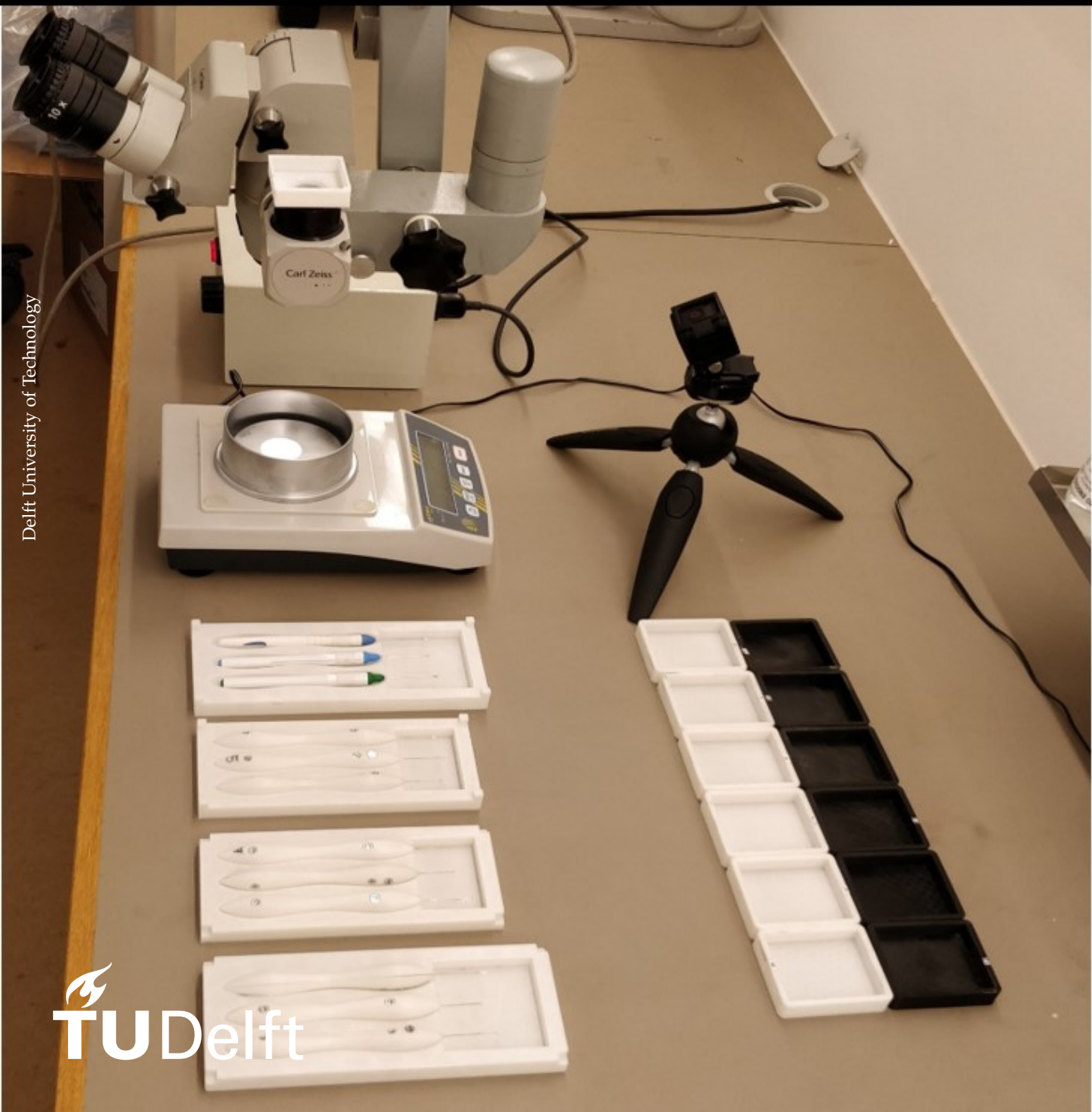
Vitreous Wipe:

A new test prototype

Valentin Lucas



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by

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to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Friday July 29, 2022 at 9:30 AM.

Student number:	4446240	
Project duration:	October 1, 2021 - July 29, 2022	
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Abstract

Retinal detachment occurs when liquid slips behind the retina and does not allow the latter to lay flat on the posterior region of the eye. It alters the vision of the patient, hence requiring surgery to be corrected. In some cases, retinal detachment can occur after the retina has been treated for other pathologies. Indeed, more than 20% of highly myopic patients who have been treated for retinal diseases are subject to retinal detachment a few months after the surgery and are required to undergo a second surgery. It is believed that a membrane, also called Vitreous Cortex Remnants (VCR), that arises due to vitreoschisis, a retinal disease, is the reason for the re-detachment. VCR is often not dealt with during surgery because its removal is time-costly, the VCR is not well visible and instruments are not optimally adapted for removing VCR. The work aims to develop and experimentally evaluate new methods of removing VCR. For that purpose, a series of test prototypes were manufactured, and three surgeons assessed the efficiency of the prototypes for removing VCR from dissected pig's eyes. Each eye was treated pre-experimentally according to a new model that tries to recreate vitreoschisis in a young porcine eye. The efficiency of each test prototype was assessed based on the force that the instrument tip exerted on the pig's retina, the number of strokes taken to remove the VCR completely, the tissue damage and the time used. Furthermore, the optimal tip length was determined based on the surgeons' feedback. The results show that the force greatly depended on the stiffness of the instrument tip and that the most efficient prototype consisted of a PVA wipe cut to size 6x1x1 mm and a 0.1 mm diameter Nitinol wire. The prototype exerted a maximum force of 0.68 gr. The number of strokes was around 40, and the optimal tip length was just under 4.5 mm. While the experiments showed that it is a promising design, the tip needs to be remodeled to comply with the low stiffness needed and to be able to fit within a 23 gauge tube.

Contents

1

Introduction

1.1. Anatomy of the Retina

1.1.1. The retina and its layers

Situated at the back of the eye, the retina is the biological tissue responsible for converting the reflected light from a scene into an electric signal. The electric signal is sent through the optic nerve to the brain and is then interpreted in order to see [1]. Figure 1.1 displays the relevant constituents of the eye.

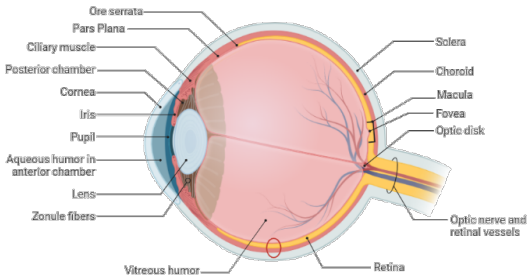


Figure 1.1: Anatomy of the eye [2]

The light is focused onto the retina due to the lens which can change its thickness thanks to the ciliary body and the choroid. The choroid is a layer of connecting tissue located behind the retina, as is the sclera [3]. The macula is the most light-sensitive region of the retina and, together with the fovea, is responsible for the precise part of the vision [4]. The vitreous makes up 80% of the eyes volume and is a gel-like structure that generates the internal pressure in the eye [5]. The pressure is necessary since the retina is only physically attached to its surrounding at two locations, namely the optic disk and the *ore serrata*. The latter is where the retina and the choroid meet, near the ciliary body. The retina is then only pressed onto the choroid thanks to the pressure generated by the vitreous. Finally, the pars plana is the zone where the least amount of blood vessels exists located before the retina starts. Hence, it is the preferred place to introduce an instrument in the eye for intraocular surgeries. Zooming in on the red circle seen in Figure 1.1, one can see that the retina is a multilayered tissue as depicted in Figure 1.2. In total, it has ten layers with six different types of cells. Each cell type plays a specific role in the vision, but is encountered in different quantities throughout the retina. Hence, the retina has a variable thickness that ranges between 0.150 to 0.350 mm [6].

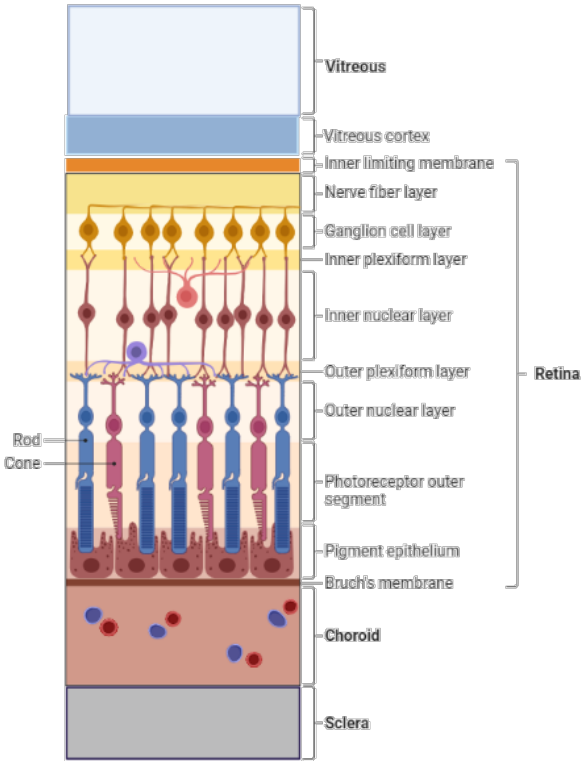


Figure 1.2: Layers of the retina [2]

The vitreous is not directly in contact with the retina, but the vitreous cortex, also called vitreous membrane or hyaloid membrane, is. The vitreous cortex is a layer of collagen that separates the vitreous and the retina [7]. It encloses the vitreous and has an average thickness of around 100 µm [8]. It comes in contact with the first layer of the retina and the only relevant one for the project, the inner limiting membrane. The latter has a thickness of

around 10 µm [9].

1.1.2. Vitreoschisis in retinal diseases

In a healthy young eye, the vitreous is attached to the inner limiting membrane with millions of intertwined fibers. Due to aging, the vitreous and vitreous cortex slowly shrink, pulling on the retina [10]. In most eyes, the fibers connecting both tissues break, which leads to a complete vitreous detachment. It does not affect vision and necessitates no further medical attention. In some cases, the fibers do not break and the shrinkage of the vitreous lead to a pulling force on the retina that results in either a macular hole, a macular pucker, a retinal tear, or a retinal detachment [11]. The patient is in need of medical attention and often requires surgery to remedy the various retinal complications.
Vitreoschisis is a particular case of vitreous cortex detachment where the cortex is only partly detached. Due to its lamellar structure, the vitreous cortex, when affected by vitreoschisis, can be split into two pieces [12]. One portion stays attached to the retina and the other is still enclosing the vitreous and detached from the retina. The leftover membrane, also called the vitreous cortex remnants (VCR) are believed to exert a traction force on the retina, being the cause for retinal redetachment post-operatively [13]. Vitreoshisis is seen in most patients with macular puckers and more than half of the patients with macular holes. Highly myopic patients are also prone to have vitreoschisis. Leaving the VCR after treating the surrounding disease is believed to lead to other retinal detachment and may be counterproductive. However, there are several challenges related to extracting VCR as explained in the next sections.

1.1.3. Challenges around vitreoschisis patients

As of now, the implications of VCR are not fully understood nor approved by all the medical boards. Consequently, VCR removal is often not addressed during surgical operations. In most cases, the eye is only treated for the various retinal pathologies listed earlier and the VCR are left behind. The first and foremost challenge to extracting VCR from the retina is the lack of instruments purposely built for it. A vitreous wipe has been developed for the purpose at hand but has some limitations as is explained in section 1.2 [14]. The other instruments used are designed for the inner limiting membrane and can raise the risk of damaging the retina [15]. Another reason is that the vitreous cortex is hard to perceive during surgery. Triamcinolone is a compatible die and can be used for staining the VCR but is currently not commonly used in the types of surgeries at hand. Finally, taking the VCR out after repairing the retina is a time-costly operation [14].

1.2. Instruments used

1.2.1. Diamond duster

Different instruments that are normally used for the inner limiting membrane have been used for VCR. A diamond duster is an instrument used to make an edge in the membrane that needs peeling. It used a rough surface to grasp onto the membrane. It has diamond dust at its tips held with glue. A picture of its tip is shown in Figure 1.3.

