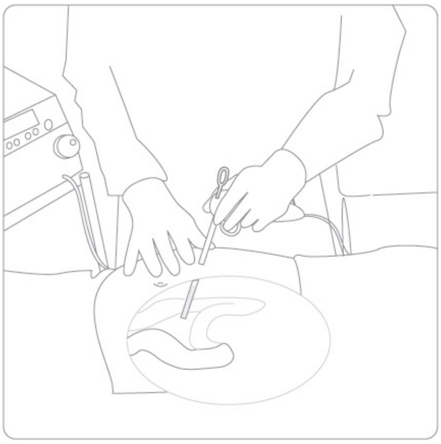
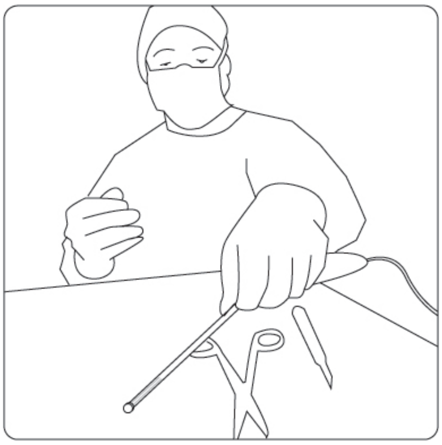
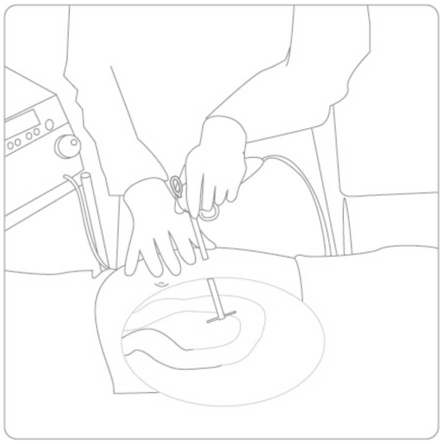
Development of a medical Bernoulli gripper

GRADUATION THESIS







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CONTENTS

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Abstract

When performing minimally invasive interventions, surgeons use grippers to grip and manipulate tissue. These grippers generally rely on their toothed profile and require pinching of the tissue for sufficient grip, entailing a risk of tissue damage. An solution should be found for this risk of damage. An alternative could be to manipulate the tissue without pinching or even touching it. Contactless gripping exists in the industrial field by using the principle of Bernoulli. This study explores the possibility of applying Bernoulli gripping for tissue manipulation during minimally invasive surgery.

A medical gripper using the principle of Bernoulli was developed. Increasing the air flow, the radius of the gripper face and the radius of the nozzle has a positive effect on the lifting force. In order to prevent tissue damage, different variants are tested that change the direction of the air flow. In an exploring experiment, a deflector was selected out of seven variants as best solution to prevent damage from the air flow. The Bernoulli gripper was made expandable and collapsible for insertion in the body of the patient with a system of living hinges. The effect of Venturi channels and the position of a membrane for an airtight surface on the lifting force were tested. The lifting force generated on the object during gripping was measured using a tensile-strength tester.

Bernoulli's theory was compared to the results of the experiments and a discrepancy was found between theory and results. This study shows that a Bernoulli gripper is feasible to lift flexible tissue.

Keywords: Bernoulli gripper, deflector, Venturi channels, tissue manipulation, minimally invasive surgery

1 INTRODUCTION

Minimally invasive surgery is a fast growing branch of surgery (Dankelman 2004). In the Netherlands alone, 29,000 minimally invasive interventions are performed per year (IGZ 2007). Instead of making a large cut in the skin, small incisions are made for instrument insertion. These instruments are inserted in the body of the patient through trocars (Figure 1). The small incisions result in smaller scars and less pain which is advantageous for the patient, but they impede the grip capacity for the surgeon. Human tissue is a difficult material to grip due to low stiffness, wet and delicate surface, and variations in texture, shape, and sizes. The current grippers used in minimally invasive surgery are long and toothed and require pinching of the tissue for sufficient grip, entailing the risk of tissue damage. Although diverse alternatives for the toothed variant have been developed (Trommelen 2010), toothed grippers are still used in the majority of minimally invasive interventions.

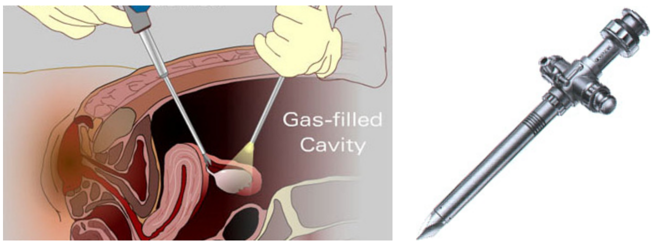


Figure 1: Left: Minimally invasive surgery (www.nzobesitysurgery.co.nz/laparoscope.html). Right: A trocar is used to insert instruments (www.websters-online-dictionary.com).

The aim of the present work is to develop and evaluate a tissue gripper that prevents tissue damage during minimally invasive surgery. This could be achieved if tissue could be gripped without contact. Contactless gripping is found in the industrial field using the principle of Bernoulli (for a selection of industrial applications of Bernoulli, see Appendix A). This technique is used for a variety of delicate materials, including thin silicon wafers (Brun 2009), woven fabrics (Ozcelik 2002, 2005), jelly blocks (Erzincanli 1994), vegetables (Davis 2008) and leather plies (Dini 2009).

In this study, the theory of the Bernoulli principle is presented and the boundary conditions for the development of a Bernoulli gripper suitable for minimally invasive interventions are set. A number of concepts is generated and explorative experiments are conducted in order to choose the best components for the concept. A prototype of the final concept is produced. The paper concludes with an evaluation of the feasibility of a Bernoulli gripper for gripping tissue.

This study focuses on the investigation of the feasibility of a Bernoulli gripper suitable for minimally invasive surgery in the abdomen, called laparoscopy. Other applications for the Bernoulli gripper can be found in Appendix B.

2 THEORY

For better understanding of the Bernoulli principle, its theory will be discussed. The theory focuses on gripping rigid objects. No theory is known about Bernoulli gripping of flexible objects, so examples from literature are used to explain about gripping flexible objects like tissue.

2.1 *GRIPPING RIGID OBJECTS*

A Bernoulli gripper consists of a disc with a central circular channel (Figure 2). The disc is referred to as the gripper face. A compressed air or fluid flow is supplied through the circular channel and exits at a nozzle located in the centre of the gripper face. The principle of Bernoulli can work with either fluid or air. Here we focus on Bernoulli grippers functioning with air. When the gripper face is held close to an object, the air is forced in lateral direction in the narrow gap between the gripper face and the object, thereby flowing out over the shape of the gripper face. The principle of Bernoulli is based on the law of conservation of energy, according to which the pressure decreases when the velocity increases in the region between the object and the gripper face. The Bernoulli's principle is given by

$$(\frac{1}{2}\rho v^2 + P)_1 = (\frac{1}{2}\rho v^2 + P)_2 \tag{1}$$

where ρ is the density of the air, v is the velocity and P is the pressure in Region 1 or Region 2 of the gripper (Figure 2). The total lifting force on the object is the residue of the rejecting force and the attracting force of the system

$$F_{tot} = F_{attract} - F_{reject} \tag{2}$$

The derivation of the equations for the rejecting and attracting force can be found in Appendix C. The attracting force is dependent on the pressure difference, created between the object and the gripper, and the surface of the gripper face. Bernoulli's principle (1) can be used to rewrite the pressure difference. Together with the conservation of mass it is found that

$$F_{attract} = \frac{\rho Q^2}{4\pi h^2}\left[\ln(\frac{R}{R_c}) - \frac{1}{2}(1-(\frac{R_c}{R})^2\right] \quad (3)$$

where Q is the air flow, h is the height between the object and the gripper, R is the radius of the gripper and R_c is the radius of the nozzle. Additionally, the compressed air flow from the nozzle also causes a rejecting force that pushes the object away from the gripper. This rejecting force is also dependent of the pressure difference and the surface. When combined with the dynamic pressure, the rejecting force can be written as

$$F_{reject} = \rho \frac{Q^2}{\pi R_c^{\ 2}} \quad (4)$$

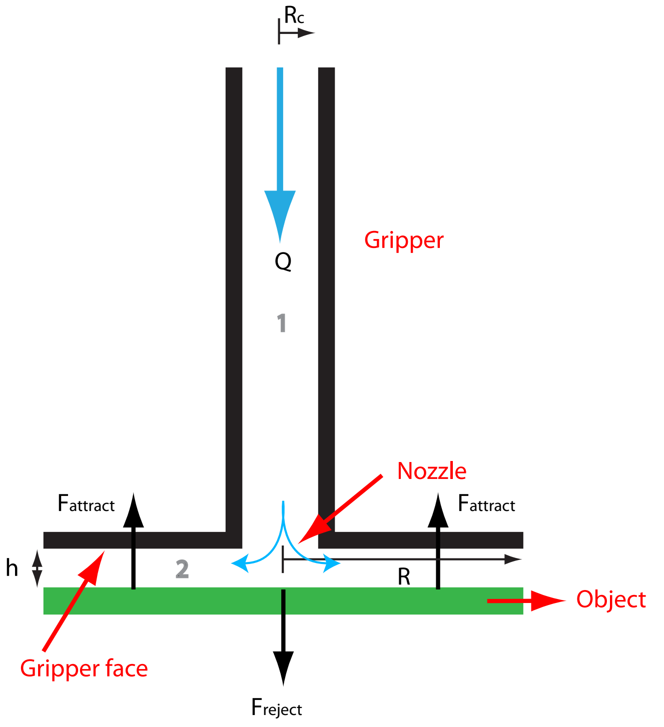


Figure 2: A cross section of a Bernoulli gripper.

If the total lifting force is larger than the weight of the object, the object can be lifted. The height h at which the object will be gripped can be calculated using the conservation of mass. At a height larger than zero, the object is gripped without touching the gripper.

Bernoulli grippers presented in past studies can grip objects with varying weights and sizes. The smallest gripped object described in literature is a silicon chip of 4 x 4 mm gripped by a gripper with a nozzle radius R_c of 0.1 mm and a gripper face radius R of 4 mm (Grutzeck 2002). The lifting force F_{tot} with an air flow Q of 2 L/min was 5 mN. The largest lifting force F_{tot} in the literature was found in Dini (2009), where up to 50 N was measured with a gripper with a nozzle radius R_c of 4 mm and a gripper face radius R of 45 mm with an air flow Q of 288 L/min. These two examples prove what is found in theory, namely that the total lifting force increase when increasing the radius of the gripper face R, the air flow Q and the radius of the nozzle R_c (for more details, see Appendix C).

The behaviour of the air flow velocity v and the pressure P varies when moving from the centre to the edge of the gripper face. This behaviour is shown in Figure 3.

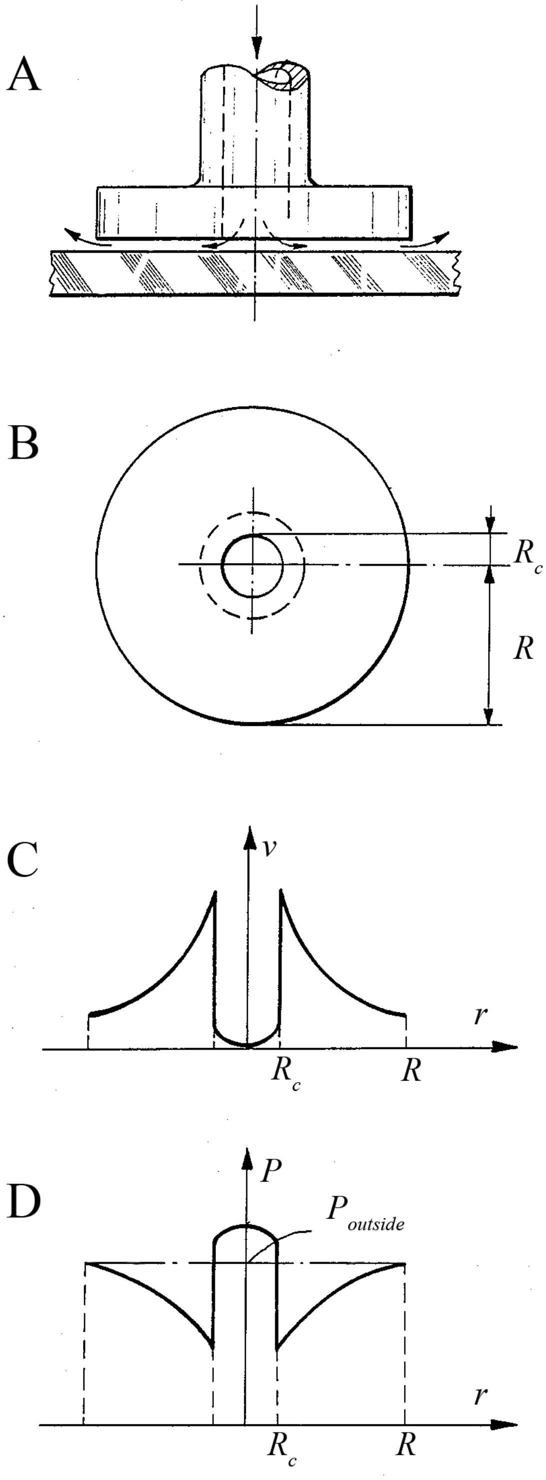


Figure 3: **A:** Side view of Bernoulli gripper with a rigid object. **B:** Bottom view of Bernoulli gripper. **C:** Qualitative air flow velocity v between the gripper face and the object plotted to the variable radius r. **D:** Qualitative pressure P between the gripper face and the object plotted to the variable radius r. The pressure outside the gripper $P_{outside}$ is indicated by a horizontal line. The figure is adapted from Carlomagno (1990).

Theory shows that an increase of air flow results in larger lifting forces. However, it should be noted that there is an important transition between subsonic and supersonic flow. Flow can be calculated by multiplying the velocity by the surface. Supersonic flow is at a velocity that is larger than the velocity of sound, which is approximately 330 m/s. Gripping at these speeds has the undesirable effects such as shock waves. These shock waves are associated with a sonic boom, sounding like an explosion.

2.2 GRIPPING FLEXIBLE OBJECTS

The theory described in the previous section does not hold for flexible objects. Naturally, when a Bernoulli gripper grips a flexible object, the forces are not evenly spread along the surface of the object. Instead, right beneath the nozzle, the air flow causes a deformation of the flexible object. There is a large risk that the object will vibrate rapidly and block the airway. If the object is in an unstable position, the object is blown away (Food Refrigeration and Process Engineering Research Center 2010). The Bernoulli gripper needs to be modified when gripping flexible objects to solve the problem of the high air flow blowing directly on the object. A number of solutions have been found in scientific literature in which flexible objects are handled using an adapted nozzle shape. Different shapes are discussed below.

A cone can be placed in the nozzle (Figure 4), so that the air flow bends before reaching the object and the impact on the object is reduced. The cone can stick out of the nozzle (Carlomagno 1990), but can also be integrated, where the bottom of the cone is at the same height as the surface of the gripper, to prevent contact with the object. In the article of Dini (2009) a Bernoulli gripper with an integrated cone was developed to handle leather plies (Figure 4). The cone can have different angles α. Erzincanli (1994) applied the same technique for handling of sliced meats and jelly blocks and Ozcelik (2002) and (2005) used a similar device in the textile industry.

The problem of the strong air flow can also be solved with a deflector, which sticks out of the nozzle and forces the air flow to bent 90 degrees. In the study of Davis (2008) a Bernoulli gripper with a deflector was developed for handling slices of fruit and vegetables (Figure 5). A disadvantage is that the object will have contact with the deflector when gripping so the gripper is not completely contactless anymore. This could be prevented by integrating the bottom of the deflector with the surface of the gripper. This can be created when the surface of the gripper is made conical like suggested by Okugi (2002).

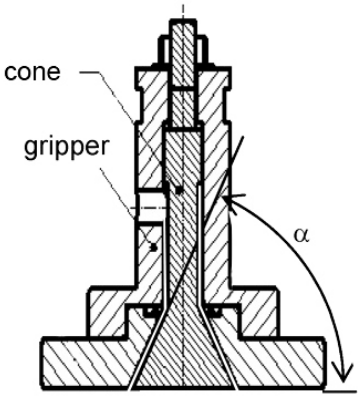


Figure 4: Leather gripper with an integrated cone. The figure is adapted from Dini (2009).

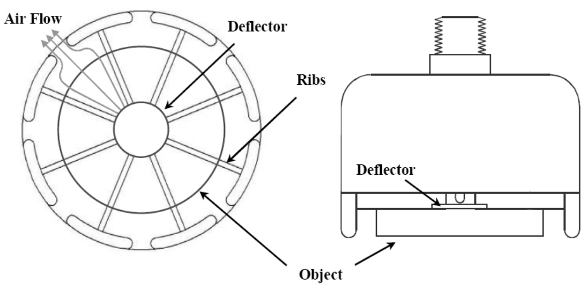


Figure 5: Fruit gripper with deflector and ribs. The figure is adapted from Davis (2008).

Another solution is to distribute the strong air flow over multiple smaller holes, to decrease the effect of a single hole. This results in a nozzle called the 'Showerhead' (Binder 2003, Cronquist 1959, Klein 2006).

The last nozzle shape found is a nozzle adapted by edging, creating a chamfer at the end of the nozzle (Akashi 1991, Carlomagno 1990). The effect of this streamline when gripping flexible objects is not clear from these articles.

Another interesting shape is found, which does not solve the problem of the high air flow, but could have a positive effect on gripping. The lifting force can be increased by further accelerating the air flow under the gripper by means of Venturi channels (Figure 6). The acceleration causes extra low pressure at the channels, which adds up to the low pressure from the gripper. In the study of Dini, adding radial Venturi channels in the surface of the gripper increased force up to 10 N (Figure 7). The Venturi channels are 3 mm in width and the height ranges from 2 mm to 1 mm to 2 mm over the radius of the gripper (Dini 2009).

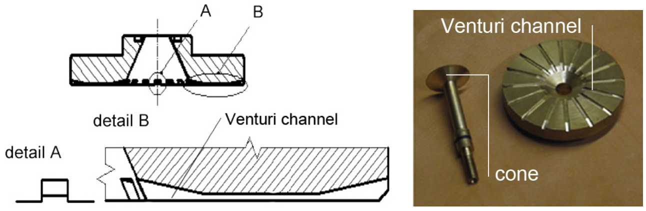


Figure 6: Left: Detail of leather gripper with cone and Venturi channels. Right: The cone and the gripper face with radial Venturi channels. The figures are adapted from Dini (2009).

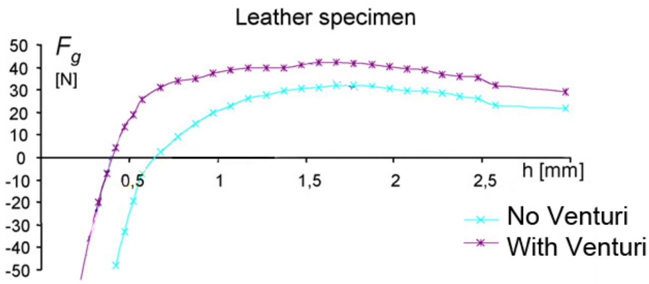


Figure 7: Lifting force of Bernoulli grippers of the same size, one with and one without Venturi channels, comparing the effect of Venturi channels. The figure is adapted from Dini (2009).

3 BOUNDARY CONDITIONS

For a Bernoulli gripper to be successful in minimally invasive surgery two boundary conditions need to be met: (a) the gripper has to pass through a standard 5-mm trocar and (b) the gripper has to generate sufficient forces for tissue manipulation. There is a lack of information about the forces required for tissue and organ manipulation during laparoscopy. Typical values range between 2.5 and 5 N (Dankelman 2009). Reaching this range of forces will be a boundary condition for the Bernoulli gripper.

The aim was to develop a tissue gripper using Bernoulli's principle that prevents tissue damage. To solve this problem, it was divided in six subproblems:

- *How to change the direction of the strong air flow?*
- *How to make the system expandable/collapsible?*
- *How to prevent the object from sliding?*
- *How to prevent blowing away of other objects?*
- *How to generate a large force?*
- *How to remove pressure excess from the patients' abdomen?*

In a morphological analysis many solutions for these subproblems were generated (see Appendix D). To prove the feasibility of the gripper, the most important steps are that the instrument has to pass the trocar to reach the tissue and the instrument has to grip the tissue. Therefore, two subproblems were selected that had priority. These two most important decision areas are discussed below and were developed during this research.

Decision Area 1. How to change the direction of the strong air flow?
The most suitable nozzle shape for gripping tissue will be selected out of the range of shapes described in Section 2.2. To find out which shape is best for gripping tissue an exploring test was carried out (Section 4).

Decision Area 2. How to make an expandable/collapsible system?
A large gripper face and nozzle size are variables which have a positive effect on the lifting force. To make the system profitable, the system has to be expandable and collapsible. The best expandable and collapsible system were explored by the use of idea generation and selection with the help of the boundary conditions. (Section 5).

4 EXPLORING TEST

To get insight in Decision Area 1, an exploring test was performed. The aim of this experiment was to investigate how to change the direction of the air flow. The performance of eight different models was compared in terms of lifting capacity for flexible objects. The best nozzle shape was selected.

4.1 *MATERIALS & METHODS*

Eight nozzle shapes from articles and patents described in Section 2.2 were implemented in a Bernoulli gripper. A schematic 2D view of each model and the real model is shown in Table 1. It was decided to use these nozzle shapes in the exploring test:

1. A **standard** nozzle was used as a reference.
2. A **streamline** was created by adding a small chamfer at the end of the nozzle.
3. **Venturi** channels were implemented in a gripper with a standard nozzle.
4. A **deflector** was added in the standard nozzle.
5. A **cone** with the angle of 30 degrees was chosen for this experiment, because it was found by Dini (2009) that a 30 degrees cone performed better than a 60 degrees cone.
6. A **cone integrated** in the gripper.
7. A **deflector integrated** in the gripper.
8. A **showerhead** distributing the air flow.

