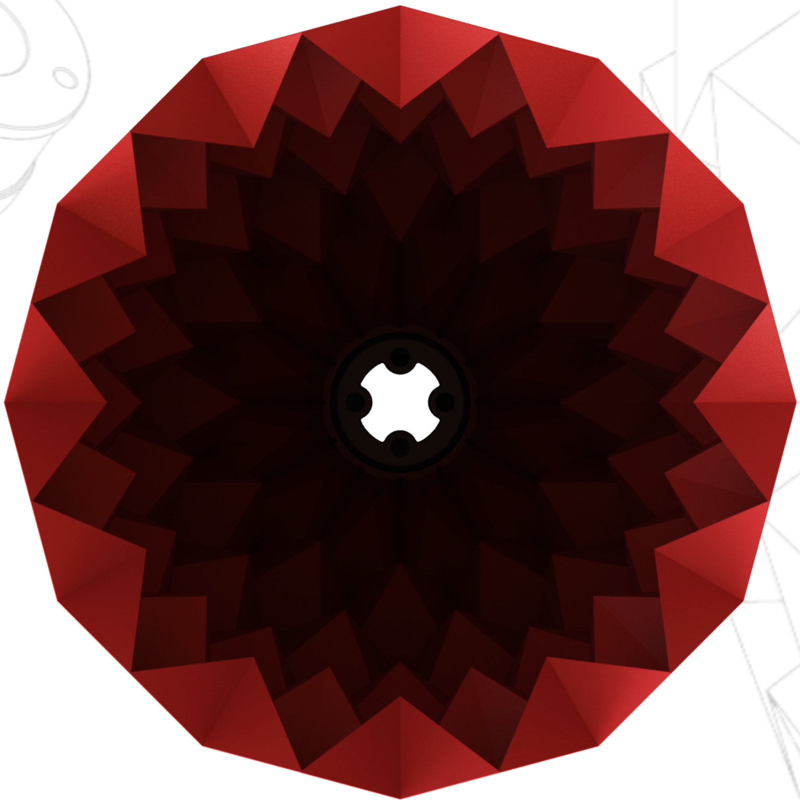
# An Innovative Pretreatment Method For Automatic Cow Milking

*by*

**Bart van der Hee**



TU Delft

LELY

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to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Monday June 26, 2023 at 09:30 AM.

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|---|---|---|
| Student number: | 4535847 | |
| Project duration: | September 2022 – June 2023 | |
| Thesis committee: | Prof. dr. J. Dankelman, | TU Delft, supervisor |
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*This thesis is confidential and cannot be made public until June 26, 2025.*

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# Abstract

Automatic milking of cows has been around for more than 30 years, making the milking process more efficient, less labour intensive and more cow friendly. Before a cow can be milked, three stages of udder pretreatment have to be completed: cleaning, stimulation and premilking. There is no clearly superior pretreatment technique for automatic milking systems and the three main manufacturers of milking robots (Lely, DeLaval and GEA) each use different systems. Lely uses two counter rotating brushes that the teat is inserted in between, with good cleaning and stimulation results. However, their R&D department is looking for innovative alternatives. The goal of this thesis is therefore to find an innovative alternative for Lely's current pretreatment system with at least as good cleaning and stimulating properties. Preferably the premilking stage is also included, which Lely's current system is unable to perform in contrast to its competitors. A morphological chart is used to design three concepts. Prototypes are then evaluated based on a field test with a real cow and a cleaning test using a fake test-teat. Based on a weighted Harris profile, the Origami Vacuum Gripper concept was chosen to further iterate into a final design and prototype. The device is essentially a gripper that functions like a foldable milking cup that sprays, grips and then brushes the teat by being pulled downward off the teat. The folding is based on the Waterbomb origami pattern and is actuated using vacuum and an airtight skin that is wrapped around it. A brush liner is positioned inside the gripper and the dirt is removed at the bottom through a vacuum tube. A final field test showed that the device fulfilled all requirements, being able to properly clean and stimulate the teats and leaving them dry enough to attach the milking cups. Unfortunately, the device was not able to premilk the cow. The compression of the teat by the gripper prevented the milk from being pulled out by the vacuum inside the gripper. Finally, a gripping force test is performed to see the effect of different origami skeleton geometries on the gripping force applied to the teat. It was concluded that the skeleton with shorter folding edges applies a larger force to the teat with the same vacuum applied to the airtight skin. More research is needed on the folding geometries in order to find an optimal design for the gripper.

# Contents

# 1 Introduction

Automatic milking systems for cows been around for more than 30 years now, making the milking process more efficient, less labour intensive and more cow friendly. Before the cow can be milked, the cow's teats have to be cleaned, stimulated and premilked. These three pretreatment stages will be discussed in section 1.1. Numerous methods for this pretreatment have been invented. However, as has been concluded in the literature and patent study conducted prior to this thesis [8], there is no pretreatment system that is clearly superior to its alternatives. Lely, DeLaval and GEA, the three biggest manufacturers of automatic milking machines, each use different techniques that have their own pros and cons. Furthermore, almost 50 patents have been found describing pretreatment devices. This makes it an interesting field to explore and combine with other new fields of technology, like for example 3D printing and 'soft robotics'.

## 1.1. The Milking Pretreatment Process

Background information on machine milking and automatic milking can be found in appendix A. This appendix is the literature and patent study executed prior to this thesis to gain knowledge on the milking process and existing pretreatment techniques, and how the pretreatment should be performed. More references to this study will be made throughout this thesis.

Before a cow can be milked, its udders have to be pretreated in order to establish optimal milk yield, avoid infections and cross-contamination and maintain udder health [8]. This pretreatment consists of three stages: **cleaning, stimulation and premilking.** The cleaning of the teats prior to milking is important to avoid the bulk milk to be contaminated with dirt and manure that accumulate on the teats in between milking and avoid udder infections (mastitis). Stimulation of the teats makes sure that the milk activation reflex is activated. This releases the hormone oxytocin, which enables the milk to be removed from the udders. This also makes the milking process faster and results in less machine-on time, which is healthier for the udders. Furthermore, without stimulation, only 20% of the milk can be removed. The premilking stage consists of removing and discarding the first few streams of milk since these contain the most bacteria, which is required by law in the Netherlands. Furthermore, the premilk can be used to check if a cow has mastitis. In figure 1.1 the manual milking technique and a mechanical technique using a teat cup are illustrated. For the milk to leave the cow's teat, the pressure inside the teat has to be higher than the pressure outside it. The milk will then leave the teat through the teat orifice at the bottom. The main difference between the manual and the mechanical technique is that the former increases the pressure inside the teat, while the latter decreases the pressure outside the teat. When done manually, the milker's index finger and thumb pinch off the milk flow at the base of the teat after which the rest of the hand closes from top to bottom in a fluent way to increase the pressure inside [13]. The mechanical technique does not block the milk flow to the teat, but a vacuum is applied inside the milking cup attached to the teat, effectively sucking the milk out through the teats orifice. The applied vacuum pulsates to prevent edema in the teats walls, which would hurt the cow and block the milk flow.

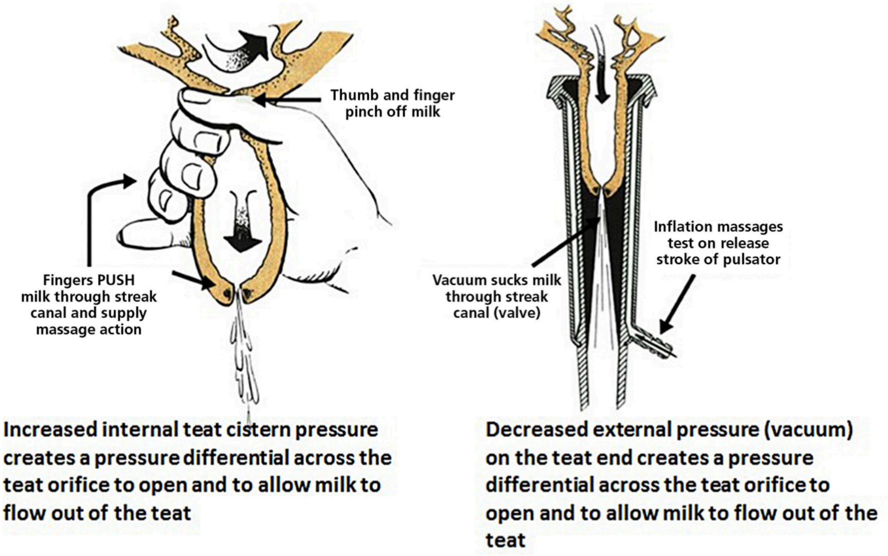



Figure 1.1: Left shows the manual milking technique and right shows the use of a milking cup with vacuum [4]

The three pretreatment stages are not separated, but overlap in practice. For instance, stimulation is not an actual separate stage, but occurs during cleaning and/or premilking. A more detailed elaboration of the pretreatment process and the milking process in general can be found in appendix A.

## 1.2. State of the Art

The three biggest manufacturers of automatic milking systems (AMS) are Lely, DeLaval and GEA. This section is taken from the literature and patent study [8] and can be found in appendix A.

### 1.2.1. Lely Astronaut A5

The Lely Astronaut A5 uses two rotating cylindrical brushes attached to a robotic arm in order to clean and stimulate the cow's teats before milking, as can be seen in figure 1.2. The brushes are positioned horizontally and parallel, counter-rotating towards each other. After the pretreatment and during the milking process, the brushes are thoroughly cleaned by jets of water and disinfectant and rotated in order to dry. [9].

(a) (b)

Figure 1.2: (a) The two counter rotating brushes of the Lely Astronaut A5 clean and stimulate the teat (b) the brushes get disinfected after the pretreatment [10].

### 1.2.2. DeLaval VMS V300

DeLaval has chosen to clean, stimulate and premilk the cow before milking in a separate set of teat cups [2], as can be seen in figure 1.3. This all takes place in a separate system to prevent cross contamination when milking. The teats are washed inside the teat cups with jets of water, air and optionally soap and blow dried before milking.

(a) (b)

Figure 1.3: (a) The cup from the DeLaval VMS V300 cleans, stimulates and premilks the cow (b) a cross section pictures the flowing of the water/soap and air inside the cup [2].

### 1.2.3. GEA DairyRobot R9500

In contrast to its competitors, GEA performs the whole pretreatment process in the same teat cup that's used for milking [6], as can be seen in figure 1.4. The teats are cleaned by injecting water into the cups at intervals, washing them clean. Simultaneously the teats are stimulated by pulsating/vibrating the liner inside the teat cup, which is very similar to the milking technique but with less power.

(a) (b)

Figure 1.4: (a) The GEA DairyRobot R9500 executes the pretreatment and milking process in the same teat cup (b) stimulation of the teat is done by vibrating the liner inside the cup, similar to the milking technique but with less power [6].

## 1.3. Problem Analysis

This paper focuses on designing an alternative for Lely's pretreatment system on the Lely Astronaut A5. The rotating brushes Lely uses have a good cleaning and stimulating effect, and 'catching' of the cow's teats is relatively easy due to the size of the brushes and the teats being pulled inward by them. However, the brushes do not always clean the teat perfectly and are considered big and bulky. Furthermore, an aspect that is missing from Lely's pretreatment system compared to its competitors is its ability to premilk the cow. Lely performs the premilking performed using the milking system of the milking robot by keeping the first few streams of milk separated. They have been using the same pretreatment technique for 30 years and their R&D department wants to explore new ideas to improve the pretreatment performance of the milking robot and potentially add new functionalities, like premilking.

When designing an automatic pretreatment device that is used on a milking robot, multiple challenges arise. Like stated before, the three pretreatment stages (cleaning, stimulation and premilking) have to be properly performed for the milking process to be executed safely and efficiently. The teats have to be cleaned properly to prevent mastitis and contamination of the bulk milk, the milk ejection reflex has to be activated, and the first few streams of milk have to be discarded. Furthermore, the device has to be applied to the cow by a robot in a reliable and safe way.

### 1.3.1. Requirements and wishes

Requirements and wishes for the device are devised in order to make sure it functions as desired. These are shown below.

**Requirements:**

1. *Clean teat.* The device can clean the teat at least as properly as Lely's current system. This means that the teats are visually clean, except for a few small spots of dirt in extreme scenarios (see section 2.4.2).
2. *Stimulate teat.* The teat is stimulated properly, activating the milk ejection reflex. Stimulation is a very difficult aspect to measure, and since proper cleaning will most likely have a sufficient stimulating effect [8], it is assumed that if the cleaning requirement is met, the stimulation requirement is met as well.
3. *Innovative.* It is considered important that the solution is innovative, to explore new techniques and methods instead of improving existing ones.
4. *Teats semi-dry before milking.* Before the attachment of the milking system, the teats cannot be wet, since this will cause bruising at the base of the teat due to the vacuum [8]. Semi-dry means it can be moist, but no drops of water can be hanging from the teat.
5. *Safe.* The device can never harm the cow.
6. *Fit all teats of Holstein cows.* According to [7] The range of teat sizes of Holstein cows is as follows: teat length = 30-80 mm, teat barrel diameter = 14-50 mm, teat apex diameter = 14-30 mm. See section 3.1 for more elaboration. Holstein cows are chosen since these are the most common dairy cows in the Netherlands.
7. *Smaller than 3 liters.* The device has to be more compact than Lely's pretreatment system.

**Wishes:**

1. *Premilking.* If the device is able to also perform the premilking stage would mean that Lely does not have to do the premilking with their milking system, simplifying it.
2. *Simple.* Keeping the design and its actuation simple is a big advantage when having to fit it on the robot and most likely makes it cheaper and more durable.
3. *Compact.* Making the device as compact as possible when its not deployed makes it more space efficient and easier to attach to the milking robot.

## 1.4. Goal and Structure

The goal of this thesis is the following:

**Goal:** *Design an innovative alternative for Lely's pretreatment system, with at least equal cleaning and stimulating performance.*

This thesis is structured as follows. First, three concepts are devised and a prototype is built for each concept. These prototypes are then tested on a cow and a simulated cleaning test is performed. Based on these results, one concept is chosen to iterate further and create a final design and prototype that is tested on a cow once more. Furthermore, a test is performed to measure the effect of different designs on the force exerted on the teat with. The results of the tests are argued in the discussion and finally the report is ended with a conclusion.

# 2
# Concepts

The concept ideation phase resulted in a morphological chart from which three concepts were chosen and further elaborated until a prototype could be made (see appendix B). These concepts are the following:

- *Origami Vacuum Gripper (OVG)*
- *Alternating Rotating Brushes (ARB)*
- *Stepwise Compressing Tubes (SCT)*

Two tests are conducted to evaluate the concepts: a field test in section 2.4.1 to see how they perform on a cow and a cleaning test in section 2.4.2 to analyse their cleaning capabilities. The results are then discussed in section 2.4.3.

For the first prototypes of the concepts, it is chosen to require them to fit the dimensions of a rubber test-teat, so they could be tested without requiring an actual cow. It is assumed that the test teat roughly resembles the dimensions of an average teat.

## 2.1. Origami Vacuum Gripper

This concept utilizes compliant origami structures that are actuated with vacuum and therefore fits in the so called 'soft robotics' field. The working principle of this concept is inspired by a gripper designed by researchers from Harvard and MIT [11]. It consists of an origami-inspired cone shaped skeleton that is encapsulated by a balloon, forming an airtight skin. When air is then sucked out of the balloon it shrinks and force the skeleton to fold, creating a gripping motion. This makes it suitable for gripping a large range of objects, from heavy rigid objects like food cans to more delicate objects like fruits. This 'soft' gripping motion could also be used to 'catch' cow teats and perform the pretreatment before milking. By closing the gripper around the teat and pulling it down, a motion similar to that of a farmer's hand while cleaning the cows teat is created. It also shows potential for premilking the cow, based on the same motion. Manual milking techniques are further explained in section 2.3.