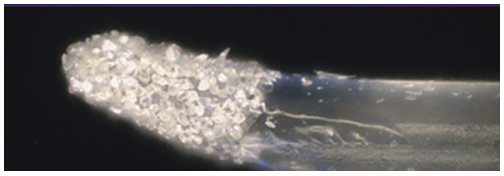


Figure 1.3: Tip of diamond duster [16]

A drawback of the diamond duster is that it leaves residues inside the eye. Specifically, there have been studies that analyzed the particles left over after treating the eye and found diamond dust particles over the retina [17]. Moreover, the instrument has a variable indent profile meaning that depending on which part of the tip is in contact with the membrane, its depth of indents varies. With vitreoschisis, the thickness of the VCR left on the retina is variable. If it is a large thickness, the diamond duster may be used on it without yielding damage to the underlying tissues, but if the thickness of the VCR is smaller, damage is most likely to occur. Due to the varying thickness of the epiretinal membrane, it is not advised to use the diamond duster at every location over the retina [18].

1.2.2. Finesse Flexloop

The finesse loop is an instrument consisting of an indented loop as seen in Figure 1.4. It is also designed for inner limiting membrane peeling. It uses a constant indentation profile and the same principle as the diamond duster.

Figure 1.4: Tip of Finesse Flexloop [16]

Similar to the diamond duster, the flexloop creates

an edge in the membrane, and then forceps (surgical pliers) are used to grab the membrane and peel it. The instrument is not damage-free. Inner retinal hemorrhages have been seen in close to 40% of the eyes operated with it. But the amount of hemorrhage is higher for the diamond duster than for the flexloop [16]. It should be noted that both the diamond duster and the flexloop are not meant to scrape the entire retinal surface but, to make an edge to be grasped by another instrument.

1.2.3. Vitreous wipe

A vitreous wipe consists of a PVA sponge held by intraocular forceps. Unlike the two previously presented instruments, the vitreous wipe does not rely on the indentation of the membrane in order to grasp it. Instead, it uses the properties of PVA which when wet, acts like a sponge. The PVA sponge is porous and has a hole size of 130 µm. Figure 1.5 shows the instrument within the eye. The sponge held at the tip is 1x2x3 mm in size [14].

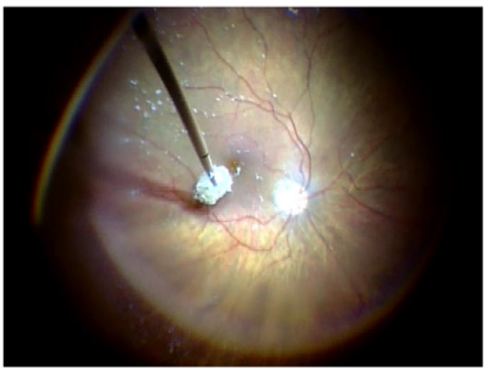


Figure 1.5: Tip of intraocular forceps with vitreous wipe [14]

The vitreous wipe does not damage the retina. The wipe can be used on all retinal surfaces, even the more sensitive ones. Hence, compared to the other instruments, it tends towards a complete damage-free surgery. The main problem is that the vitreous wipe does not fit within a 23 gauge trocar. When the wipe is used, the trocar that serves as an opening for the instruments is removed, a larger cut is done and the wipe is directly introduced into the eye.

1.3. Objectives

From the overview of the existing instrumentation described above, it can be seen that there is a need for a new instrument that does not damage the retina and that has enough surface area to remove the VCR in a time-efficient manner, yet small enough to fit in a 23 gauge trocar.

Accordingly, the aim of the work was to develop and experimentally evaluate a series of test prototypes with different tip materials and geometries in terms of their efficiency at removing VCR from the retinal surface.

1.4. Layout of the report

The report is structured according to the following scheme. In chapter 2, the prototype's design requirements are defined. A concept overview according to the dimensional requirements is provided in chapter 3. From the concept selection, test prototypes are generated and manufactured as described in chapter 4. The method of how the test prototypes are tested and analyzed is described in chapter 5. Results are presented in chapter 6. Discussion on the results and future work is presented in chapter 7 and is ended with the conclusion.

2

Design Requirements

2.1. Functional requirements

A test prototype is the first step toward the creation of a surgical instrument. The requirements are created specifically for the test prototype but have been formulated by taking into consideration the required functionality of the envisioned instrument. Throughout the report, the word 'prototype' refers to either the entire prototype or just its tip. The instrument is introduced into the eye via a small opening; if the tip of the instrument had the same size as the opening, it would be too small to be efficient. Hence, the tip must be deployable. It must also be retractable in order to take the instrument out of the eye. Moreover, the instrument should be swept over the retina, which means the tip must be able to align with the retina surface.

2.2. Safety requirements

The instrument must be atraumatic for the patient. Compared to the diamond duster, no residue is allowed to be left in the eye to prevent post-operative damage.
Also, the usage of the instrument over the retina should not induce any damage. Looking at the finesse flex loop and the diamond duster, they both use indentation of the tissue in order to grasp it. This action is unwanted since the VCR can vary in thickness. If the thickness is less than the indentation depth, damage might be induced to the underlying retina. The tip must thus not contain any sharp section that could potentially penetrate the retina.

2.3. Dimensional requirements

The instrument will be used inside the eye that is reached through a trocar. A trocar is a small valve that is placed at the *ore serrata* and used to bring the instrument in and out of the eye. It allows to keep the fluid inside the eye without leakage while offering an opening to introduce the instrument. A picture of three trocars in an eye can be seen in Figure 2.1. The trocars are seen in blue. As

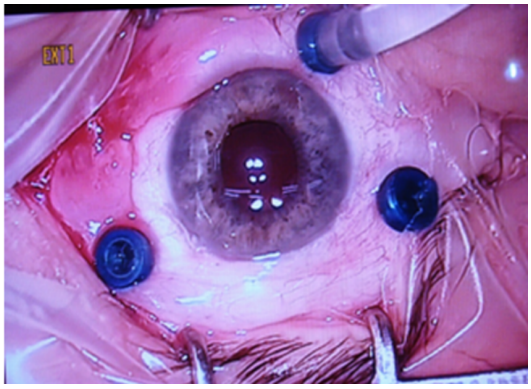


Figure 2.1: Trocars placement at the ore serrata in the eye [19]

stated earlier, there is a need for sutureless surgery since it greatly improves recovery and yields less bleeding. Sutureless ophthalmic surgery can be achieved with 23 gauges trocar [20]. Hence, the test prototype must fit through a 23 gauge hole. In millimeters, it yields a hole diameter of 0.64 mm [21]. Moreover, the length of the tube that is the test prototype must be suitable for surgeons to use. Looking at other instruments that are used through 23 gauge trocars, it seems that the length of the shaft is between 20 and 40 mm. That shall then be the required length of the test prototype.

2.4. User requirements

Surgeons use one instrument in each hand. To be able to test the prototype in a surgical setting, the prototype must be held-able and actuated with one hand.

2.5. Material requirements

The test prototype must be made out of medical-grade materials. These include but are not limited to stainless steel, titanium, nitinol, FDA-approved sponges, and polymers.
Table 2.1 gives an overview of all the requirements

Table 2.1: Requirements test prototype

Functional requirements	The tip should be flexible to allow a bend for enabling sweeping parallel to the retina The tip should be easy to deploy into its final shape The tip should be easy to retract back into the tube
Safety requirements	The tip should NOT contain any sharp section that could damage any of the surrounding tissues The tip should NOT leave any residue from the instrument behind
Dimensional requirements	The test prototype should fit into 0.6 mm (23 gauge) trocar The test prototype's shaft should be within length range [30 – 40 mm]
User requirements	The test prototype should be held with one hand The test prototype should be actuated with one hand
Material requirement	The test prototype must be made out of medical-grade material

as discussed.

3

Concepts

3.1. Concepts generation

3.1.1. Elements that fit in a 23 gauge trocar

As mentioned in the previous chapter, the outer diameter of the tube fitting the tip must be smaller than 0.64 mm. It is decided to use stainless steel since it offers more rigidity at this size than other medical-grade materials. Off-the-shelf stainless steel tubes can be made with a wall thickness down to 0.1 mm. Hence, the space available for the tip of the test prototype in the retracted position is a circle with a diameter of 0.44mm [22]. The following elements could be fitted in a tube with goals to be deployed.

1. Compressible solids
2. Tubes with opened or closed cross section
3. Wires & fibers either with an opened or closed end

Figure 3.1 provides an overview of concepts belonging to the three solution categories.

Compressible solids
The first element includes all solids that can be compressed in the tube and that when they emerge from the tube, are able to expand again to their original shape. One could think of a sponge for example. The compressible solids must be able to reach a cross-section area of 0.152 mm^2 while compressed.

Tubes
Smaller tubes than the outer shell can also be used. Each must have an outside diameter that is equal to or smaller than 0.44 mm. Each tube needs at least 0.1 mm of wall thickness. One can thus place only a single tube within the outer shell. Looking at the cross-section of a tube, it can either be closed or opened, where a tube with an open cross-section can deploy and increase its contact area.

Wires
Wires can be used inside of the tube. The wires used have three dimensions, namely 0.2, 0.15, and 0.1 mm. It is done such that the smallest wire size is the same as the wall thickness of the tube. The wires can be opened end or closed-end. A closed-end wire is a wire that when deployed does not have an ending, hence creating a loop. An opened end wire has one of its ends deployed as it is extracted out of the tube.

Combination of elements
A combination of any of the aforementioned individual elements is feasible and can be fitted within the outer tube. The only combination that would not be feasible is a closed cross-section tube with a closed-end wire. Due to the remaining space left after a tube is introduced, it is only possible to have a single wire.

3.1.2. Elements that deploy

There are different ways in which elements can be deployed. Figure 3.2 provides an overview of possible deployment concepts.

Finite number of solutions
Compressible solids and tubes offer a finite amount of solutions. Since the sponge is bounded to its compression ratio when it deploys from the tube, it offers only one possible shape. Also, the closed section tube can only deploy in a single shape. It can be argued that the tube could be bent, but even so, it only deploys in a telescopic manner. Hence, it has a finite number of solutions. The tubes with an open section offer more possibilities once deployed due to the fact that they unfold as extracted from the tube. They can create, for example, a spoon-like shape. The deployed shape could be altered slightly but the maximum width is still bonded by the inner circumference of the test prototype. A possible combination is to have an opened section tube that gives support to a compressible solid.