According to Equation (3) and (4), a gripper with a large nozzle

Table 1: Nozzle shapes and results of exploring test. Objects that could be gripped are in green. Objects that could not be gripped are in red.

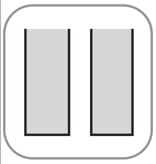
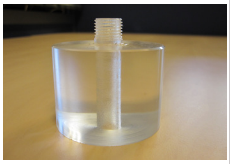
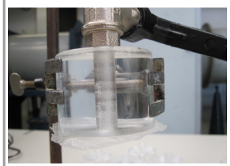
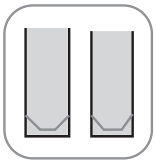
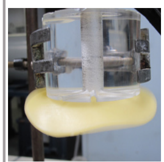
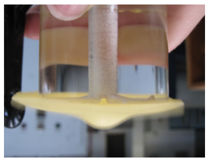
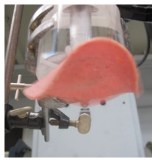
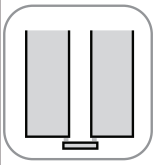
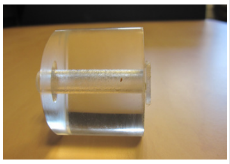
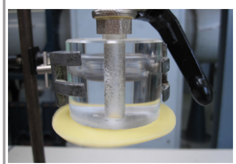
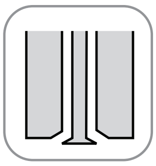
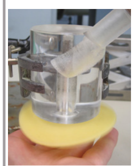
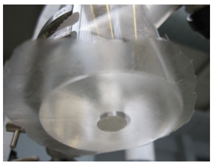
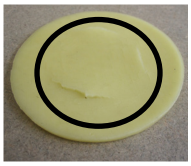
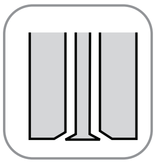
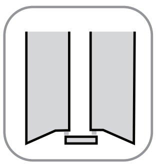
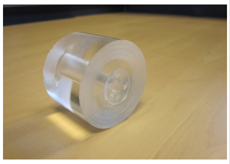
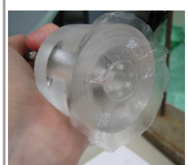
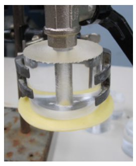
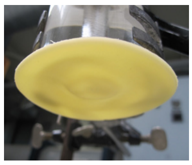
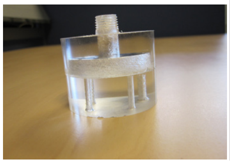
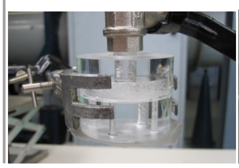
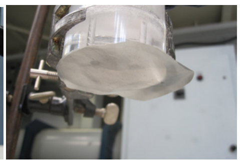
Type of nozzle	Schematic	Models	Results	Remarks	Examples
Standard			+ sandwich & garbage bag - cheese and sausage	strong air jet against object resulting in vibrations	 
Streamline			- all objects	unstable grip (object slid off)	
Venturi			- all objects	object could be gripped, but not for long and with damage afterwards due to vibrations	  
Deflector			+ all objects	not contactless, due to deflector (imprint seen on object)	 
Cone			+ sandwich & garbage bag - cheese and sausage	cheese and sausage could be gripped, but not for long and with damage afterwards due to vibrations	  
Cone Integrated			- all objects	unstable grip (object slid off)	
Deflector Integrated			+ all objects	not contactless, due to deflector (imprint seen on object)	  
Showerhead			- all objects	garbage bag could be gripped, but not for 30 seconds	 

Table 2: Details of the materials used for the exploring test.

Material	Weight	Air flow rate needed for successful gripping
pre-cut young cheese	8.5 g	2L/sec
pre-cut Berliner sausage	8.2 g	2L/sec
sandwich bag	< 0.1 g	0.2L/sec
garbage bag	< 0.1 g	0.3L/sec

radius has a smaller rejecting force and a larger attracting force. The standard gas connection used for the exploring test allowed a hole with a maximum of 7.5 mm, so this was chosen for the nozzle diameter. For this test, the lifting capacity was explored for the following flexible objects: pre-cut young cheese, pre-cut Berliner sausage, sandwich bag and garbage bag. Young cheese was chosen because it is a biological material and, compared to other cheeses, most flexible. Berliner sausage was chosen because it is a biological material made of animal tissue. Sandwich bag and garbage bag were chosen, because they are flexible. All materials have a diameter of 7 cm and a weight between 0.1 and 8.5 g. Details about the materials are shown in Table 2.

Considering the size of organs in the abdomen, a gripper with a radius of 2.5 cm is a maximal value for practical use. To compare the different nozzles, all other variables should be kept constant. Therefore, all the nozzles had the same surface area of the nozzle as the standard nozzle.

The experimental set-up is shown in Figure 8. Compressed air was guided through an air regulator (type Lorch 1523 G1/4 37705, Figure 9, left) to reduce the pressure. A calibrated flow sensor (type Rota G1.630-2645, Figure 9, middle) was used to measure the flow. The Bernoulli gripper was fixated with a clamp and connected to the air flow (Figure 9, right). The object was held below the gripper while the air flow was regulated from zero until the gripper generated enough lifting force. The objects were tested at different volumetric flow rates from 0 to 4 L/s. We considered gripping successful if constant gripping without falling off during 30 seconds was obtained. The experiments were repeated three times for each gripper. A new slice of cheese and sausage was used for every nozzle type. Only one sample of the sandwich bag and the garbage bag were used.

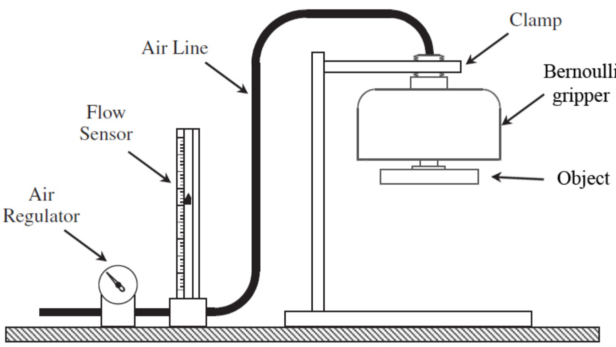


Figure 8: Experimental set-up of the exploring test.

Figure 9: Left: Air regulator. Middle: Flow sensor. Right: Bernoulli gripper in the clamp gripping an object.

4.2 RESULTS

The results for every model are shown in Table 1. The models Deflector and Deflector Integrated created stable gripping without damage during this test. The models Streamline, Cone Integrated and Showerhead could not grip any object, because the objects slid off. However, the model Venturi had a positive effect on gripping. The gripper lifted a slice of cheese and sausage for 3 seconds.

The model Streamline could not grip any object, because the area around the nozzle at which the lifting force is the highest was removed. The models Cone and Cone Integrated did not work. A possible explanation for this failure could be the oblique direction of the air flow, which blows the object away. The model Showerhead did not work in this experiment; despite an elaborated example that was found in literature (Binder 2003). A possible improvement of model Showerhead could be a larger space between the nozzles or smaller nozzles, so that the air flow of the different nozzles have less influence on each other.

4.3 CONCLUSIONS & DISCUSSION

The aim of the exploring test was to investigate how to change the direction of the air flow. A deflector is a suitable addition to change this direction. In this explorative experiment no difference in lifting force was found between the Deflector and the Deflector Integrated, except for the shape of the object when gripping. Combining Venturi channels with a deflector could increase the lifting force of the gripper.

A print of the deflector after long contact was noticed using the deflector and deflector integrated. Moreover, damage due to strong vibration was observed when using the outside cone and Venturi. The exploring test indicates that tissue gripping is best with a Bernoulli gripper using a nozzle with a deflector and Venturi channels.

5 DESIGN CHOICES

In this section, a solution for Decision Area 2 ‘make system expandable/collapsible’ will be explored. In Section 5.1, ideas will be generated and selected. In Section 5.2, the selected ideas will be developed to concepts. In the concept generation, all subproblems were taken into account. Finally, the best concept was selected.

5.1 IDEAS AND IDEA SELECTION

A series of idea sketches have been made (see Appendix E) of which three ideas have been selected that meet the boundary conditions. These ideas are all based on different kinds of working principles and are shown in Figures 10, 11 and 12.

Figure 10 shows the first idea that creates expansion of wires by releasing tension of the material. Prebent Shape Memory Alloy (SMA) wires are forced in a tube. When the wires are pushed down, they will spread out and create, together with a membrane, the surface of the gripper. The membrane is needed to make the surface airtight.

Figure 11 shows the second idea that uses expansion by inflation. An inflatable ring is blown up in the body with the air channels. A membrane of thin rubber covers the surface of the gripper.

Figure 12 shows the third idea that uses expansion by pushing down. With the use of hinges, the system will expand when pushing the outer tube down and keeping the inner tube in position. Venturi channels can be integrated in the ribs. A membrane is needed for an airtight surface.

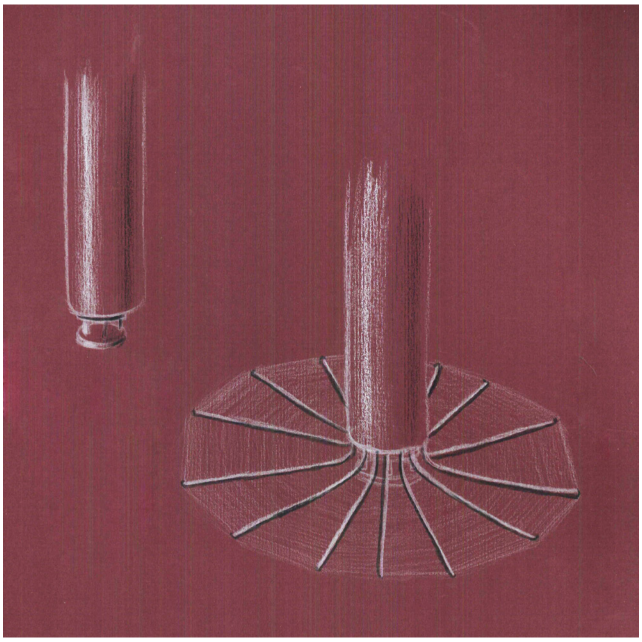


Figure 10: Releasing Tension.

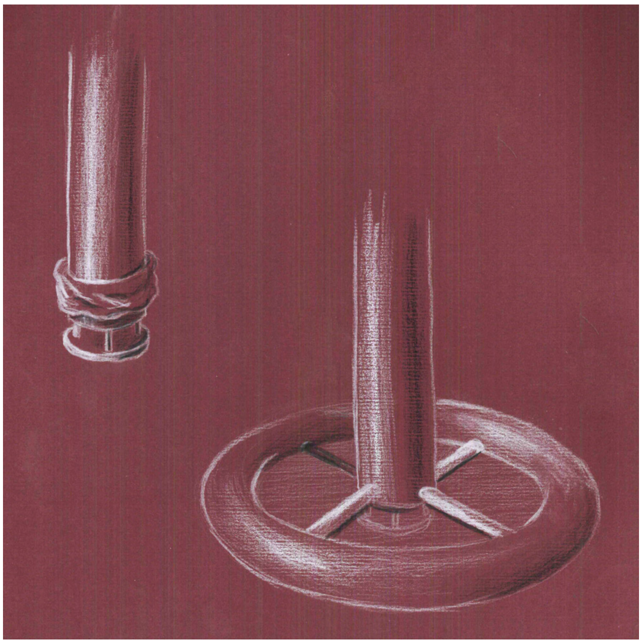


Figure 11: Blowing Up.

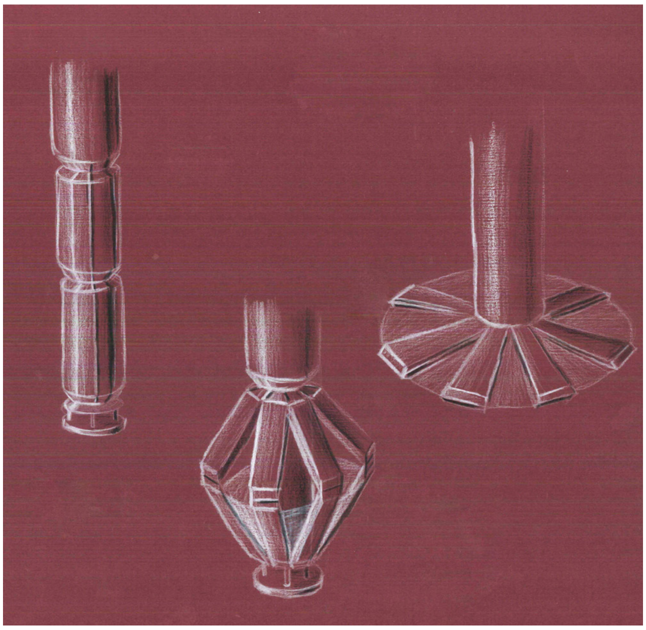


Figure 12: Pushing Down.

5.2 CONCEPTS AND CONCEPT SELECTION

The three ideas were developed into concepts containing solutions for all decision areas discussed in Section 3. Details of the concepts can be found in Table 3. The most important requirement is the concept which is best possible to produce in a prototype. Availability and complexity of the production method were also considered.

Concept 'Releasing tension' uses SMA. Shape Memory Alloy is corrosion resistant, bio-compatible and can be fabricated into small sizes (Ashby 2002). However, it needs specific production methods and is therefore difficult for prototype production. The concept 'Blowing up' is difficult to produce for a single prototype, due to the unusual production methods needed to fabricate the donut-shaped balloon. Therefore, the concept 'Pushing down' has been chosen. The others could be investigated in the future.

6 COMPONENT SELECTION

After concept selection, most components were defined. However, the membrane could be positioned on two locations, namely on the top and on the bottom of the expanded bottom ribs (Figure 13). The position of the membrane changes the shape of the gripper and can cause a change in lifting force. An advantage of the membrane placed on top of the ribs is that the membrane is protected by the ribs during insertion in a trocar. When placing the membrane on the bottom, there is a risk of damaging the membrane during insertion in the trocar.

Another component which must be selected is the Venturi channel. The effect of Venturi channels on the lifting force when combined with a deflector has to be tested. To acquire knowledge about the effect of the location of the membrane and Venturi channels on the lifting force, an experiment was done. A comparison was made of the lifting force for a gripper with a straight surface, to a gripper with Venturi channels in the surface. In order to find out more about the membrane, a comparison was made in the lifting force when placing the membrane on the top or on the bottom of the collapsible ribs.

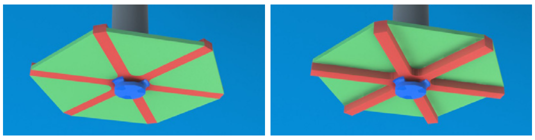


Figure 13: Left: Membrane on the top of the expanded bottom ribs. Right: Membrane on the bottom of the expanded bottom ribs.

This experiment was carried out with a simplified model of the 'Pushing Down' concept. The cross section of the gripper in Figure 14 shows the different components of this simplified model. The grey tube guides the air flow. The red ribs simulate the expandable ribs. Expansion is not possible with the simplified model; it was only used for testing the effect on the lifting force. There are six ribs, each with a width of 1.5 mm. On the top or on the bottom of these ribs, a membrane was placed for the air distribution. To eliminate variation, the membrane was printed in rigid plastic. A deflector was used to protect the flexible tissue from the strong air flow. Venturi channels were added to increase the lifting force. Due to the small size of the ribs, the Venturi channels have been scaled down relative to the gripper face radius and the width of the ribs.

The radius of the gripping face of all grippers was 1.25 cm, because this is accordance with the size of a standard laparoscopic gripper. The height and thickness of all deflectors was 0.5 mm. According to Equation (3), the closer the deflector is to the gripper face, the higher the lifting force. However, there is a boundary, because air friction will start to play a role when the deflector almost touches the gripper face. To reduce the imprint in the object, the thickness of the deflector was chosen as thin as possible, while it could still be produced with the 3D-print machine. The height is chosen based on other experiments lifting the same weight range. The diameters of the nozzles were 2 and 4 mm.

The hypothesis was that the Venturi channels have a positive effect on the lifting force. Further, it was expected that the placement

Table 3: Three design concepts for a medical Bernoulli gripper.

Design concept 'Releasing Tension'	**Design concept 'Blowing Up'**	**Design concept 'Pushing Down'**
Material Ribs: SMA Membrane: Rubber/silicon **Working principle** When the gripper is inserted in the body, the prebent SMA ribs and the membrane are pushed out and will spread in the right position. Air excess in the body of the patient caused by the air inflow during gripping can be removed during gripping using active outflow. If the gripper has to be removed, the ribs and membrane are pulled in the holder again and removed through the trocar. **Comments** - The membrane needs a lot of space. - The SMA is expensive, so the design is primarily suitable for reusable instruments. The membrane material is very difficult to reuse, so this part shall be disposable, making the design partly reusable and partly disposable. **Components in horizontal section** 6 parts in 5 mm	**Material** Inflatable ring: Butyl or rubber Membrane: Rubber/silicon **Working principle** When the instrument is inserted in the body, the deflector is collapsed and air can flow to the inflatable ring, which is inflated until the tension is optimal for gripping. If the deflector is expanded, the air flow can be used to grip tissue. Holes in top of the cylinder remove the excess air in the body of the patient caused by the air inflow during gripping. For removal, the deflector has to be closed again and active outflow removes the air in the ring. **Comments** - Rubber is sensitive for sharp instruments. - Air flow is not coupled with the inflatable part. - The four ducts create extra rigidity. - Production will only be possible in disposable version, because of the steralizability of the materials used. **Components in horizontal section** 2 parts in 5 mm	**Material** Ribs: Plastic/metal with elastic properties Membrane: Rubber/silicon **Working principle** An outer cylinder is pushed down with respect to an inner cylinder. The ribs are then forced to spread out. Holes in top of the cylinder remove the excess air in the body of the patient caused by the air inflow during gripping. When the instrument has to be removed, the opposite movement is applied to collapse the system. **Comments** - Venturi channels can be integrated in the ribs. - This concept can be disposable or reusable, dependent on the materials used. However, the membrane will always be disposable, for hygienic properties. **Components in horizontal section** 4 parts in 5 mm

of the membrane under the ribs would lead to higher lifting forces, because the air flow is not blocked by the ribs.

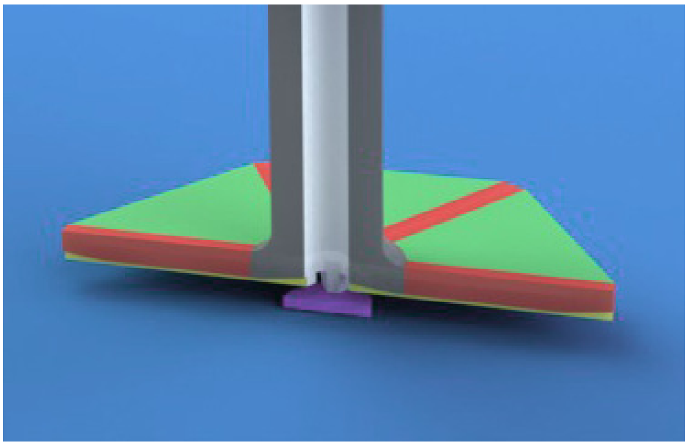


Figure 14: Cross section of the simplified gripper used in Experiment 'Component Selection'. The air flow tube is grey, the ribs are red, the membrane is green, the deflector is purple, the Venturi channels are yellow.

6.1 MATERIALS & METHODS

Four different grippers were tested to measure the lifting force, combining the different variables (Table 4). The models were 3D-printed, because of their small size. A model is shown in Figure 15. The material used for all models was VeroBlack – FullCure870.

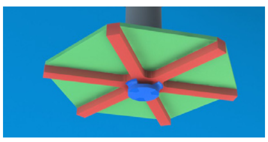
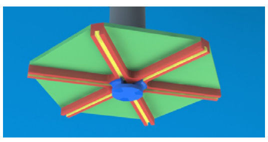
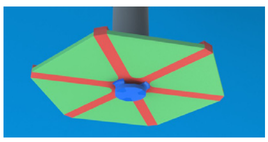
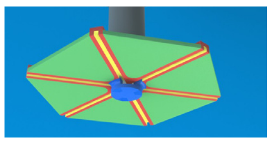
According to Equation (3), the higher the air flow, the larger the lifting force will be. However, to prevent supersonic flow, which is at a air flow velocity of 330 m/s, the velocity in the nozzle of all grippers was a fixed value during the experiment. For the 2 and 4 mm nozzle, measurements were conducted at air flow velocity of 64, 128 and 191 m/s (Table 5).

The test set-up is shown in Figure 16. A bag of latex, filled with gel and humidified with natural oil, simulates a flexible organ with slippery and wet surface and was used as the object to be gripped. Because the gripper blows off oil, same amount of oil was applied after every test. A bag of gel is used instead of slices of cheese, because it simulates the behaviour of tissue better. It was decided not to work with animal tissue, because the characteristics of tissue would change due to the dehydration effect of the air flow.

The lifting force was measured with the help of a tensile-strength tester (type Zwick 1484) with a movable test bed and a fixed force sensor at the top. The force sensor has a range of 5 N and nominal sensitivity of 2 mV/V (type HBM-U1). The gripper was attached to the force sensor. The object was attached to the test bed surface to be able to register the generated lifting force. To be sure the gripper touched the object, the initial force of the gripper of -0.08 N to the object was kept constant for every test. This pressure was set when the gripper touched the object, without air flow. The object was vertically moved downwards with a constant speed. The lifting force generated at different air flows was recorded continuously.

