Total(:,1:5))
ylabel('Maximum pulling force [N]')
title({'Boxplots of the maximum pulling force',' with 1 mm tips and 4 arms'})
set(gca,'XTickLabel',{' .45 ACP', '.22 LR', '762x51 mm', '8 mm sphere', '10 mm sphere'})
ylim([0 25])
subplot(2,2,2)
boxplot(Total(:,6:10))
ylabel('Maximum pulling force [N]')
title({'Boxplots of the maximum pulling force',' with 3 mm tips and 4 arms'})
set(gca,'XTickLabel',{' .45 ACP', '.22 LR', '762x51 mm', '8 mm sphere', '10 mm sphere'})
ylim([0 25])
subplot(2,2,3)
boxplot(Total(:,11:15))
```

```

ylabel('Maximum pulling force [N]')
title({'Boxplots of the maximum pulling force',' with 5 mm tips and 3 arms'})
set(gca,'XTickLabel',{'0.45 ACP','0.22 LR','762x51 mm','8 mm sphere','10 mm sphere'})
ylim([0 25])
subplot(2,2,4)
boxplot(Total(:,16:20))
ylabel('Maximum pulling force [N]')
title({'Boxplots of the maximum pulling force',' with 5 mm tips and 4 arms'})
set(gca,'XTickLabel',{'0.45 ACP','0.22 LR','762x51 mm','8 mm sphere','10 mm sphere'})
ylim([0 25])

Pushtotal(:,1)=ForcePush3mm4armLR; %create a vector for the push forces
Pushtotal(:,2)=ForcePush3mm4arm8;
Pushtotal(:,3)=ForcePush3mm4arm10;
Pushtotal(:,4)=ForcePush5mm4arm8;
Pushtotal(:,5)=ForcePush5mm4arm10;

figure %create a boxplot for the push forces
subplot(1,2,1)
boxplot(Pushtotal(:,1:3))
ylabel('Maximum push force [N]')
title({'Boxplots of the maximum push force',' with 3 mm tips and 4 arms'})
set(gca,'XTickLabel',{'0.22 LR','8 mm sphere','10 mm sphere'})
ylim([0 19])
subplot(1,2,2)
boxplot(Pushtotal(:,4:5))
ylabel('Maximum push force [N]')
title({'Boxplots of the maximum push force',' with 5 mm tips and 4 arms'})
set(gca,'XTickLabel',{'8 mm sphere','10 mm sphere'})
ylim([0 19])
bullets={'0.45 ACP'; '0.22 LR'; '7.62x51 mm'; '8 mm'; '10 mm' }
figure %create a bar graph for the pull forces the function errorbar is
used for the whiskers giving the standard deviation
x=1:5;
for i=1:20
    standaardafw(i)=std(Total(:,i))
end
subplot(2,2,1)
bar(x,mean(Total(:,1:5)))
hold on
er = errorbar(x,mean(Total(:,1:5)),standaardafw(1:5),standaardafw(1:5));
er.Color = [0 0 0];
er.LineStyle = 'none';
ylim([0 21])
title({'Bar graph showing the maximum pulling force',' for the 1 mm tips
with 4 arms'})
ylabel('Force [N]')
set(gca,'xticklabel',bullets)
hold off

subplot(2,2,2)
bar(x,mean(Total(:,6:10)))
hold on
er = errorbar(x,mean(Total(:,6:10)),standaardafw(6:10),standaardafw(6:10));

```

```

er.Color = [0 0 0];
er.LineStyle = 'none';
ylim([0 21])
title({'Bar graph showing the maximum pulling force',' for the 3 mm tips
with 4 arms'})
ylabel('Force [N]')
set(gca,'xticklabel',bullets)
hold off

subplot(2,2,3)
bar(x,mean(Total(:,11:15)))
hold on
er = errorbar(x,mean(Total(:,11:15)),standaardafw(11:15),standaardafw(11:15));
er.Color = [0 0 0];
er.LineStyle = 'none';
ylim([0 21])
title({'Bar graph showing the maximum pulling force',' for the 5 mm tips
with 3 arms'})
ylabel('Force [N]')
set(gca,'xticklabel',bullets)
hold off

subplot(2,2,4)
bar(x,mean(Total(:,16:20)))
hold on
er = errorbar(x,mean(Total(:,16:20)),standaardafw(16:20),standaardafw(16:20));
er.Color = [0 0 0];
er.LineStyle = 'none';
ylim([0 21])
title({'Bar graph showing the maximum pulling force',' for the 5 mm tips
with 4 arms'})
ylabel('Force [N]')
set(gca,'xticklabel',bullets)
hold off
%Do the same for the push forces
for i=1:5
standaardafwpush(i)=std(Pushtotal(:,i))
end

drie=1:3;
twee=1:2;
kogels3={'0.22 LR'; '8 mm'; '10 mm' };
kogels2={'8 mm'; '10 mm' };
figure
subplot(1,2,1)
bar(drie,mean(Pushtotal(:,1:3)))
hold on
er = errorbar(drie,mean(Pushtotal(:,1:3)),standaardafwpush(1:3),standaardafwpush(1:3));
er.Color = [0 0 0];
er.LineStyle = 'none';
ylim([0 15])
title({'Bar graph showing the maximum push force',' for the 3 mm tips with
4 arms'})
ylabel('Force [N]')
set(gca,'xticklabel',kogels3)
hold off

```

```
subplot(1,2,2)
bar(twee,mean(Pushtotal(:,4:5)))
hold on
er = errorbar(twee,mean(Pushtotal(:,4:5)),standaardafwpush(4:5),standaardafwpush(4:5));
er.Color = [0 0 0];
er.LineStyle = 'none';
ylim([0 15])
title({'Bar graph showing the maximum push force',' for the 5 mm tips with
4 arms'})
ylabel('Force [N]')
set(gca,'xticklabel',kogels2)
```