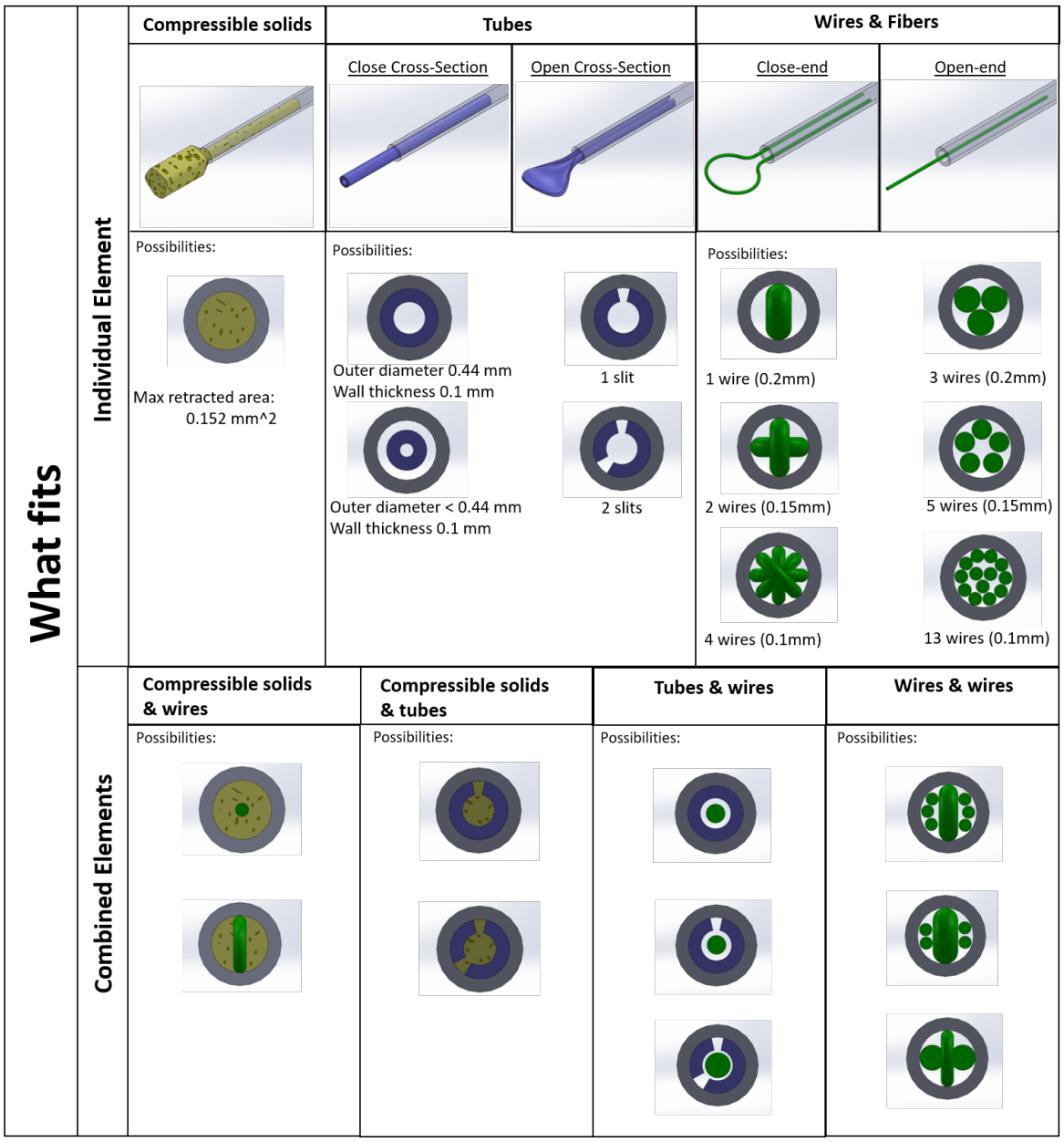


Figure 3.1: Overview of elements that can be fitted in 23 ga tube

Infinite amount of solutions
Wires offer an infinite number of solutions. Wires can be bent at numerous places along their length and in different directions. Both open-end and closed-end wires offer infinite deployment solutions, as well as when combined. On the contrary, the wires, when combined with other elements, do not always offer infinite solutions. If the wire affects the shape of the combined element, it will offer more deployment possibilities. Note that while four closed-end wires and 13 opened-end wires can theoretically be fitted in the available space, 0.1 mm thick wires can be easily entangled with one another. Hence, such prototypes might not be manufacturable. Moreover, in the concept with eight extracted wires at the top right of Figure 3.2, all wires are bent with the same bending radius and are extracted at the same time to create the umbrella shape. In real life, it might be close to impossible to achieve since the wires deploy at random.

3.2. Concepts selection

3.2.1. Method of assessment and assumptions

The above-described concepts are assessed using a Harris profile. Each concept is assessed based on each design criterion. Criteria high up in the profile are the most relevant and concepts scoring very poorly in those criteria are likely to be eliminated. For each criterion, the concept can either score a -2,-1,1, or 2. There is no middle value with a Harris profile, so not a concept can score a 0 to avoid

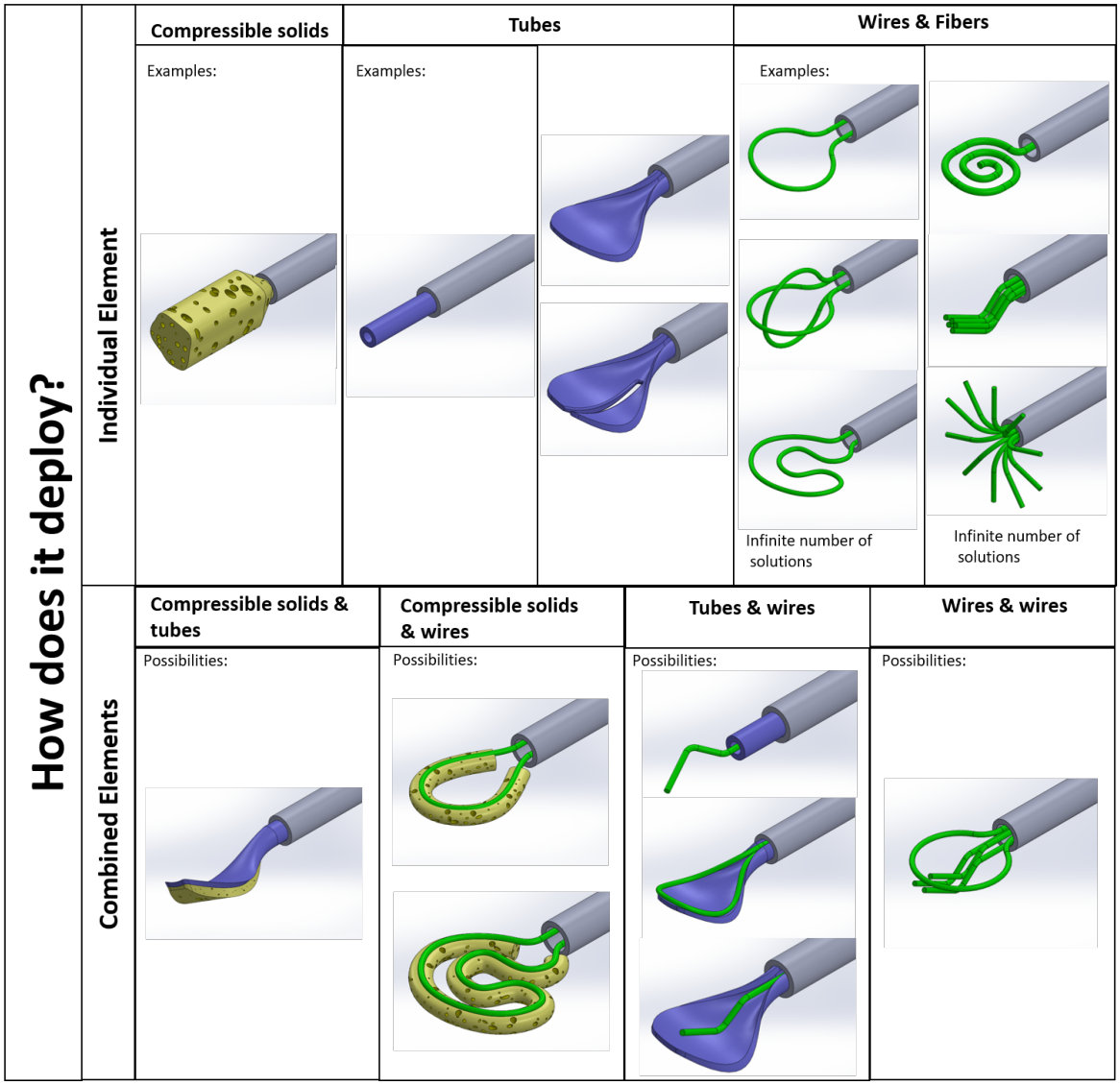


Figure 3.2: Overview of possibilities for deployment

perfectly average concepts.
Note that, from all the possible combinations and deployment presented, it is clear that the closed section tube is the worst for the purpose at hand. The deployment size is the same as the size available within the tube and it does not combine well with other elements. For these reasons, the closed-end tube is discarded from the Harris profile.
Out of the remaining four elements, i.e. compressible solids, opened and closed-end wires, and opened cross-section tubes, four concepts are created: the "Sponge", the "Spoon", the "Umbrella", and the "Loop".

3.2.2. Criteria

Table 3.1 shows the criteria used to assess the different elements that can be chosen for the tip.

Table 3.1: Assessment criteria for Harris profile

Criteria
1. No sharp section
2. No remaining residue
3. Degree of deployability
4. Degree of variability
5. Directional flexibility
6. Controllabilty of deployment
7. Ease of retraction

The first two criteria are related to safety. It is primordial that any damage should be avoided. Hence, the tip must not have any sharp section that could damage the surrounding tissues. The tip will rub against the tube while it is deployed and retracted in and out of it. It follows that no residue should be generated through the motion. From the functional requirements, there must be a certain degree of deployability. The variability of the extracted tip represents of much the final deployment shape can be changed compared to its retracted state. The directional flexibility represents the ability the tip has to come in contact parallel to the retina. The controllability of deployment and ease of retraction depict the control and ease to extract and retract the tip.

3.2.3. Harris profile first selection

First, the individual elements are used as concepts. Without the tube, it yields four concepts. The corresponding Harris profile is seen in Figure 3.3. The best possible outcome from the Harris profile table is the loop concept. The second best is the sponge concept, followed by the spoon and then the umbrella.

3.2.4. Harris profile second selection

From Figure 3.3, the worst concept was eliminated. From the three remaining concepts, combinations were realized. Figure 3.4 shows a second Harris profile, now for the combined elements. It is seen that the Spoon + Sponge concept appears as the best performing. Nevertheless, all three concepts presented in Figure 3.4 are further developed into test prototypes.