The skeleton is fabricated using a 3D printer and the flexible material TPU. The gripper built by Harvard and MIT was made using two manufacturing techniques: using 3D printed molds to cast a silicon origami skeleton or laser cut self-folding sheets [11]. However, for this thesis, it was decided that directly 3D printing the skeleton with flexible material would be the most efficient and easy manufacturing method.

The first iteration of the Origami Vacuum Gripper (OVG) has a 3D printed TPU skeleton (Prusa i3 MK3 FDM 3D printer, and 'NinjaFlex' filament), which design is based on the origami 'magic-ball'. The magic-ball is based on a repeating waterbomb pattern and folded from a rectangular piece of paper, featuring squares with diagonal folds and a vertical fold in the middle [11], as shown in figure 2.1. This pattern is then offset by a half-unit the next row, repeated every row for the whole sheet. The two opposing vertical edges of the paper are then connected, creating a structure that can reversibly change from a spherical shape to a cylindrical shape. The skeleton for the OVG is dimensioned in a

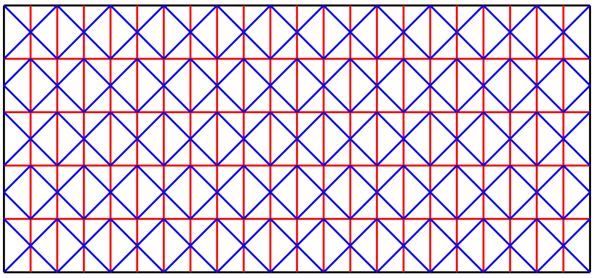
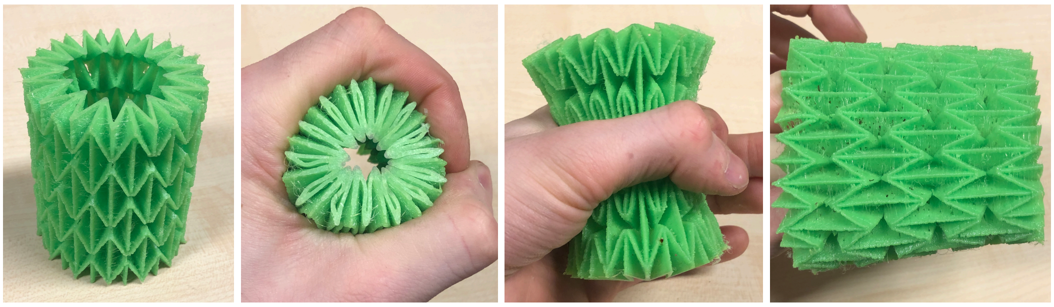


Figure 2.1: Waterbomb tessellation folding pattern in 2D [11]

way that it can alter between half a spherical shape and a cylindrical shape, giving it the ability to grab objects.

Before printing the half-spherical skeleton, multiple cylindrical shaped waterbomb tessellations were 3D printed to test the folding technique, as is shown in figure 2.2. The use of printed support (extra material that can later be removed in order to support for example overhanging parts) was not possible since, in contrary to printing with PLA, the TPU support cannot easily be scraped off due to its flexibility. The results of the first prints were promising and the waterbomb tessellation folded correctly with a wall-thickness of one layer (with a nozzle of 0.6 mm). However, since no support could be added and the material is flexible, the print quality was poor with gaps between printing layers.

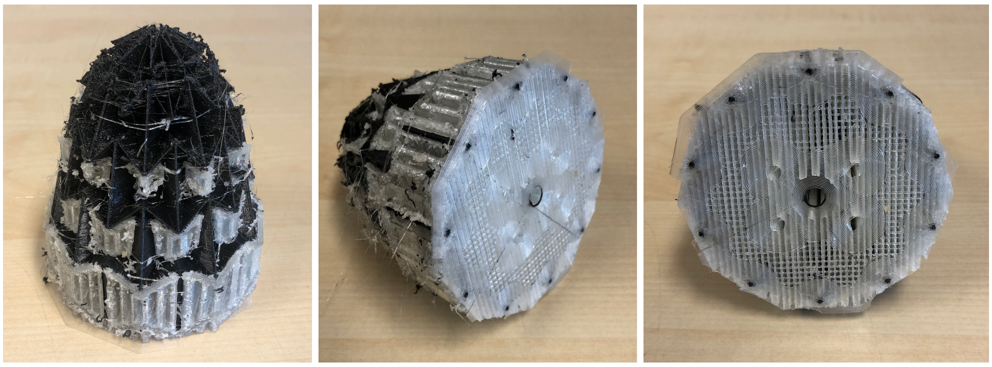


(a) (b) (c) (d)

Figure 2.2: One of the first test prints of the cylindrical waterbomb structure. (a) The cylinder in unfolded state. (b)&(c) Demonstration of its folding capabilities (d) Gaps between the layers show the poor print quality.

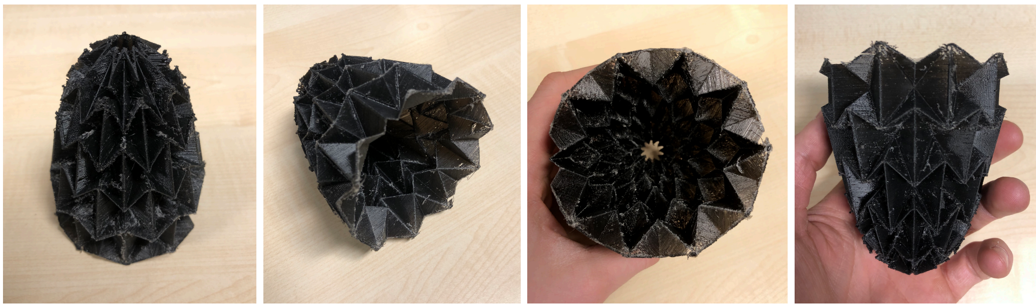
After 3D printing origami structures gave promising results, multiple half-spherical skeletons were printed with different wall thicknesses. Since the half-spherical shape would result in even more overhanging parts of the print and thus gaps between layers, it was decided to use an Ultimaker S5 3D printer with two nozzles, one printing TPU and one printing PVA. PVA dissolves in water and is therefore perfect as a support material as it can be removed from hard to reach places without damaging the print by simply putting it in a bucket of water for a few days. The 3D printed origami skeleton including the PVA support is shown in figure 2.2. It can be seen that 'stringing' occurred during printing, leaving small strings of TPU between gaps in the model. These strings are later removed with a small lighter. The PVA support improved the print quality greatly and made it possible for the waterbomb tessellation to be printed in a half-spherical shape, enabling it to make the gripping motion. Three models with a wall thickness of 0.4 mm, 0.6 mm and 0.8 mm were printed and examined. The 0.4 mm version's lower stiffness was desired, but with such a thin wall thickness (one layer), the skeleton showed gaps between the layers and was therefore too fragile. Therefore, the 0.6 mm model was chosen for the first prototype, shown in figure 2.4.

For the first prototype of the OVG the air tight skin was an ordinary latex balloon with a 3D printed connector that holds the skeleton in place and to which the balloon and a tube connected to the vacuum pump are attached. The connector has several holes to connect the cavity inside the balloon to the vacuum tube. A vacuum reducer was placed between the gripper and the vacuum pump, providing control over the gripping force. An extra hole was added to the connector outside of the balloon, making it possible to switch between sucking air from either outside the balloon or inside the balloon



(a) (b) (c)

Figure 2.3: The origami skeleton including the PVA support material (white) before it's dissolved in water and washed off. In (a) 'stringing' of the TPU is visible, which is later removed with a small lighter.



(a) (b) (c) (d)

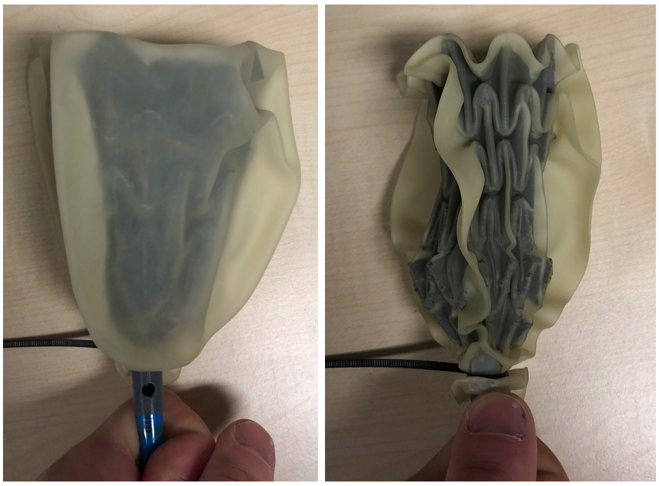
Figure 2.4: The half-spherical waterbomb magic-ball skeleton with a 0.6 mm wall thickness.

by covering it with ones finger. Although there seems to be potential for performing premilking, this concept in this stage is focused on cleaning and stimulation of the teat.

## 2.2. Alternating Rotating Brushes

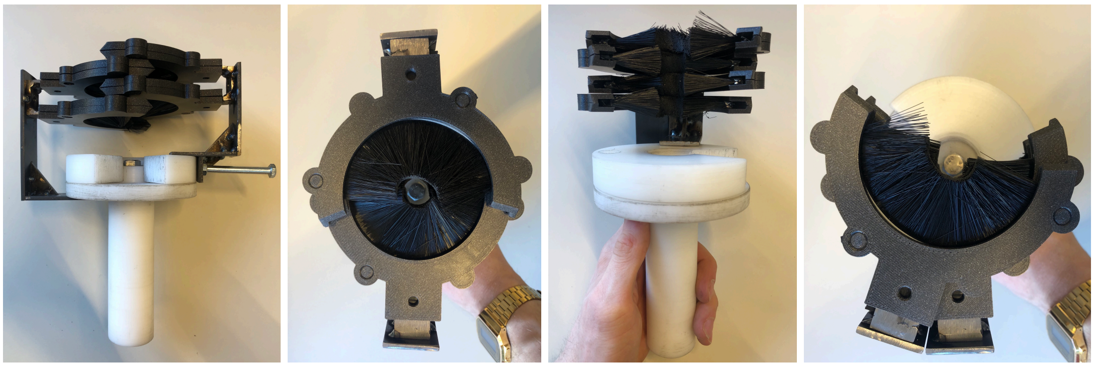
This concept consists of four semi-circular brushes stacked on top of each other, as can be seen in figure 2.6. The first and third brush are connected to each other, as well as the second and the fourth. These two pairs of brushes then rotate in opposite directions around the same Z-axis, cleaning and stimulating the teat that's positioned on the same axis. By rotating the pairs of brushes in opposite directions, the rotations cancel each other out and prevent the teat from twisting. The rotating parts are shaped in such a way that the pairs of brushes can rotating roughly 340 degrees relatively to each other. In order to insert the teat, the brushes are aligned as much as possible, creating an opening on one side. The brushes are then positioned against the teat and 'catch' it by rotating around it. After brushing, the device can simply be pulled off or the brushes can be rotated to open again. This concept does not perform the premilking stage, only cleaning and stimulating.

The prototype consists of a plastic handle with a rotating plastic ring on top. Two upwards pointing steel strips are attached to the handle and the ring. To these vertical strips the four brushes are connected, two to each strip. The brushes are made from an aluminium weather strip. This was found to be the best option for a prototype brush that can be bent into the semicircular shape. Each brush is then clamped between two semi-circular 3D printed PLA parts and attached to the upward pointing steel strips. The inner diameter of the semi-circular brush-holders is 80 mm, with brush hairs of 30 mm, leaving a 10 mm opening for the teat.



(a) (b)

Figure 2.5: The first prototype of the OVG. (a) shows the gripper in unfolded state. In (b) the hole in the connector outside of the balloon is covered, closing the gripper.



(a) (b) (c) (d)

Figure 2.6: The Alternating Rotating Brushes prototype. (a)(b) The brushes in closed position, side view and top view, respectively. (c)(d) The brushes in open position, side view and top view, respectively.

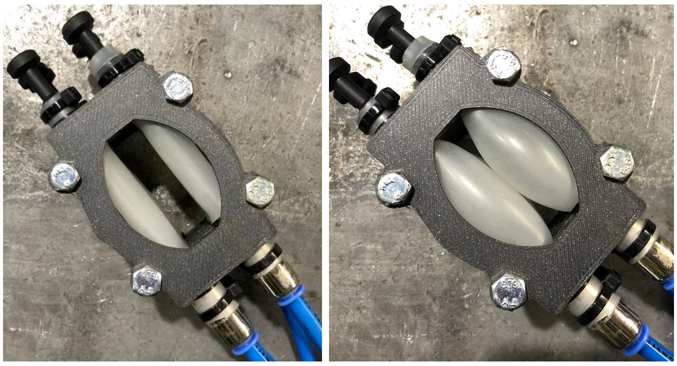
## 2.3. Stepwise Compressing Tubes

This concept consists of three pairs of inflatable silicon tubes stacked on top of each other, that can be actuated individually while the teat is inserted between them. By inflating the top pair first and subsequently the second and third in a stepwise manner, a peristaltic motion is created, much like the manual milking technique discussed in 1.1. The housing consists of four 3D printed PLA pieces that are stacked and clamped together with four bolts. It contains the in total six silicon tubes, as shown in figure 2.7. The silicon tubes have a wall thickness of 1 mm and a diameter of 12 mm. Each 'step' consists of two tubes that are connected to a switch that is connected to a compressor. This way all three steps can be actuated individually and create the top-down squeezing motion. Keeping the distance between the pairs of tubes as small as possible will create the highest pressure inside the teat. The cleaning of the teat is based on scraping the dirt off from base to tip using the inflated tubes and pulling the device down. This concept focuses mainly on the premilking stage.

The prototype has an ellipse shaped opening of 50 mm by 38 mm and the pairs of tubes running parallel to the long side of the ellipse, as can be seen in figure 2.8. This resulted in the tubes having to be inflated less to squeeze the teat and prevents buckling of the tubes. This is further explained in appendix C.

(a) (b)

Figure 2.7: The Stepwise Compressing Tubes prototype. (a) Disassembled, showing the four 3D printed pieces that are stacked, with the six inflatable tubes. (b) Assembled.



(a) (b)

Figure 2.8: The second Stepwise Compressing Tubes prototype. (a) Non-inflated running straight. (b) Inflated, showing no buckling in the tubes.

## 2.4. Methods and Results

### 2.4.1. Concepts Field Test

The concepts and their prototypes discussed in the previous chapter were tested on real cows to see if they were capable of catching the teat and (if applicable) perform the premilking. The cow teats were not dirty enough to test the cleaning performance, so a separate cleaning test is conducted in chapter 2.4.2.

**Origami vacuum gripper** Prior to testing the OVG, the force that would be applied by the gripper was adjusted with the vacuum reducer to a force that would firmly grab the cow's teat but did not cause discomfort. The gripper was then placed on the teat, covering it completely. By closing the air hole on the connector, the gripper closed and was pulled down in closed state until it was pulled of the teat.

The gripper performed well: it closed and opened smoothly by applying the thumb to the connector hole and the cow did not seem to be bothered during the process. The grip was strong, confirming the cleaning and stimulating potential of the concept, which could be enhanced by adding a textured liner inside the gripper. There was no premilking during the test. It is thought that the structure of the skeleton was too pointy and therefore does not apply a uniform radial force to the teat to close it off sufficiently. Furthermore, the gripper was too short to grip up to the base of the teat. However, the strong grip did show potential for premilking later in the design process.