The maximal lifting force is the largest lifting force when the gripper is in full contact with the object. This gives an estimate of the gripper's performance to lift tissue. The measurement with each gripper was repeated four times at the same air flow.

Table 4: Four different grippers used in Experiment 'Component Selection'.

Gripper				
Membrane	up	up	under	under
Venturi	no	yes	no	yes

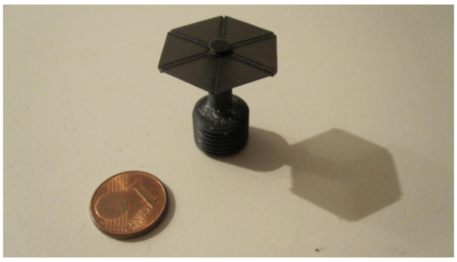
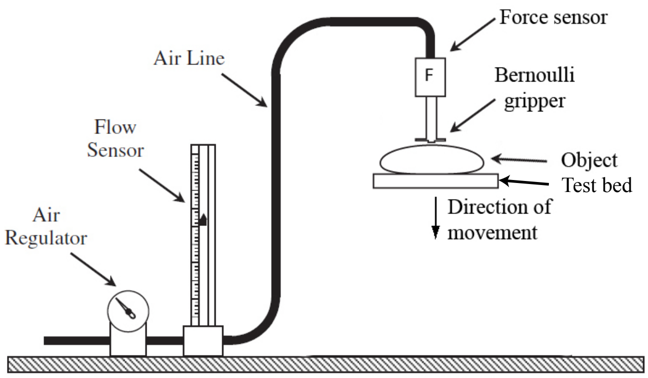


Figure 15: Bottom view of a gripper used in Experiment 'Component Selection'.



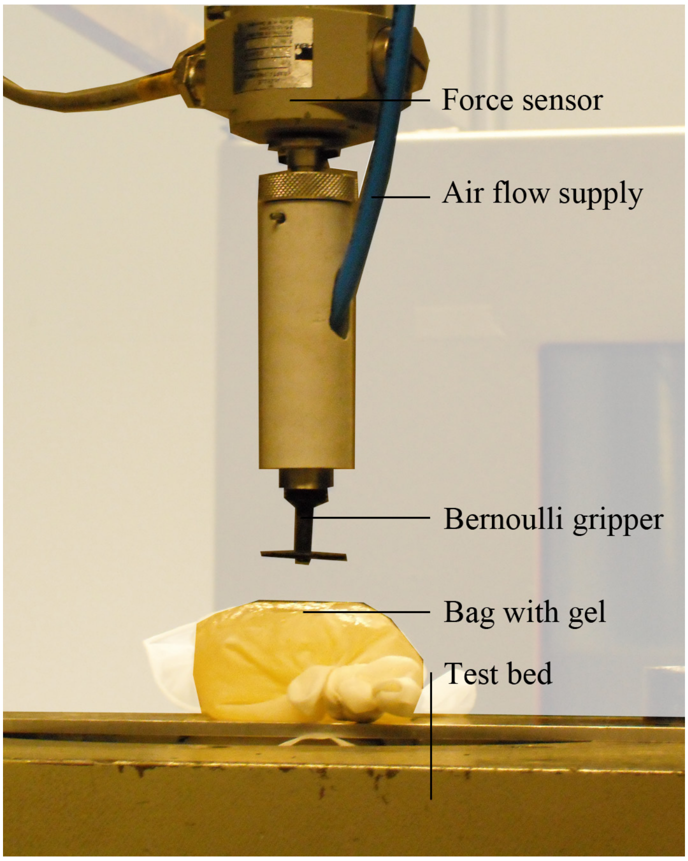


Figure 16: Experimental set-up of the Experiment 'Component Selection'.

Table 5: Air flow Q and velocity v at the nozzle in Experiment 'Component Selection'.

2 mm nozzle		**4 mm nozzle**	
Q (L/s)	***v (m/s)***	***Q (L/s)***	***v (m/s)***
0.2	64	0.8	64
0.4	128	1.6	128
0.6	191	2.4	191

6.2 RESULTS

A force-distance curve is shown in Figure 17. The lifting force increases until the maximum is reached. After reaching the maximum, the object releases partly until complete release. The experiment showed that the gripper could also grip with a part of the surface of the gripper. All maximal lifting forces were plotted in a graph and compared to the theoretical calculated forces (Figure 18).

The results vary for every velocity. At 64 m/s, the best gripper was the 2 mm gripper 'Membrane under' and the worst gripper was the 2 mm gripper 'Membrane up'. At 128 m/s, the best gripper was the 2 mm gripper 'Membrane up' and the worst gripper was the 2 mm gripper 'Venturi, membrane under'. At 191 m/s, the best gripper was the 2 mm gripper 'Membrane under' and the worst gripper was again the 2 mm gripper 'Venturi, membrane under'. From these results, it seems that the 2 mm gripper 'Membrane under' had the highest lifting forces, but it was noticed that strong vibrations occur during gripping.

It was noticed that at 64 and 128 m/s, the measured lifting force of the gripper with the 2 mm nozzle corresponded to the theoretical values, but that at 191 m/s the value was lower than the one predicted by theory. The reason for this could be that for Bernoulli's principle, the fluid should be incompressible. However, air is compressible and the limit of the flow velocity for compressible fluids is until 100 m/s (Petterson 2010). This could explain the lower lifting forces.

Theory predicted that the 4 mm nozzle would grip a higher force at the same velocity than the gripper with a 2 mm gripper. In this experiment, however, the 2 mm and 4 mm grippers had a comparable lifting force at the same velocity.

The oiled bag with gel was heavily damaged at an air flow velocity of 128 m/s when using the gripper with a 4 mm nozzle. This was probably due to the strong vibrations caused by the high air flow. This indicates that a velocity of 128 m/s is the upper limit for gripping for this experiment with a 4 mm nozzle. The lifting force at 191 m/s was not measured.

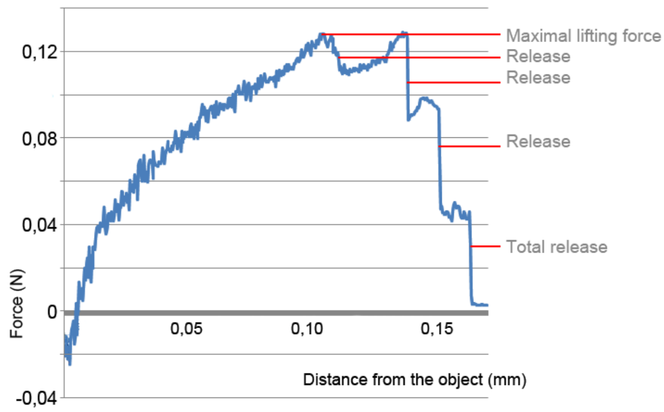


Figure 17: Experiment 'Component Selection': test result of a gripper with 2 mm nozzle and an air flow velocity of 128 m/s.

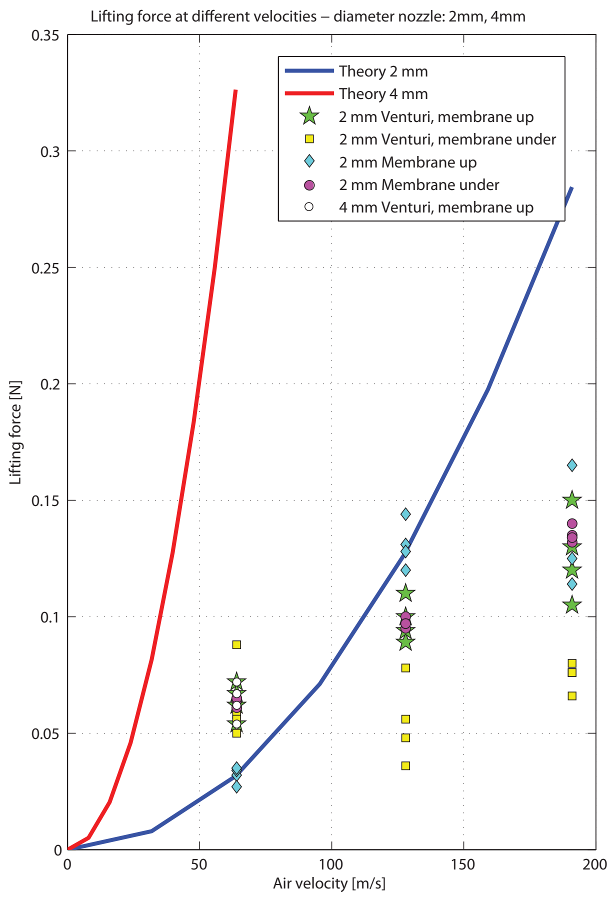


Figure 18: Experiment 'Component Selection': maximal lifting forces with 2 mm and 4 mm nozzles when gripping a flexible object. (Variables used for theory: R_c=0.001 and R_c=0.002, ρ=1.2, h=0.0005, R=0.0125.)

6.3 CONCLUSIONS & DISCUSSION

The aim of Experiment 'Component Selection' was to acquire knowledge about the effect of Venturi channels and the location of the membrane on the lifting force. The hypothesis that the Venturi channels have a positive effect on the lifting force is not confirmed by the experiment. At all velocities the lifting force of the gripper with Venturi channels was almost identical to the gripper without Venturi channels. This could be because the width of the Venturi channels was only 0.5 mm at this scale, therefore having a negligible effect. The expectation that the placement of the membrane at the bottom of the ribs has higher lifting forces than on the top of the ribs is not seen in the data. At all velocities the lifting force of the gripper with the 'membrane up' was almost identical to the gripper with the 'membrane under'. However, it was noticed that the gripper with a membrane under the ribs produced noisy vibrations during gripping, whereas the gripper with a membrane on top of the ribs did not. Vibrations can cause damage, like seen in the exploring test and Experiment 'Component Selection' at 128 m/s with a 4 mm gripper.

It is found that velocities above 128 m/s could damage the tissue. Another reason to use velocities below 128 m/s is because of the loud noise during gripping, especially at high air flows. A whistling sound was produced by the gripper for velocities of 128 m/s and higher. This was caused by the transition from laminar to turbulent flow and by the vibrations of the membrane and the surface of the object.

The experimental conditions did not match the assumptions of the theory. This could explain the difference between the theory and the results. Another explanation of the low forces could be the large spacers of the deflector. The size of the spacers was kept the same for both nozzles to keep the variation in shape as small as possible, because the only variable is the air flow. Therefore, the inflow surface (in blue, Figure 19) was compared to the outflow surface (in pink, Figure 19) for both nozzle sizes. Calculations show that the outflow surface is two times smaller than the inflow surface for the 4 mm nozzle. That could result in a velocity two times the velocity as calculated in the 4 mm nozzle. This could explain the damage of the object. Both surfaces of the gripper with the 2 mm nozzle were calculated as well, but these surfaces were of similar size.

In the results was found that the 2 mm gripper 'Membrane under' had the highest lifting forces, but due to strong vibrations this gripper was not selected for further development. The gripper with the membrane on the top of the ribs and without Venturi channels was chosen for further development, because effect of the channels was negligible and less vibrations were noticed, while still having a high lifting force.

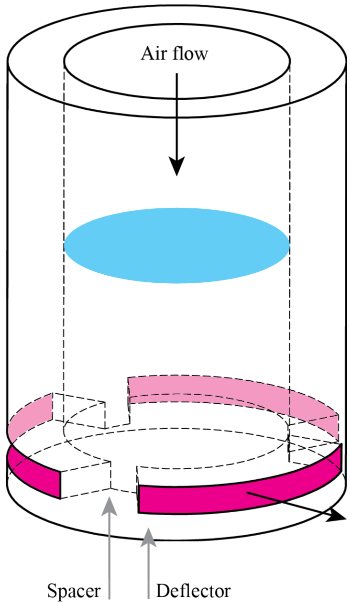


Figure 19: Detail of the nozzle of a model, where the blue surface is the inflow surface and the pink surface is the outflow surface.

7 COMPONENT DIMENSIONING

The components were selected in the previous experiment, but low lifting forces are measured for the 4 mm nozzle. The aim of Experiment 'Component Dimensioning' was to find an explanation for the low lifting force of the gripper with the 4 mm nozzle by changing the dimension of components. Two factors were identified that could influence the performance. The first factor was the dimension of the spacers of the deflector. As described before, the outflow surface above the deflector was decreased, which could result in an increase of speed. The second factor was the dimension of the gripper face. This radius was first chosen to be comparable to other gripper instruments. However, enlarging the surface could help stabilizing the air flow after the nozzle and would increase the lifting force according to the theory.

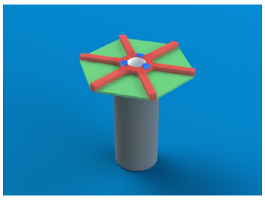
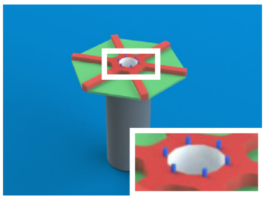
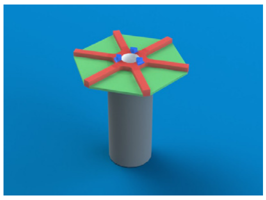
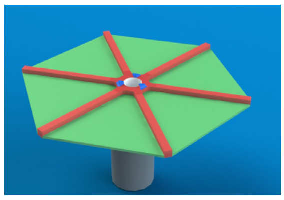
7.1 MATERIALS & METHODS

The chosen gripper with the membrane on the top of the ribs and without Venturi channels and a 4 mm nozzle was used as reference gripper. The lifting forces of three new models were compared with the reference gripper.

1. '**Smaller Spacers':** increasing of the outlet surface can be done by replacing the three large spacers by six smaller spacers.
2. '**Higher Deflector':** another way of increasing the outlet surface is to heighten the spacers from 0.5 mm to 1 mm.
3. '**Larger Gripper Face':** the radius of the gripper face was doubled from 1.25 cm to 2.5 cm.

All four models were 3D-printed. In Table 6 all models that were used are shown. Experiments were done on a solid material to decrease the discrepancy between the experimental conditions and the assumptions

Table 6: Four different grippers used in Experiment 'Component Dimensioning'. Deflectors are not shown.

Name model	Reference	Smaller Spacers	Higher Deflector	Larger Gripper Face
Gripper ***(deflector is removed to see the spacers, but present in the models)***				
Radius gripper face	1.25 cm	1.25 cm	1.25 cm	2.5 cm
Deflector	0.5 mm high	0.5 mm high	1 mm high	0.5 mm high
Spacers	3	6 small	3	3

of the theory. A plate of glass was used. The rest of the set-up was similar to Experiment 'Component Selection'. The model 'Smaller Spacers' is expected to work best, because this model approaches the theory best.

The height between the membrane and the object was different, now that the object is solid. The maximal lifting force with the solid object was reached at measured distance above the object. This extra height and the height from the ribs were added to the height of the deflector, resulting in the total height used for theory.

7.2 RESULTS

The results of the experiment are shown in Figure 20. The theory is also plotted to compare with the results. Increasing the surface of the outlet at the deflector did not have a positive effect on the lifting force. The models 'Smaller Spacers' and 'Higher Deflector' performed worse than the reference gripper. The model 'Larger Gripping Face' had the highest lifting forces. Likewise, the lifting force strongly increases with the air flow. The values between 0 and 64 m/s were not measured, because of the fear for inaccuracies in the measurement set-up when measuring lifting forces below 0.1 N.

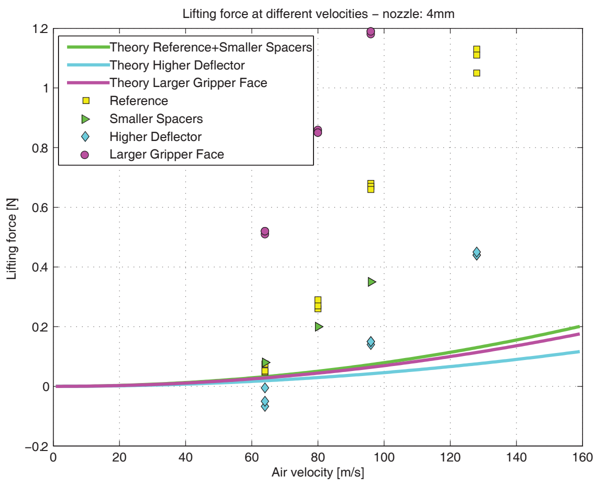


Figure 20: Experiment 'Component Dimensioning': maximal lifting forces of the four different models when gripping a rigid object. (Variables used for theory: Reference & Smaller Spacers: R_c=0.002, ρ=1.2, h=0.0016, R=0.0125, Higher Deflector: h=0.0021, Larger Gripper Face: h=0.0021, R=0.025.)

7.3 CONCLUSIONS & DISCUSSION

The aim of the experiment was to find an explanation for the low lifting force of the gripper with the 4 mm nozzle. The measured values did not agree with the theory, but were higher than expected. It can be concluded that the increase of the surface of the gripper face determines the highest lifting forces.

The discrepancy between the theory and the results of the experiment is possibly caused by viscosity of the air, which is not included in the theory of Bernoulli. To get more insight, a new equation for the Bernoulli equation was suggested (Armengol 2008) which includes a correction for viscosity:

$$F_{att,\mu} = \frac{54\rho Q^2}{140\pi h^2}\left[\ln(\frac{R}{R_c}) - \frac{1}{2}(1-(\frac{R_c}{R})^2\right] + \frac{12Q\mu}{h^3}\left[-\frac{1}{2}R_c^{\,2}\ln(\frac{R}{R_c}) - \frac{1}{4}R_c^{\,2} + \frac{1}{4}R^2\right] \qquad (5)$$

The derivation of this equation can be found in Appendix C. In Figure 21, the results according to the equation of Armengol (5) are compared to the results according to the equation of Bernoulli (3). The equation of Armengol shows a slight increase in lifting force, but still does not predict the measured values.

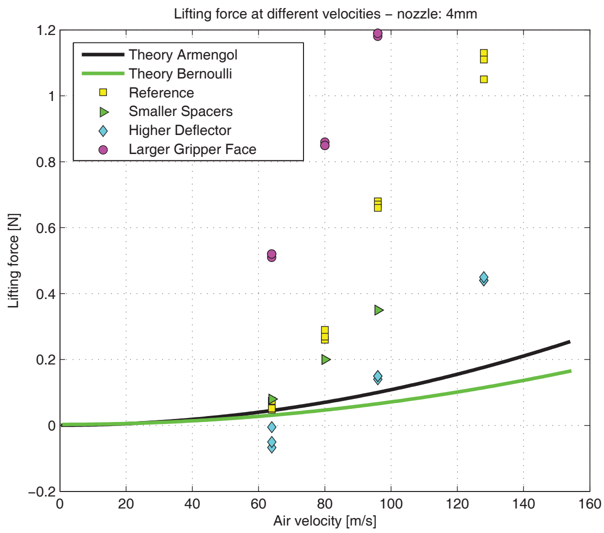


Figure 21: Experiment 'Component Dimensioning': maximal lifting forces of the four different models compared to Bernoulli's theory and Armengol's theory. *Theory Bernoulli* gives the theory of Bernoulli for a Reference gripper and *Theory Armengol* gives the theory of Armengol for a Reference gripper. (Variables used for theory: Theory Armengol & Bernoulli: R_c=0.002, ρ=1.2, h=0.0016, R=0.0125.)

An additional explanation for the unexpected high values might be found in the flexibility of the gripper surface. The surface of the gripper can be pulled closer to the object during gripping due to its elasticity and the pressure decrease. This would result in an increase of the flow velocity and thus a higher lifting force. From this experiment can be concluded that gripping solid objects gives higher lifting forces.

It can be concluded that increasing the surface of the gripper face has a larger influence on the lifting force than initially was assumed according to the theory. Further increase of the surface is expected to increase the lifting force even further. The relation between R and R_c can be plotted to search for an optimum (Figure 22). The relation between the lifting force and the ratio between R and R_c is declining growth. Unfortunately, there is no optimum in this relation. Further research could be done in future experiments.

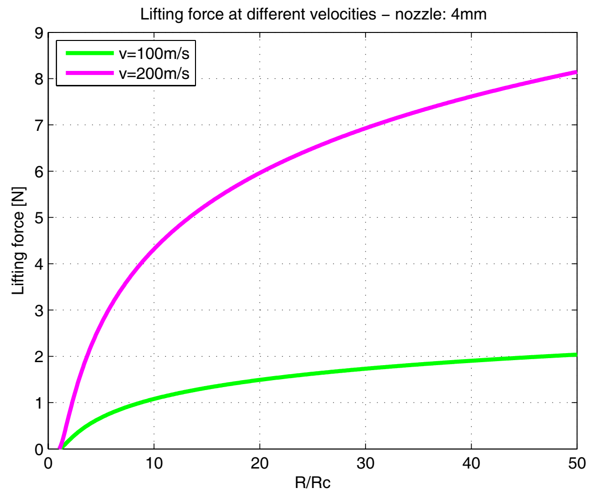


Figure 22: The ratio R/R_c plotted to the lifting force at two velocities for the model 'Reference'. (Variables used: h=0.0005, ρ=1.2.)

8 USER TEST

In the previous experiments, the object was fixated to get comparable data from the different measurements. The focus has been on the lifting force of the gripper. In this user test, some tests were done to learn more about the behaviour of the object when it is not fixated, like during surgery.