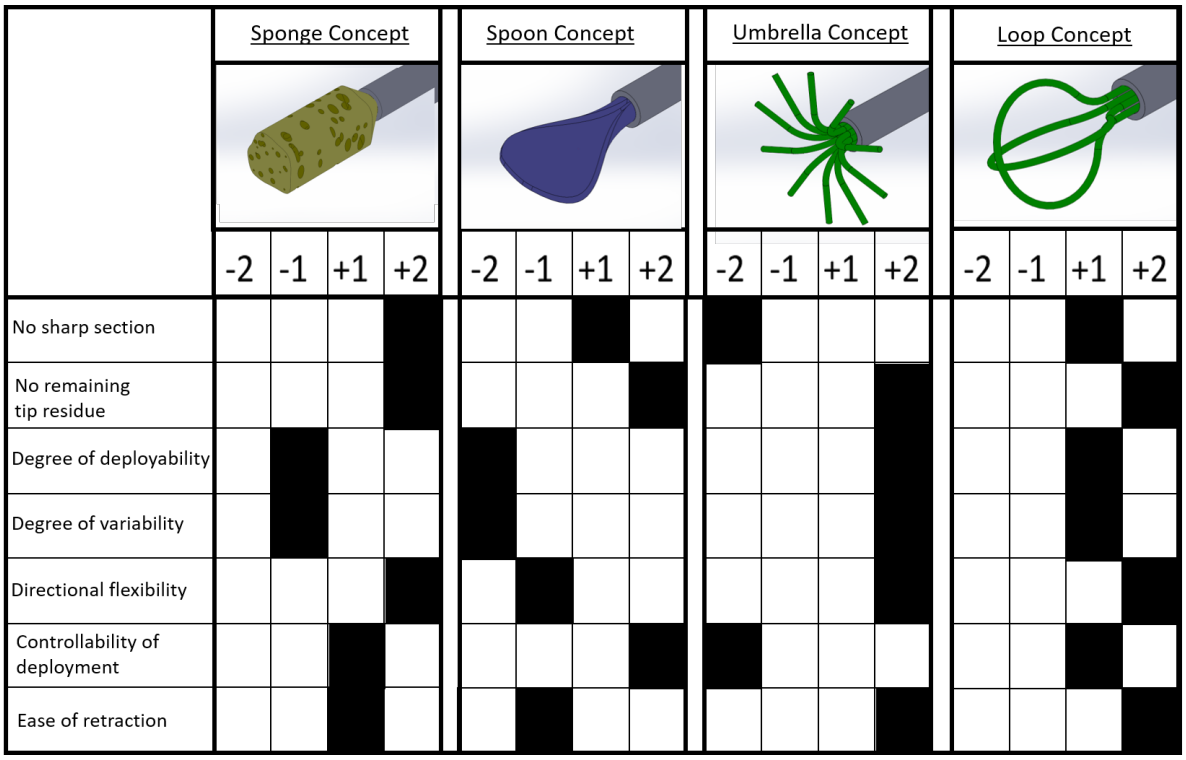


Figure 3.3: Harris profile of each individual element

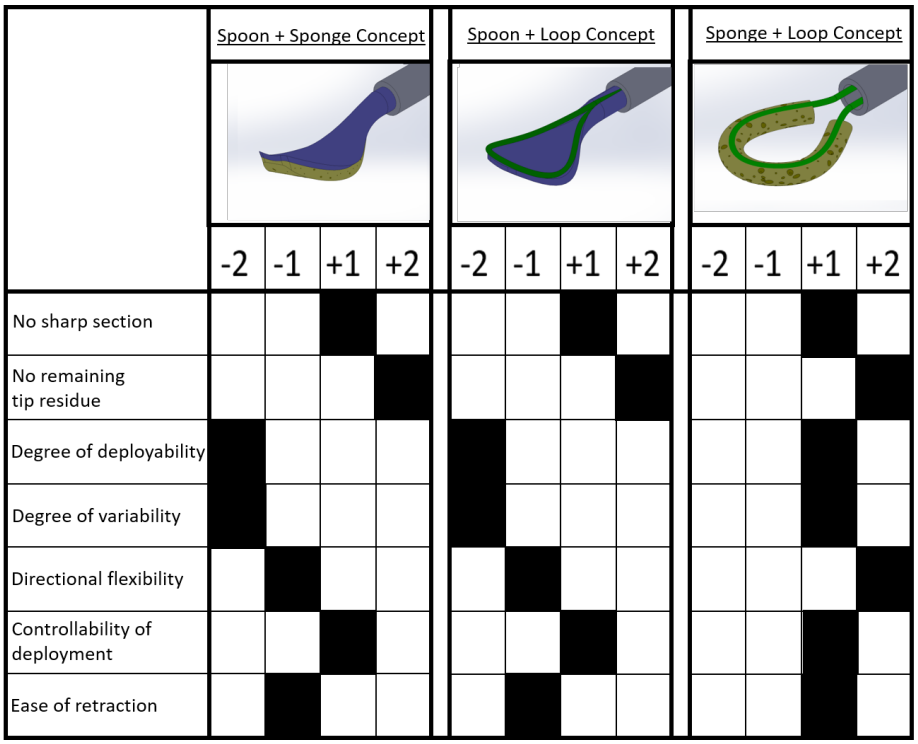


Figure 3.4: Harris profile of each combined element

4

Development of the test-prototype

4.1. Test prototype tip

From the results of the Harris profile in Figure 3.4, three concepts for prototype tips emerge. It was decided to build and experimentally evaluate prototypes for all three concepts.
Next to the three concepts, the vitreous wipe as presented in section 1.2 which is the first instrument designed purposefully for removing VCR, will be tested for comparison purposes. For each concept, three test prototypes tip of different sizes (small-medium-large) are manufactured to investigate the effect of size on efficiency and performance.

4.1.1. Material used

The wipe is made of a medical-grade PVA produced by EYETEC [23]. The sponge that makes two of the three concepts is also made from the EYETEC wipe. A different kind of PVA is used to make the surface forming the "spoon" in Figure 3.4. The latter is made from PVA granula mixed with distilled water to form a PVA solution with a high viscosity. Since Nitinol is commonly used in medical instruments due to its mechanical properties, it is chosen for making the loop that makes two concepts [24]. In summary, the following three materials are used to manufacture all test prototype tips.

- ⌀0.1 mm Nitinol wire
- 1 mm thick PVA instrument wipe from EYETEC
- PVA granula SELVOL 165 from SEKISUI [25]

4.1.2. From concepts to test prototypes

Each concept was manufactured in three sizes with corresponding extracted lengths of 3 mm (small), 4.5 mm (medium), and 6 mm (large). Note that the extracted length is not the length of the wire outside of the tube but the distance from the tip of the wire to the entry of the tube, as depicted in Figure 4.1.
A step-by-step guide on how to manufacture all the tips is present in Appendix A. In brief, the manufacturing process consisted of the following steps:

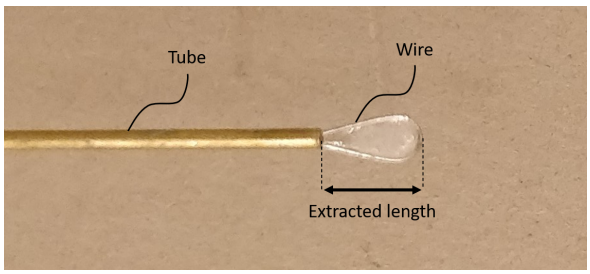


Figure 4.1: Depiction of the extracted length

1. The Wipe test prototype tip was manufactured by cutting a piece from EYETEC PVA wipe with dimension 3x2x1 mm and holding it in place with micro-forceps.
2. The sponge + loop concept was manufactured by cutting a piece of PVA wipe and passing a Nitinol wire through the cut PVA piece. The PVA piece has a dimension of 4x1x1 mm, 6x1x1 mm, and 8x1x1 mm for the small, medium, and large prototype respectively. The wire was passed through the long axis of the cut piece of the wipe. The wire and wipe were then constrained in a tube, making a loop at their extraction point.
3. The spoon+loop concept was made by running the 0.1 mm Nitinol wire and constraining it in the 23 gauge tube such that it makes a loop. The tip was then dipped in the PVA solution and placed in the freeze. Later, the tip was put at room temperature to thaw and crystallize twice for around 20 minutes.
4. The Spoon+sponge was not feasible to do with only the PVA wipe from EYETEC and the PVA solution prepared. Instead, the preparation was the same as for the Spoon+loop concepts, except that during the freezing process, a piece of PVA wipe was cut according to the dimension of the tip. The tip was then

taken out of the freezer and as it started to thaw, pressed against the cut PVA wipe and let to crystallize together before placing it back in the freezer for the second time.

4.2. Test prototypes housing

The housing (also called handle) is designed to enable quick swapping of the tip of the prototype and to secure it in place. It consists of three 3D printed parts from PLA, one steel tube of size 23 gauge, and three bolts with two nuts. Figure 4.2 shows an exploded view of all components part of the handle. The two largest parts form the body of

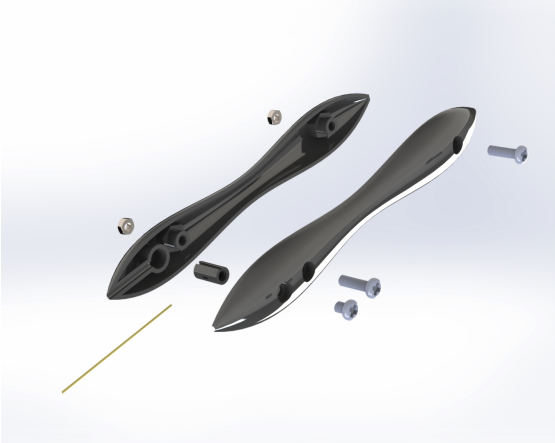


Figure 4.2: Exploded view of the prototype's handle

the handle where the surgeon's hand grips. The cylinder in between the two body parts is used to lock the prototype's tip in place. All prototypes, except the "Wipe", make use of a wire in their design. The wire is introduced to the housing via the tube opening. The tube is seen in gold in Figure 4.2. The wire is secured on the other hand of the tube. It passes through the tightening cylinder, which through rotation and friction, secured the wire at the desired extracted length.
Figure 4.3 shows a close-up of the simple locking mechanism present in the handle of the test prototypes. Once the tip is well secured to the handle, the two other screws are tightened. Figure 4.4 shows the complete test prototype handle, without the tip.

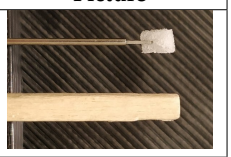
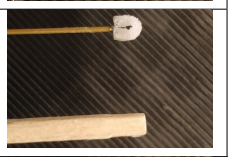
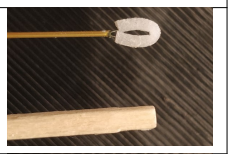
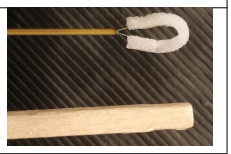
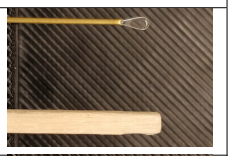
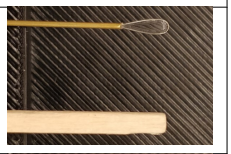
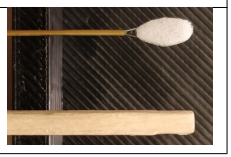
Figure 4.3: Close up of the locking mechanism

Figure 4.4: Assembled handle of the test prototype

4.3. Overview

Table 4.1 shows all 12 test prototype tips, their identification, and their characteristics. A match of standard sizes is present for size reference.

Table 4.1: Overview of test prototype tips

Tip Category Name	Tip Identification	Originating Concept	Extracted Length (mm)	Picture
Wipe	Wip	Vitreous wipe	Size: 1x2x3	
Wire-Wip	WirWip-S	Sponge + Loop	3	
	WirWip-M		4.5	
	WirWip-L		6	
Wire-PVA	WirP-S	Spoon + Loop	3	
	WirP-M		4.5	
	WirP-L		6	
Wire-Wipe-PVA	WirWipP-S	Spoon + Sponge	3	
	WirWipP-M		4.5	
	WirWipP-L		6	

5

Testing Method

5.1. Prior to the experiments

5.1.1. Experimental model

The test was carried *ex vivo* on porcine eyes. A swine eye is anatomically and bio-mechanically the closest to human eyes and is thus deemed to be a good representation of the main attributes of human eyes [26].

To avoid a change in tissue properties, the eyes were received soon after the animal was sacrificed and were kept in a cold environment around 5°C until testing. All tests were carried out within 12 hours from dissection.

On average, pigs are slaughtered at 6 months of age in Europe [27]. It yields very young eyes for testing compared to the older eye being treated during surgery. There are major differences between a young and old eye in terms of physiology and tissue behavior. The vitreous, normally gelatinous, tends to liquefy and shrink over the years [28]. The reason why are still unknown but it is speculated that it happens due to light interaction or constant heat from the body. In humans, the process begins around the age of 9-10 years old and slowly but gradually it continues to liquefy until an advanced age where it is completely liquid [29]. There are a lot of unknowns regarding the process and not enough studies are done. It is thought that most of the eye diseases could be circumvented if the liquefaction process of the vitreous is stopped [30]. Vitreoschisis is no exemption. If the vitreous does not liquefy and shrink, it would not separate itself from the retina and vitreoschisis would, most likely, not be a problem.

For the tests at hand, the liquefaction needs to be inhibited to make a young eye behave like an older eye that has gone through liquefaction. During experimentation, it was discovered by the author of this thesis that freezing the specimen yields to a slow liquefaction of the vitreous. The cause of the phenomenon is unknown and no studies have been found reporting any findings on the topic.

For the test, the dissected eyes were placed in a freezer at -20°C for 2 hours. While it was not enough to liquefy the entirety of the vitreous, it resulted in a reduction in gelatinous body volume. Further studies need to be done to determine the reasons why the vitreous liquefies through a lack of heat.

The eyes treated during surgery are affected with vitreoschisis, the partial detachment of the vitreous cortex. Vitreoschisis yields that a portion of the cortex thickness stays attached to the retina and applies a traction force on it that might yield complications. Contrary to other diseases such as cataract or glaucoma, which have been successfully induced in a pig's eye, there exists no porcine model of vitreoschisis and there is no information available in the literature about how vitreoschisis could be generated within a pig's eye since the cause of it is largely unknown [31][32]. Since the tests are carried on a young pig's eye, the connective forces between the vitreous cortex and the retina are larger than on an older eye [7]. It means that the test is considered to be the worst-case scenario of vitreoschisis, where the entire thickness of the vitreous cortex stayed attached to the retina.