An important aspect of the concept that would have to be improved was its lack of adaptability to different teat shapes and sizes. Although an improved version of skeleton's shape and size could fit all teat sizes, the force applied to the teat in closed state depended heavily on the amount of vacuum inside the balloon and the diameter of the teat itself: the gripper had a very high stiffness in closed state. Therefore, the pressure inside the balloon would have to be adjusted for each teat size, which was not ideal. This could most likely be resolved by using a more flexible origami skeleton, meaning that a smaller vacuum is needed to close the gripper and therefore less force will be applied to the teat. This would result in a bigger range of suitable teat diameters.

]


(a) (b) (c)

Figure 2.9: (a) Placing the gripper around the teat (b) Closing the gripper by covering the connector hole (c) Pulling the device down.

**Alternating rotating brushes** The brushes were aligned to one side and pressed against the teat, so that the teat could then be ’caught’ by the brushes by rotating them around it. The brushes were then rotated multiple times. In order to release the teat, the brushes would then be aligned again, or the device would be simply pulled down.

The ARB prototype also performed well: the brushes reached all around the teat and the alternating rotation of the brushes prevented the teat from being twisted in one direction. Furthermore, the catching of the teat by rotating the brushes around it went smoothly. It was assumed that the device also has a stimulating effect, based on the brushing motion and tactile stimulation being considered the most effective method [8]. The cow did not seem to be bothered by the device.

It was found that the catching technique only worked for smaller diameter teats, since wider teats would get pushed out by the brushes and possibly get stuck between the rotating parts. This problem could be solved by using larger radius brushes with softer hairs and a larger opening. This would give more room for the teat to be inserted in and make it less likely to be pushed out. However, the fact that there were gaps that a teat could get stuck in between is unacceptable and safety features would have to be added to prevent this.

(a) (b) (c)

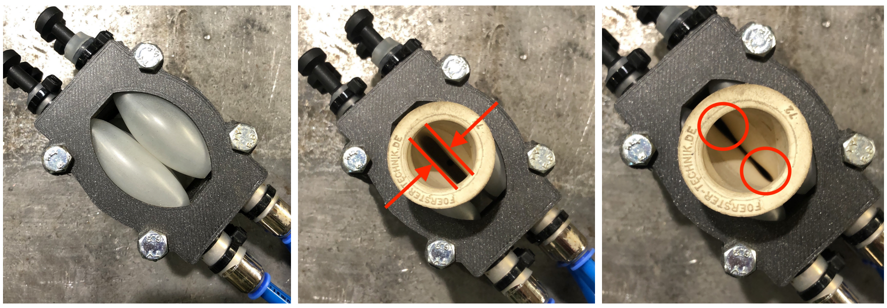
Figure 2.10: (a) Opening the brushes and place teat in the center (b) Rotating the brushes around the teat (c) Rotating the brushes around the teat for cleaning.

**Stepwise Compressing Tubes** Prior to the test, the force that would be applied to the teat was adjusted with a pressure regulator and tested by inserting one's thumb to ensure not to hurt the cow. A pressure of 1.2 bar was found to firmly squeeze the thumb without feeling discomfortable. The teat was inserted in the top opening, after which the three sets of tubes were inflated in sequence, top to bottom, and then deflated all at once. This process was repeated several times. The switching of the valves was done manually with three valves connected to the three pairs of inflatable tubes and the compressor. The interval between the switching of the valves was roughly one second for the first test. After seeing no premilking results, the pressure was increased to 1.5 bar, the maximum without hurting one's thumb. Furthermore, the interval between inflating the stages was reduced to about 0.6 s, which was the fastest possible with this setup. To make the premilking easier for the second test, the cow was milked a few streams manually to fill the teat with milk. Still, the SCT prototype did not perform the premilking. The tubes inflated nearly evenly and it was clear that the teat was being compressed as it also elongated slightly, but there was no result.

(a) (b)

Figure 2.11: (a) Placing the teat inside the device, between the tubes (b) Inflating the tubes stepwise, from top to bottom and releasing all at once.

It is thought that the premilking failed because one (or more) of the following reasons, shown in figure 2.12. Firstly, the teat is compressed from only two directions, deforming the teat into an elliptical or even flat shape, but not decreasing its cross-sectional area enough to stop the milk from flowing back up into the udder. Secondly, the silicon tubes don't evenly increase in diameter along their length when inflated, but instead are the widest at the center. This could result in the teat being compressed the most in the middle, while having an opening at the sides, as shown in figure 2.12. The final reason could be that the pairs of tubes have too much distance between them to create a peristaltic motion. Instead of pushing the milk downward, some milk is pushed back up between the tubes when the next pair of tubes is inflated, resulting in a lower pressure inside the teat.



(a) (b) (c)

Figure 2.12: The Stepwise Compressing Tubes. (a) A pair of inflated silicon tubes, showing a much larger diameter in the centre. (b) An inserted rubber test teat is inserted and shows how the two silicon tubes only compress the cow's teat from two directions, resulting in a ellipse opening instead of closing it. (c) When compressed further, it is evident that the center of the teat is more compressed, leaving an opening at both sides.

### 2.4.2. Concepts Cleaning Test

To evaluate the prototypes their ability to clean a cow's teats, a cleaning test is conducted. Test teats are made dirty using mud from a ditch and then cleaned using the prototypes. The teats were cleaned using the prototypes until the test-teat was clean, or as clean as possible with that prototype. The cleaning test is performed three times: once with wet mud, once with semi-dry mud and once with dry mud. It became clear that the drier the mud, the more difficult it was to remove it. Only the cleaning tests with semi-dry mud are shown in this chapter, since these are thought to give the best impression of the device's cleaning capabilities. Images of all cleaning tests can be found in the appendix D. What should be kept in mind is that these are extreme scenarios, and that teats encountered by a milking robot are mainly a lot less dirty. However, it's valuable to know how a concept would function in such a scenario. The current system used by Lely is also tested to set a benchmark for the level of cleanliness the final design has to be able to accomplish (Requirement 1).

**Lely Rotating Brushes** The rotating brushes used by Lely were made slightly wet before testing. When operated by the Astronaut A5 automatic milking system, the rotating brushes are positioned against the teat from below and moved up and down along the teat once, for roughly two seconds. To simulate this process, the test-teat was inserted between the brushes for two seconds as well. When inserting the teat, a significant force could be felt applied to it by the brushes, pulling it in between them.

(a) (b) (c)

Figure 2.13: The test-teat covered in semi-dry mud (a), the test teat inserted between the rotating Lely pretreatment brushes (b), the cleaning result (c).

As can be seen in figure 2.13, the test-teat was not completely clean after cleaning a test-teat covered in semi-dry mud, leaving a few spots of dirt, mainly at the area where the two brushes meet.

**Origami Vacuum Gripper** As can be seen in figure 2.14, a textured liner (green) much like that of scouring sponge was added to improve its cleaning abilities, since it was found that without any texture the latex balloon would just spread the mud instead of removing it. Furthermore, the liner is made wet before testing. Similar to the field test, the gripper was closed around the teat as far up as possible, and pulled down until the teat is removed. This is then repeated until the teat is clean.

With the liner, the OVG did a decent job at removing the dirt, but it was found that the liner got clogged up quickly with the large amounts of mud that were being removed. A less dense, more brush-like type of liner and some kind of suction/dirt-removal system would most likely improve the results.

**Alternating Rotating Brushes** The ARB were also made wet before testing. Similar to the field test, the brushes are wrapped around the teat and subsequently rotated back and forth until the teat is clean.

The ARB prototype performed very well and cleaned the test-teats with ease, as can be seen in image 2.15. It had to be moved up and down slightly to clean the whole teat, but this could be fixed by for example using bigger brushes or adding an extra brush. Furthermore, the brush hairs could be pointed slightly upward, improving the cleaning effect on the tip of the teat.

(a) (b) (c)

Figure 2.14: The test-teat covered in semi-dry mud (a), gripping of the OVG (b) and result (c) of the OVG cleaning a semi-wet test-teat.

(a) (b) (c)

Figure 2.15: The test-teat covered in semi-dry mud (a), rotating motion of the ARB (b) and result (c) of the ARB cleaning a semi-wet test-teat.

**Stepwise Compressing Tubes** In order to clean with the SCT, the test-teat was inserted into the prototype, the top set of tubes would be inflated and the device was pulled down, removing the dirt along the way. Although the SCT did not focus specifically on the cleaning stage, this wiping motion worked surprisingly well on the wet teat. However, two streaks of mud would remain on the sides where the tubes do not touch the teat. Furthermore, with the more dry mud, the tubes can't apply enough force to wipe the dirt of the test-teats, as can be seen in figure 2.16. A liner made of the same material as that of the OVG was added and it improved the dirt-removal, but it was still far from sufficient.

**Results** Table 2.1 shows the results of the concept cleaning tests. The amount of repetitions, level of cleanness and whether the tip of the test-teat is cleaned are indicated. The tip of the teat is given extra attention, because the dirt that is still on there while milking will have the biggest chance of ending up in the bulk milk.

During testing, it was concluded that all concepts would most likely clean better when a spraying system is added that can rinse the teat clean, since the wet dirt was significantly easier to remove than dried up dirt. This is also true for the Lely brushing system. The tips of the test-teats were only clean twice, both with the wet dirt tests of the OVG and ARB. Whatever concept will be chosen, this has to be improved.

It is evident that the ARB has the best cleaning results of the concepts and even the Lely brushes. However, the Lely brushes were only used for one repetition and the ARB were used until the teat was clean (or as clean as possible). The OVG also performed well, but needed roughly twice as much repetitions than the ARB. Especially the OVG would benefit from a spraying system. Like already mentioned before, the SCT performed poorly during the cleaning test. This concept would have to be

(a) (b) (c)

Figure 2.16: The test-teat covered in semi-dry mud (a), attaching and inflating of the SCP (b) and result (c) of the SCP cleaning a semi-wet test-teat.

combined with another concept in order to be able to clean properly.

| Concepts | Test | # repetitions | Clean (1-3)* | Tip clean |
|---|---|---|---|---|
| **OVG** | Wet | 4 | 2 | x |
| | Semi-dry | 8 | 2 | |
| | Dry | 15 | 2 | |
| **ARB** | Wet | 2 | 3 | x |
| | Semi-dry | 4 | 2 | |
| | Dry | 8 | 2 | |
| **SCT** | Wet | 1 | 2 | |
| | Semi-dry | - | 1 | |
| | Dry | - | 1 | |
| **Lely brushes** | Wet | x** | 3 | |
| | Semi-dry | x** | 2 | |
| | Dry | x** | 2 | |

Table 2.1: The results of the concepts cleaning test. *: 1 = not clean, 2 = needs rinsing with water, and 3 = clean (visually clean, a few small spots of dirt is acceptable). **: For the Lely brushes, one stroke means inserting the test-teat for 2 seconds like their milking robot does. It is only done once to see what results the system has, the way it's used now by Lely.

### 2.4.3. Concepts Conclusion

Based on the field test and the cleaning test, one of the three concepts was chosen to be iterated further into a final design. In order to give an overview of all the findings during testing a weighted Harris profile is created (table 2.2). Criteria are listed and per concept a value of double minus (–), minus (-), plus (+) and double plus (++) can be given per criteria. Furthermore, the criteria are given weights from 1 to 5 (with 5 being the highest weight), depending on the importance the criteria is valued to have. The meaning of these values per criterion and the reasoning behind the criterion's weights are given in section 2.4.4. The criteria are listed from highest to lowest weight.

### 2.4.4. Criterion values and weights

When evaluating these values and assigning their weights, it was considered that the prototypes that were being evaluated were still in the early phase of the design process. Therefore, the criteria were evaluated partly on the performance of the prototype but also on the results their final design and prototype are estimated to achieve. A good example is the cleaning results that will most likely significantly improve when a spraying system is added, or the premilking effect that had not yet been achieved with the OVG. Furthermore, even though Safety and Size were considered important criteria, they were given low weights, since these aspects could be improved, but it's hard to estimate to what extent.

**Cleaning** This is considered the most important criterion (Requirement 1) and therefore given a weight of five, since it's the main objective of the device. The values are described as follows, based on the cleaning results from section 2.4.2:

– Not able to clean the teat at all

\- Not able to clean the teat sufficiently

\+ Almost able to clean the teat sufficiently

++ Same cleaning result as the Lely brushes or better

**Simple** This criterion is based on Wish 2 and given a weight of four. It's considered important to keep the design and its actuation simple. Furthermore, being able to actuate the device from a distance, by using for example pneumatics, simplifies the design.

– Multiple actuators in the device or multiple actuators at a distance, multiple rotating or sliding parts, multiple actions needed for pretreatment

\- Multiple actuators in the device or multiple actuators at a distance, one rotating or sliding part, multiple actions needed for pretreatment

\+ One actuator in the device or multiple actuators at a distance, one rotating or sliding part, multiple actions needed for pretreatment

++ One actuator in the device or one actuator at a distance, one rotating or sliding part, one action needed for pretreatment

**Premilking** Premilking is given a weight of four, since it would be a big improvement from Lely's current system (Wish 1).

– No premilking results, cannot be achieved

\- No premilking results, but can potentially be achieved

\+ Premilking results, but needs to be improved

++ Sufficient premilking results

**Safety** Safety is a very important criterion (Requirement 5) since the cow must not get hurt during the pretreatment. However, improvements can be made to the prototypes to improve their safety, which is why the criterion has a weight of three.

– Aspects with a chance of hurting the cow, that cannot be improved

\- Aspects with a chance of hurting the cow, that can potentially be improved

\+ Aspects with a chance of hurting the cow, that can be improved

++ No aspects to that can hurt the cow at all

**Size** Requirement 7 states that the devices has to be smaller than the existing Lely pretreatment system (3 liter), and Wish 3 states that it should be as compact as possible when not deployed. The weight is only two, since the size can most likely be improved when iterating the designs.

– Bigger than the Lely pretreatment system when not deployed

\- Between the size of a milking cup and the Lely pretreatment system when not deployed

\+ Roughly the size of a milking cup when not deployed

++ Smaller than a milking cup when not deployed

| | | OVG | | | | ARB | | | | SCT | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Criteria* | *Weight (1-5)* | **–** | **-** | **+** | **++** | **–** | **-** | **+** | **++** | **–** | **-** | **+** | **++** |
| **Cleaning** | 5 | | | x | | | | x | x | x | x | | |
| **Simple** | 4 | | | x | | | | x | x | | | x | |
| **Premilking** | 4 | | x | | | x | x | | | x | x | | |
| **Innovative** | 3 | | | x | x | | | x | | | | x | |
| **Safety** | 3 | | | x | x | | x | | | | | x | x |
| **Size** | 2 | | | x | | | | x | | | | x | x |
| **Total score** | | **19** | | | | **12** | | | | **-1** | | | |

Table 2.2: The weighted Harris profile used to choose the concept for the final design and prototype.

**Innovative** It's considered important that the device is based on a technique or method that's new in the world of pretreatment techniques (Wish 3). This evaluation is based on the literature and patent study [8], that can be found in appendix A. However, this is a difficult criterion to measure, which is why it's given a weight of two.