8.1 MATERIALS & METHODS

Two grippers with a gripper face radius of 1.25 cm and 2.5 cm were used, because of suitable size for the organs and highest measured lifting force. The set-up was identical to the exploring test. For the object, slices of young cheese and chicken skin were used. For details on the cheese, see Table 7.

Table 7: User test: Different sizes of the cheese with their weight.

Size (cm)	Weight (g)
1 x 1	0.22
2 x 2	0.86
3 x 3	1.89
4 x 4	3.40
5 x 5	5.50

8.2 RESULTS

All different sizes of the cheese could be gripped with both grippers. However, the gripper with the 2.5 cm gripper face needed a larger air flow than the gripper with the 5 cm gripper face to grip the same object. Gripping the chicken skin was problematic. Because the material is more flexible than the young cheese, this caused three problems:
- Many vibrations during gripping,
- The chicken skin was blown away when approaching,
- The chicken skin was gripped only around the deflector and the rest was hanging down (Figure 23, left). This caused a less stable grip.

Other things that have been noticed are: When gripping, objects in the close environment could be blown away. The smallest sizes of the cheese (1 and 2 cm) could stick to the deflector after shutting the air flow due to capillary or adhesive forces. The higher the air flow, the closer the object was to the gripper (Figure 23, middle) and a small imprint of the deflector was seen on the object after gripping (Figure 23, right). If the object was gripped and the air flow was doubled the amount at the moment of gripping, damage was brought to the object. The object did not slide of the gripper in any position. The object could also stay attached during shaking for 30 seconds.

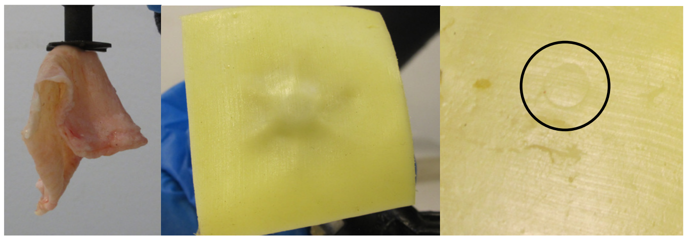


Figure 23: Left: The chicken skin is hanging down. Middle: The object is very close to the gripper at high air flow. Right: An imprint of the deflector in the cheese.

8.3 CONCLUSIONS & DISCUSSION

The aim of this experiment was to observe the effects when gripping cheese and animal tissue with different velocities. It is found that flexibility plays a bigger role than first expected. Also, a solution for the air flow outside the gripper is needed.

9 PROTOTYPE DEVELOPMENT

It was found that the lifting forces do not meet the boundary condition. There are a lot of drawbacks, but there is potential if improvements are made. Therefore, a start of the instrument design is made. The design includes the conclusions from Decision Area 1 and 2.

In the experiments, it was seen that at this scale Venturi channels had no effect. It was therefore decided not to use Venturi in the prototype. The membrane was placed on top of the ribs, because this location reduces vibrations and gives protection during insertion in a trocar. The diameter of the nozzle and the gripper face should be large to create a large lifting force. The diameter of the nozzle is limited to 4 mm due to the trocar size. The diameter of the gripper face was not specified yet, but has not influence on the design of the prototype and was therefore chosen 2.5 cm.

9.1 TIP DESIGN

Figure 24 shows the exploded view of the prototype. For all experiments, simplified models were used. Now, a prototype was produced to test the working principle of the instrument with a focus on the tip design. The tip design includes the gripping part of the instrument.

The prototype needs to be connected to the air flow and the threaded part of the middle tube ensures this connection. The air flows through the hole in the middle tube. At the end of the middle tube, the inner tube is fixated. The inner tube contains the deflector to change the direction of the air flow. The deflector has three spacers. To expand and collapse the ribs, the ribs need to be pushed down. The outer tube is designed to push the ribs down with easy grip for two fingers. The outer tube slides over the cylindrical part of the middle tube and can be fixated in the expanded and collapsed position by a ball-spring-system. The living hinge is made of film material and fixated to the outer tube and between the middle and inner tube. The cylindrical part of the middle tube has two slots in which pins of the outer tube slide to prevent rotation of the living hinge material. The ribs are glued to the living hinge for reinforcement. Because the ribs are angular, the middle tube and the inner tube have a hexagonal part which supports the ribs in their position. The highest part of the bottom rib is angled to stimulate expanding. The top rib has the same angle at the lowest part. The highest part of the top rib has an angle of 45° which suits with the angle of the lowest part of the outer tube. The membrane is placed on the bottom of the ribs, because of production limitations.

It was found that it is not possible to print a living hinge with the materials used in the 3D-print machine of the available printers. The material broke after one time use. After comparing diverse hinge systems, it was decided to make custom-made living hinges from a film material. For all technical drawings, see Appendix F.

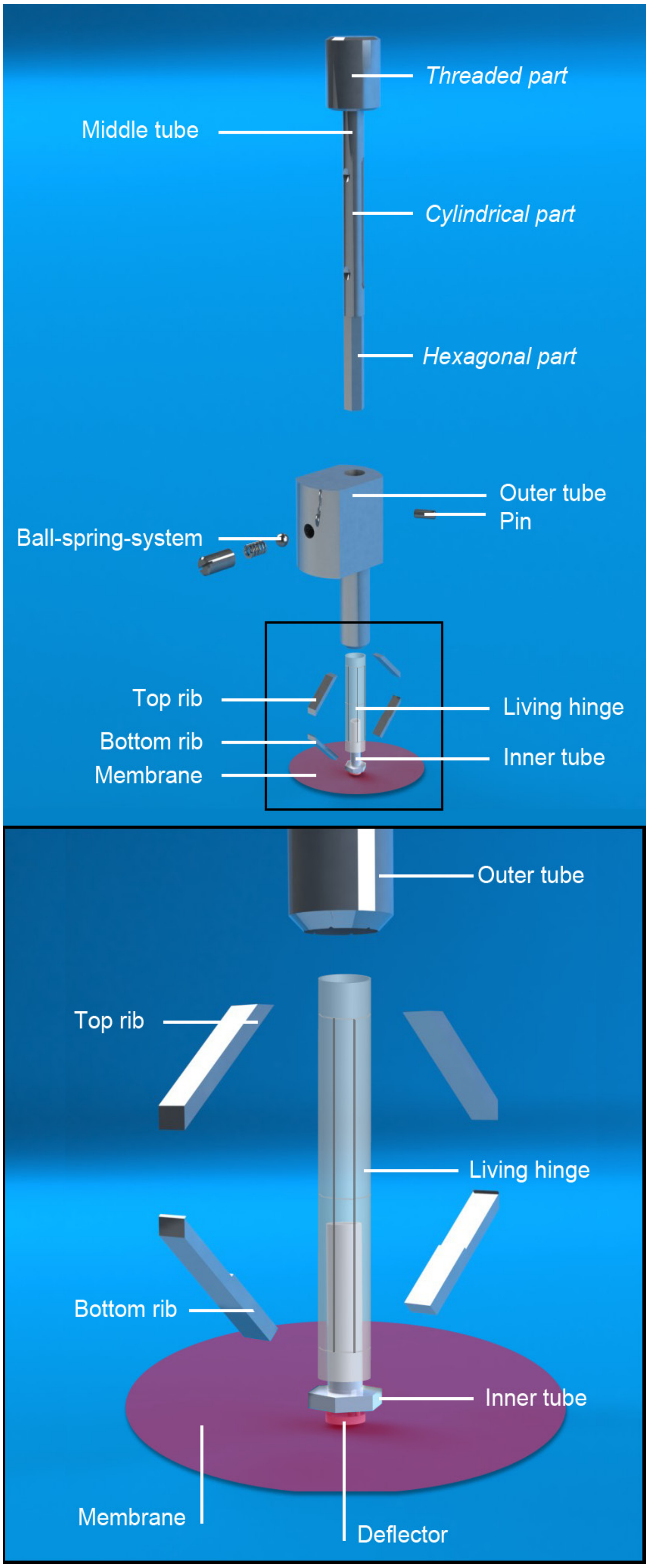


Figure 24: Exploded view of the prototype with a detail of the tip design.

The living hinge material is selected on crack compatibility and ductility. The prototype is made of aluminium. A milling cutter and a lathe are used for production. The inner tube was made by wire erosion, because it is suitable for small sizes.

The prototype is shown in Figure 25. Due to production limitations, it was not possible to use the prototype for experiments. Assembling the instrument by hand caused irregularities in the membrane. If the membrane is irregular, no pressure difference can be build up and there is no lifting force. Additionally, collapsing was not fully possible due to size imperfections.

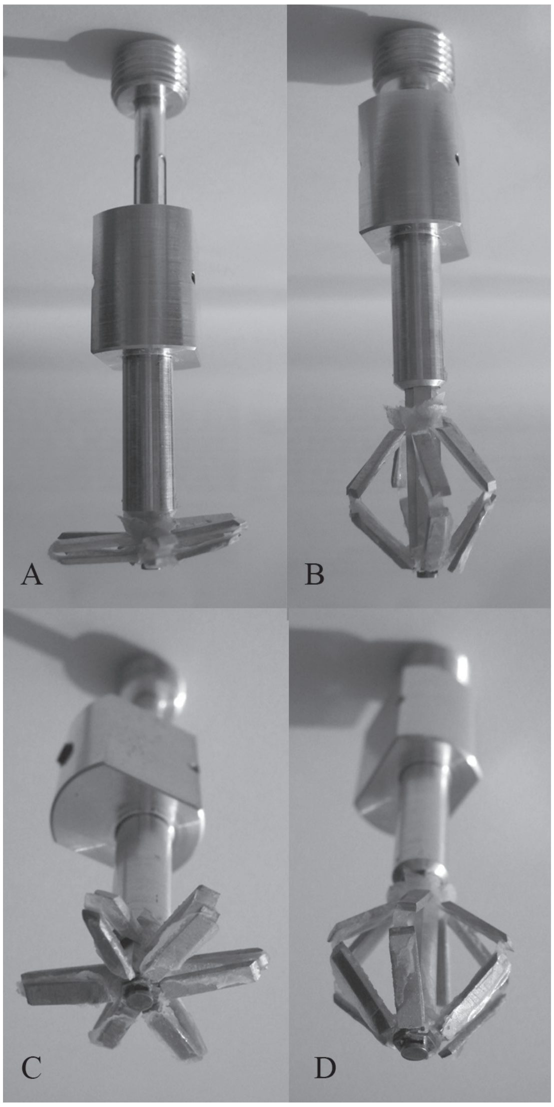


Figure 25: Different views of the prototype without a membrane. **A:** The side view of the prototype expanded. **B:** The side view of the prototype collapsed. **C:** The top view of the prototype expanded. **D:** The top view of the prototype collapsed.

9.2 HANDGRIP DESIGN

The production changes when moving from a single prototype to mass production. Some details about possible mass production are discussed. A suggestion for a disposable handgrip of the Bernoulli gripper is proposed in Figure 26. A section view is shown in Figure 27. The handgrip integrates the following functions: air flow regulation, in and outlet of the air flow, expand and collapse of the gripper and fixation of the outer and inner tube. The surgeon can expand and collapse the gripper by moving the sliding system with his thumb. The sliding system is connected to the conducting tube. This tube defines the movement of the sliding system. The outer tube is clicked in the sliding system. This construction is fixated by the insertion of the inner tube, which will be glued in the handgrip. This keeps the whole firmly together, but makes movement of the outer tube over the inner tube possible. The inner tube is connected to the air inflow. The amount of air flowing in and out the handgrip is regulated with valves. The position of the trigger defines the position of the air valve. These will eliminate the pressure excess caused by the air inflow of the Bernoulli gripper. These valves can be regulated by the surgeon with the trigger. When pulling the trigger, a gear rack changes the position of the valve. The in- and outlet of the air flow enters and leaves the handgrip respectively by two separate tubes. These lead to the air regulator. This regulator reduces the pressure from the air source and can add extra moisture to reduce the dehydration of tissue when needed.

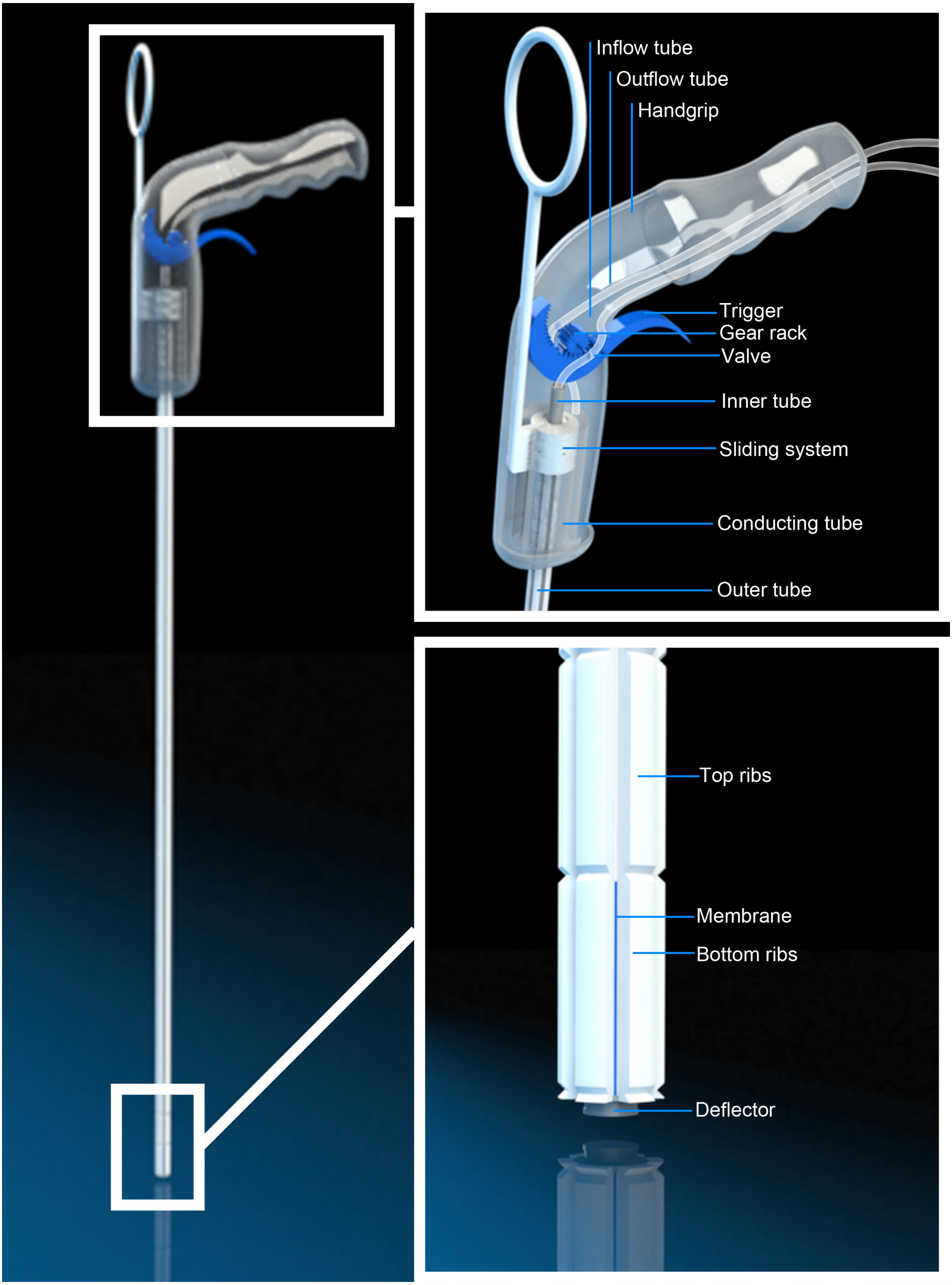


Figure 26: Detail of the handgrip design.

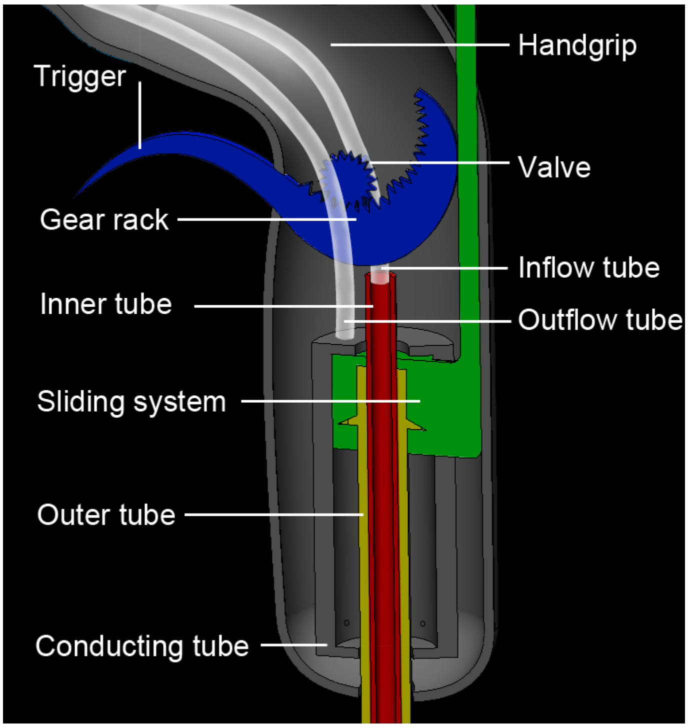


Figure 27: Section view of the handgrip.

A suggestion for a disposable living hinge can be found in Appendix G. Some detail about the membrane and the inner tube are suggested here. Flexible material will be used for the membrane, because this uses less space. Because elastomers are difficult to re-use in the medical world, the membrane will be disposable. The membrane can be molded together with the ribs with the help of 2-component injection molding.

The inner tube is a long thin-walled tube which guides the outer tube at the outside and the air flow at the inside. The inner tube could be made of plastic or metal. The metal would be more expensive to produce, but have advantages for the stiffness of the instrument. A plastic inner tube would be cheap, so easy disposable. Because the inner tube is thin-walled, there is chosen for stiff metal. The main tube can be extruded. The upper and lower part have to be welded to the main tube. Both parts can be shaped using a stamping, when using a die to get it in the right shape.

10 DISCUSSION

The goal of this research was to explore the possibility of Bernoulli gripping in minimally invasive surgery. In the morphological analysis in Appendix D, diverse subproblems were identified. Two of those subproblems were chosen as the main decision areas and have been solved during this research. These were:

- *How to change the direction of the strong air flow?*
- *How to make a expandable/collapsible system?*

It was found that a deflector can change the direction of the air flow. A system consisting of ribs with living hinges was selected for the expandable system. Lifting forces were measured during experiments and the production of a prototype and an instrument was suggested. The product interaction and usage are shown in Appendix H.

Two other subproblems are discussed here, namely 'prevention of sliding' and 'elimination of pressure excess'. Two other important subproblems that arise during the research will also be discussed. These are 'dehydration' and 'prevention of damage'.

The subproblem 'Prevent from blowing away' is discussed in Appendix C, Section C.7. The last subproblem is how to 'generate a large force' and more details about this will be given in Section 12.

How to prevent dehydration of the tissue?
In Experiment 'Component Dimensioning', it was noticed that the rapid air flow of the Bernoulli gripper dehydrates the upper surface of the object. This mainly occurred when blowing for prolonged time and when using high air flows. Research at dehydration has been done by Davis (2008) for slices of cucumber and tomato. The drying effect is measured by weighting the mass loss of the slices (Davis 2008). The result is shown in Table 8. For Davis (2008), the removal of moisture was an advantage, because wet cucumber and tomato slices would make the bread for the sandwich soggy. For a medical gripper, the dehydration is a disadvantage and it is advised to include a moisturizer in the air supplier for the instrument to avoid dehydration.
The moisturizing of air will result in an increase the density when looking at Bernoulli's principle. The effect of this increase can be described by the Bernoulli's principle. If the velocity outside the gripper is assumed to be zero (see also Appendix C, Section C.1), Bernoulli' principle can also be written as

$$P_{inside} = P_{outside} - \frac{1}{2}\rho v_{inside}{}^{2} \tag{5}$$

where P_{inside} is the pressure inside the gripper, $P_{outside}$ is the pressure outside the gripper and ρ is the density and v_{inside} is the velocity inside the gripper. Increasing the density can work out in two ways, either the pressure inside the gripper drops extra low or the velocity can be decreased. Both options seem to be advantageous for gripping tissue. Future research should be done with different values of the density.

Table 8: Percentage loss of mass (Davis 2008).

Handling Time (s)	% Loss of Mass
1	0.98
2	1.31
5	2.50

How to prevent damage to the tissue?
Damage can be caused by excessive vibrations of the surface of the object against the gripper. In the experiments, it was found that the higher air flow, the higher the vibrations. To prevent this damage, the air flow should be kept as low as possible. To find out for which values of the air flow the object is damaged, a new experiment should be set up.

How to ensure that the sliding object stays in place?
In a Bernoulli gripper, the object can slide parallel to the gripper face if there is no restriction. There are several solutions proposed to prevent this side effect. Davis (2008) suggested a gripper equipped with a barred restraining wall (Figure 28). In the final design of the gripper, the sliding is prevented by the friction of the deflector that works on the object. The deflector has the disadvantage of touching the tissue, but the advantage of keeping the object in place during gripping.

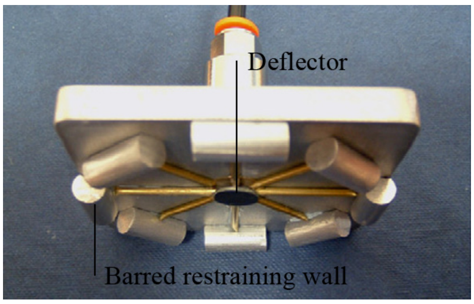


Figure 28: The Bernoulli gripper of Davis (2008) with a barred restraining wall to prevent the object from sliding. The figure is adapted from Davis (2008).