5.1.2. Preparation of the eyes

A total of 36 eyes were prepared. Firstly, the eyes were collected through the Eye Hospital of Rotterdam at the WELLINK B.V. slaughterhouse. They were kept in a cold environment (around 5°C) for the entire time up to the test. To prevent tissue dehydration that would occur if preparing the eyes in advance of the experiment, the eye was "peeled" from its external layer, the sclera. It also enabled to prepare the eyes with the least interaction with the retina. A complete overview of the eye preparation with recommendations is present in Appendix A. In brief, the preparation of the eyes included the following steps:

1. The eyes were collected with the surrounding muscles, hence clearing the extra tissues was needed.

2. The optic nerve was cut off as closely as possible to the sclera.

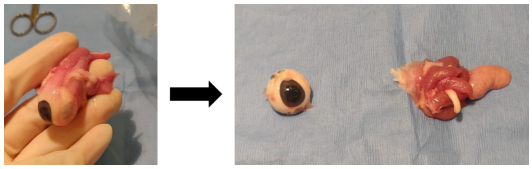


Figure 5.1: Removal of surrounding tissues

3. An incision was made through the sclera without cutting through chroroid. The latter must not be pierced as it is used as a protective layer to keep the retina and vitreous untouched from the external environment.

Figure 5.2: Incision through sclera

4. Sliding a thin cutter in between the sclera and choroid, the two were separate and piece by piece the sclera was cut and removed.
5. Portions of the sclera were removed and the leftovers were used to delimit the surface onto which the surgeons would be using the test prototypes. It enables to define the wiping surface before the eye is opened and the retina is exposed. Figure 5.3 shows how to remove the scleral layer around the optic nerve.

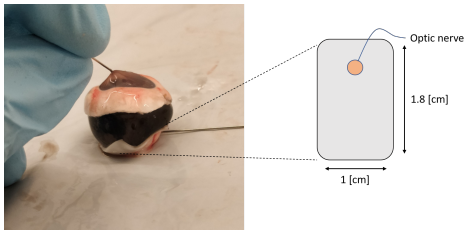


Figure 5.3: Sclera delimiting the testing surface

6. The above 5 steps were repeated for all eyes that had to be prepared.
7. Using a container filled with solidifying PVA, the choroid was cut with scissors as closely as possible to the pars plana, and the posterior of the eye was delicately let to touch the PVA and fixate itself as seen in Figure 5.4. It is done for all eyes at the same time.

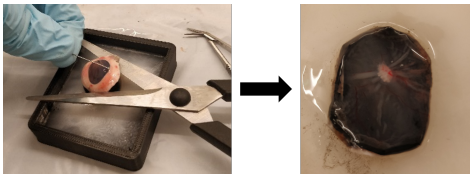


Figure 5.4: Dissected pig's specimen

8. Finally, all eyes were placed in the freezer for 2 hours to liquefy a portion of the vitreous.
9. The eyes were taken out of the freezer 1.5 hour before the test is carried. Once unfrozen, the portion of the vitreous that is liquid was taken out with a syringe, and using a saline solution a few drops were placed on the specimen to clean it.
10. Finally, triamcinolone was used as a dye to visualize the vitreous cortex and left-over vitreous.

5.2. During the experiments

5.2.1. Test set up and experimental conditions

The test setup consists of a microscope, two cameras, and a scale. For each surgeon, 12 test prototypes' tips were evaluated by wiping the VCR and leftover vitreous off a dissected eye. Hence, each test prototype was tested three times by three different surgeons. It yields a total of 36 tests. The surgeon was seated in front of the microscope and carried out all tests looking through the microscope. The scale, that is used to log the force in grams was positioned under the microscope. A camera was positioned in the microscope to record what the surgeon sees. Another camera was on a tripod and recorded the scale. Each prepared eye was placed on the scale to begin testing. The tests ended when the surgeon cleared all VCR and leftover vitreous off the dissected eye. Finally, the tests were carried out at room temperature. The lights in the room were dimmed during all tests such that the microscope light is the only source of light in the room.

5.2.2. Instruction given to Surgeons

The following instructions were given orally to each surgeon:

1. The aim of the experiment is to remove the VCR and vitreous in the most efficient manner.
2. The amount of strokes, the time, the force and the damage are monitored and logged.
3. The experiment consists of 12 test prototypes used separately on 12 dissected eyes.

4. After each test, a questionnaire need be answered about the freshly used test prototype.
5. Try to imitate as closely as possible surgery conditions with regards to the force applied, the time pressure, and the way the test prototype is handled.
6. At the end of the batch of tests, four questions will be asked to determine your preferred choice of test prototypes.
7. The test should be done within a hour.

5.2.3. Order for testing

To reduce bias, the order of testing for each surgeon was randomized as shown in Table 5.1.

Table 5.1: Test order per surgeons

		Surgeon #1	Surgeon #2	Surgeon #3
Order	1st	WirWip-S	Wip	WirWip-L
	2nd	WirP-S	WirWip-M	Wip
	3rd	Wip	WirP-L	Wip
	4th	Wip	Wip	WirP-L
	5th	WirWipP-L	WirWipP-S	WirP-S
	6th	WirWipP-M	WirWipP-L	WirWipP-S
	7th	WirP-L	Wip	Wip
	8th	Wip	WirP-M	WirP-M
	9th	WirWip-M	WirWip-L	WirWipP-L
	10th	WirP-M	WirP-S	WirWipP-M
	11th	WirWip-L	WirWip-S	WirWip-M
	12th	WirWipP-S	WirWipP-M	WirWip-S

5.3. After the experiments

5.3.1. Data assessed

In total, six types of data were collected. The scale was used to log the force applied on the specimen. The amount of time, together with the number of strokes were obtained through the video recordings of each test. The damage was assessed by analyzing pre- and post-experimental pictures. After the use of each prototype, questions related to the requirements presented in Table 2.1 were answered on a scale from 1 (strongly disagree) and 5 (strongly agree) (Table 5.2).

Table 5.2: Questionnaire given to each surgeon after each test prototype

#	Question
1	Is the test prototype tip likely to damaging the retina
2	Is the prototype tip easy to handle
3	Does the test prototype tip enable well wiping parallel to the retina?
4	Does the test prototype tip grips well onto the cortex remnants
5	Is the prototype tip of ideal length

Finally, after all tests were done, four final questions were asked regarding the surgeon's thoughts on the efficiency and optimal extracted length of the test prototypes. The questions were as follows:

1. What is the most efficient prototype of the lot?
2. What is the least efficient prototype of the lot?
3. What is the efficient extracted length between small medium and large?
4. Rank from best to worst the prototypes categories.

5.3.2. Data analysis

From the measured forces, peak values were extracted and the maximum value is averaged over the three tests that the prototype had undergone. It yielded the mean maximum force applied per prototype and was plotted. Next, the extracted peak values were averaged to find the mean force per test. The resulting value was then averaged over the three tests and plotted. The strokes taken were counted, averaged over the three tests the prototype had undergone and the value was plotted. From the video data, the time was assessed as the time between the test prototype's tip first touch on the retina until it was lifted off when the VCR and the leftover vitreous were cleared. The time value found was then plotted. The number of strokes taken per unit time was computed and plotted. Following, the damage was visually assessed by the author of the thesis, based on photos taken before and after the removal of the VCR. Damage was reported if the retina had been ruptured or if the blood vessels had been broken. Finally, the results of the questionnaire were analyzed and plotted. In total, six graphs were made to compare each test prototype.

6 Results

6.1. Forces applied on test specimen

6.1.1. Maximum force

Figure 6.1 displays the mean of the maximum force per prototype. Most test prototypes were tested three times or more. A number of tests smaller than three occurred in cases of structural failure of the prototype during testing. The prototypes with the smallest force were the "Wipe", followed by the "Wire-Wipe", the "Wire-PVA" and the "Wire-Wipe-PVA" category. The lowest maximum force is achieved by the "Wip" with a value of 0.58 gr. It is slightly lower than "WirWip-M" with 0.68 gr and "WirWip-L" with 0.72 gr. The ranking from

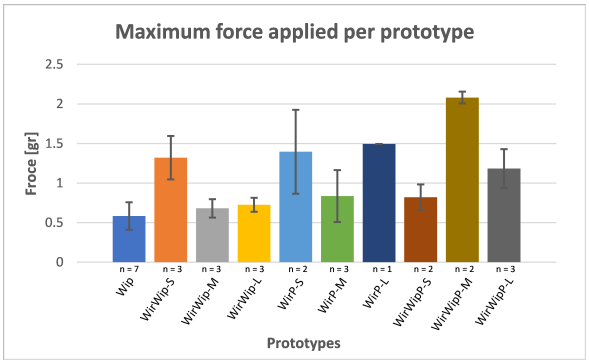


Figure 6.1: Maximum force applied per prototypes

smallest to the highest force of each individual test-prototype is displayed in Table 6.1.

Table 6.1: Ranking from smallest to highest (left to right) performing prototype according to the maximum force

1st	2nd	3rd	4th	5th
Wip	WirWip-M	WirWip-L	WirWipP-S	WirP-M
6th	**7th**	**8th**	**9th**	**10th**
WirWipP-L	WirWip-S	WirP-S	WirP-L	WirWipP-M

6.1.2. Average force

Figure 6.2 shows the average force applied per prototype. It can be seen that again the smallest

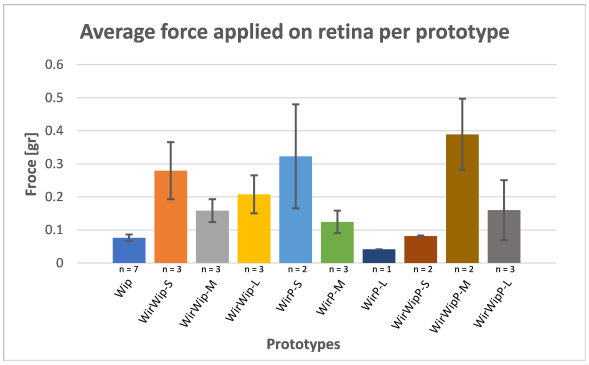


Figure 6.2: Average force applied per prototypes

forces were generated by the "Wipe" category, followed by the "Wire-Wipe-PVA", the "Wire-PVA" and finally the "Wire-Wipe". The lowest value belonged to "WirP-L" with 0.0418 gr while the highest was generated by "WirWipP-M" at 0.388 gr. For both for "Wipe-wire" and "Wire-PVA" categories, the smallest test prototypes tips ("WirWip-S" and "WirP-S" respectively) generated larger forces than large-sized tips as "WirWip-M", "WirWip-L", "WirP-M" and "WirP-L". The ranking from lowest force to highest average force is displayed in Table 6.2.

Table 6.2: Ranking from smallest to highest (left to right) performing prototype according to the average force

1st	2nd	3rd	4th	5th
Wip-L	Wip	WirWipP-S	WirP-M	WirWip-M
6th	**7th**	**8th**	**9th**	**10th**
WirWipP-L	WirWip-L	WirWip-S	WirP-S	WirWipP-M

6.2. Strokes

The amount of strokes per prototypes is displayed in Figure 6.3. The "Wire-Wipe" category performs best with the lowest average amount of strokes, followed by the "Wipe", then the "Wire-Wipe-PVA" and finally the "Wire-PVA". The highest value was achieved by "WirP- S" and the lowest by "WirWip-S" with an average of 33 strokes per test. The ranking

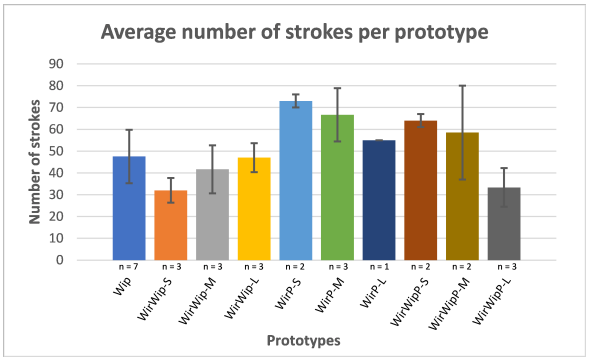


Figure 6.3: Number of strokes per prototypes

from the smallest amount of strokes to the highest is seen in Table 6.3.