– The technique is not new and already used by manufacturers of automated pretreatment techniques

\- The technique is not new, but a new variation on one or a combination of techniques

\+ The technique is not new, but is not used by manufacturers of automated pretreatment techniques

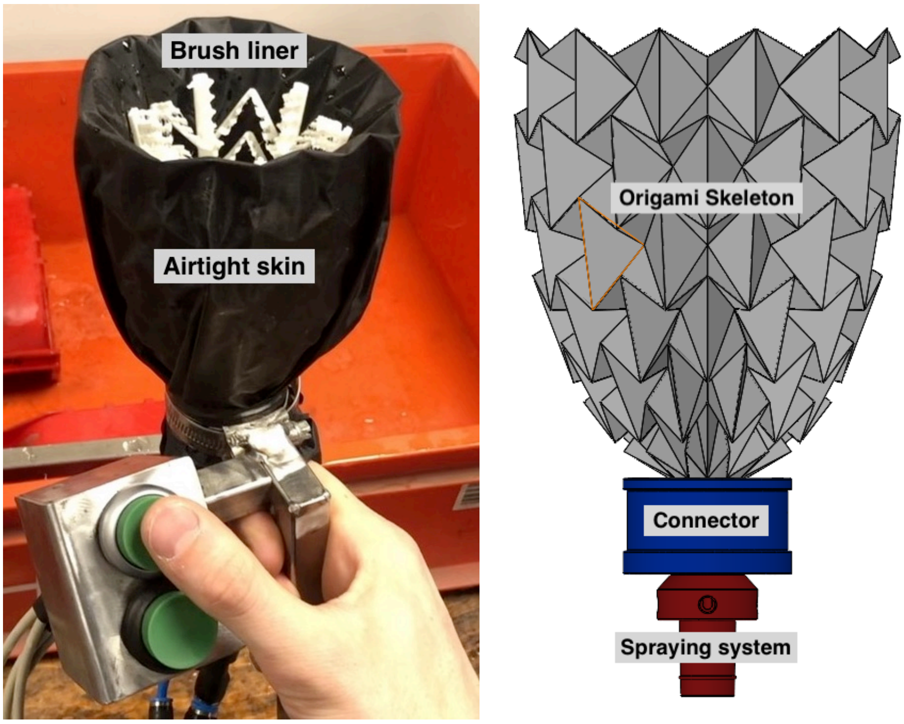
++ The technique is completely new in the field of automated pretreatment techniques

**Conclusion** The weighted Harris profile shown in table 2.2 resulted in the following total scores per concept: 19 points for the OVG, 12 points for the ARB and minus 1 point for the SCT. Based on these scores it wis decided that the OVG has the most potential for fulfilling the requirements and wishes to the largest extend when it's further iterated into the final design.

The following aspects of the design needed to be improved. The dimensions of the gripper had to be adjusted so it can fit all teat sizes of the Holstein cow. An alternative to the latex balloon had to be found to fit this bigger skeleton. Research on the optimal geometry of the origami skeleton could improve its gripping performance. By adding a linear actuator, preferably also based on a vacuum actuated origami structure, the robot arm could stay still while the OVG pretreats each teat. A spraying system had to be added to improve the cleaning performance. A more advanced connector had to be designed that connects this spraying system, the airtight skin around the skeleton and the vacuum tubes for the gripper. Furthermore, by adding a suction tube at the bottom of the gripper, much like a milking cup, the water and dirt could be removed from inside the gripper. This vacuum inside the gripper could also help performing the premilking. Finally, a textured liner had to be added that does not get clogged with dirt and open and close with the gripper.

# 3 Final Design

In this chapter, the final design based on the Origami Vacuum Gripper concept is elaborated. The final design can be seen in figure 3.1, together with a schematic illustration of the device. This illustration shows the different components of the device, which are discussed separately in the following sections. Finally, a field test is conducted once more to evaluate the final design and it's prototype, and the grip strength of different origami skeleton dimensions is tested.




(a) (b)

Figure 3.1: The final prototype in real life (a) and schematic (b), labeled with the names of the different components.

## 3.1. Teat Dimensions

Cow teats differ greatly in shape and size, as can be seen in figure 3.2. This was also confirmed during the first field test in section 2.4.1, considering how some teats would have a good fit while others were too big or too narrow.

(a) (b) (c)

Figure 3.2: Three examples of different teat dimensions, shapes and orientation seen at the test farm. (a) Wide, short and stubby. (b) Narrow, long and more pointy. (c) Orientated inward.

As stated in the requirements, the final design should be able to fit all teat variations of Holstein cows. A paper was found on the teat dimensions before and after milking of Holstein cows [7], on which the range of teat dimensions that is required to fit inside the device is based. The relevant dimensions and portions are illustrated in figure 3.3 and the dimensions are given in table 3.1. The teat apex is about 25% of the total teat's length, at the end of the teat.

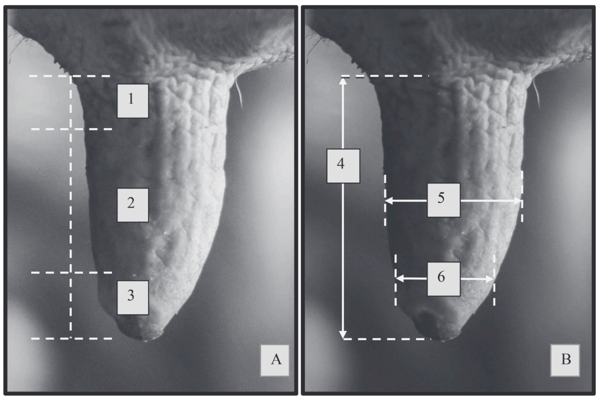



Figure 3.3: "Anatomical portions of the teat and measured segments. (A) Anatomical division of the teats: (1) teat base, (2) teat barrel, and (3) teat apex. (B) Teat segment measured before unit attachment and immediately after automatic unit detachment: (4) teat length, (5) teat barrel diameter, and (6) teat apex diameter." [7]

Table 3.1: Teat dimensions range and mean of Holstein cows before milking [7].

| | Range (mm) | Mean (mm) |
|---|---|---|
| **Teat length** | 30-80 | 46 |
| **Teat barrel diameter** | 14-50 | 24.58 |
| **Teat apex diameter** | 14-30 | 19.63 |

According to this data the OVG needs to be big enough to fit a teat that is 80 mm long with a barrel diameter of 50 mm and apex diameter of 30 mm. Furthermore, it has to be able to fold small enough to be able to properly grip a teat that's 30 mm long with a 14 mm barrel diameter and 14 mm apex diameter.

## 3.2. Origami Skeleton

In the previous section 3.1 the required dimensions for the skeleton are given. The relevant points on the origami skeleton that have to meet these criteria are shown in figure 3.4. Instead of giving the unfolded skeleton the same inner dimensions as the largest theoretical teat, it is chosen to give the opening of the gripper a diameter that's three times the diameter of the mean teat. This makes 'catching' of the teat with the robot arm easier and creates room for the water to be sprayed around the teat while it's inside the gripper.

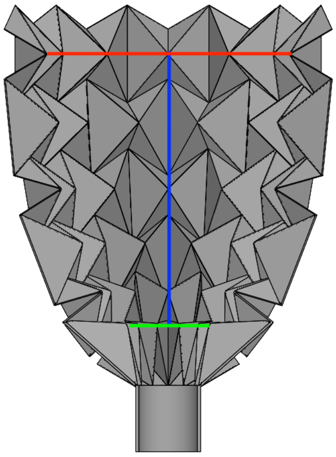
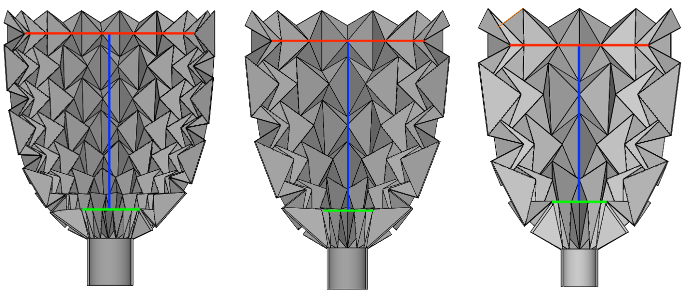


Figure 3.4: The teat dimensions translated to the dimensions of the origami skeleton: opening diameter of gripper (red) = 75 mm, length of gripper (blue) = 80 mm and bottom diameter of gripper (green) = 30 mm. The opening diameter is three times the average teat barrel diameter, the length of the gripper is equal to the maximum length of the teat and the bottom inner diameter of the gripper is the maximum teat apex diameter.

During the design of the origami skeleton the question arose whether it would be more beneficial to have larger 'squares' in the skeleton's pattern. This would result in fewer squares per row to reach the desired inner diameter and therefore less folds. Smaller squares would result in more squares per row and thus more folds. This could have an impact on the stiffness of the skeleton, the required vacuum to fold it to the teat's diameter and eventually the force exerted on the teat. The ideal scenario would be to be able to apply the same force to different diameters of teats using the same level of vacuum, keeping the actuation as simple as possible and having the most consistent pretreatment results.

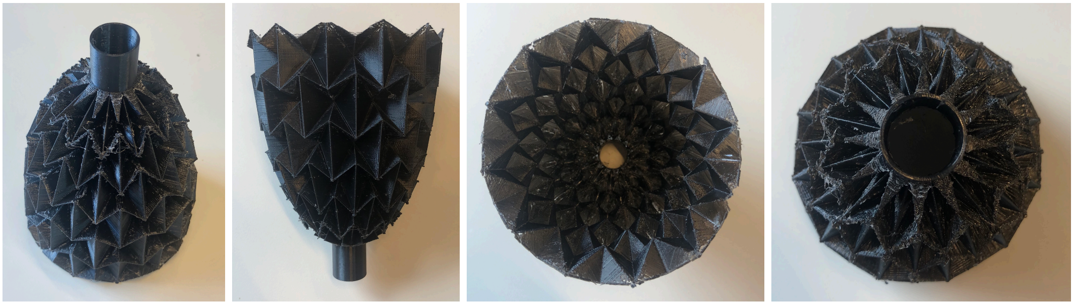
Three different skeletons were designed with three different edge lengths of the squares: 20 mm, 30 mm and 40 mm. The same inner dimensions are used for the skeletons, as can be seen in figure 3.5. The differences in force applied to the teat by the different geometries are researched in section 3.9. These skeletons are 3D printed using a technique called Multi Jet Fusion with the material Ultrasint TPU 90A-01. In section 3.9 these skeletons will be further discussed.



(a) (b) (c)

Figure 3.5: The 20 mm (a), 30 mm (b) and 40 mm (c) skeleton models. The indicated inner dimensions are similar for the three models: red = 75 mm, blue = 80 mm and green = 30 mm.

Due to a long delivery time for the three MJF models, an extra 30 mm square sides model is printed in the meantime using the faster FDM method with the water soluble support like the first prototypes (see figure 3.6). This model was assumed to work sufficiently, since it's very similar to the first prototype's origami skeleton.

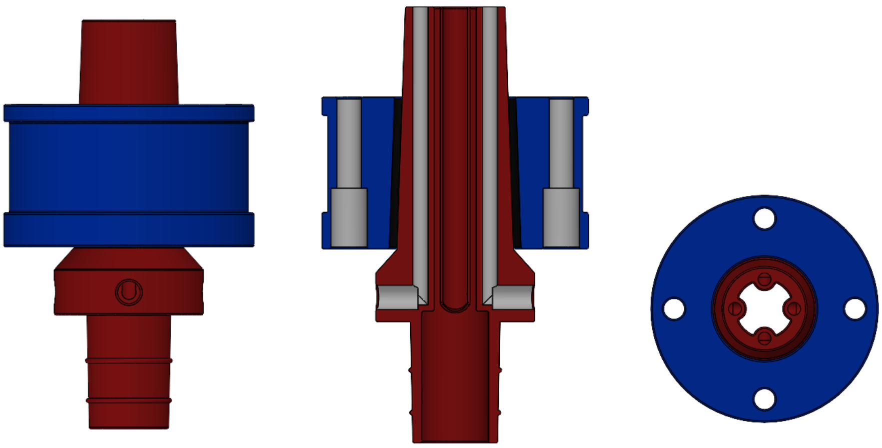


(a) (b) (c) (d)

Figure 3.6: The FDM printed TPU skeleton with the correct dimensions and 0.4 mm wall thickness, that is used for the final field test.

## 3.3. Connector

A new connector (see figure 3.7) has been designed where the vacuum tubes actuating the gripper, the water tubes for the spraying system and the vacuum tube for removing the dirt from inside the gripper can all be connected to. Furthermore, it seals off the airtight skin around the origami skeleton. Finally, it provides a solid base that can be used to secure the OVG to a grip including buttons for easier handling of the device or to a test setup's frame. The connector is 3D printed using a standard Ultimaker S5 (0.4 mm nozzle) FDM printer and PLA as material.



(a) (b) (c)

Figure 3.7: The final connector, consisting of an inner red and outer (blue) part. (a) Side view of the assembled connector. (b) A cross-section, the inner cavities to connect the vacuum and water are shown in grey. (c) Top view of the connector, assembled.

The connector consists of an inner and an outer part. These are shaped conically on the outside and inside, respectively, and clamp into each other (see figure 3.7). This way the skeleton, the inside of the airtight skin and the brush liner are secured in place in an airtight manner. The inner connector functions like a tube, through which the water and dirt are sucked out of the gripper. At the bottom a 14 mm diameter silicon hose is attached, connected to the vacuum tank of a milking system. Furthermore, there are in total four canals inside the walls of the inner connector directing the water for the spraying. These start at the side and perpendicular to the wall, where the tubes providing the spraying water are connected. Then they make a 90 degree turn and run to the top of the connector, where they create four small openings. In each of the openings a thin brass tube is inserted to guide the water further in the right direction. The brass tubes are longer than the connector to make sure that the water is sprayed into the gripper from just below the brush liner. More information on tested spraying methods and their results can be found in appendix E. The outer connector is like a ring that has got four extra holes going through its wall that end inside the airtight skin. The vacuum pump actuating the gripper is connected to these four holes with flexible tubes. Furthermore, the outside of the airtight skin is wrapped around the outer connector and sealed tightly using tape and a stainless steel hose clamp. This hose clamp can be welded to a grip or a test setup, like mentioned before.

## 3.4. Airtight skin

A regular latex balloon was the correct size to be wrapped around the first prototype's skeleton, but it was too small for the final skeleton design. A bigger balloon was sought for, but no realistic alternative could be found. Therefore, it was decided to create a custom airtight skin. It was considered that since the skin would be pulled vacuum instead of inflated, the elastic characteristic of the latex has no function. Furthermore, the new design has a hole in the bottom of the gripper and therefore the airtight skin needs to have an extra opening as well.

Inspiration was found in the paper describing the origami gripper that the initial design is based on [11], where in addition to using a latex balloon the researchers made a custom airtight skin from TPU coated nylon fabric. This material is used for for example waterproof bags, kites and rafts. It's waterproof and can easily be welded to each other with a heating iron [3]. This TPU coating is the same material that is used for the 3D printed origami skeleton and the brush liner, so the fabric can also be welded onto these parts.

The first design of this custom made airtight skin consisted of one large and one smaller conical shape put inside each other and welded together at the top, between which the origami skeleton fitted. However, the welds at the top were big and impractical and difficult to make airtight, so this concept was dropped. In appendix F, this design of the airtight skin is further discussed and what exact types of fabric were used. The final design consists of one big conical shape, shown in figure 3.8. The narrow end is put inside the skeleton and then the other end is wrapped around it, after which it is clamped to the connector. The downside of this design compared to the first is that the radius of the big opening of the cone is considerably larger than the connector it has to be clamped around. However, this turned out not to be an issue, as long as the hose clamp around the connector is tightened far enough. Furthermore, a small tube made from a slightly thicker fabric is welded to the small inner opening, that is clamped inside the connector. This way the two openings of the airtight skin are attached to the connector with an small amount of leakage that the vacuum pump can compensate for.