How to eliminate the pressure excess in the abdomen of the patient?
In minimally invasive surgery, the abdomen is inflated with carbon dioxide to create a working space for the surgeon (Figure 1, left). Therefore, carbon dioxide will be used for the Bernoulli gripper. This carbon dioxide flow enters the abdomen in high quantities when gripping. This constant air flow will create a pressure excess in the abdomen, which has to be prevented to guarantee the patient safety. In the current design, the outer tube has small outflow channels integrated which are auto controlled in a way that the amount of air leaving the

body is identical to the amount of air entering the body. If there is a difference found in the air controller between the inflow and the outflow, the flow should be stopped automatically. This prevents high pressure in the abdomen of the patient. A double check that could be done during gripping is checking the values of the patient's cardiopulmonary function, because increase of the pressure will immediately result in changing values. Another way of solving the pressure excess is by using a pressure valve. This valve reliefs air from the abdomen if the pressure exceeds a set value. To prevent the whole problem of the pressure excess, the instrument could be used for open surgery.

11 CONCLUSIONS

In this research, the goal was to explore the possibility of applying Bernoulli gripping for tissue manipulation during minimally invasive surgery. Three important factors have been evaluated and resulted in the following conclusions:

Forces
The instrument is able to grip flexible objects, but measured forces are too low to meet the boundary conditions. The instrument can not handle forces until 5 N in the measured sizes without going in the supersonic area. Forces up till 1 N are measured. More research should be done to understand and increase the forces when using a low velocity.

Damage
The gripper is not completely contactless, but it has minimal contact with the tissue due to the deflector, which is to prevent the tissue from damage due to the air flow. However, the rapid air flow over the surface of the object causes dehydration and vibrations. To prevent this, a moisturized low air flow is suggested. Another risk is the large inflow of air in the patient. If the outflow system would fail, the pressure in the abdomen would increase fast. Therefore, it would be better to use the Bernoulli gripper for open surgery.

Size
It is feasible that the instrument can be introduced and removed through a trocar with a diameter of 5 mm. A suitable and proven working principle is found to introduce the instrument in the trocar.

Despite the limitations of the gripper, it still seems an interesting opportunity to the medical world and it is advised that the gripper is best suited for objects below 1 N.

12 RECOMMENDATIONS

A series of recommendations is made concerning the improvement of the design of the gripper, its cost estimation, and general recommendations for further research.

Small force
The largest limitation of the current design is the small amount of force the gripper provides. The relation between air flow and force is exponential, but restricted by the supersonic area and vibrations. The smaller the nozzle, the earlier the supersonic region is reached. The small force limits the interventions where the instrument can be used for. Different solutions to increase the lifting force can be proposed. These include different variants in shape of the gripper, because small adaptations in shape can have large consequences like seen in the exploring test. To understand what is happening during gripping, simulations of the shape variables should be made. The calculations made in this research are for a basic Bernoulli gripper and do not include all variables. In the model, specific shape variables could be varied to find the optimal values.

When increasing the surface of the gripper face, the lifting force increased strongly. Multiple grippers can also be used to increase the lifting force. However, this does not meet the demands of minimally invasive surgery, because multiple incisions have to be made as well.

Another solution for the small forces produced could be the development of a three dimensional Bernoulli gripper for tissue. Most organs are not planar shaped and this results in a too wide gap for gripping, because the surface quickly curves away from the gripper face (Pettersson 2010). Pettersson (2010) developed a 3D Bernoulli gripper based on a matrix pin board to increase the lifting capabilities of non-planar objects (Figure 29). An increase of 65% in lifting force was achieved when using a three dimensional gripper instead of a two dimensional gripper. This concept could be very useful for gripping tissue in the medical field, but the system is too complex to be used in minimally invasive surgery. However, for other applications in the medical field, this could solve the low lifting forces of the gripper.

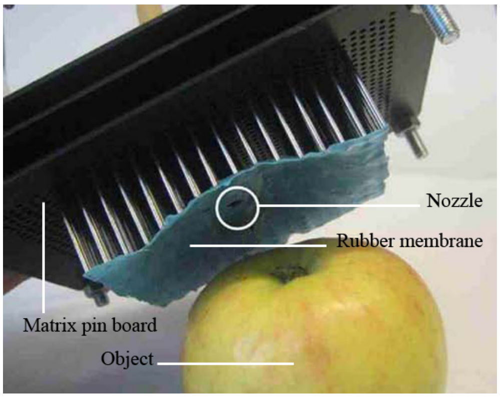


Figure 29: A three dimensional Bernoulli gripper. The figure is adapted from Pettersson (2010).

Other
Further research could be performed to the effect on the underlying tissue layers when gripping tissue from above. It is also advised to examine the tissue damage with microscopic studies, endurance tests and with in vivo tests.

Also a combination of gripping methods could be suggested. For example, when combining Bernoulli with suction (Binder 2003) or with shape gripping (Sam 2010), this could lead to interesting possibilities. Further research should be done to the specific shape of the spacers, the height of the deflector and the elasticity of the membrane.

Another point of improvement is that if the tissue is not located perpendicular to the direction of the shaft of the instrument, it is more difficult to grip it. Due to the negative pressure caused by Bernoulli, it will bend to the optimal position for gripping, but if the angle is too large this becomes difficult. A next step could be to make the instrument steerable, so that a piece of tissue is always approached in a good angle.

A rough estimation can be made of the price (Appendix I). The purchasing price estimated for the disposable Bernoulli gripper is € 34.39. A comparable instrument is a re-usable gripper of Karl Storz, which has a purchasing price of € 645.82 and is used approximately 20 times. The prices of the re-usable gripper and the disposable Bernoulli gripper are corresponding.

In laparoscopy, the forces are limited because of the limited size and air flow. Due to these limitations, the application of a Bernoulli gripper in minimally invasive surgery is not the best choice, but it is recommended to search for other suitable applications in the medical field (Appendix B).

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A INDUSTRIAL APPLICATIONS OF A BERNOULLI GRIPPER

Not many articles have been found on Bernoulli grippers. Therefore, the complete field of patents on Bernoulli gripper has been studied. In total, 86 patents in class 294/64.300 of Free Patents Online (freepatentsonline.com) have been found. Of those 86 patents, 58 were selected fitting the criteria of a Bernoulli gripper. These three patents are described, because they are relevant for the design.

Patent (Tosimi 1988)

Figure 1 shows a gripper for plates using the Bernoulli principle. A suction pipe is built around the gripped plate to inhale and re-circulate the fluid delivered by the gripper. The goal is to prevent the introduction of dust.

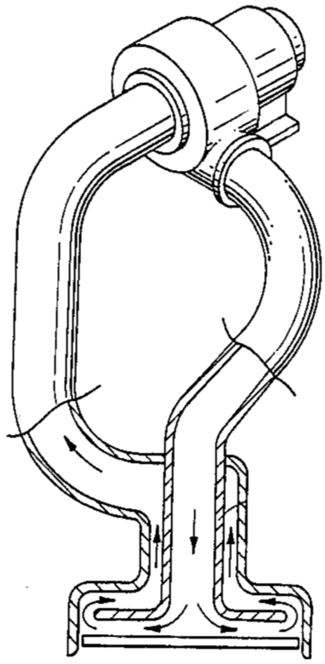


Figure 1: Bernoulli gripper with suction function. The figure is adapted from Tosimi (1988).

Interesting is that the edges of the suction tube also can be used as preventers for sliding. The air can be recycled and no extern air flow is needed and the effect on the environment is kept minimal when removing the air.

Patent (Carlomagno 1990)

Different nozzles for grasping hot glass plates are suggested (Figure 2). It cannot be concluded from the patent which is best, but this is interesting to use for different solutions to the problem of tissue grasping.

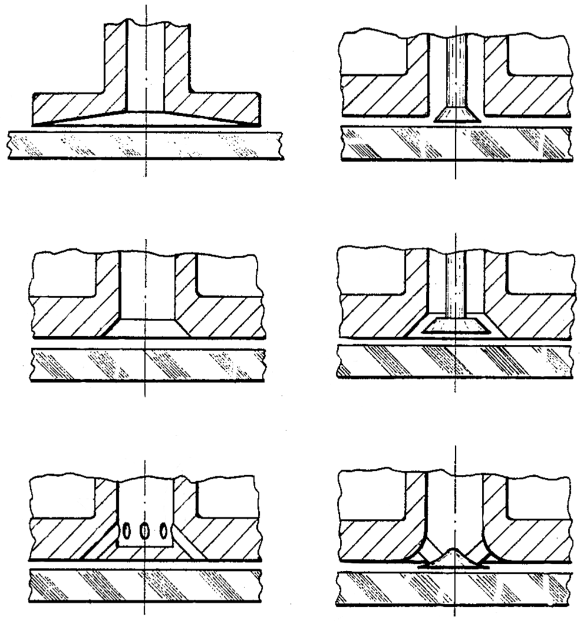


Figure 2: Different Bernoulli gripper nozzles. The figure is adapted from Carlomagno (1990).

Patent (Okugi 2002)

The gripper in Figure 3 uses the Bernoulli principle in an outstanding shape. With the application in mind, an expandable system is likely. The design of this patent has similarities with an umbrella, which has a good expanding function. The design could be used in the idea phase.

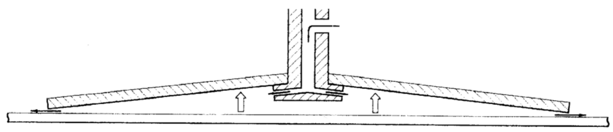


Figure 3: Bernoulli gripper with umbrella shape. The figure is adapted from Okugi (2002).

B MEDICAL APPLICATIONS OF A BERNOULLI GRIPPER

Bowel manipulation
The manipulation of the bowel is risky during minimally invasive surgery. This is because the tissue is vulnerable. Only 2% of the colon resections are done by minimally invasive surgery in 2001 (Dankelman 2009). One of the reasons is the lack of safe instruments. The force needed has an average of 2.5 N and a maximum of 5 N (Dankelman 2009).

To hold an organ away
During surgery, organs get often in the field where the surgeon wants to work. An assistant keeps these organs away with the help of a gripper or by pushing with a stick. I have been talking to different doctors, who wanted something to keep the organs fixed at a safe distance from the working area. A double Bernoulli gripper could be used to achieve this (Figure 4). In the example, a bowel is hung up against the abdomen.

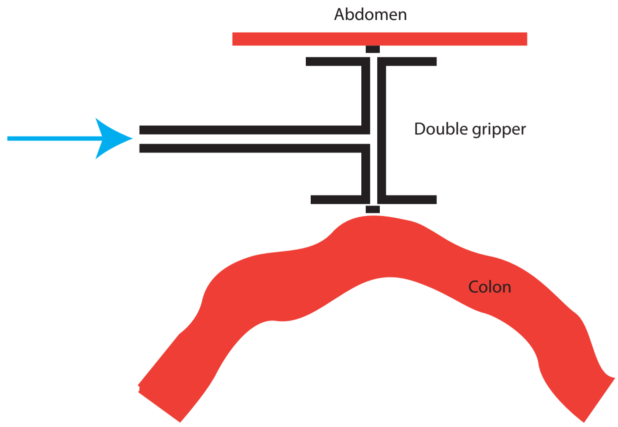


Figure 4: Gripping the colon with a double Bernoulli gripper.

Eye surgery
In the field of eye surgery, a lot of extremely delicate tissues are handled. Like described before, the principle could be used for transplantation of these delicate tissues. The instrument should be developed extremely small, but a first step is to make a macro-variant.

In the uterus
Grasping of a fetus and maneuvering in a certain position would be a solution to different treatments of fetuses. This could be used because the fetus is in the way or surgery should be done to the fetus. The fetus weights about 400 g around 22 weeks of pregnancy and floats in amniotic.

Potential other applications are gripping artificial tissue, inflamed tissue, grafts in plastic surgery, neurosurgery or forensic medicine. In forensic medicine, evidence is very important, so contactless grasping would be ideal. The focus for this master thesis will be on minimally invasive surgery.

C PRINCIPLE OF BERNOULLI

In 1738, Daniel Bernoulli published the book ‘Hydrodynamics’. Only in 1828, Willis first described the use of the principle for a gripper. The principle will be explained using Figure 5 and the variables shown below.

A	area of the total gripper (m^2)
A_{in}	area of the central channel (m^2)
g	gravitational acceleration (m/s^2)
h	height (m)
L	nozzle diameter (m)
ΔP	pressure difference (N/m^2)
P_{inside}	pressure inside the nozzle (N/m^2)
$P_{outside}$	pressure outside the gripper (N/m^2)
P_r	pressure at variable radius r (N/m^2)
P_R	pressure at radius R (N/m^2)
Q	volume flow rate (m^3/s)
r	variable radius (m)
R	radius of the gripper surface (m)
R_c	radius of the nozzle (m)
v_{in}	velocity in central channel (m/s)
$v_{outside}$	velocity outside the gripper (m/s)
v_{inside}	velocity between part and gripper (m/s)
v_r	velocity at variable radius r (m/s)
v_R	velocity at radius R (m/s)
z	elevation (m)
ρ	density (kg/m^3)
μ	viscosity (kg/s*m)

C.1 BASICS

The object is assumed to be flat and rigid. Other assumptions (Davis 2008) for the Bernoulli’s principle are:
1. fluid is incompressible; for air, which is compressible, the limit of the flow velocity is until 100 m/s (Petterson 2010).
2. fluid is non-viscous; for viscous fluids, see Section C.3 for a equation which includes viscosity (Armengol 2008).
3. fluid flow is laminar; in case of the Bernoulli gripper the Reynolds number has to be smaller than 1000, see Section C.4 for more information.

The principle of Bernoulli is based on the law of conservation of energy, according to which, the pressure decreases when the velocity increases in the region between the object and the gripper face. The Bernoulli’s principle is given by

$$(\frac{1}{2}\rho v^2 + \rho g z + P)_{inside} = (\frac{1}{2}\rho v^2 + \rho g z + P)_{outside} \quad (1)$$

The term ρgz is in the range of a few centimeters so can safely be ignored (Waltham 2003). The pressure difference is the difference between the pressure outside and inside. The standard condition for the outside pressure is 1.0 atmosphere.

$$\Delta P = P_{outside} - P_{inside} \quad (2)$$

The velocity on the streamline far outside the gripper is assumed as 0 m/s.

$$v_{outside} = 0 \quad (3)$$

The amount of fluid going in the central channel is similar to the amount of fluid leaving the gripper due to the conservation of mass. In this way, the v_{inside} can be determined.

$$v_{inside} r 2\pi h = v_{in} A_{in} \quad (4)$$

Combining (1) and (4) results in

$$P_{inside} = P_{outside} - \frac{1}{2}\rho(\frac{v_{in} A_{in}}{r 2\pi h}) \quad (5)$$

Together with conservation of mass, this problem can be solved. The pressure difference is high for a radius close to the central channel and becomes smaller towards the end of the gripper. With the correct values of the variables, inside pressures less than 1.0 atmosphere are obtained and hence an attraction force is generated.

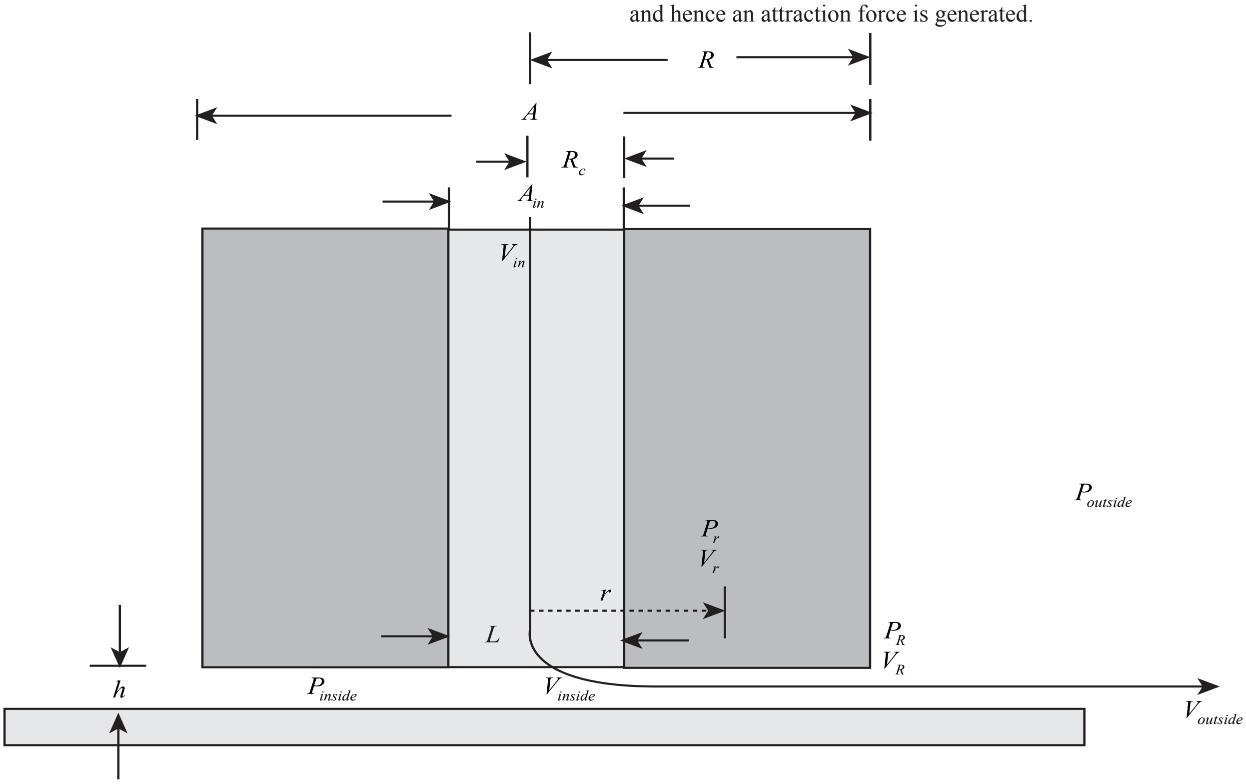


Figure 5: All variables in a schematic overview.

C.2 FORCES

When calculating forces working on the object, the equations are somewhat more difficult. The total lifting force on the object is the residue of the rejecting force and the attracting force of the system

$$F_{tot} = F_{attract} - F_{reject} \tag{6}$$

The attracting force is generated by the pressure difference created between the object and the gripper and dependent of the surface of the gripper.

$$F_{attract} = \Delta PA = \int (P_r - P_R) 2\pi r dr \tag{7}$$

The equation of the pressure difference can be derived from Bernoulli's principle as follows.

$$P_r + \frac{1}{2}\rho v_r^{\,2} = P_{outside} + \frac{1}{2}\rho v_R^{\,2} \tag{8}$$

$$(P_r - P_{outside}) = \frac{1}{2}\rho(v_r^{\,2} - v_R^{\,2}) \tag{9}$$

In this case P_R is assumed equal to $P_{outside}$. The v_r can be rewritten when using the rule of conservation of mass

$$Q = v_r 2\pi r h \tag{10}$$

$$v_r^{\,2} = \frac{Q^2}{4\pi^2 h^2}\frac{1}{r^2} \tag{11}$$

When implementing (11) in (9), the pressure difference is as follows

$$(P_r - P_{outside}) = \frac{\frac{1}{2}\rho Q^2}{4\pi^2 h^2}\left[\frac{1}{r^2} - \frac{1}{R^2}\right] \tag{12}$$

This can be integrated over the surface to calculate the $F_{attract}$

$$F_{attract} = \frac{\frac{1}{2}\rho Q^2}{4\pi^2 h^2} 2\pi \int_{R_c}^{R} r\left(\frac{1}{r^2} - \frac{1}{R^2}\right) dr \tag{13}$$

which can be simplified to the final equation of $F_{attract}$

$$= \frac{\rho Q^2}{4\pi h^2}\int_{R_c}^{R}\left[\frac{1}{r} - \frac{r}{R^2}\right] dr = \frac{\rho Q^2}{4\pi h^2}\left[\ln(r) - \frac{\frac{1}{2}r^2}{R^2}\right]_{R_c}^{R} \tag{14}$$

$$F_{attract} = \frac{\rho Q^2}{4\pi h^2}\left[\ln\left(\frac{R}{R_c}\right) - \frac{1}{2}\left(1 - \left(\frac{R_c}{R}\right)^2\right)\right] \tag{15}$$

Bernoulli's principle calculates this attracting force. Additionally, the compressed air flow from the nozzle also causes a rejecting force that pushes the object away from the gripper. This force depends also on the pressure difference and the surface. When combining this with the dynamic pressure, the rejecting force can be written as

$$F_{reject} = \rho v_{in}^{\,2} A_{in} \tag{16}$$

This can also be written as

$$v_{in} = \frac{Q}{A_{in}} \tag{17}$$

$$F_{reject} = \rho \frac{Q^2}{\pi R_c^{\,2}} \tag{18}$$

C.3 VISCOSITY

If viscosity starts to play a role, the following equation proposed by Armengol (2008) can be used

$$(P_r - P_R) = \frac{27\rho Q^2}{140\pi^2 h^2}\left[\frac{1}{r^2} - \frac{1}{R^2}\right] + \frac{6Q\mu}{\pi h^3}\ln\left(\frac{R}{r}\right) \tag{19}$$

Again, P_R is assumed equal to $P_{outside}$. This can be integrated over the surface to calculate the $F_{attract}$

$$F_{att,\mu} = \frac{27\rho Q^2}{140\pi^2 h^2} 2\pi \int_{R_c}^{R} r\left[\frac{1}{r^2} - \frac{1}{R^2}\right] dr + \frac{6Q\mu}{\pi h^3} 2\pi \int_{R_c}^{R} r \ln\left(\frac{R}{r}\right) dr \tag{20}$$

which can be simplified to the final equation of $F_{attract}$

$$F_{att,\mu} = \frac{54\rho Q^2}{140\pi h^2}\left[\ln\left(\frac{R}{R_c}\right) - \frac{1}{2}\left(1 - \left(\frac{R_c}{R}\right)^2\right)\right] + \frac{12Q\mu}{h^3}\left[-\frac{1}{2}R_c^{\,2}\ln\left(\frac{R}{R_c}\right) - \frac{1}{4}R_c^{\,2} + \frac{1}{4}R^2\right] \tag{21}$$

C.4 REYNOLDS

An assumption of Bernoulli is that the fluid flow is laminar. This means that there is no disruption in the flow and the Reynolds number has to be smaller than 2300. If the flow has a Reynolds number over 2300, the flow is turbulent. The Reynolds number is calculated by

$$\mathrm{Re} = \frac{\rho v L}{\mu} \tag{22}$$

A large Reynolds number is wished, because then the pressure difference becomes stronger (Baydar 1999). If the Reynolds number drops under 1, viscous effects take over. This has a negative effect on the lifting force, because friction plays a role.