Table 6.3: Ranking from smallest to largest (left to right) amount of strokes used by each prototype

1st	2nd	3rd	4th	5th
WirWip-S	WirWipP-L	WirWip-M	WirWip-L	Wip
6th	**7th**	**8th**	**9th**	**10th**
WirP-L	WirWipP-M	WirWipP-S	WirP-M	WirP-S

6.3. Time

Figure 6.4 shows the amount of time per prototypes averaged over the three tests carried. It is seen

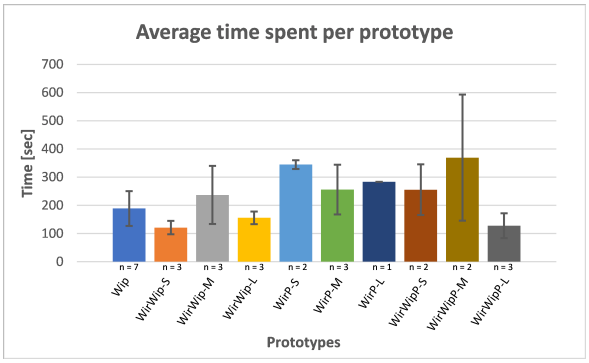


Figure 6.4: Time per prototype

that the category with the least testing time was the "Wire-Wipe", closely followed by the "Wipe", the "Wire-Wipe-PVA" and finally the "Wire-PVA". Looking at individual test prototypes, "WirWip-S" performs best with "WirWip-L" and "WirWipP-L", all under 150 seconds. "WirP-S" and "WirWipP-M" have the largest time both around 350 sec. The ranking from fastest to slowest testing time per prototype is shown in Table 6.4.

6.4. Stroke per unit time

Figure 6.5 presents the amount of strokes per unit time for each prototype.

Table 6.4: Ranking from fastest to slowest (left to right) time per prototype

1st	2nd	3rd	4th	5th
WirWip-S	WirWipP-L	WirWip-L	Wip	WirWip-M
6th	**7th**	**8th**	**9th**	**10th**
WirP-M	WirWipP-S	WirP-L	WirP-S	WirWipP-M

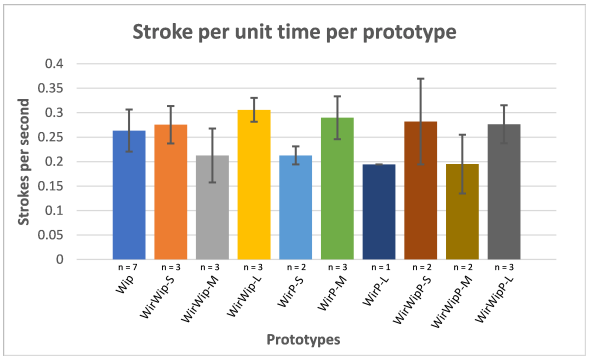


Figure 6.5: Stroke per unit time per prototype

WirWip-M", "WirP-S", "WirP-L" and "WirWipP-M" had a lower value, all around 0.2 strokes/sec, whereas the rest required around 0.28 strokes/sec. Overall, the "Wire-PVA" is the category with the lowest average stroke per second. It is followed by the "Wire-Wipe-PVA" then the "Wipe" and finally the "Wire-Wipe" category shows the highest strokes per unit time. A ranking from smallest to highest is shown in Table 6.5.

Table 6.5: Ranking from least to most (left to right) amount of strokes per second

1st	2nd	3rd	4th	5th
WirP-L	WirWipP-M	WirWip-M	WirP-S	Wip
6th	**7th**	**8th**	**9th**	**10th**
WirWip-S	WirWipP-L	WirWipP-S	WirP-M	WirWip-L

6.5. Damage

No damage was observed by comparing pre- and post-experimental photos. The blood vessels were intact after each test and the retina was not ripped. No damage was reported by the surgeons experimenting with the test prototypes neither.

6.6. Questionnaire

Figure 6.6 shows the questionnaire results per prototype. It can be seen that the "Wipe" category scored the highest, followed by the "Wire-Wipe" category, the "Wire-Wipe-PVA" and finally the "Wire-PVA". The lowest scoring prototype is "WirP-S" and together with "WirP-M" and "WirP-L", they were the worst rated prototypes.
The ranking from best performance to worst performance according to the questionnaire is seen in

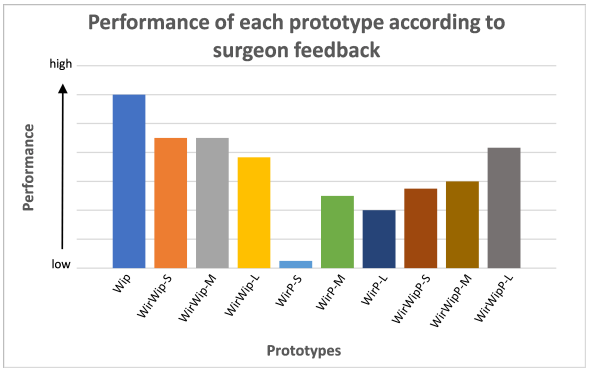


Figure 6.6: Performance of each prototype according to surgeon's feedback on the questionnaire

Table 6.6.

Table 6.6: Ranking the best to worst performing (left to right) prototypes according to questionnaire

1st	**2nd**	**3rd**	**4th**	**5th**
Wip	WirWip-M	WirWip-S	WirWipP-L	WirWip-L
6th	**7th**	**8th**	**9th**	**10th**
WirWipP-M	WirWipP-S	WirP-M	WirP-L	WirP-S

Table 6.7 shows the answers to the four post - experimental questions. Regarding the most efficient test prototypes, two surgeons believed it is part of the "Wipe" and one prefers "WirWip-M" from the "Wire-wipe" category. The least efficient prototype is part of the "Wire-PVA" category and two surgeons state that it is "WirP-S" while one believes it is "WirP-L". With respect to tip size, a medium size was preferred. One surgeon suggested that a size between small and medium might be beneficial.
Looking at the ranking from best to worst, all surgeons agree that the least efficient test prototypes belong to the category "Wire-PVA" and the second least efficient prototypes belong to "Wire-Wipe-PVA".

Table 6.7: Answers of the final four questions by each surgeon

	Most efficient test prototype [Wip-WirWip-L]	Least efficient test prototype [Wip-WirWip-L]	Best extracted tip length Small-Medium-Large	Ranking from best to worst
Surgeon #1	Wip	WirP-S	Medium	1. Wipe 2. Wipe/Wire 3. Wipe/Wire/PVA 4. Wipe/PVA
Surgeon #2	WirWip-M	WirP-S	Medium	1. Wipe/Wire 2. Wipe 3. Wipe/Wire/PVA 4. Wipe/PVA
Surgeon #3	Wip	WirP-L	Small-Medium	1. Wipe 2. Wipe/Wire 3. Wipe/Wire/PVA 4. Wipe/PVA

7 Discussion

7.1. Forces applied on test specimen

7.1.1. Maximum force

The threshold for a human to detect and feel a force is 0.06 N [33]. It represents 6 gr of force, larger than all forces shown in Figure 6.1. The surgeon cannot rely on its force sensory feedback but instead must trust its visual senses and experiences to estimate the force magnitude that he/she is applying to the retina. From oral feedback by all surgeons, the prototypes that had the most visual feedback belonged to the "Wipe" category. The "Wipe" had the most flexibility compared to the other test prototypes and yielded the least amount of force. It shows that the stiffness of the 1x2x3 mm wipe held with intraocular forceps is the adequate stiffness for the removal of VCR. The other test prototypes' tips were reported to be too stiff by the surgeons.
The results showed that there is a link between the force applied and the flexibility of the tip. Although the "Wip" had the best flexibility and yielded the smallest force of 0.58 gr, it was closely followed by "WirWip-M" and "WirWip-L" with 0.68 and 0.72 gr, respectively. The former two prototypes had significantly larger stiffness than the "Wip" due to the Nitinol wire forming the tips. Reasoning to why it is not far off in values is due to the entire prototype being rotated. It is seen in the video data that instead of using the tip flexibility, the prototype is rotated in the hand of the surgeon in order for the tip to wipe parallel to the surface. It yields results that may not be representative of the actual force that is applied by one prototype.

7.1.2. Average force

Comparing the average values with the maximum values in Figure 6.1, a large difference in magnitude between the various prototypes can be seen. Overall, the average force was only 16% of that of the maximum force achieved by the same prototypes. A possible explanation is that the surgeon was changing the force depending on where the tip is over the retina.
Another explanation is that the test prototypes were not used efficiently. Over all the experiments, no damage was seen on any dissected retina. It could mean that the maximum force seen in Figure 6.1 is the most efficient force to remove VCR. Hence, if the average force is much lower means that many strokes done do not make use of the full capacity of the test prototype, making it non-efficient.

7.2. Strokes

Two categories of test prototypes show a decrease in the number of strokes with an increase in the size of the prototype tip. In the "Wire-PVA", the smallest tip, "WirP-S", has the most strokes while the medium-sized ("WirP-M") and large-sized ("WirP-L") test prototype tip lower the number of strokes with 66 and 55 strokes on average respectively. It is seen as well for the "Wire-Wipe-PVA" category. There is a clear correlation that shows that one can diminish the number of strokes taken by increasing the contact area size.
However, an opposite phenomenon is seen in the "Wire-wipe" category. The reason is not fully understood but one could speculate that it is linked to the geometrical shape of the prototype's tip, which may perform best at smaller sizes.
For the "Wire-PVA" category, all the prototypes have a large amount of strokes compared to the rest. They showed a clear lack of gripping force which explains the results. Compared to the other prototypes, "WirP-S", "WirP-M" and "WirP- L" struggles to grasp onto the vitreous cortex and vitreous. They are the only ones that use PVA granula as main gripping material and it shows that it is not favorable for the purpose of the prototype.

7.3. Time

It has been found that the "Time" variable may not be a suitable indicator of efficiency for the test at

hand. It is due to it being too dependent on the surgeon and not on the prototype. It was observed that surgeons take different times in between strokes leading to great disparities between values for each test prototype. Because of the aforementioned reason, the time variable is not used to determine the most efficient test prototype.

7.4. Stroke per unit time

The amount of stroke per second is not representative of the prototype's efficiency but instead the confidence that the surgeon has with the prototype. A well-designed test prototype allows for a high value but the maximum value is unknown. More tests are needed in order to determine what an optimal value is. More surgeons are needed to be tested to create a database and show what is achievable with what test prototype or instrument.

7.5. Damage

The damage is hard to evaluate. No damage was visually seen on the before-after pictures that were taken during testing. As seen in Figure 1.2, which shows the layers within the retinal cross-section, many cells are present. There have been studies that highlight which cells are the most load-bearing under tensile stress. Under compressive stress, there is a lack of information in literature. No studies have been able to link a compressive force with damage to a patient's vision. Instead, the retina, due to its 70% water content, is considered a liquid and incompressible under a load [3].
Looking at the force values in Figure 6.1, two plateaus can be seen with compressive forces around 0.65 gr and the second roughly around 1.5 gr. We cannot conclude that the maximum allowed force on the retina is 1.5 gr since the implication of that force is not known. Even if no damage was seen at the top surface of the retina under the load, it can not be assumed that, for example, the photoreceptive layer was damage-free.

7.6. Questionnaire & final four questions

Regarding the questionnaire, the individual answers per surgeon and prototype are presented in section B.2. It is seen that the "Wip" is the only prototype to have scored the highest regarding the damage and the ability to wipe parallel to the surface. It highlights the main issue of the other prototypes and why they did not score as high as "Wip" on the questionnaire. The questionnaire results complement the observation as described in section 7.1, where the stiffer prototypes were rotated to be parallel to the surface.
Regarding the answers to the four final questions, they show that, according to the surgeons, the preferred prototype size is medium. It yields an optimal extracted length of 4.5 mm. The least preferred prototypes are from the "Wire-PVA" and "Wire-Wipe-PVA" categories. They are the only prototypes made from PVA granula. It is concluded that it is not an appropriate material to design an efficient prototype to remove VCR. Two surgeons described the "Wip" as the most efficient test prototype, while one preferred the "WirWip-M". Both of which applied the least amount of force.