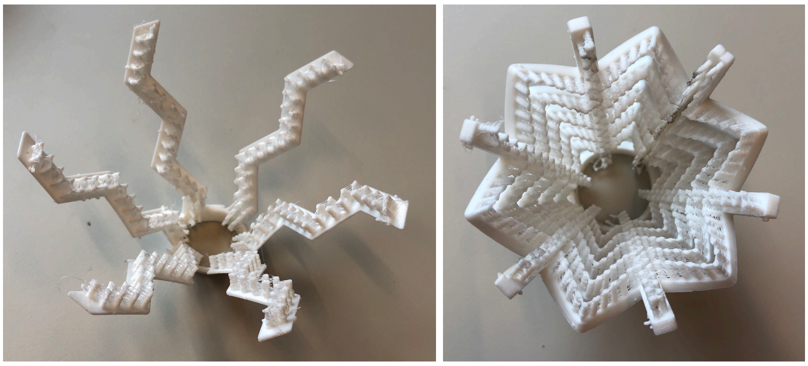
(a) (b)

Figure 3.8: The final airtight skin design. (a) the conical shape of the fabric and (b) the skin wrapped around the origami skeleton and attached to the connector.

## 3.5. Brush Liner

In order to improve the cleaning and stimulating effect of the OVG, a 3D printed TPU (same printer and material as the skeleton) brush liner is designed. The brush liner sits in the gripper directly against the teat, with three pieces of TPU coated nylon fabric attached to it, that are clamped in the connector to secure it.

The brush hairs have to scrape of the dirt and stimulate the teat, but still let water through. This way the dirt can be rinsed off the brush hairs and avoid it getting clogged like the scraping sponge liner in the first cleaning test in section 2.4.2. The liner also has to be able to open and close along with the gripper. Two designs were chosen to test: a puzzle-like design (Puzzle Liner) that has sections that can slide into each other, and one that looks like a badminton-shuttle (Shuttle Liner) with vertical strips of brushes connected with thinner strips that can bend (see figure 3.9.



(a) (b)

Figure 3.9: The two 3D printed brush liner designs: (a) the Puzzle Liner and (b) the Shuttle Liner.

After 3D printing the Puzzle Liner it was clear that the change in diameter of the gripper is too big to make the sliding of the sections work. When folded open, there were large areas not covered by the brush and the sections are too flexible to stay in place. A solution to this could be attaching the flaps to the skeleton's skin, but this was considered impractical with the fabric having lots of creases and folds, and dirt likely accumulating between the liner and the fabric.

The Shuttle Liner however did look promising. Since all sections are connected, it stays in place, while also being able to change in diameter with the gripper. One more slim and flexible version with longer brush hairs was built subsequently to improve it's folding capabilities, shown in figure 3.10.


(a) (b) (c)

Figure 3.10: The improved version of the Shuttle Liner, shown from the top (a), from the side with the flaps that are secured in the connector to keep it in position (b), and inserted in the gripper (c).

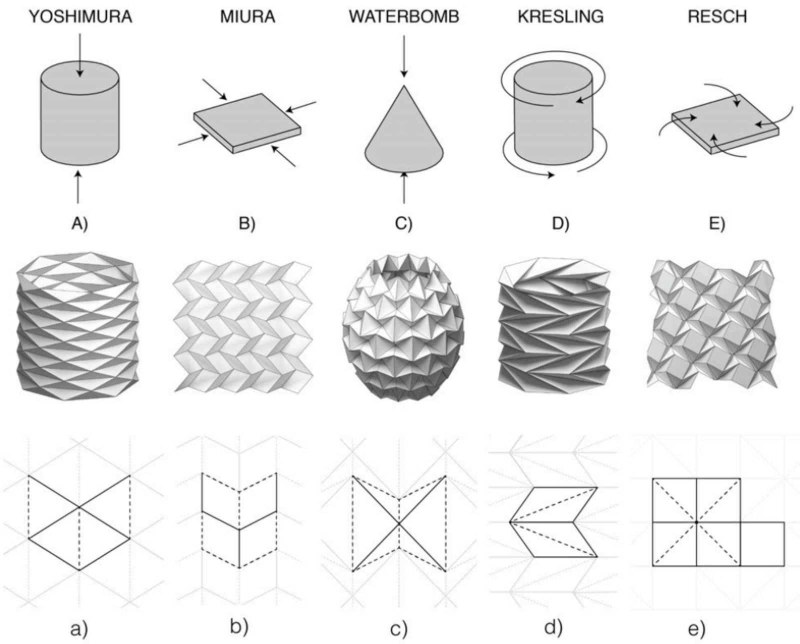



Figure 3.11: Basic origami structures and their geometric relationship between forces and fold patterns. a) Yoshimura cylindrical compression b) Miura transverse planar compression c) Waterbomb conical compression d) Kresling rotational-twist-compression of cylinder e) Resch torsional compression of the plane [5].

# 3.6. Linear Actuation

With Lely's current pretreatment system, the brushes are attached to a robot arm that moves the brushes to the teat, up and down the teat while brushing them, and then to the next teat or to the disinfection station. This could be done in a similar fashion with the OVG, but this device has to be moved up and down the teat multiple times instead of just once. Having a linear actuator that can do this relatively small vertical translation (roughly 10 cm) of the gripper instead of the heavy robot arm would make the system more efficient. Adding an extra actuator would make the system more complex, but if it can be actuated using vacuum like with the gripper, this effect would be minimal. Therefore, research has been done on different origami structures to see if a solution can be found. Figure 3.11 shows five structures and their geometric relationship between forces and fold patterns. The Waterbomb structure is already implemented in the half-spherical gripper design, which can alternate between half-sphere to cylinder. To create a vertical translation, the Yoshimura structure can be used, which is essentially a linear spring. This is interesting for the OVG, since the gripper could be pulled down using vacuum and then be brought back up using the spring's stored energy. Furthermore, the Yoshimura structure has a tube shape that can easily be attached to the OVG's connector and maybe even have the water and vacuum tubes run through it.

Multiple test-prints have been made of the Yoshimura structure with different designs to see what dimensions work best for this application. The diameter of the structures was 50 mm, and there were three variables: the amount of sides per row, the height of a row and the wall-thickness. The models were printed using the same technique as the OVG's origami skeleton, using TPU with PVA support material. In appendix G all test models are shown.

It is measured that the Yoshimura reduces roughly by half in length when completely folded, which is why for the final design a structure of 90 mm is necessary. This way, the gripper would move 45 mm down when the Yoshimura spring is activated, enough to completely move up and down an average teat, which has a length of 46 mm (see section 3.1). The final model is shown in figure 3.12. The model showed good potential for functioning as a vacuum activated spring, but due to limited time and long manufacturing times this was not tested. It was noticed that the origami spring is not only flexible along the Z-axes, but can also bend around the X- and Y-axes. This could help with keeping the gripper attached to the cow when it's slightly moving.

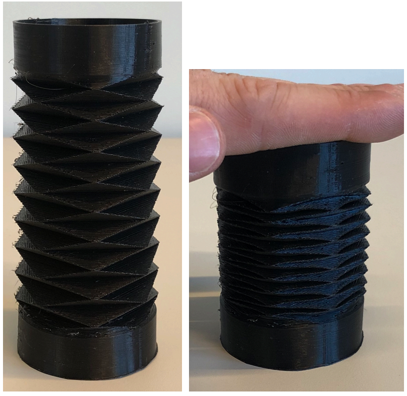


Figure 3.12: The final model of the Yoshimura linear spring, extended (a) and compressed (b).

## 3.7. Premilking

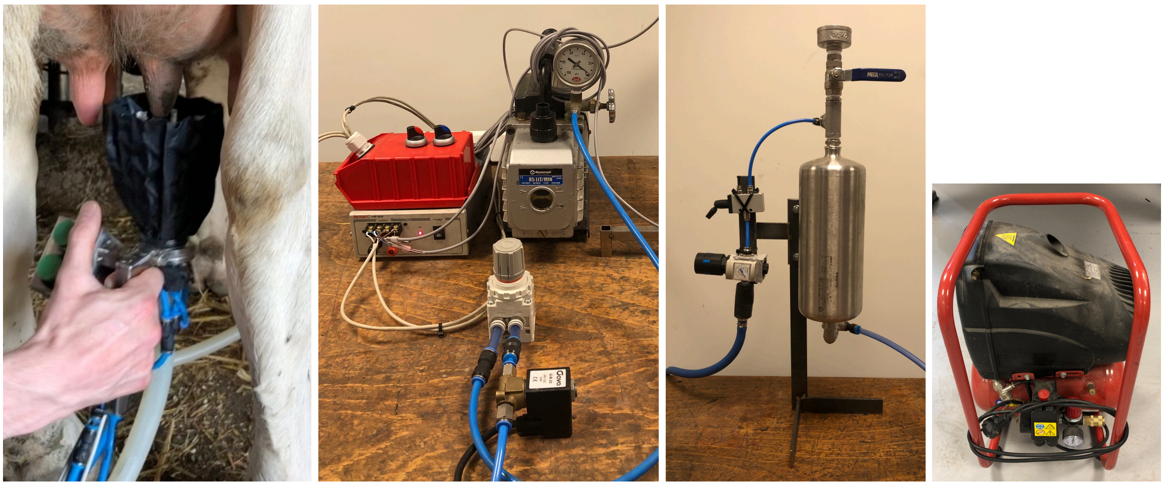
Based on the test results in the concept phase, the OVG was thought to have good potential for being able to also premilk the cow. However, the gripping force of the first OVG prototype was not sufficient to extract any milk from the teat. For the final design, the hypothesis was that a taller origami skeleton that wraps further around the base of the teat in combination with the vacuum applied inside the gripper would create enough pressure difference between the teat and the inside of the gripper to remove a few streams of milk. This is essentially a combination of the two milking techniques described in figure 1.1, with the gripper increasing the pressure inside the teat, and the vacuum inside the gripper decreasing the pressure around the teat.

## 3.8. Final Design Field Test

The final field test consisted of testing the final prototype on multiple cows just before they were machine milked by the farmer. The used test setup is shown in figure 3.13 and consisted of the following components: two solenoid valves for the vacuum tube and water tube, a 24V power supply for powering the solenoid valves, a vacuum pump with a vacuum reducer for actuating the gripper at the desired vacuum level, a pressure tank filled with water for the spraying and a pressure regulator to control the pressure inside the tank. When testing in the field, the silicon vacuum tube for removing the dirt in the gripper is connected to the milking system installed in the barn. Furthermore, a portable compressor is used for pressurizing the water tank. A handle is attached to the connector with two press-buttons. One button activates the solenoid for applying the vacuum to the gripper and the other activates the solenoid of the water spraying system. The device can therefore be controlled using one hand, making testing easier.

Based on the spraying tests in appendix E and empirical evidence while testing on the cows, the following list of steps is considered the most effective technique for pretreating a cow with the device. The technique is demonstrated in figure 3.14.

1. Position the open gripper around the teat.
2. Spray water onto the teat by pressing the bottom button for one second, while keeping the gripper open.
3. Press the gripper against the udder until it sticks due to the suction.
4. Stop spraying and close the gripper by pressing the top button.
5. Pull the closed gripper down, brushing the teat clean.
6. Open the gripper once the teat is pulled out by pressing the top button again.
7. Repeat the previous steps until the teat is clean.
8. One last repetition without the spraying to dry off the teat.



(a) (b) (c) (d)

Figure 3.13: The test setup used for the final field test. It consists of: the final design's prototype including the grip with two buttons and the silicon vacuum tube attached to the bottom (a), a 24V power supply, vacuum pump, vacuum reducer and solenoid valve (b), a pressurized water tank after which a solenoid valve is attached as well (c) and a compressor (d).

(a) (b) (c) (d) (e)

Figure 3.14: The pretreatment technique of the final prototype step-by-step. The dirty teat is shown in (a). Step 1 and 2: Position the open gripper around the teat and spray water with the gripper still open (b). Step 3: Press the gripper against the udder (c) Step 4: Close the gripper around the teat (d). Step 5: Pull the gripper down, brushing the teat clean.

The third step was only discovered when testing at the farm, since there was no milking system available to provide the vacuum needed for the removal of dirt and water before. The vacuum created inside the gripper through the silicon tube at the bottom was proven useful for helping the origami skeleton fold at the top of the gripper. By pressing the opening of the gripper against the udder, a vacuum is created inside the gripper that pulls the edges of the skeleton around the base of the teat. Furthermore, the gripper sticks to the udder because of the vacuum and can hang on its own, like a regular milking cup.

### 3.8.1. Test Results

The field test with the final prototype was successful. As can be seen in figure 3.15, all teats were clean and dry enough after pretreating with the device. Also the tips of the teats were clean, since the water is sprayed from the bottom of the gripper onto the tip. Between two and four repetitions of spraying and brushing were needed per teat, depending on how dirty they were. It's important to consider that the cows that were chosen for the test had been outside all day in a wet field, resulting in extremely dirty teats covered in dried up dirt. For some wider teats (right teat (f) and left front teat (h) in figure 3.15) there was still some dirt in the creases of the skin at the base. This area is the hardest to reach with spraying, and the brush only reaches it briefly while the bottom of the teat gets brushed during the whole pulling motion of the gripper. Like mentioned before, pushing the gripper against the udder to create a seal helped folding the top of the gripper. However, due to the folds at the edge of the gripper, sometimes this seal was not possible. Furthermore, the gripper would often be held at the tip of the teat while spraying, so the water would reach further up to the base of the teat.

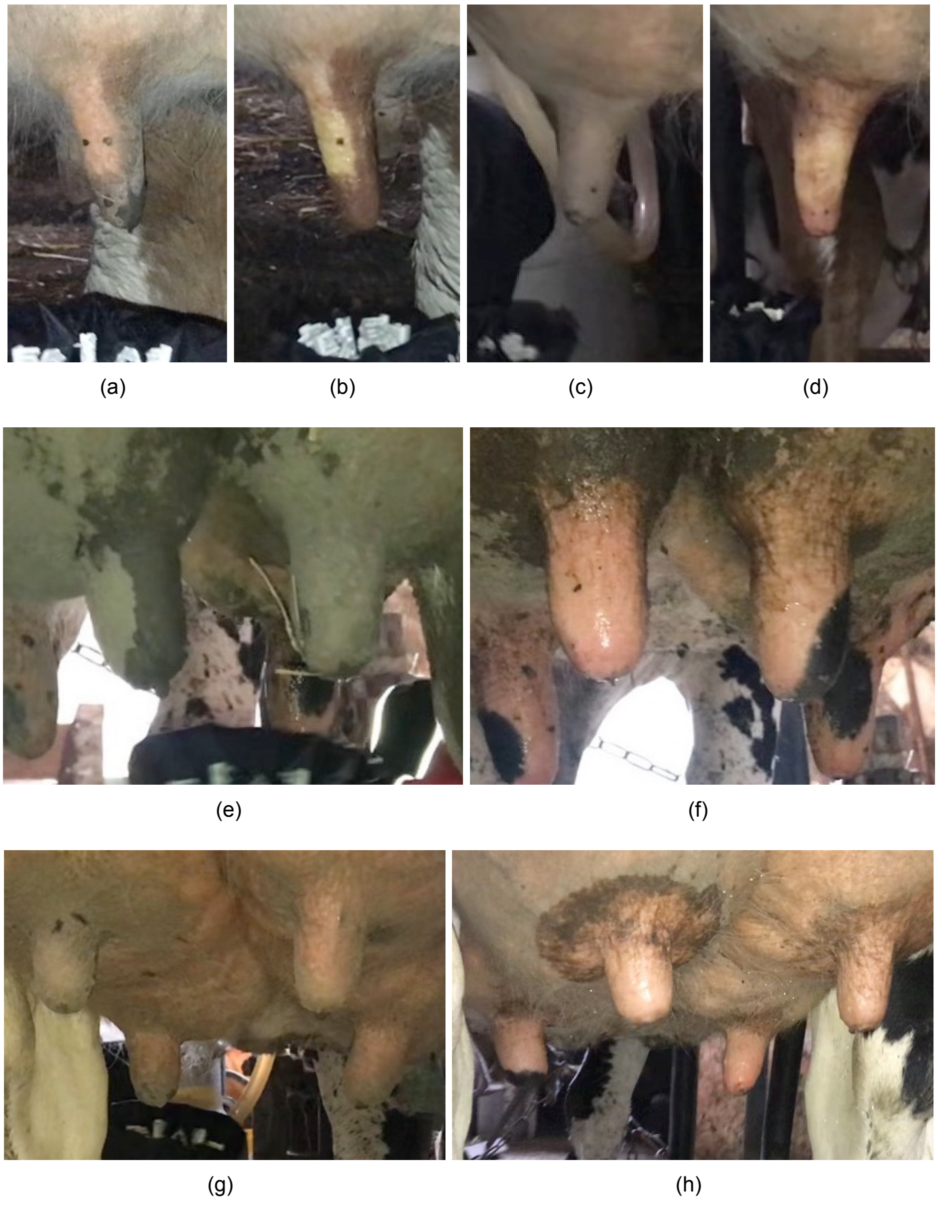
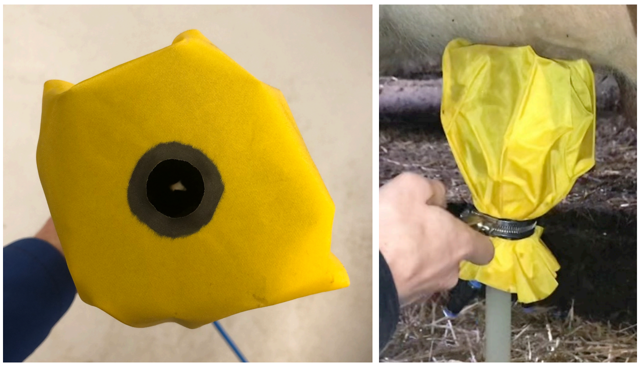


Figure 3.15: Cleaning results from final test with the final prototype. (a) and (b), (c) and (d), (e) and (f), and (g) and (h) show the teats before and after cleaning, respectively, from different cows. Most of the small dark spots remaining after cleaning are skin pigment.