C.5 MATLAB CODE

Matlab is used to simplify the calculation of different values.

```
%Values
Q = 0.002
Rc = 0.00375
Ain = pi*Rc^2
rho = 1.2
h = 0.0015
R = 0.025

%Equations
Vin = Q / Ain
Frej=rho*Vin^2*Ain
Fatt=(((rho*Q^2)/(4*pi*h^2))*(log(R/Rc)-1/2*(1-(Rc/R)^2)))
```

C.6 EXAMPLE & VARIABLES

A basic example is calculated.

Values

$$Q = 2L/s$$

$$A_{in} = 50mm^2$$

$$\rho = 1.2kg/m^3$$

$$h = 1.5mm$$

$$R = 25mm$$

$$R_c = 3.75mm$$

Results

$$v_{inside} = 45m/s$$

$$F_{reject} = 0.1N$$

$$F_{attract} = 0.25N$$

The total force is the attracting force minus the rejecting force. In this case, a total lifting force of 0.15N is left. This means, an object of maximal 15 g can be lifted. If a deflector is used, the total lifting force will increase, because the rejecting force is compensated by the gripper.

If the volume flow rate is increased twice, the velocity will increase twice and the F_{reject} and $F_{attract}$ both increase four times (Figure 6). If the height of the object is decreased twice, the velocity and the F_{reject} do not change, but the $F_{attract}$ becomes four times as large (Figure 6). If the radius R is doubled, the velocity and the F_{reject} do not change, but the $F_{attract}$ becomes a 1.5 times as large (Figure 7). If you double the radius of the nozzle R_c, the area of the central channel quadruples. If the velocity of the air flow is kept constant, the F_{reject} increases four times. The $F_{attract}$ increases 10 times (Figure 8). All variables are shown in Table 1.

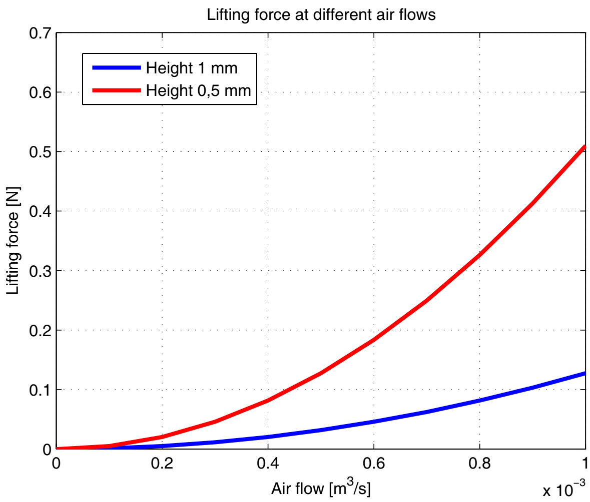


Figure 6: Lifting force increases four times if the height is decreased twice and if the volume flow rate is increased twice.

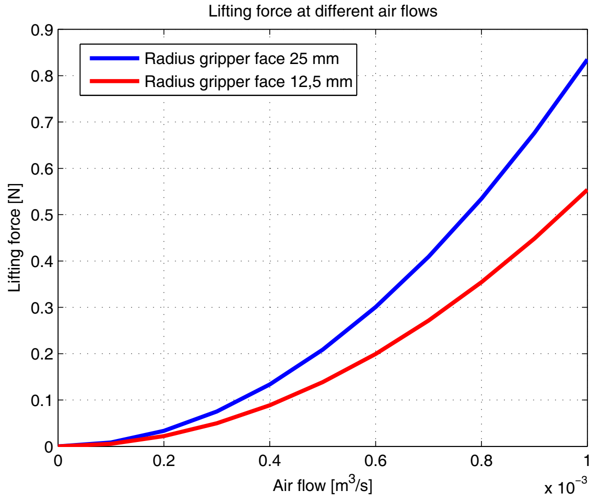


Figure 7: Lifting force becomes 1.5 times as large if the radius of the gripper face is doubled.

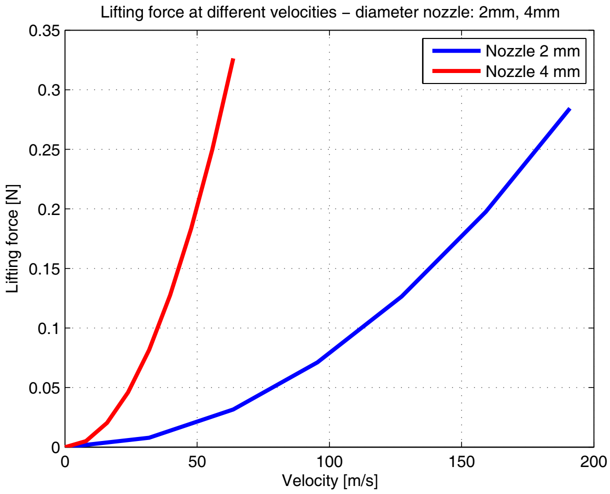


Figure 8: Lifting force becomes 10 times as large if the radius of the nozzle is doubled and the velocity is kept constant.

Table 1: Effects in short overview.

	Q x2	h x2	R x2	R_c x2
F_{rej}	4x	=	=	4x
F_{att}	4x	4x	1.5x	10x

C.6 SCALABILITY

The principle is used in the macro world, but has the potential to be scaled down. The potential to scale this method to micro scale can be assessed by the relation between the gripping to inertia forces. When looking at the scale laws, the lower the exponent of the scale factor L, the larger the influence on micro scale. The relation for Bernoulli is L^{-1} according to (Grutzeck 2002), so it has good potential on micro scale. However, the viscosity will start to play a role. This has a negative effect on the lifting force.

Limitations in reducing size are also caused by maximal velocity. If the maximal velocity coming from the nozzle exceeds the subsonic limit (330 m/s) adverse effects will occur. This will have a negative influence on the surrounding tissue and the gripped tissue.

C.7 EXAMPLE FROM PRACTICE

An experiment is done by (Huber 2009) and the results are shown here to explain more about the application in practice. A standard Bernoulli gripper is used with a nozzle of 1.5 mm nozzle at different velocities. The lifting force is measured at different distances from the gripper. This distance is the gap distance.

On the left side of Figure 9 the gap distance is (almost) zero and the force on the object is positive so a rejection force on the object is found. This rejecting force transforms very fast in a negative force if the gap distance is increased slightly. Figure 10 shows the detail of the lifting force peek. Here can be seen that the maximum force for different pressures is reached within 1 mm distance from the gripper. The lifting force decreases to 0 N when the object moves from the gripper. This point is reached for all the different pressures at 17 mm. This zone is called the safe zone and this can be used to prevent the object from blowing away. Beyond 17 mm, the rejecting forces cause again a positive force on the object, which results in blowing away the object.

An example is given. Consider a plate of 150 g and a pressure of 300 kPa. When the plate is hold at a large distance of 100 mm, a rejecting force of 0.75 N will work on the plate. If the plate approaches the gripper until 17 mm, the rejecting force will drop and go to 0 N. As the object comes closer, a lifting force is applied to the plate. However, 1.5 N is needed to overcome the gravity force. This is first reached at 1 mm. At this point, the plate is unstable, because if it gets closer to the gripper results in a larger lifting force. The plate will be sucked towards the gripper. The plate is stable again at 0.3 mm, where the force of 1.5 N is reached again. Further approach results in rejecting force caused by the force of the air flow. A force of 5 N is necessary to overcome the 6.5 N maximum lifting force. This explains that the Bernoulli gripper is self-stabilizing.

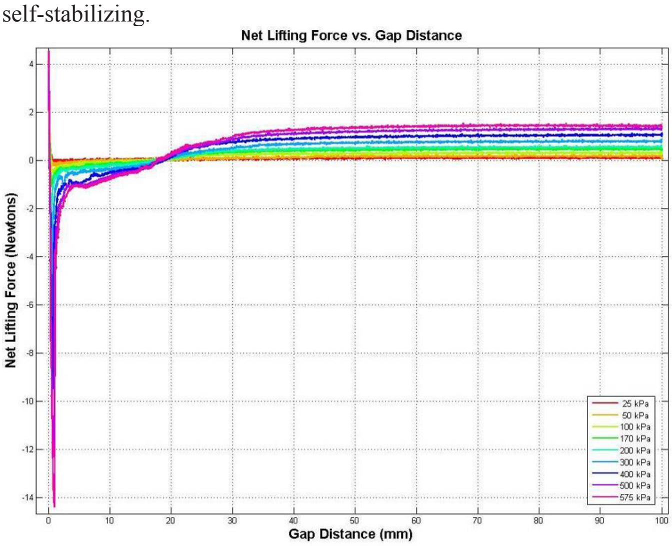


Figure 9: Lifting force vs. gap distance.

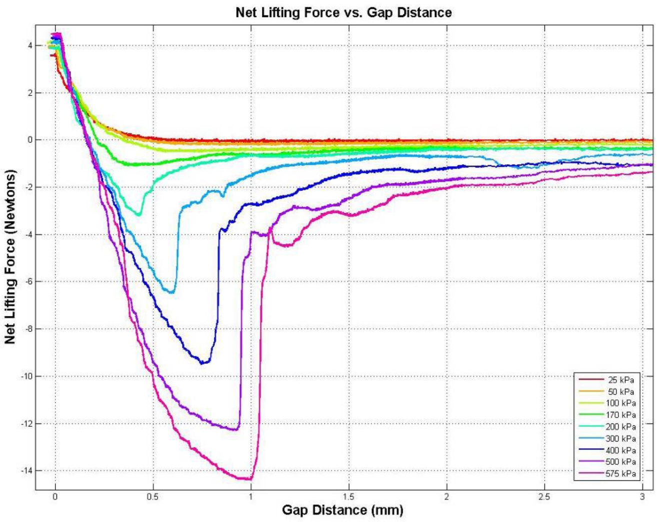
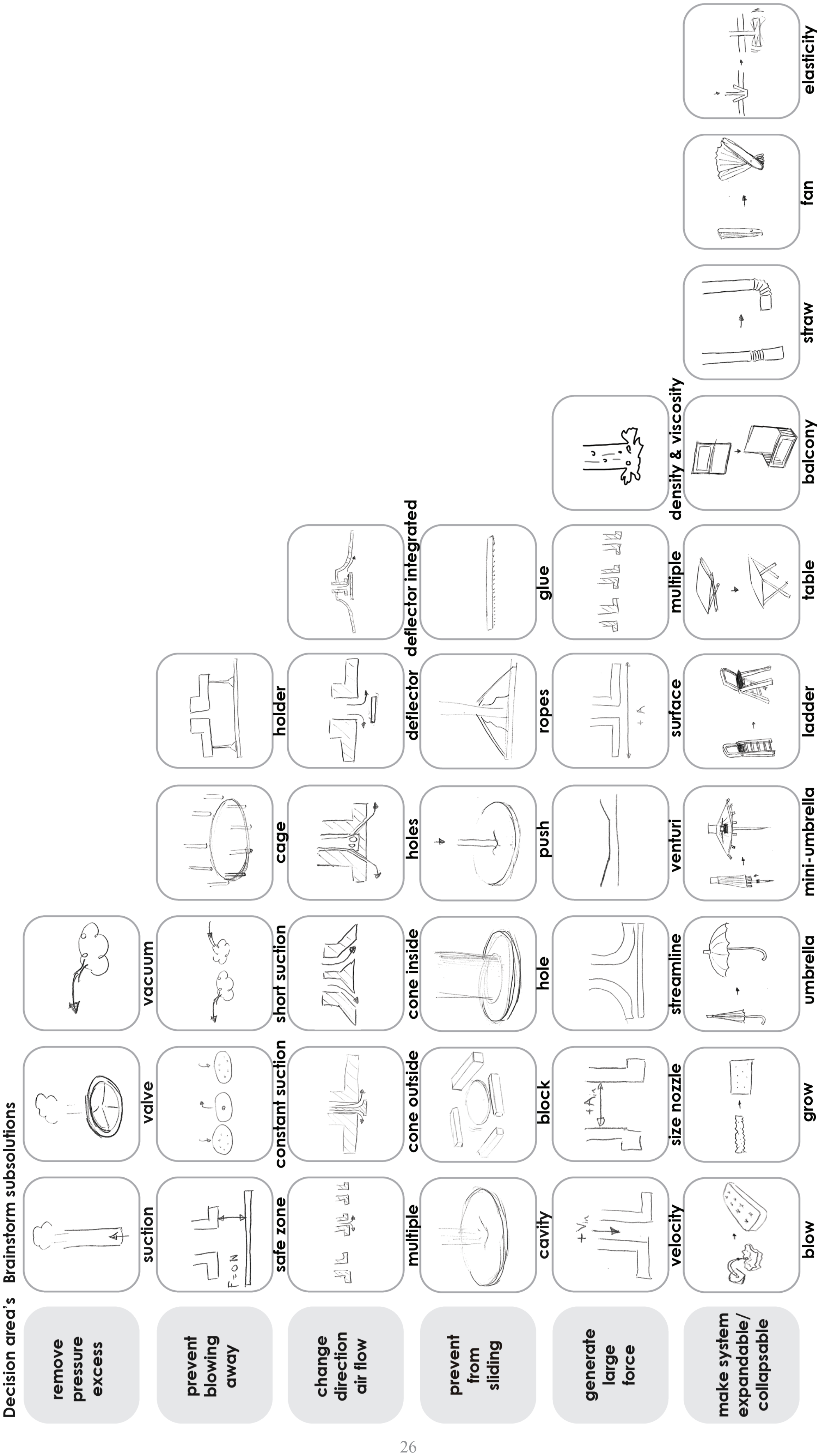


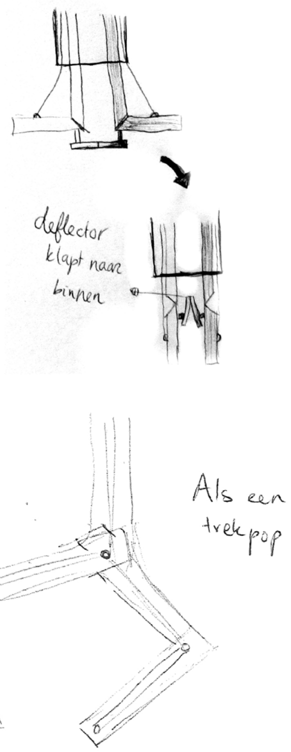
Figure 10: Detail of the graph lifting force vs. gap distance.