7.7. Most efficient prototype

According to the number of strokes, the maximum force applied, and the surgeons' feedback on the questionnaire and final four questions, two prototypes perform best overall ie. the "Wip" and the "WirWip-M". Looking at the requirements, seen in Table 2.1 that each test prototype should fulfill, it can be said that "WirWip-M" does not perform well enough on the functional requirements: "Tip should be flexible to allow a bend for enabling sweeping parallel to the retina". It does fulfill all the other requirements so far. The "Wipe" does not fulfill two functional requirements and one dimensional requirement ie. :

1. Tip should be easy to deploy into its final shape.
2. Tip should be easy to retract back into the tube.
3. The test prototype should fit into a 0.6 mm (23 gauge) trocar.

It was tried by a professional company to place the 3x2x1 mm wipe into a 23 gauge tube but the results were without success. It is due to the size of the wipe being considerably larger compared to the opening of the tube (0.4 mm), since "WirWip-M" offers a smaller cross-section than the wipe, it complies with the requirements listed above.
As a result, two prototypes are efficient at removing VCR but both have flaws. The "Wip's" flaw limits its further development due to its geometrical constraints, while the flaws of prototype "WirWip-M" could be remediated with new designs and further testings. Due to the aforementioned reasons, "WirWip-M" is deemed to be the most efficient and promising prototype design for removing VCR from the retina during surgery.

7.8. Limitation

The scope was to design and manufactured a total of 12 test prototypes to be used and assessed

on dissected pig's eyes. For that purpose, an experimental model was developed to recreate to a maximum vitreoschisis. Due to the testing conditions and fabricating process of the prototypes, the work has several limitations.
The number of tests conducted was too small for the natural variability that is expected from biological tissues. Hence, more tests need to be done to verify the observation stated earlier.
The tests were carried out on dissected eyes and not on closed full eyes as during surgery. It was done for two reasons. Firstly, a lot of pig's eyes once cut off, show an opaque lens making it complicated to see through conventional surgery tools. Moreover, the vitreous was prepared unconventionally through a freeze and thaw process, it would not be feasible if the eye was not dissected and opened.
An implication of dissecting the eye is that the tests can be described as "free hand" tests. During surgery, the instrument is constrained at the pars plana due to the trocar and opening of the eye. Because of it, the tip has four degrees of freedom. If there is a need to continue testing on open/dissected eyes with a surgeon, a jig must be constructed to recreate the constraints. Since the constraints were not present during the experiments, it is suspected that the stiffer test prototypes had the advantage to wipe parallel to the surface and did not show the actual values of the force applied. By constraining the tip, only its flexibility will allow it to wipe parallel to the surface.
One surgeon reported that the vitreous was be slightly stuck by the side of the sclera and retina for two of the experiments. It yielded a larger amount of force, more strokes, and a longer time to remove completely the vitreous cortex and vitreous. It was not known which experiments were affected by it but it was considered minimal and did not invalidate the results.
More information is needed on the effect of freezing the test specimen in order to liquefy the vitreous. Liquefaction is of uttermost importance since it is thought to be the source of multiple diseases. So far, not many studies have reported on it and it is not a well-understood process. A better understanding of the process would enable to reproduce more closely vitreoschisis in young's pig eyes and yield more complete results post-testing.
The time was omitted to determine the most efficient prototype. However, time is an important factor during surgery and one of the reasons VCR are not always taken out. There is a need to involve it in the analysis of the performance of the test prototypes. A new test should be carried out where the variable time is put forward and assessed in a better way.

Regarding the test prototypes, four ("WirP-S", "WirP-L", "WirWipP-S", and "WirWipP-M") had one or more structural failures during the test. It was found that the crystallized surface formed by the PVA detached itself from the wire that delimits the contour. Two types of failure were seen during testing. Either the PVA failed because of a force exerted while stroking or it was due to a delay in testing. One test prototype was seen to have thawed for too long and had shrunk and detached from the contouring wire. It follows that PVA granula is not a suitable material for the scope at hand.
Another limitation was that the "Wip" was known by the surgeons beforehand and had already been used by the surgeons before the tests began. It leads to possible bias and gives an unfair advantage compared to the other test prototype.
The best-performing prototypes had major flaws which limited the results. Nevertheless, the series of tests yielded valuable information for further redesigns. The findings are as follows:

1. The optimal extracted length of the prototype's tip is 4.5 mm.
2. 0.6 gr is an acceptable force for removing VCR.
3. The stiffness of the wipe is optimal and should be matched in the redesign.

The listed information should be the start of the requirements for the redesign of the test prototype. The stiffness was quite limited to the minimum diameter of the wires (0.1 mm) and should be made smaller.
Finally, some surgeons reported that larger-sized tips made it hard to visualize what is being done on the retina. How much a tip gives visual feedback might be a new assessment variable for a new setup. The cross-section of the wipe and stiffness are parameters linked to the new testing variable.

7.9. Conclusion

A number of prototypes for VCR removal were developed and experimentally evaluated. Four categories of prototypes were created: The "Wipe", the "Wire-Wipe", the "Wire-PVA" or the "Wire-Wipe-PVA". Experiments on dissected porcine eyes showed that "Wire-PVA" and "Wire-Wipe-PVA" are not reliable designs for removing VCR. It is mainly due to their structural failure and lack of grip on the vitreous and vitreous cortex. On the contrary, the "Wipe" and "Wire-wipe" have performed well during testing. Both designs could remove VCR but looking at the performance numbers, the "WirWip-M" is the most efficient individual test prototype.

It yields the design that manages to remove completely the vitreous cortex and vitreous off the dissected retina in the least amount of strokes and least amount of force without contradicting the requirements.

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A

A.1. Step by step guide to manufacturing test prototypes

A.1.1. Wire-wipe test prototypes

Materials needed: PVA wipe, 0.1 mm Nitinol wire, 0.1 mm Spring steel wire, prototype's handle, scalpel/scissors.

1. Take a part of PVA wipe and make a path with the steel wire, then remove the wire
2. Cut a 15 mm long wire of Nitinol
3. Introduce the Nitinol wire in the already made path
4. Trim the PVA sponge along 0.5 mm on each long side of the wire
5. Bring the cut PVA wipe at the end of the wire, and cut it to desired size (4,6 or 8 mm)
6. Bringing the wipe back in the center of the wire's length, place both end of wire into tube attached to handle
7. Running the wire through the roulette, tighten it until desired extracted length is achieved
8. Test prototype ready to be used

A.1.2. Wire-PVA Prototypes

Materials needed to make a PVA solution: A scale, a magnetic stirrer and hot plate, a magnet, distilled water, and PVA granula, glass container, aluminium foil, 0.1 mm Nitinol wire, prototype's handle, scalpel/scissors.

1. Place glass container on the **cold** magnetic stirrer plate and add desired amount of distilled water in it and start stirrer at the maximum speed that does not allow air in the liquid
2. Progressively add the PVA while continuously stirring
3. Desired water content and granula weight is determined through Equation A.1

$$PVA_{Dry\ weight} = \frac{X \times Y}{1 - \%totalvolatiles} \tag{A.1}$$

   X is the desired solution solid content, for Selvol 165 PVA used in this research, it has a maximum solid content of 7%. Y i the Net weight of the final solution, hence the PVA plus the weight of the water. And the % total volatiles is 5% for the PVA used.
4. Cover top of container with aluminium to avoid losing too much heat
5. Continuing to stir, raise the temperature of solution to 95°C
6. After 30 minutes at 95°C the solution is now ready can be cooled off and used.
7. **Attention** Once the PVA solution is made it has a shelf life of around 3 to 4 hours
8. Cut a 15 mm long wire of Nitinol
9. Place both end of wire into tube attached to handle

10. Running the wire through the roulette, tighten it until desired extracted length is achieved (according to size of tip)
11. Dip the tip of the wire in the PVA solution such that PVA makes a surface delimited by the wire making a loop
12. Place test prototype in the freezer for at least 20 minutes
13. Take test prototype out of the freezer and let sit for 20 minutes
14. Place once again in the freezer for more than 20 minutes
15. Take out of freezer 30 minutes before testing

A.1.3. Wire-Wipe-PVA Prototypes

Materials needed to make a PVA solution: A scale, a magnetic stirrer and hot plate, a magnet, distilled water, and PVA granula, glass container, aluminium foil, PVA wipe, 0.1 mm Nitinol wire, prototype's handle, scalpel/scissors.

1. Repeat step 1 to 7 in Wire-PVA prototypes instructions
2. Cut a 15 mm long wire of Nitinol
3. Place both end of wire into tube attached to handle
4. Running the wire through the roulette, tighten it until desired extracted length is achieved (according to size of tip)
5. Dip the tip of the wire in the PVA solution such that PVA makes a surface delimited by the wire making a loop
6. Place test prototype in the freezer for at least 20 minutes
7. Take test prototype out of the freezer and let sit for 5 minutes
8. During those 5 minutes, cut a portion of the wipe, that is 1 mm in thickness and other dimension being the same as the loop formed by the wire at the tip of the prototype
9. After 5 minutes, apply the thawing PVA tip onto the cut wipe of same size, let the components sit for 10 more minutes and then place back in the freezer for more than 20 minutes
10. Take specimen out of freezer 30 minutes before testing

A.2. Eye Preparation and Observations

This section is meant to describe various observations seen throughout the thesis period mainly concerning the pig's eyes and their preparation.
Regarding the dissection, the sclera is cut off the eye and the choroid is kept, enclosing the retina and vitreous, etc. It is needed to separate the two, as seen through the pictures in subsection 5.1.2. When it is done, be very careful not to go too fast because tears are very easily done through the attachment points in between the sclera and choroid. These attachment points have been found at random locations throughout, and are quite sturdy. An incision done at the root of them should separate both tissues well enough to avoid a tear. If a hole is pierced through the choroid, the retina will likely be damaged as well. Hence wondering when a specimen should often be discarded, the following rule can be applied. If the hole is around or less than 2.5 mm in diameter (and away from the desired retinal testing zone), the dissection can be kept. If the whole is larger, it is likely that the retina will appear unfit for testing due to possible damages.
The optic nerve needs to be properly cut. Often a dissection does not appear flat on the surface because a remaining of the nerve is still present under the sclera. The best way to cut it is to use curved clippers and follow the curvature of the sclera. The closest it is to choroid connection points laying at the nerve location, the better it is. It will require some practice but will lead to great dissection with more reproducibility since they will be flatter.
As stated, it had been found that the vitreous liquefies through a freezing process. The reason why is unknown. In literature, it is speculated that the liquefaction naturally occurs due to body heat and light interaction breaking the collagen molecules. Not many tests could be done on the subject since it is not the main objective at hand. Freezing a specimen yields to the liquefaction of its vitreous, the process is not instantaneous but requires a few hours. It is expected to need just above 24 hours to fully liquefy the whole. (Data obtained through 1 carried test). For the experiments with the surgeons, the eyes were left for less time in the freezer. Another observation seen is that the vitreous may have a liquefaction

direction. It means that it will first liquefy closer to the retina and then the vitreous region close to the lens. There is a need for further tests for it.