Unfortunately, no premilking occurred during the final field test discussed in section 3.8. It was clear that the cleaning process gave plenty of stimulation, since often milk was leaking from the teats. However, when attaching the OVG, no milk was removed from the teats, not even from the ones that were already leaking milk. A piece of fabric with a hole in the center sealing off the teat was added to eliminate leakage through the brush liner and increase the vacuum inside the gripper (see figure 3.16, but this did not suffice. Also pulsating the vacuum inside the gripper like a milking cup did not help.



(a) (b)

Figure 3.16: The circular piece of fabric with a 20 mm hole in the middle (a), wrapped around the OVG to increase the vacuum inside the gripper to improve the premilking and tested on a cow (c)

## 3.9. Gripping Force Test

Like mentioned in section 3.2, it is desired that the same amount of force is applied to different diameters of teats, while applying the same vacuum to the skeleton's skin. Applying the same force results in a consistent cleaning performance for all teats and requiring only one level of vacuum simplifies actuation. In order to test the gripping force of different origami geometries, three skeletons with different geometries were 3D printed using a technique called Multi Jet Fusion. The main difference between Multi Jet Fusion (MJF) and the Fused Deposition Modelling (FDM) is that instead of laying down layers of molten material on a for example steel printing bed, MJF uses a powder bed where it deposits tiny drops of fusion agent that fuse the powdered material together when heated with infrared lights [1]. This is then repeated for every layer, without the need for extra printed support material, since the powder bed around the model offers the required support. The idea was to test if the origami skeleton could have a lower stiffness by printing its walls thinner than the 0.4 mm that the FDM printed model is limited to. However, the company where the parts are ordered, Materialise [12], recommends a wall thickness of at least 0.8 mm to ensure good printing quality. In order to test if a thinner wall thickness would have sufficient quality for this model, test prints are made. However, due to the long delivery times, two options are tested simultaneously: test printing thinner walls, and printing a version of the skeleton with 0.8 mm walls with gaps at the vertices of the folds that potentially lower its stiffness (see appendix G for more information). Based on the test 3D prints, it was concluded that a wall thickness of 0.2 mm was of sufficient quality with the MJF technique, but the skeleton with the holes at the vertices was considered too stiff to be useful and the concept was dropped.

Three different skeleton geometries were printed with the 0.2 mm wall thickness and 20 mm, 30 mm, or 40 mm edges, as discussed in section 3.2 and shown in figure 3.17. The quality of the prints was not as good as the test models, especially that of the 40 mm model since it has the biggest surfaces, but good enough for the gripping force test. More figures of these models can be found in appendix G. Although the 20 mm model had the best printing quality, it turned out that because of the many squares and thus folds, it could not reach an inner diameter small enough to actually compress the test-teat when fully folded. Therefore, the gripping force test had to be executed with just the 30 mm and 40 mm model.

In order to test what the effect of the size of the skeleton's squares on the gripping force is, a test setup was built, shown in figure 3.18. It consists of a latex glove finger suspended in a frame, representing a test-teat. The test-teat is filled with water and connected to a pressure sensor above it through a small tube. The pressure sensor measures the air pressure of the small pocket of air in the tube, which is related to the pressure inside the test-teat. The pocket of air inside the tube is so small that its compression is neglected. The values the pressure sensor reads don't have a meaning in the absolute sense, but its readings with different gripper geometries and gripper vacuum levels can be compared to each other. The gripper is attached to the frame, positioned to completely wrap around the test-teat. Another pressure sensor is set up between the vacuum pump and the gripper, just before the gripper. This sensor is used to make sure that same amount of vacuum is applied to the different types of skeletons. Any leakage in the gripper is compensated with the vacuum reducer. A big and a

(a)

Figure 3.17: The three 3D prints of the 20 mm, 30 mm and 40 mm models made by Materialize with the Multi Jet Fusion technique.

small test-teat are used for this test. The big test-teat has a diameter of 25 mm and a length of 65 mm and the small test-teat has a diameter of 18 mm and a length of 60 mm.

When the test-teat is not compressed, the pressure sensor attached to it reads a negative pressure between -0.6 kPa and -1.4 kPa during the tests. It is chosen to ignore these readings, since they were almost identical for all testing combinations and don't seem to have an influence on the pressure readings when the test-teat is compressed. Immediately after the vacuum valve is opened and the gripper closes around the test-teat, the reading of the pressure-sensor is written down by the researcher. Then, the subsequent values are noted every 5 seconds for 25 seconds in total. The test is repeated ten times per combination of gripper pressure, gripper geometry and test-teat size.

The mean pressure of the test-teat is measured for combinations of the follow variables: a pressure inside the gripper of -20, -25, -30, -35 and -40 kPa. This range is chosen, since a pressure lower than -20 kPa creates a force too small to grip a cow's teat, and the system could not reach a vacuum bigger than -40 kPa with the gripper. Furthermore, the 30 mm and 40 mm skeletons and the large and small test teat are used for the tests.

### 3.9.1. Results and Discussion

Immediately after closing the gripper, the pressure inside the test-teat peaks. The pressure then drops over time, stagnating after 20 seconds (all data can be found in appendix H). The pressure values also decline every repetition for the first five repetitions, after which they are very similar every repetition. This is presumably due to leakage of the test-teat during the first five repetitions, which is refilled with water every new test. Therefore, only the data of the last five repetitions of each test is used.

A boxplot of these last five repetitions for every tested combination is shown in figure 3.19. Here, a positive correlation between the pressure inside the gripper ($P_{Gripper}$) and the mean pressure inside the test-teat ($P_{Test\text{-}teat}$) can be seen, which was expected. By applying a larger vacuum to the gripper, it will press harder into the test-teat. It is also clear that the 30 mm model applies a larger force to the test-teat than the 40 mm model with the same $P_{Gripper}$. For the 30 mm model $P_{Test\text{-}teat}$ is 1.23 kPa higher on average. This was not expected, since the 40 mm skeleton feels more flexible when folding it by hand.

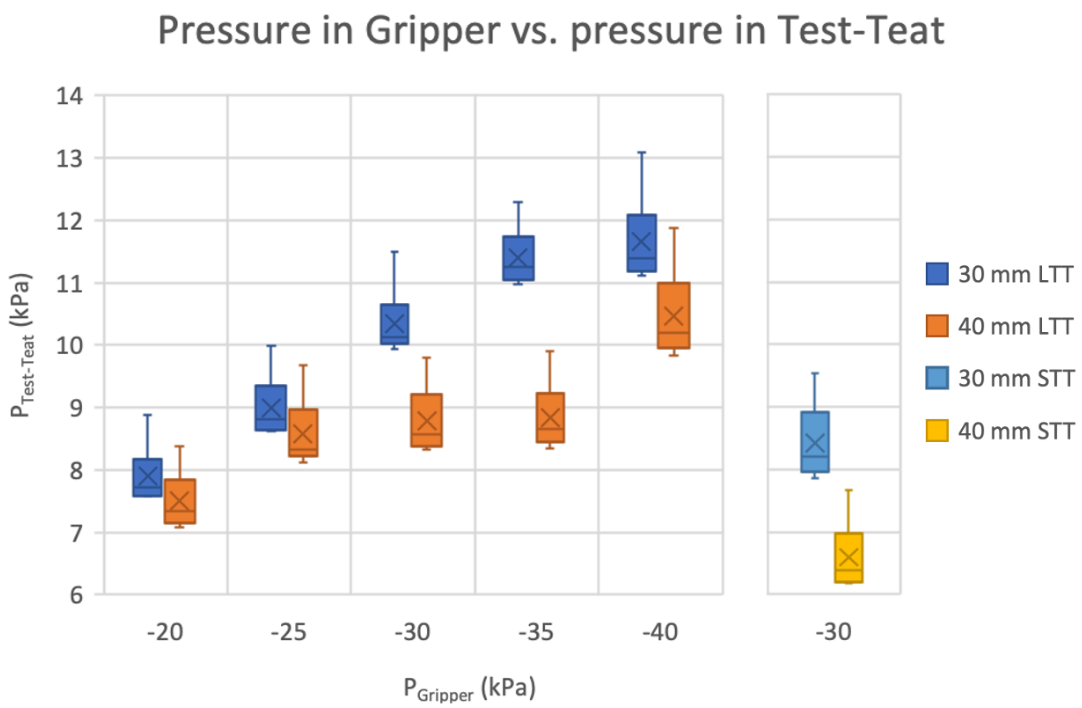
The initial understanding of the folding motion of the gripper was that when the origami skeleton has a lower folding stiffness, a smaller pulling force inwards by the balloon is required to fold it. This is assumed to be the case for the first concept of the OVG where a regular balloon is wrapped around the skeleton, and where the air is sucked out of the balloon through the connector from inside the gripper. This vacuum then pulls the balloon and subsequently the skeleton inwards, creating the gripping motion. However, with the final design the airtight skin is not a simple balloon, but an airtight skin wrapped around the skeleton with a hole added inside the gripper at the bottom. So instead of leaving an air pocket in the middle of the gripper, the airtight skin follows the contours of the origami skeleton. Another aspect to consider is that with the final design the air is sucked out of the airtight skin through the connector from the outer cavity between skeleton and airtight skin, instead of from the inside.


(a) (b) (c) (d)

Figure 3.18: The test setup used for the gripping force test. The complete setup is shown in (a). (b) Shows the test-teat made from a latex glove-finger, (c) The open gripper around the test-teat. (d) The gripper is now closed. The numbers correspond to the following parts: 1: The OVG. 2: Pressure sensor. 3: Solenoid valve. 4: Vacuum reducer. 5: Vacuum pump. 6: Switches for the solenoids. 7: Buttons for controlling the solenoids. 8: 24V power supply. 9: Pressure sensor. 10: Test-teat suspended in frame.

Although air from the inner cavities can still be removed through the creases of the airtight skin, this different location where the air is removed from potentially affects the the folding behaviour. Finally, the airtight skin is pulled into the folds and cavities of the origami skeleton. For the 40 mm model, these surfaces are considerably larger, which likely has an effect on the gripper force of the gripper. These three aspects of the final design and the different skeleton geometries are assumed to result in the gripper not behaving the way it was expected to, namely creating a higher gripping force with an origami skeleton that has a higher folding stiffness, while applying the same level of vacuum to the gripper.

Figure 3.19 suggests that the gripping force of the 30 mm model with the LTT has reached a limit at Pgripper = -40 kPa. The mean increase of $P_{Test\text{-}teat}$ is 1.17 kPa per 5 kPa decrease of $P_{Gripper}$ between $P_{Gripper}$ = -20 kPa to -35 kPa. However, $P_{Test\text{-}teat}$ only climbs 0.26 kPa from $P_{Gripper}$ = -35 kPa to -40 kPa. This suggests that the gripper cannot fold any further, so increasing the pressure does not result in more gripping force on the test-teat. When looking at the data of the 40 mm model with the large test-teat (LTT), the $P_{Test\text{-}teat}$ values only increase very little (0.11 kPa and 0.06 kPa) between $P_{Gripper}$ of -25, -30 and -35 kPa. This suggests that the 40 mm model also reached a folding-limit, but $P_{Test\text{-}teat}$ rises again with 1.63 kPa between $P_{Gripper}$ = -35 kPa and -40 kPa. There might be some sort of buckling occurring within the origami skeleton, which causes it to fold further only at a pressure lower than -35 kPa. When testing with the Small Test Teat (STT), $P_{Test\text{-}teat}$ is 19% lower compared to the LTT with the 30 mm skeleton and 25% lower with the 40 mm skeleton, respectively. This drop in $P_{Test\text{-}teat}$ is likely due to the skeletons having to fold further to grip the STT, which requires more force and therefore less force is applied to the test-teat.




(a)

Figure 3.19: A boxplot of the gripping forces of the large and small test-teats in combination with gripper pressures of -20 kPa to -40 kPa and the 30 mm or 40 mm gripper. LTT = Large Test-Teat, STT = Small Test Teat. Each data set contains six data points.

### 3.9.2. Conclusion

Based on these results, it can be concluded that the 30 mm model is the better option for the Origami Vacuum Gripper than the 40 mm version, since a lower vacuum in the gripper is required to apply the same force to the teat. Furthermore, $P_{Test\text{-}teat}$ has the most linear relationship with $P_{Gripper}$ with the 30 mm model between -20 kPa and -40 kPa.

# 4 Discussion

## 4.1. Summary of Main Findings

Below the requirements from section 1.3 are listed once more. Based on the results from the final tests, it is evaluated whether the requirements and wishes are met and the main findings are discussed.

**Requirements:**

1. ✓ *Clean teat.* The Origami Vacuum Gripper final prototype is capable of cleaning the cow's teats properly before milking. With wider teats, traces of dirt remain at the base of the teat, but the results are sufficient for attaching a milking machine.
2. ✓ *Stimulate teat.* It was assumed that if the cow's teat is cleaned properly, this would result in enough stimulation for the milk ejection reflex to be activated. Furthermore, milk could be seen leaking from the teats after cleaning them, which confirms the activation of the milk ejection reflex.
3. ✓ *Innovative.* The device is considered innovative, since there are no patents or literature describing folding origami structures in the field of pretreatment techniques for automatic milking systems [8].
4. ✓ *Teat semi-dry before milking.* The teats showed no remaining water drops after the final dry brush-stroke, which is dry enough for the attachment of the milking cups.
5. ✓ *Safe.* The device has no moving parts or sharp edges that the cow could be hurt with. The gripper is flexible and the forces exerted on the teat are limited by the vacuum (maximum pressure difference of one bar) used to actuate it.
6. ✓ *Fits all teats of Holstein cows.* The dimensions of the final concept are chosen so it can fit the whole range of possible teat dimensions of Holstein cows, with the opening of the gripper being three times the diameter of the average teat.
7. ✓ *Smaller than 3 liters when not deployed.* Storing the device in folded state is more space efficient. The device's dimensions when folded are: 180 mm x ∅ 50 mm . This results in 0.4 liters volume, which is smaller than the 3 liters of the Lely pretreatment system.