D MORPHOLOGICAL ANALYSIS

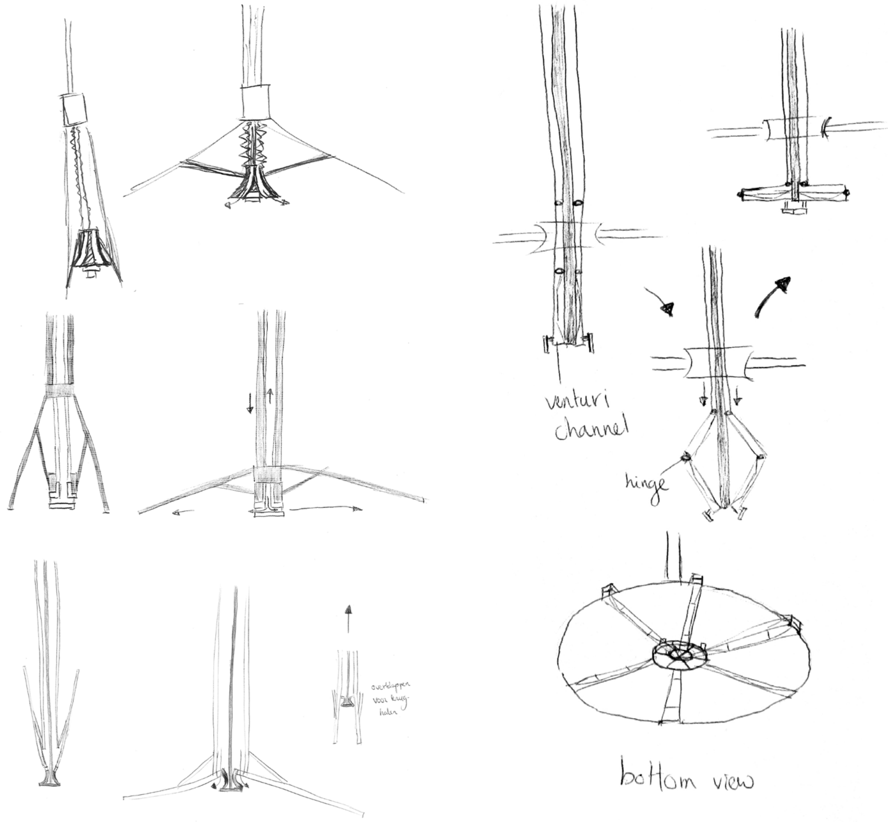


E IDEAS AND IDEA SELECTION

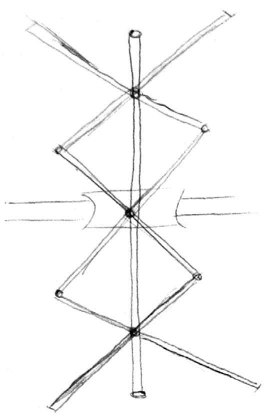
Pulling up



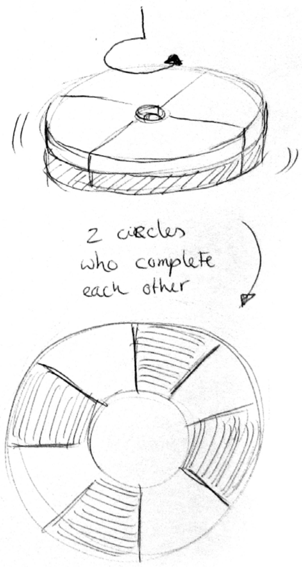
Pushing down



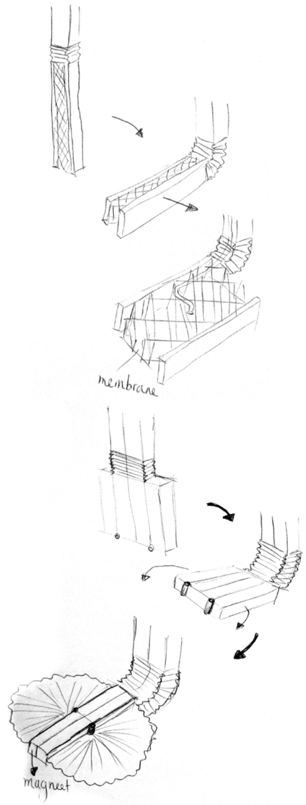
Pinching



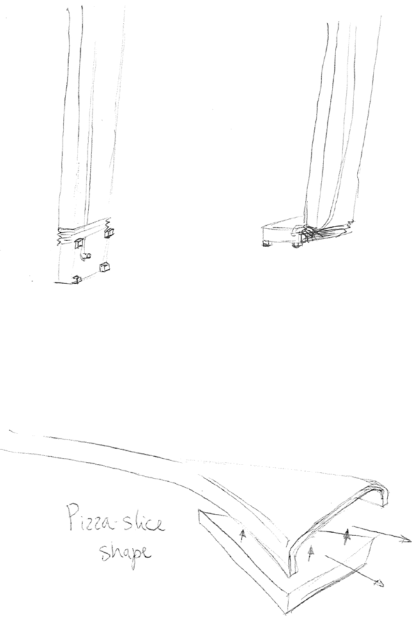
Turning



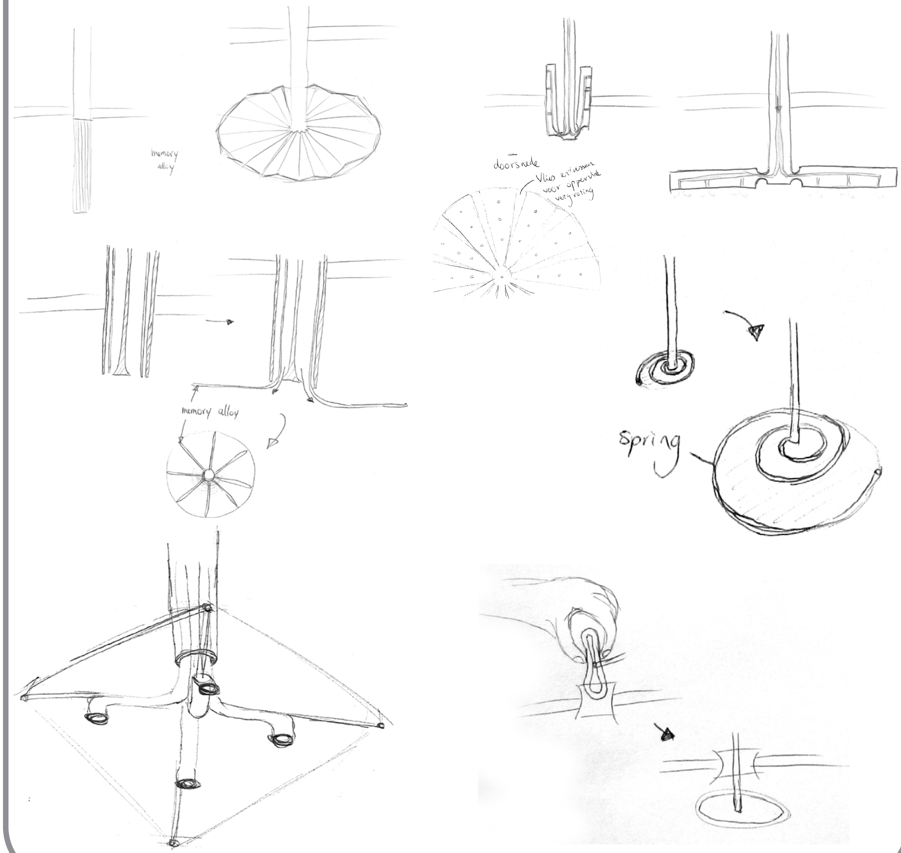
Opening to the side/180°



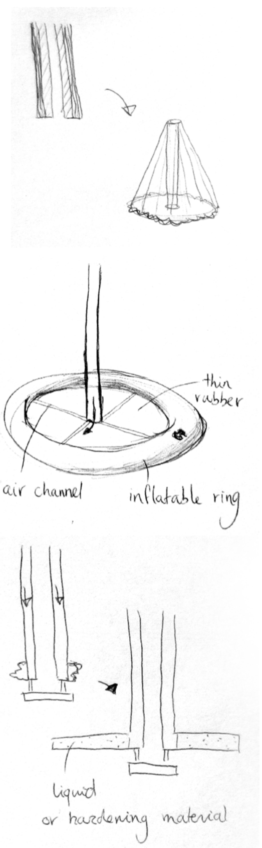
Not expanding



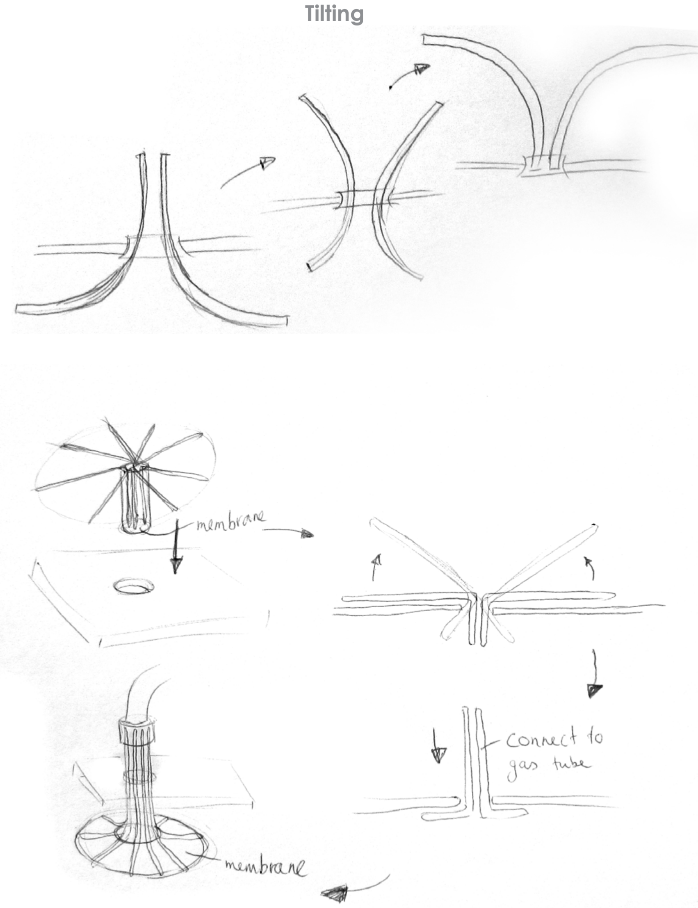
Releasing tension



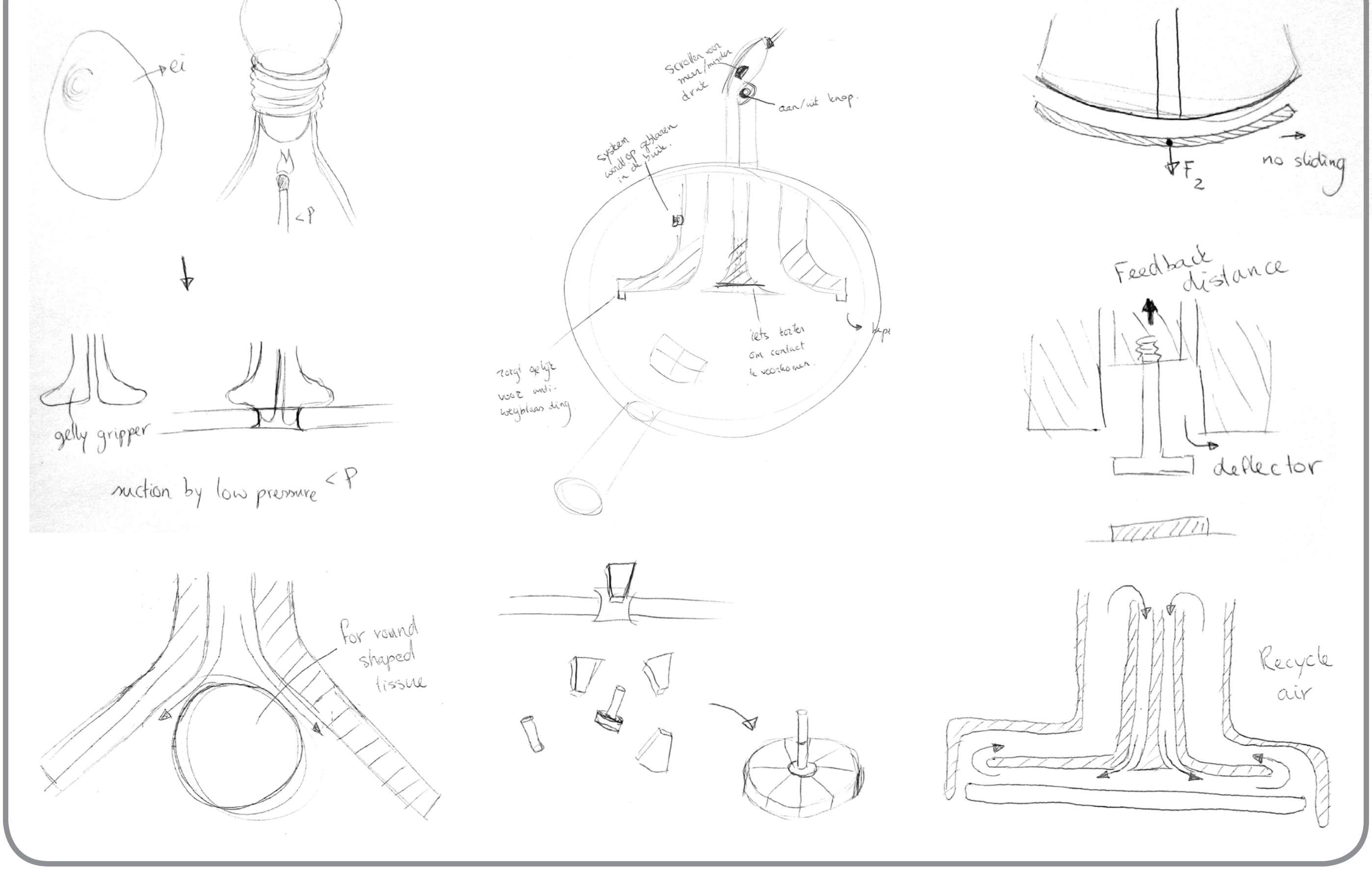
Blowing up



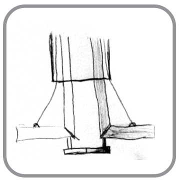
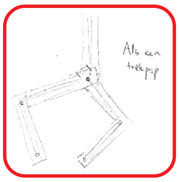
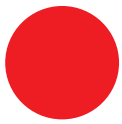
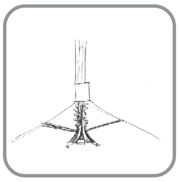
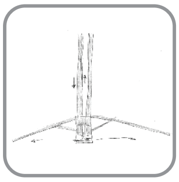
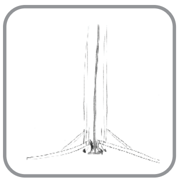
Tilting

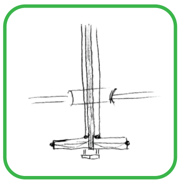
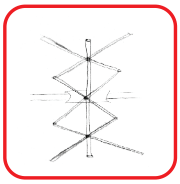
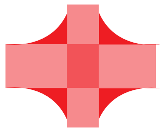
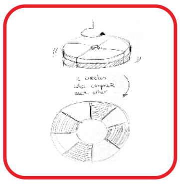
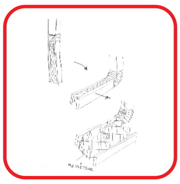
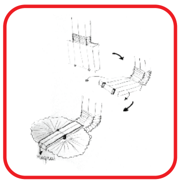
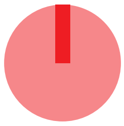
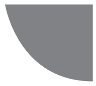
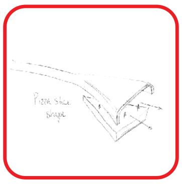
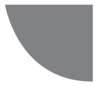
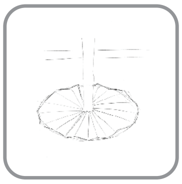
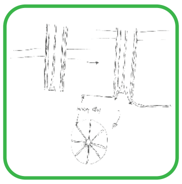
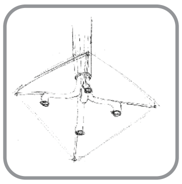


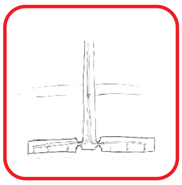
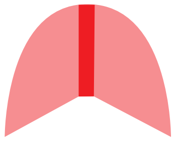
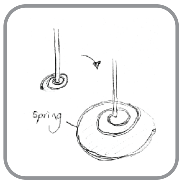
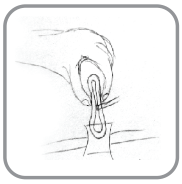
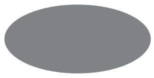
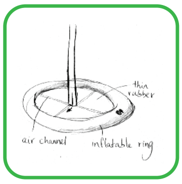
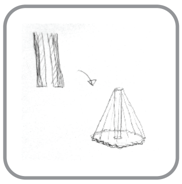
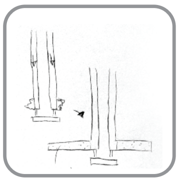
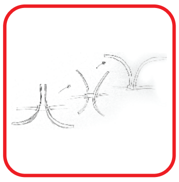
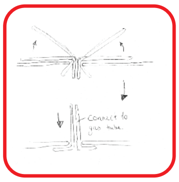
Diverse ideas



IDEA SELECTION

	Description	Number of actions	Complexity	Expanding space	Other comments
	**Pulling up** Pulling robes in combination with shape fit results in a rigid construction.	1	3 parts 1 hinge		- where to attach ropes? - how to overcome death center?
	**Pulling up** With this pull doll principle, a large range of shapes can be gripped.	2 or more	3 parts 2 hinges		- too complicated
	**Pushing down** The principle of the umbrella is used to expand the gripper very fast to a rigid state.	1	4 parts 3 hinges		- proven technology in the party umbrella - gripping surface has slope and hinge
	**Pushing down** The umbrella design, but now integrated with a deflector.	1	4 parts 3 hinges		- proven technology in the party umbrella - gripping surface has slope and hinge
	**Pushing down** The idea is to inverse an umbrella, so that the hinge is not on the gripping side.	1	4 parts 3 hinges		- proven technology in the party umbrella - gripping surface has slope

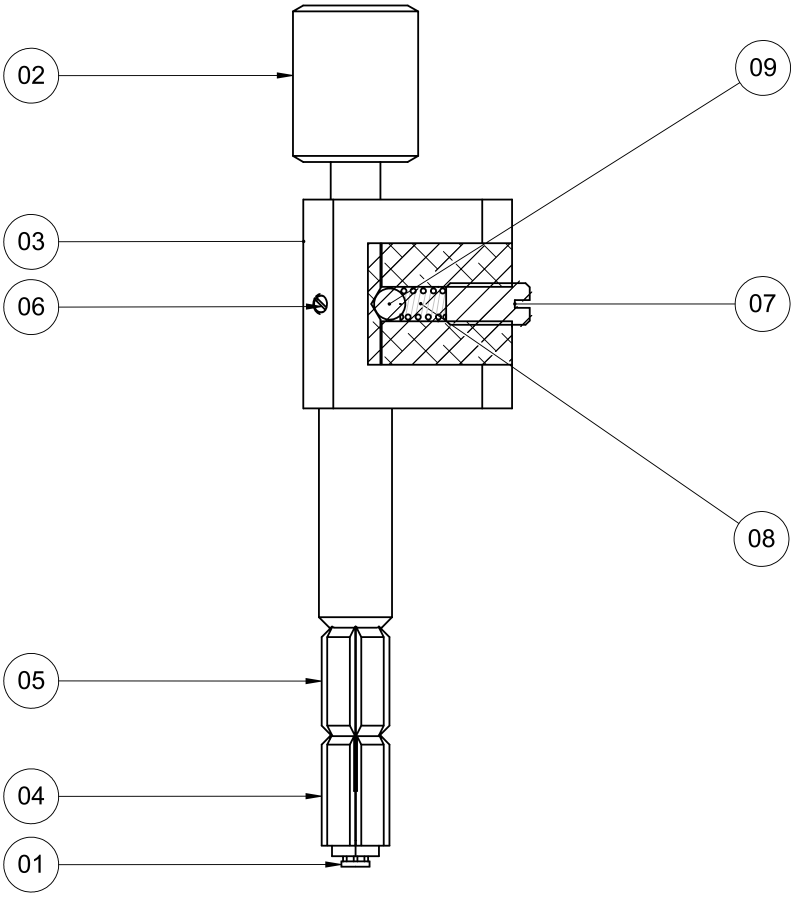
	Description	Number of actions	Complexity	Expanding space	Other comments
	**Pushing down** The simplified umbrella system, with horizontal plane and no hinges on the gripping plane.	1	4 parts 3 hinges		- all advantages of the umbrella design
	**Pinching** With a simple scissors principle, the system can made expandable.	1	4 parts 5 hinges		
	**Turning** If you turn the two discs, smaller planes move out. At a certain point, the smaller planes of the two discs fall into each other and integrate to a bigger disc.	1	unknown		- how to open?
	**Openinging to the side** The idea comes from a collapsable framework.	2	>10 parts >10 hinges		- difficult to minimize - how to open?
	**Opening 180 degrees** Surface increase by the expanding of a fan. Because it is used on both sides, a round surface is obtained.	2	>10 parts >10 hinges		- difficult to minimize - irregular surface - how to open?
	**Not expanding** Compact design for lifting extemely small pieces. Design fits through 5 mm hole and needs to be bent for the right orientation.	1	2 parts 1 hinge		- no difficult expanding methods - small forces
	**Not expanding** Compact design for lifting extremely small pizza shaped pieces. Design fits through 5 mm hole and needs to be bent for the right orientation.	1	2 parts 1 hinge		- no difficult expanding methods - small forces
	**Releasing tension** Expanding with the help of memory alloy. Back in original shape when released.	0 or 1	2 parts		- expensive
	**Releasing tension** Expanding with the help of memory alloy. Back in original shape when released.	0 or 1	2 parts		- expensive
	**Releasing tension** Expanding with the help of memory alloy. Back in original shape when released.	0 or 1	2 parts		- expensive

	Description	Number of actions	Complexity	Expanding space	Other comments
	**Releasing tension** By using elastic materials like plastic, deformations will return in the original position.	0 or 1	1 part		- can used passive steering
	**Releasing tension** By using elastic materials like plastic, deformations will return in the original position.	0 or 1	1 part		- can used passive steering
	**Releasing tension** By using elastic materials like plastic, deformations will return in the original position.	0 or 1	1 part		- can used passive steering
	**Blowing up** Compressed air from the Bernoulli principle can be used to inflate the gripper inside the body. A ring is inflated.	1	1 part		- loss of power - difficult control of optimal volume
	**Blowing up** Compressed air from the Bernoulli principle can be used to inflate the gripper inside the body. In this shape, the rigidity is improved.	1	1 part		- loss of power - difficult control of optimal volume
	**Blowing up** Compressed air from the Bernoulli principle can be used to inflate the gripper inside the body. The gripping surface is blown up.	1	1 part		- loss of power - difficult control of optimal volume
	**Tilting** The skin is used as hinge for the rigid shapes.	2 or more	1 part		- complicated control for the user
	**Tilting** The skin is used as hinge for the rigid shapes. The gripper can now be moved in the body.	2 or more	1 part		- complicated control for the user

IDEA SELECTION

Ideas have been generated and during a group session with four students (two Industrial Design Students, one Mechanical Engineering student and one Civil Engineering student). The ideas are divided in groups selected by the expanding principle. The first page of the Appendix shows the ideas where the expansion needs hinges and they are ordered by the number of hinges from low to high. The next page shows the ideas where the expansion is without hinges. The last page with ideas shows diverse ideas. In this Appendix, a short description for every idea is given. When continuing to the concept generation, the best ideas of this decision area is selected. A selection of appropriate ideas has been made with the help of a number of criteria. The criteria for evaluation are derived from the boundary conditions. In the general description, the ideas that are not able to handle different weights are eliminated. When looking at the complexity, the instrument is inserted in a 5 mm trocar, so should have a minimal amount of parts. The ideas with more than 10 parts or hinges are eliminated. The instrument must grip as fast as or faster than with normal grasper, so ideas with more than one action for expanding or collapsing were eliminated. To meet the safety requirements, the instrument must be introduced and removed without damaging surrounding tissue. Ideas with a too large expanding space are eliminated. Too large is defined as more than half a circle with the radius of the original shape. If the idea does not meet the criteria, the idea is eliminated. The eliminated ideas are circled by a red line. The best ideas of each group are selected for the concept phase. The best idea of the group has the least amount of parts, the least amount of actions and minimal expanding space. The best ideas are circled by a green line.