B

B.1. Force data

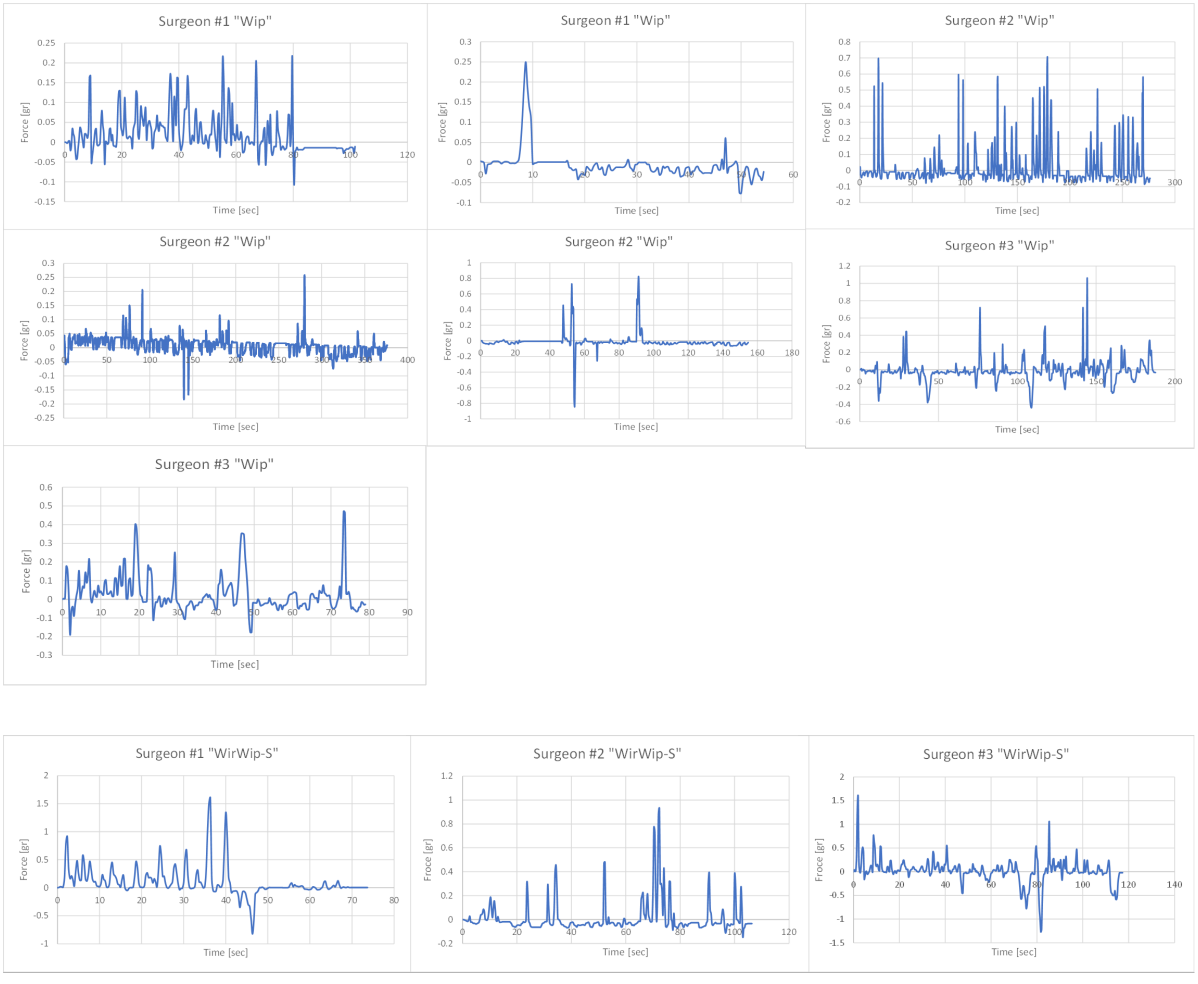

Figure B.1: "Wip" & "WirWip-S" force results

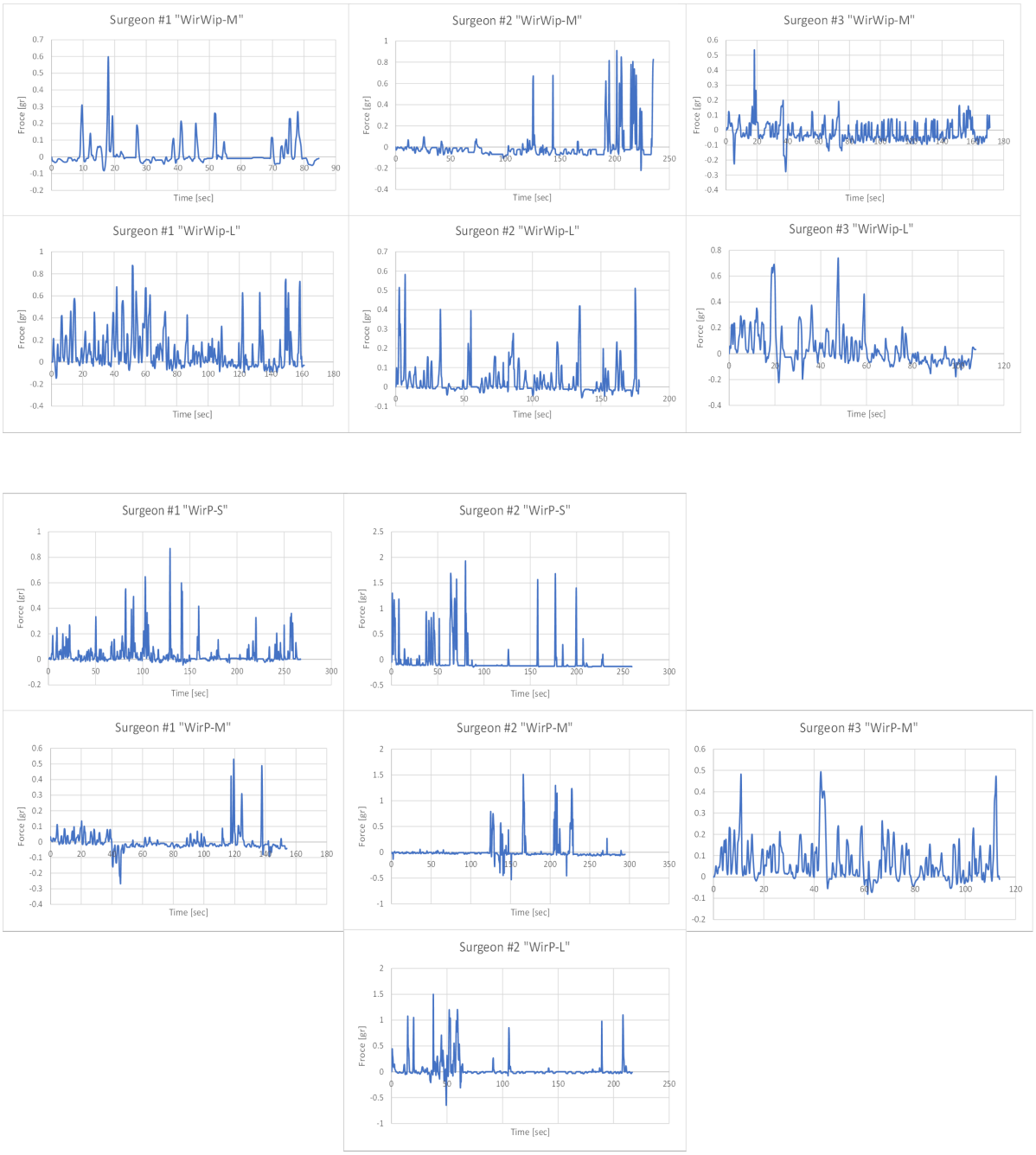

Figure B.2: "WirWip" & "WirP" force results

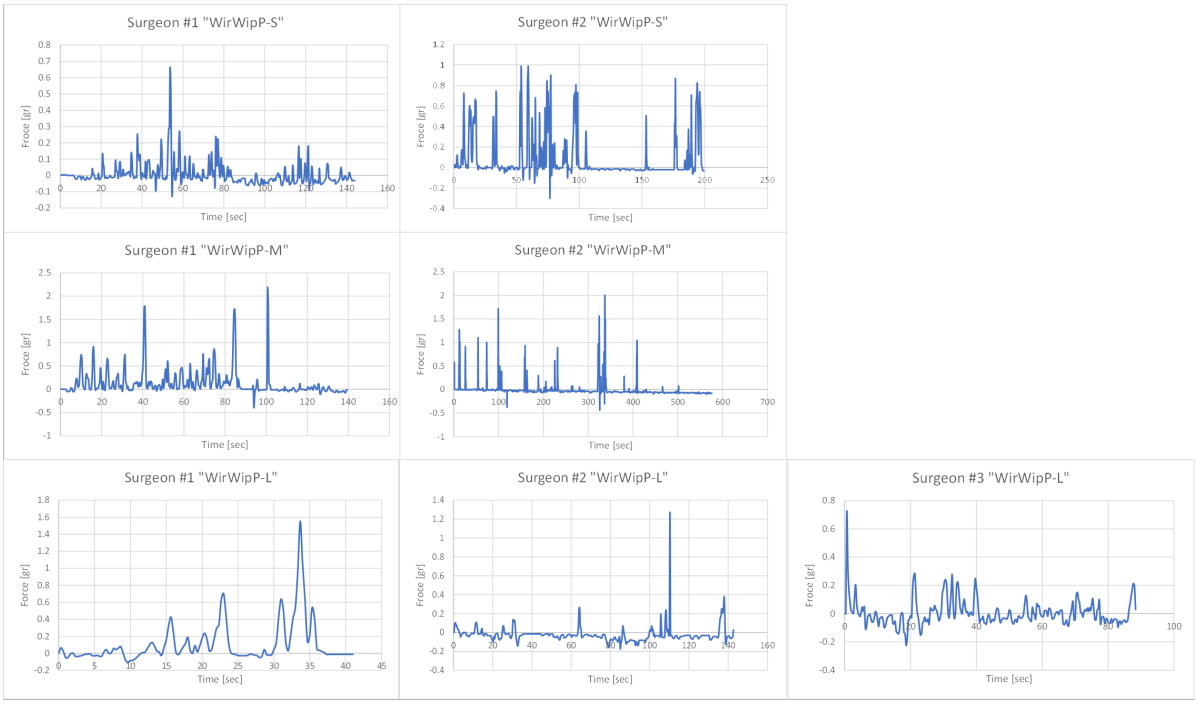

Figure B.3: "WirWipP" force results

B.2. Questionnaire

The questionnaire answered after each test consisted of 5 questions, with response options between 1 (Strongly disagree) to 5 (Strongly agree). Table B.1 show the response of each surgeon.

Table B.1: Answers to questionnaire

	Surgeon #1											
	Wip	Wip	Wip	WirWip-S	WirWip-M	Wirwip-L	WirP-S	WirP-M	WirP-L	WirWipP-S	WirWipP-M	WirWipP-L
Is the prototype tip likely to not damage the retina?	5	4		3	4	3	2	2	2	3	3	4
Is the prototype tip easy to handle?	5	4		4	4	4	4	3	2	4	4	4
Does the prototype tip enables well wiping parallel to retina?	5	5		3	2	3	3	2	2	2	3	4
Does prototype tip grips well onto the cortex remnants?	5	4		3	5	4	2	3	4	3	3	4
Is the prototype tip of ideal extracted length?	5	5		4	5	3	4	4	2	3	4	3
	Surgeon #2											
Is the prototype tip likely to not damage the retina?	4	5	5	4	3	4	2	3	3	3	4	2
Is the prototype tip easy to handle?	3	4	4	4	3	4	1	4	4	3	4	2
Does the prototype tip enables well wiping parallel to retina?	3	4	5	3	3	4	1	3	3	3	3	2
Does prototype tip grips well onto the cortex remnants?	4	4	4	4	4	4	1	3	2	3	3	4
Is the prototype tip of ideal extracted length?	3	5	4	2	4	3	1	2	3	4	3	2
	Surgeon #3											
Is the prototype tip likely to not damage the retina?	4		5	4	4	4		4			4	4
Is the prototype tip easy to handle?	5		5	5	4	5		3			-	5
Does the prototype tip enables well wiping parallel to retina?	3		5	5	4	5		2			-	5
Does prototype tip grips well onto the cortex remnants?	4		5	5	4	1		2			5	5
Is the prototype tip of ideal extracted length?	5		5	5	4	2		5			5	5