**Wishes:**

1. × *Premilking.* Unfortunately, the concept of premilking the cow using the gripping force in combination with the vacuum applied inside the gripper was no success. There was no premilking, which is thought to be caused by the gripper closing the teat off by compressing it.
2. - *Simple.*
3. - *Compact.*

The final design meets all requirements stated at the beginning of this research. However, it does not fulfil the premilking wish. Wish 2 and 3, simple and compact, were not quantified but used to choose between concepts and design choices and are therefore not indicated as fulfilled or not.

**Cleaning** The area that the device has the most trouble with cleaning is the base of the larger teats. The brush barely reaches it and the gripper has the least compressing force at the opening. The solution to this issue can therefore most likely be found in the brush liner's design and the origami skeleton's geometry and actuation. By making the brush liner longer and adding more brush hairs to the top, the base of the teat is reached better. The geometry of the skeleton can likely be improved so it folds better at the top, but this could be a complex puzzle. Two other, simpler solutions might also improve the compression at the top area. Firstly, the top rim of the skeleton can be made more smooth, like a ring. This would make it easier to make an airtight seal against the udder, creating the vacuum inside the gripper that helps folding the top section. Secondly, moving the location where the air gets sucked out of the airtight skin up towards the edge could create more gripping force at the top section.

The spraying of water from the connector at the bottom of the gripper yielded good cleaning results, but only if the teat was sprayed with the gripper positioned below the teat instead of the teat being inside the gripper. With the teat inside the gripper the water could not flow past the tip of the teat. However, spraying with the teat inserted is desired, since it prevents the water from splashing around. Spraying from the sides or the top of the gripper could overcome this problem. Spraying from behind the brush liner was tested and not successful, so most likely spraying inwards from the top of the gripper would give the best results. Furthermore, replacing the brass tubes with actual miniature nozzles that widen the spraying pattern would potentially help spraying around the teat towards the base. Using a nozzle could also help reduce the water consumption while maintaining spraying distance. The device used between 0.5 and 1 liter water per cow during the final test, which would be roughly 90 liters of water per device per day, when milking 60 cows per robot.

**Premilking** Even though the concept showed good potential for being able to premilk the cow, no premilking could be performed with the prototype. Two causes for the premilking to fail were hypothesized: The compression of the teat by the gripper closed the teat instead of pushing the milk out, or the vacuum inside the gripper was not big enough to pull the milk out. The first hypothesis could not be tested without drastically altering the design: Even without activating the vacuum inside the skeletons airtight skin, the skeleton compresses the teat due to the vacuum applied inside the gripper. In order to prevent this, the skeleton would have to be actively prevented from closing. The second hypothesis was tested by adding the extra seal around the teat and therefore increasing the vacuum inside the gripper. This however did not result in the removal of milk, which means that the closing of the gripper around the teat prevents the milk from being pulled out of the teat by the vacuum.

**Gripper geometry** The gripping force test showed that the 30 mm skeleton is better suited for the OVG than the 40 mm model, since it requires less force to fold. Furthermore, the 40 mm skeleton is considered too fragile for this purpose. The 3D printing quality was low, having gaps in its surfaces due to the thin wall thickness of the model. The skeleton was also deformed after the tests, showing buckling at the edges.

**Linear actuation** The Yoshimura structure showed good potential for acting as a linear actuator for the OVG, but like mentioned before was not tested with an actual airtight skin or attached to the gripper. This would be a great feature to add and test with the next iteration of the OVG. Furthermore, the Yoshimura structure's flexibility around the horizontal axes could give some margin for the cow to move within while the gripper is attached to its udder, without it immediately falling off.

## 4.2. Limitations

### 4.2.1. Design Limitations

**Premilking** Arguably one of the biggest limitations of this design of the Origami Vacuum Gripper is its lack of premilking ability. Although it was not a requirement nor the goal of this thesis, having this function implemented in the device would make it even more innovative. The solution to being able to premilk is likely by preventing the gripper from folding and compressing the teat during the premilking, but this would make the gripper more complex.

Another limitation inherent to the design is that the tip of the teat is cleaned more thoroughly than the base due to the pulling down cleaning motion. The tip of the teat is cleaned during the entire pulling motion, while the base of the teat is only cleaned briefly by the top part of the brush liner.

Finally, the gripping and pulling motion of the device is not one fluent motion, but has to be repeated several times. This means that the teat has to be 'caught' multiple times, which could be difficult when the cow moves during the pretreatment.

### 4.2.2. Test Limitations

The test setup for the gripping force test worked as intended, but it had its limitations. For example, how the gripper was positioned when closed around the test-teat had a large effect on the pressure readings of the test-teat. Furthermore, leakage in the gripper was inevitable. Although this was compensated for with the vacuum reducer, it is possible that the amount of leakage would vary during the tests.

## 4.3. Recommendations and further research

**Cleaning** An important aspect that has not been given much attention is the cleaning of the device itself during cleaning of the teat and in between cows. During cleaning of the teat, the spraying system washed away most of the dirt that got stuck between the brush hairs. However, after cleaning a cow, the device needs to be disinfected before cleaning the next cow to avoid cross-contamination. This would most likely be similar to how the milking cups are cleaned in a milking robot, by inserting a nozzle that sprays disinfectant or steam.

**Gripper geometry** Although the gripping force test gave some insight into what skeleton geometry would be optimal, it also showed how complex the folding of the skeleton is in combination with the airtight skin. Plenty of research can still be done on the folding geometries, for example by using FEM analysis to try and understand what stresses occur in the material. Furthermore, by using varying wall thicknesses or folding geometries, the origami skeleton's gripping characteristics can be tuned. Finally, although the 20 mm skeleton could not fold far enough to grip the test-teat, a 25 mm model could be tested. It might be able to grip the test-teat and since the 30 mm model performed better than the 40 mm version, a 25 mm model might perform even better.

**Attachment to milking robot** What the best location for the device is on the milking robot has not been researched, but is very important. In order to be moved from teat to teat, the device would have to be attached to a robot arm. The brushes Lely uses are located roughly halfway up the arm that moves the milking cups, but the OVG might be better positioned like a milking cup at the end of the arm, due to its similar shape and size.

As discussed in section 3.6, a linear actuator based on the Yoshimura structure could be used for the linear translation of the cleaning process so the robot arm only has to move the device from teat to teat. Although the concept of using it as a spring has been proven, it has not been tested with an airtight skin or attached to the gripper.

**Manufacturing** Another aspect that has to be researched further is the OVG's manufacturability and especially that of the origami skeleton. Roughly 25,000 Lely Astronauts are being used at farms at the moment, of which the brushes have to be replaced twice a year. So if for example the origami skeleton has to be replaced as frequently, roughly 50,000 skeletons have to be produced per year. For quantities this large, 3D printing of the skeleton is assumed to be too expensive and time consuming. An alternative could be casting the skeleton out of silicon, as was described in the MIT and Harvard paper the initial concept was based on [11]. These researchers 3D printed a mold from PLA, that could be taken apart into multiple sections. Injection molding would likely be a suitable production method for large numbers of skeletons.

**Durability** No research has been done on the durability of the device. The two aspects that are considered to be most prone to wear and tear are the origami skeleton and the airtight skin. Even though there are no rotating or sliding parts, it's important to know the effect the large amount of folding repetitions has on the skeleton's material.

# 5
# Conclusion

The goal of this thesis was to discover an innovative alternative for Lely's pretreatment system with at least equal cleaning and stimulating performance, and preferably include premilking. The final design is essentially a gripper that functions like a foldable milking cup, using a brush liner and water to clean and stimulate the teat while dirt is removed from inside the gripper. The folding motion is based on the Waterbomb origami pattern, and actuated by removing the air from the airtight skin wrapped around it. The final field test showed the design's ability to properly clean and stimulate the cow's teats while leaving them dry enough to apply the milking cups. The cleaning performance can be further improved, with mainly the brush liner and spraying system having difficulties with cleaning the base of larger teats. Nonetheless, the device meets all requirements stated at the start of this research. The premilking wish could however not be fulfilled. The gripper folds and compresses the teat when the vacuum for the premilking is applied, preventing milk from flowing out. This could possibly be solved by actively keeping the gripper open while premilking. Finally, the gripping force test shows that there is plenty of room for optimisation of the origami skeleton by adjusting dimensions, wall-thicknesses or maybe even folding patterns.

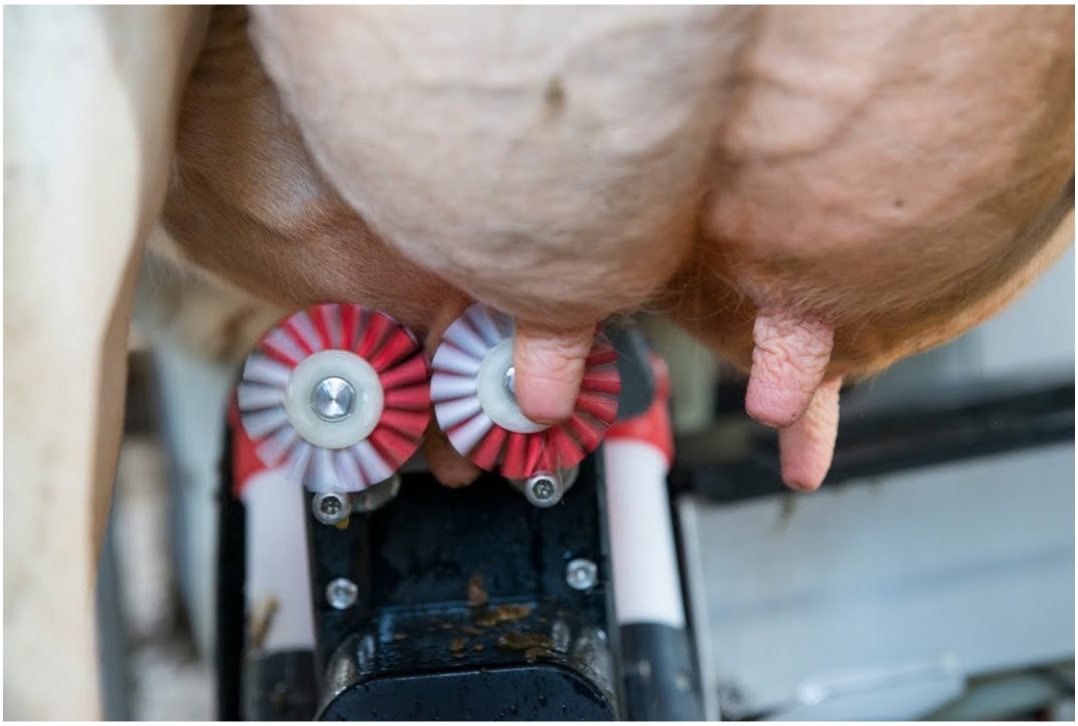
It is concluded that the Origami Vacuum Gripper final design fulfils the goal of this thesis, being innovative and able to clean and stimulate at least as thoroughly as the Lely pretreatment brushes do. The premilking wish could not be fulfilled, but this might still be feasible with the right improvements.

# A

# Literature and Patent Study

# Cow pretreatment techniques before milking

## Literature and patent study



Bart van der Hee (4535847)
December 7, 2022

# Contents

# 1 Abstract

Before a cow is milked, three stages of pretreatment are performed. The first stage is cleaning of the teats in order to prevent contamination of the milk and udder infections (mastitis). The second stage is stimulation of the udders to activate the milk ejection reflex and ensure the milk can be removed quickly. The final stage is premilking, where the first few squirts of milk are removed to prevent contamination of the bulk milk. This paper explains the importance of pretreatment before milking and how to execute it, and gives an overview of existing or experimental pretreatment techniques that could be used in an automatic milking system. It does so by performing a literature research in the Scopus database for each of the three pretreatment stages and a patent study in the Espacenet database on pretreatment techniques and devices. In total, 29 papers and 43 patents are incorporated in this study.

Literature suggests that there is not one best cleaning method and that different methods are preferred in different contexts. As for stimulation, it is clear that mechanical or tactile stimulation where the teat is physically 'touched' is most effective. Furthermore, the time that the teats should be stimulated depends on how full the udders are, and a pause between stimulation and milking does not lower oxytocin levels. In literature, only little attention is paid to premilking and it is performed manually in experiments. The sequence in which the three stages are executed is suggested to largely depend on the methods used and the context. However, the teats should always be dry before milking.

The patents presented in this study suggest that the use of 2 or 3 parallel horizontal rollers is the most popular technique to clean and stimulate the teats, which is in line with what the literature states about tactile stimulation. Also, the Lely Astronaut A5 uses this technique with 2 brushes. However, spraying fluids on the teats is also a technique often described in the patents and is used by DeLaval and GEA in their newest pretreatment systems. The systems of DeLaval and GEA are different in the way that DeLaval uses a separate teat cup for pretreatment and GEA performs all three stages in the same teat cups as the milking system uses.

Furthermore, there is no pretreatment technique that is clearly superior to its alternatives and little literature could be found on automatic pretreatment techniques. This suggests that not all effective techniques have yet been explored and better alternatives can still be found.

# 2

# Introduction

## 2.1. Background

The first successful practical milking machine was devised in 1900 and rapid mechanization of milking started in Australia and New Zealand. However, the farmers in the northern hemisphere only got interested in this new concept for the following half century, along with most agricultural scientists. Since the 1950s there have been studies in developing fully automatic milking machines in order to make the milking process more efficient and less labour intense [65]. These ideas were really put into practice in the 70s with rising labor cost in many countries, with especially the Netherlands being the leader in scientific developments. This resulted in the first experimental milking robot in 1986 in Lelystad by the company Gascoigne Melotte and finally the purchase of the first four milking robots in 1992, made by Lely Industries N.V., also in the Netherlands. Automatic milking systems have been a growing trend ever since, with 1754 automatic milking machines in the world in 1992, more then 16,000 in 2010 and more than 35,000 in 2017 [65]. The biggest automatic milking system manufacturers are at the moment Lely (the Netherlands), DeLaval (Sweden) and GEA (Germany) [25]. An automatic milking system or robot consists of one or multiple boxes where cows walk into freely and are fed before or after the milking. The system has a multi-functional robot arm that prepares the udders for milking, attaches the milking cups and sometimes disinfects the teats after milking [65]. There are many advantages of using automatic milking systems: ”higher mean frequency of milking events and milk production; better herd health and reproductive rates; potential for better herd management regarding information collection and management; fewer workforce needs and increased labor flexibility; greater profitability and quality of life for owners.” [25]. In figure 2.1 the Lely Astronaut A5 automatic milking system is shown.

Figure 2.1: The Lely Astronaut A5 automatic milking system [55].