F TECHNICAL DRAWINGS OF THE PROTOTYPE



09	1	Ball	ASTM/AISI 316	∅2,5 ISO 3290	bestellen
08	1	Spring	EN 10270-1-SH		bestellen
07	1	Headless slotted screw S	ASTM/AISI 304	DIN 427 M4 x 8	bestellen
06	2	Headless slotted screw L	ASTM/AISI 304	DIN 427 M2 x 5	bestellen
05	6	Top rib	Al 7075-T651	30 x 15 x 2,5	draadvonken
04	6	Bottom rib	Al 7075-T651	30 x 15 x 2,5	draadvonken
03	1	Outer tube	Al 7075-T651	∅22 x51	CNC-draaien
02	1	Middle tube	Al 7075-T651	∅15 x 90	CNC-draaien
01	1	Inner tube	Al 7075-T651	40 mm	CNC-draaien
STUK-NUMMER	AANTAL	BENAMING	MATERIAAL EN/OF HALFFABRIKAAT	NORMAANDUIDING EN/OF AFMETINGEN	OPMERKING

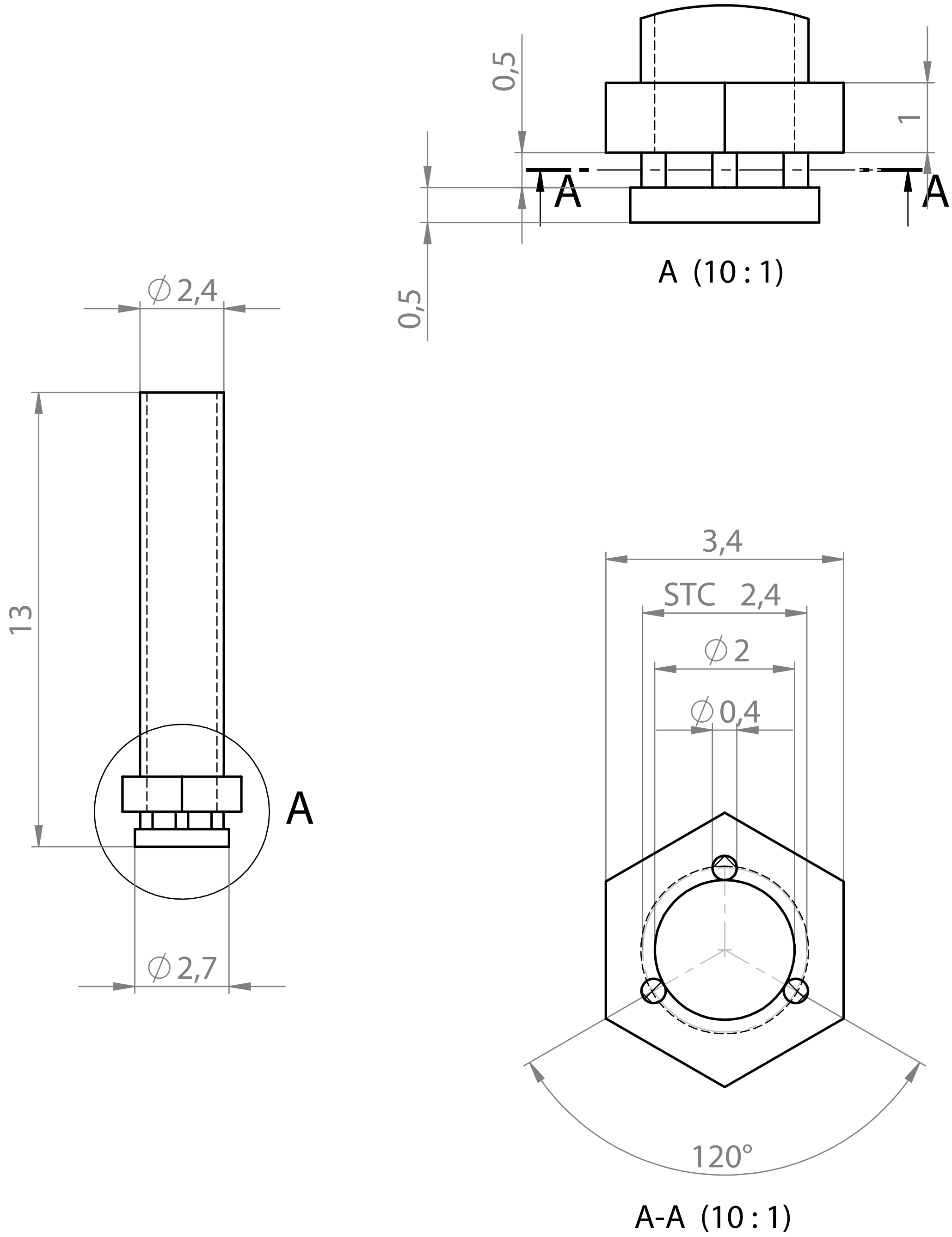
schaal	2:1	datum	opmerkingen anodiseren
maateenheid	mm	24-11-2010	
getekend	Remi van Starkenburg		
groep	BME		

benaming **00 Assembly**

TU Delft
Industrial Design Engineering

formaat A3

tekeningnummer 00,000



benaming **01 Inner tube**

maateenheid mm

formaat A4

tekeningnummer 01,000

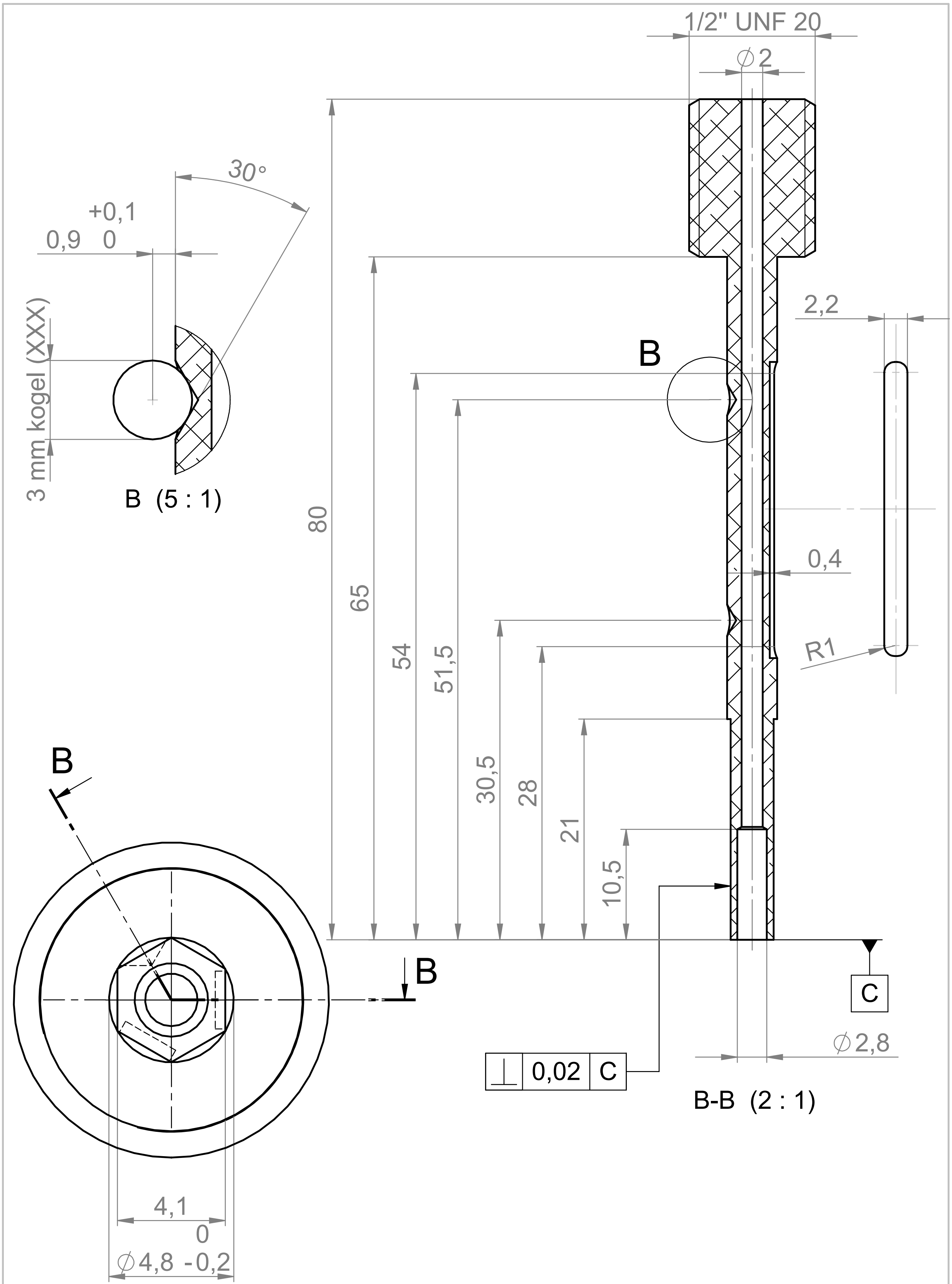
TU Delft
Industrial Design Engineering

schaal 5:1

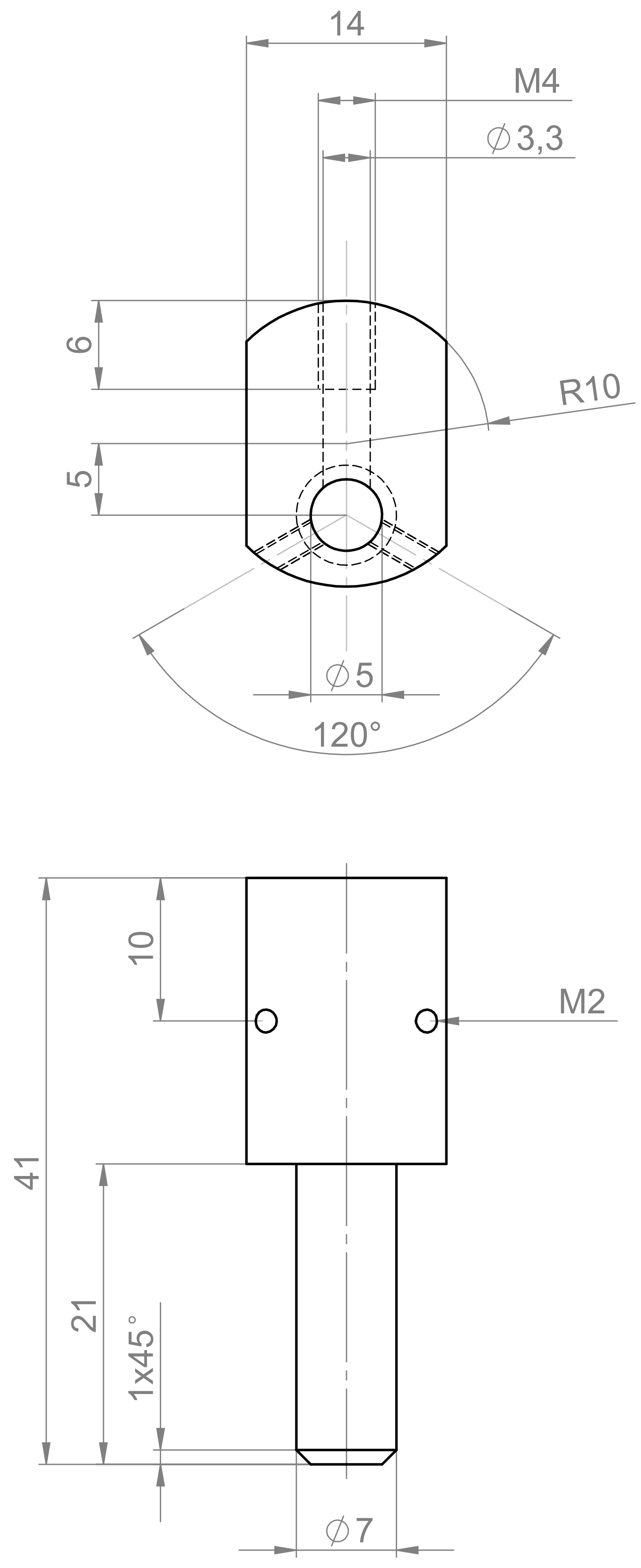
datum 24-11-2010

getekend Remi van Starkenburg

groep BME

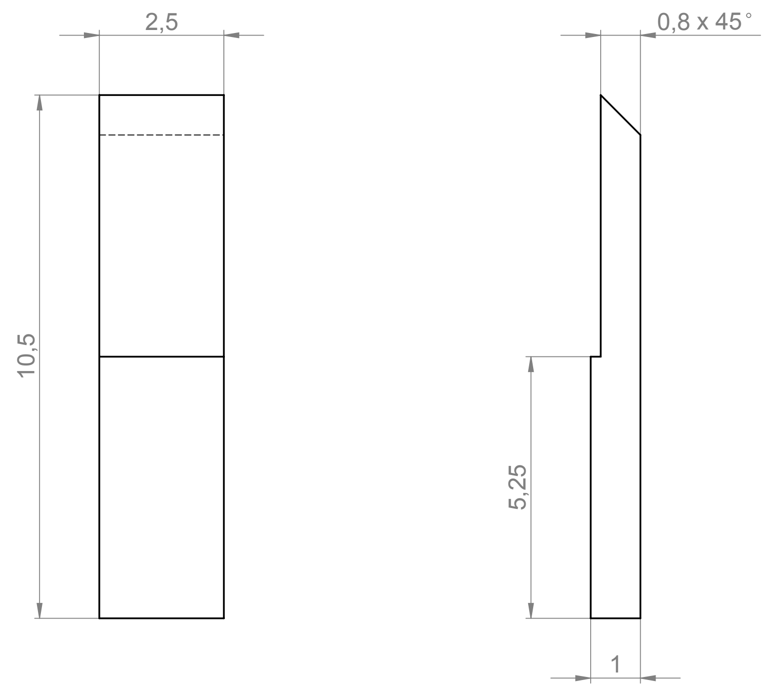


benaming **02 Middle tube**			maateenheid mm
		formaat A4	tekeningnummer 02,000
TU Delft Industrial Design Engineering	schaal 5:1	datum 24-11-2010	
	getekend Remi van Starkenburg		groep BME



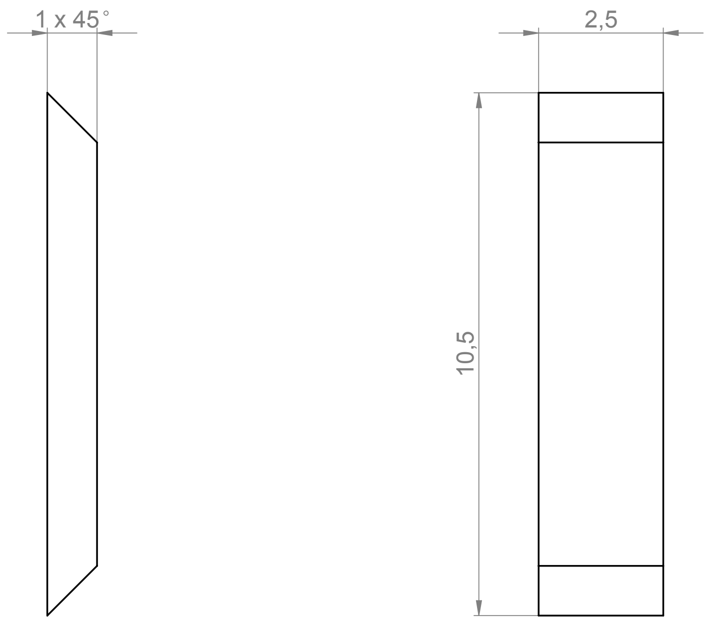
benaming **03 Outer tube**			maateenheid mm
		formaat A4	tekeningnummer 03,000
TU Delft Industrial Design Engineering	schaal 2:1	datum 24-11-2010	
	getekend Remi van Starkenburg		groep BME

6x



TU Delft Industrial Design Engineering	benaming 04 Bottom rib		datum 24-11-2010		maateenheid mm
		schaal 10:1	groep BME	formaat A4	tekeningnummer 04,000
		getekend Remi van Starkenburg			

6x



TU Delft Industrial Design Engineering	benaming 05 Top rib		datum 24-11-2010		maateenheid mm
		schaal 10:1	groep BME	formaat A4	tekeningnummer 05,000
		getekend Remi van Starkenburg			

G LIVING HINGE

A living hinge is a thin flexible hinge made of plastic that connects two parts and allows them to bend. The chosen concept uses these living hinges for expanding and collapsing. Inspiration is found a hollow wall plug (Figure 11). This is a simple and cheap product, which also uses living hinges for expansion.

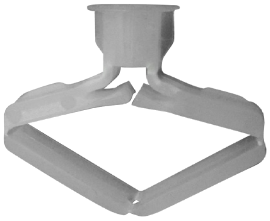


Figure 11: Hollow wall plug (www.duko.com/catalogus/product/05.02.03.001).

Like the hollow wall plug, the ribs of the instrument will be connected to each other with living hinges. There are standard sizes for construction of these living hinges. The sizes of Figure 12 will be used. A detail of the living hinge between the bottom and top rib will look like in Figure 13.

Polypropylene is a suitable material for producing a living hinge in mass production and the most used resin by the medical device industry (Portnoy 1998). Additionally, polypropylene is an FDA approved material. Injection molding is a suitable method for the mass production of polypropylene living hinges. Injection molding is widely used for manufacturing a variety of parts.

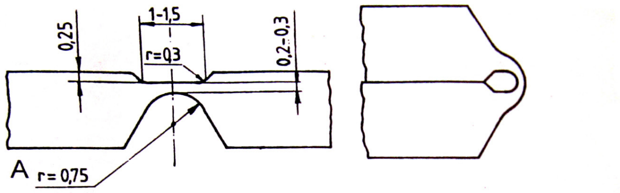


Figure 12: Sizes for a living hinge for movement between 0 and 180 degrees. The figure is adapted from Anemaat (2003).

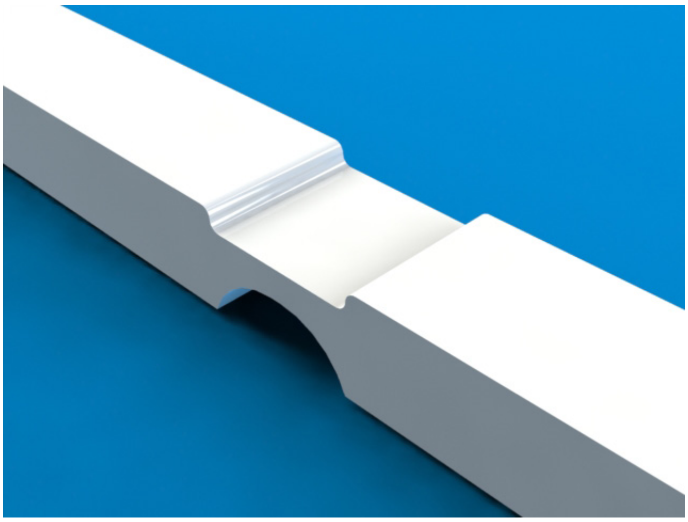


Figure 13: 3D image of the living hinge between the two ribs.

H PRODUCT INTERACTION AND USAGE

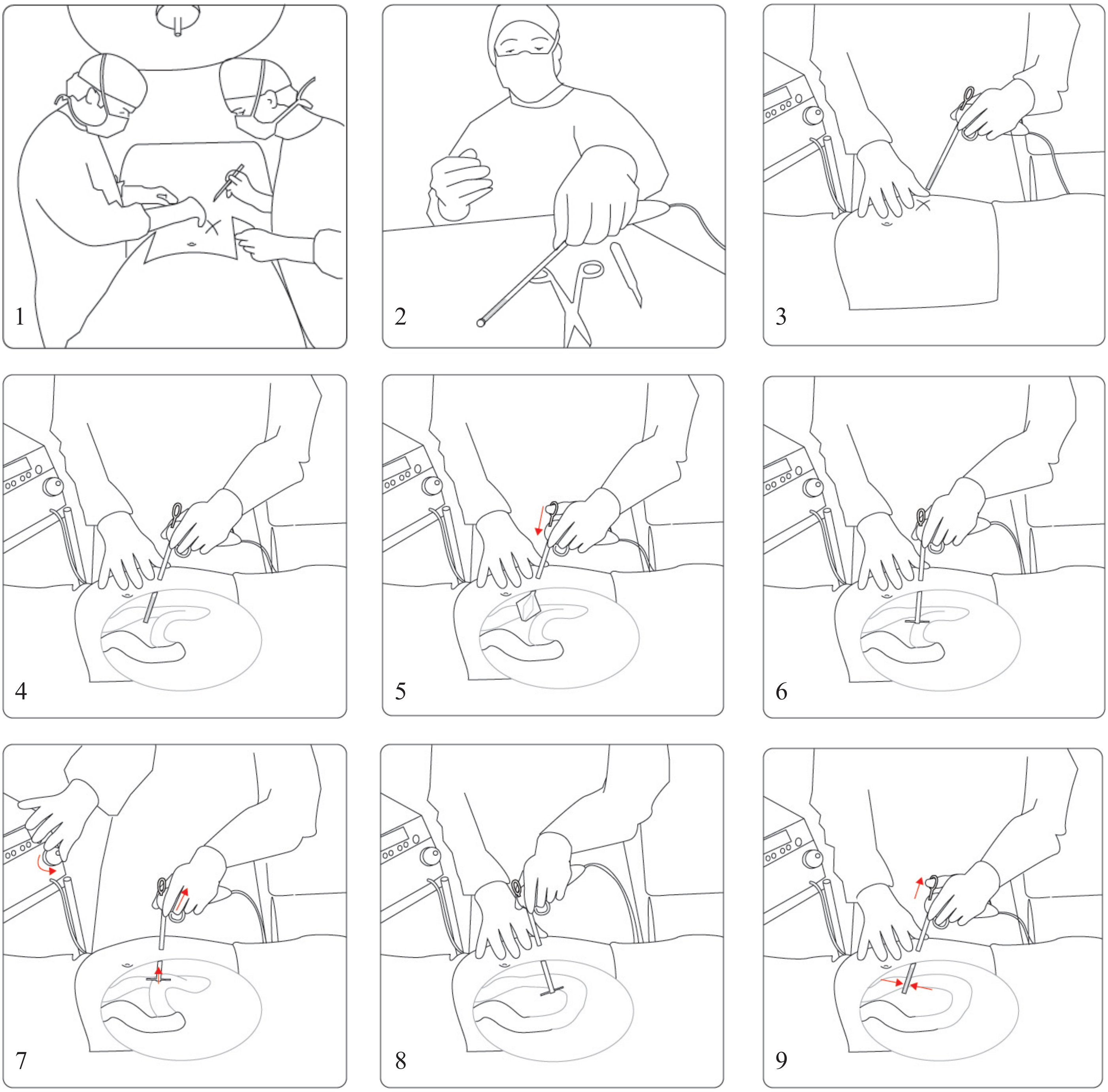


Figure 14: Intervention usage.

The intended interaction between the instrument and the user is presented in a scenario inspired on a laparoscopic surgery (Figure 14). First the abdomen is blown up and a hole is cut for the trocar (1). The surgeon takes the instruments from the instrument table (2). The instrument is inserted in the patient's abdomen (3). In the abdomen lies the target object which has to be moved (4). If the surgeon moves the sliding system down with his thumb, the instrument starts expanding (5). If the sliding system is fully moved down, the instrument is fully expanded (6). The surgeon can turn on the air flow for immediate gripping and control the air flow with the trigger (7). The surgeon can move the target object to the desired position and location (8). If the manipulation is ready, the sliding system is moved back and the instrument will collapse (9).

I PRODUCTION COST ESTIMATION*

# Instruments per year:	10,000
Depreciation period (years):	3
Currency:	euro

Materials and manufacturing process

Part name	*Material*	*Start cost*	*Quantity*	*Cost*
Hand piece	PP		1	€ 6.50
Trigger	ABS		1	€ 1.30
Spring	steel		1	€ 0.10
Gear	ABS		1	€ 0.30
Outer tube	PP & rubber	€ 50,000	1	€ 6.00
Sliding system	Teflon	€ 30,000	1	€ 1.00
Conducting tube	Teflon	€ 30,000	1	€ 1.00
Inner tube	Stainless steel 316		1	€ 2.00
Deflector	Stainless steel 316	€ 5,000	1	€ 0.50
Tubes for air	Rubber		2	€ 0.50
			subtotal:	€ 19.20

Postprocess

Assembly		€ 2.50
Quality control		€ 1.00
Packaging		€ 2.00
Sterilization		€ 0.50
	subtotal:	€ 25.20

Other (work preparations, sales, warranty)		8%	€ 27.22
Overhead		3%	€ 28.03
Profit margin		9%	€ 30.56
total start costs:	€ 115,000		
3 years depreciation:			**€ 34.39**

*Based on cost estimation of DEAM

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