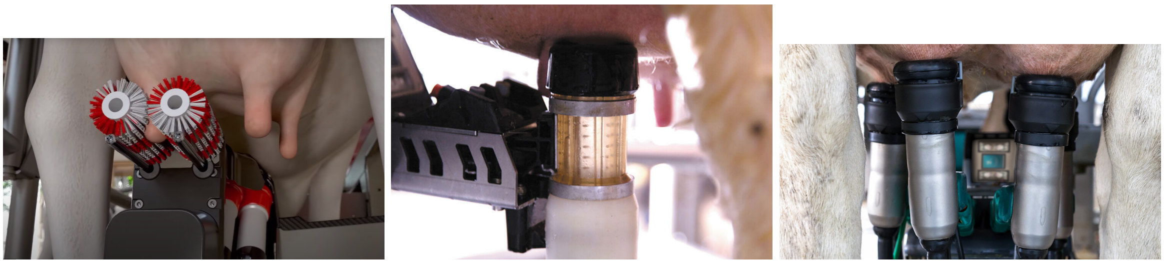
## 2.2. Problem analysis

Before the milking of a cow, three steps of pretreatment are necessary in order to establish optimal milk yield, avoid infections, cross-contamination and assure udder health in general. The first step is the cleaning of the teats, which makes sure no dirt or contamination from for example the barn floor can enter the milking system or cause udder infections (mastitis). Next, the teats are stimulated in order to release the hormone oxytocin and activate the milk ejaculation reflex. This results in higher peak milk flow and shorter milking time, which is better for the teat tissue and udder health in general [47]. The final step is premilking, which means a few squirts of milk are discarded before the actual milking process starts. This premilk contains the most bacteria and therefore has to be discarded in order to prevent cross contamination, which is also required by law in the Netherlands [72]. In practice these steps can overlap, since the cleaning of the teats or the premilking can be sufficiently stimulating to activate the milk ejection reflex.

Multiple challenges arise when designing an automatic pretreatment device for the milking process. Like stated before, the cow's teats need to be properly cleaned and stimulated, and cross-contamination between cows has to be prevented. Furthermore, the cow has to be premilked and this milk has to be kept separate from the bulk milk to prevent contamination. Timing is also important when pretreating. When stimulated too short, the cow's oxytocin levels are not high enough and if there is too much time between stimulation and milking the oxytocin levels will have dropped again. However, milking should also not be performed too shortly after stimulation, since there is a delay between stimulation and a cow's oxytocin production.

## 2.3. State of the art

The newest automatic milking systems of the biggest manufacturers at the moment are: the Astronaut A5 by Lely [40], VMS V300 by DeLaval [11] and DairyRobot R9500 by GEA [30]. These three systems all use different pretreatment techniques, shown in figure 2.2 below. These techniques will be discussed in section 4.1.



(a) (b) (c)

Figure 2.2: (a) The Lely Astronaut A5 uses two rotating brushes for cleaning and stimulation. Premilking takes place in the milking cups [40] (b) The DeLaval VMS V300 uses separate teat cups for cleaning, stimulation and premilking [11] (c) The GEA DairyRobot R9500 executes the pretreatment in milking cups [30].

## 2.4. Goal and structure

The aim of this paper is to explain the importance of proper pretreatment before a cow is milked and how it should be performed, and to give a comprehensive overview of existing and experimental pretreatment techniques that could be used in an automatic milking system. With this background knowledge and overview, insight can be gained for improving existing pretreatment systems or designing a novel type of system.

This paper consists of two parts. In chapter 3, the fundamental knowledge of different aspects in the milking process is given: a brief overview of the anatomy of the udder in section 3.1, the three pretreatment stages in section 3.2, the milking machine in section 3.3 and the post-treatment process in 3.4. In chapter 4 multiple researches are conducted, including a literature research and a patent study in order to create a comprehensive overview of existing and experimental pretreatment systems. In section 4.1 the pretreatment methods of the newest automatic milking systems from the three biggest manufacturers are analysed. In section 4.2 the methods and results of three literature researches (one for each pretreatment stage) are given and the order in which they should be performed is discussed. It turned out that there is little literature to be found on automated pretreatment systems, since most articles are focused on conventional (manual) pretreatment methods and why it's beneficial to pre-treat in general. In section 4.3 the patent study on pretreatment devices is presented, with the results categorized based on the different types of methods used.

# 3

# The Milking Process

## 3.1. Anatomy of the cow udder

The udder of the dairy cow yields far more milk than a calf can consume and what it was originally designed for. This in combination with the implementation of a milking machine imposes unnatural stresses upon the cow's udder. This has to be kept in mind when milking the cow, since the milking technique and machine operation have direct influence on udder health and milk production [8]. In this section a brief overview of the cow's anatomy relevant to the milking process is given.

A cow's udder comprises four separate mammary glands called quarters. Each quarter produces milk that is drained by a separate teat. There are two fore quarters and two rear quarters, which are roughly the same size for modern cows. The udder is covered with small hairs but the teats are hairless. It's also quite common for cows to have an extra or supernumerary teat that is nonfunctional and should be removed to prevent infections. The size and shape of the udder and teats can differ widely from cow to cow [8].

The milk is produced in the alveoli. In between milkings the milk accumulates in different storage spaces, namely the alveoli, ducts and cisterns, which are shown in figure 3.1. A cow's milk production is not constant throughout the lactation period. After calving, a cow's lactation period starts and milk yield peaks two to eight weeks after parturition. It is common to maintain a 12-month calving interval by inseminating the cow 85 days into the lactation period and milk yield declines sharply around the fifth month of gestation. Furthermore, it is common to 'dry off' the cow, by ceasing to milk 45-60 days prior to the next expected partition date. This gives the cow some rest and the ability to put more energy into the calving.

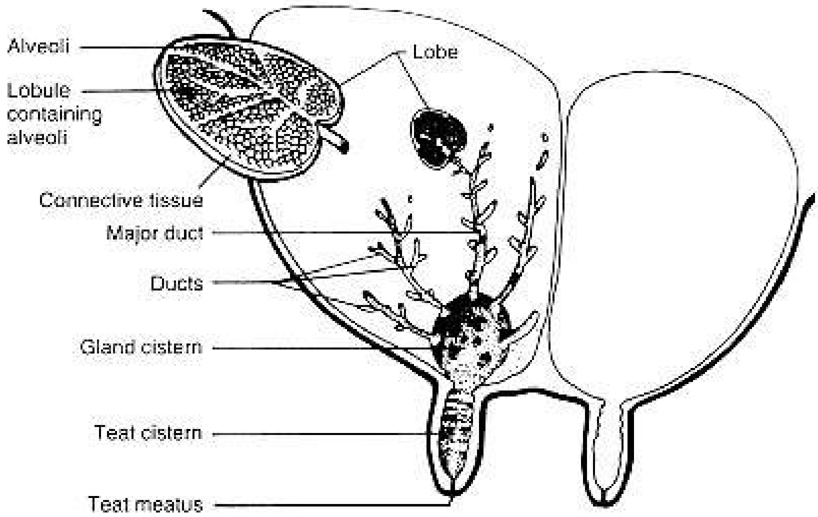



Figure 3.1: Cow udder cross section [21]

Some important terminology concerning the flow of milk in the udders:

- **Milk secretion:** milk is moved from milk producing components into storage spaces within the udder.
- **Milk let-down:** the forceful ejection of milk from the storage spaces.
- **Milk removal:** the physical evacuation of milk from the udder.

## 3.2. Pretreatment

Like mentioned before, there are three stages of pretreatment before milking: cleaning, stimulation and premilking. These will be discussed in the following subsections. In subsection 4.2.4 the correct sequence of pretreatment will be further discussed.

### 3.2.1. Cleaning

In between milking, ”teats become soiled with dung, litter, soil and mud, all of which contain a high and mixed bacterial population” [8]. Therefore, the teats (and preferably a small part of the udder) have to be cleaned properly before milking, in order to avoid contaminating the milk and prevent the cow from getting mastitis. Bacterial spores in contaminated milk can survive pasteurization and therefore cause problems for the dairy industry [54]. For example, the presence of the Bacillus cereus can reduce the milk’s shelf life or even cause food poisoning and spore forming bacteria of the Clostridium species can negatively impact the cheese making process. Mastitis is the inflammation of the cow’s udders and is caused by a bacterial infection, which is most often treated with antibiotics. The mastitis pathogens enter the mammary gland through the teat canal [5]. With clinical mastitis the infected quarter stiffens and the consistency of the produced milk changes. However, with subclinical mastitis the infection causes no visible symptons which makes it harder to detect. Mastitis reduces the cow’s milk production (up to 50% in extreme cases) and when the infection progresses the cow can get seriously ill.

Furthermore, cleaning the teats and udder is required by EU law [71]. When done manually, the teats are usually washed by hand with water and optionally a disinfectant and then dried with a fresh paper towel [8]. In an automated milking machine, rotating brushes or jets of water and air are used. Existing cleaning methods are further researched in section 4.2.1.

### 3.2.2. Stimulation

In order to remove the milk from the alveoli and small ducts the teats have to be stimulated to activate the milk ejection reflex. This neuro-hormonal reflex releases the hormone oxytocin that starts the milk let-down, ejecting the milk from the storage spaces. Without milk ejection or let-down, only the milk stored in cisterns or large ducts can be removed, which is only up to 20% of the milk in the udder [70]. During milking with an automated milking machine the teats are automatically stimulated by the vacuum cycle that removes the milk from the udders, but tactile stimulating of the teats before milking has great benefits. Although the total milk yield is not different for cows milked with premilking stimulation as compared with those without, the peak milk flow rate is higher with premilking stimulation [47] and a transient cessation of milk flow after the cisternal milk is removed is avoided [82]. This results in a higher average flow rate and thus a shorter machine-on time, which is better for the teat tissue and udder health in general. Another benefit of premilking teat stimulation is that it might help teat cup attachment, since teats are firmer after milk ejection [42]. The stimulation of the teats can be a calf suckling, manual stimulation by a farmer’s hands or the rotating brushes of an automatic milking system. Massaging or squeezing the udder also results in milk let-down from the alveoli without the need of oxytocin. However, oxytocin is the primary cause of ejection. The milk ejection reflex caused by a calf’s or milker’s stimulation of the teats is an unconditioned or involuntary response. Other stimuli, like the sounds or sights that the cow associates with the milking procedure can cause a conditioned response and thus release of oxytocin. Therefore, in order to achieve maximum milk production the unconditional milk reflex has to be stimulated maximally, while standardizing all other factors that can evoke conditioned reflexes [8]. When the cow is under stress, the release of oxytocin and therefore milk ejection is prohibited. This can be caused by unfamiliar surroundings for the cow or when the cow is primiparous and therefore not familiar with the milking process [9]. Existing stimulation methods are further researched in section 4.2.2.

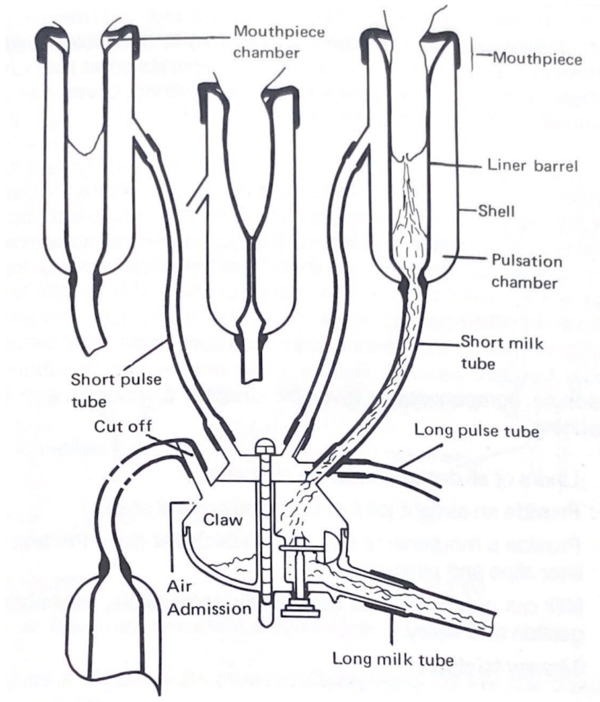



Figure 3.2: Teat cup cluster cross-section showing all components [8].

### 3.2.3. Premilking

”The highest concentration of somatic cells and microorganisms is in the milk of the teat cistern” [66], which is why the first squirts of milk per udder quarter are to be kept separate from the bulk milk in order to prevent contamination and when milking by hand to check the cow for clinical mastitis [78] [72]. This is called premilking or forestripping and is required by law in the European Union [71]. Premilking can be done manually by compressing the teat by hand or mechanically by an automatic milking system. An automatic milking system can use the same technique used for milking or have it implemented in its cleaning and/or stimulation technique. Existing premilking techniques are further researched in subsection 4.2.3.

## 3.3. Machine milking

The actual milking unit itself consists of a cluster, pulsation equipment and milk holding or metering devices [8]. As can be seen in figure 3.2, the cluster consists of four teat cups, the claw, the long milk tube and the long pulse tube. The claw connects the short milk and pulse tubes to the long milk and pulse tubes and can ’cut off’ the vacuum from the tubes if for example a milking cup falls, preventing contamination of the milk. However, the claw and other components of the milking unit except the teat cup are not considered relevant for this research and thus not discussed any further. A teat cup has a rigid cylindrical shell with a flexible liner inside, a short milk tube and a short pulse tube. The liner enveloping the cow’s teat is the only component of the milking unit touching the cow. The milking process proceeds as follows: the air pressure inside the liner is about 40-50% below the ambient atmospheric pressure, while the air pressure within the pulsation chamber varies from atmospheric pressure to the same level as inside the liner. This pressure difference makes the liner open and close around the teats, which pulsates around 50-60 times a minute (often 650 ms open and 350 ms closed) and creates the milking motion that evacuates the milk from the cow’s teats and udders.

## 3.4. Post-treatment

After milking, the teats are often dipped in or sprayed with a post-treatment agent to remove milk droplets that remain after milking to prevent mastitis. These milk droplets ”can serve as a breeding ground for surrounding pathogenic microorganisms” [45]. There are two types of post-treatment agents, one that disinfects the teat and one that forms a thin layer over the teat orifice, which shields it for infections through the teat canal. Spraying or dipping the teats after milking is especially common with automatic milking machines.

# 4

# Pretreatment Techniques

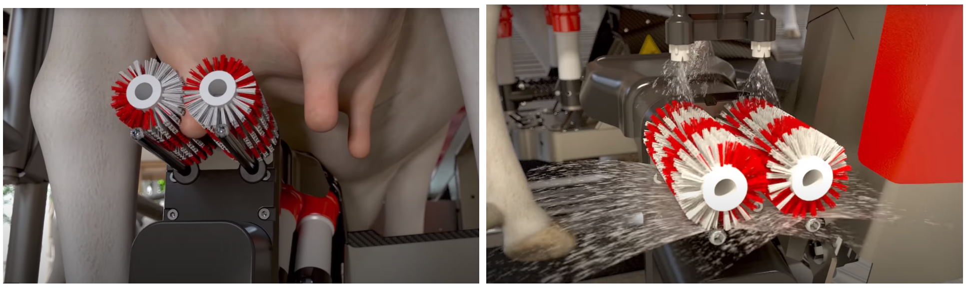
The goal of this chapter is to give a comprehensive overview of existing or experimental pretreatment techniques. Section 4.1 analyses the newest systems of the three biggest automatic milking system manufacturers. In section 4.2 three literature researches in the Scopus database [18] for each of the pretreatment stages are given. Finally, in section 4.3 a patent study is presented on patented pretreatment methods found in the Espacenet database. The literature research and patent study are both conducted according to the PRISMA method [61].

## 4.1. Current pretreatment techniques

Like mentioned before, the top three manufacturers of automatic milking systems are Lely, DeLaval and GEA. In this section their flag ship systems' pretreatment systems are investigated.

### 4.1.1. Lely Astronaut A5

The Lely Astronaut A5 uses two rotating cylindrical brushes attached to a robotic arm in order to clean and stimulate the cow's teats before milking, as can be seen in figure 4.1. The brushes are positioned horizontally and parallel, counter-rotating towards each other. After the pretreatment and during the milking process, the brushes are thoroughly cleaned by jets of water and disinfectant and rotated in order to dry. [39].

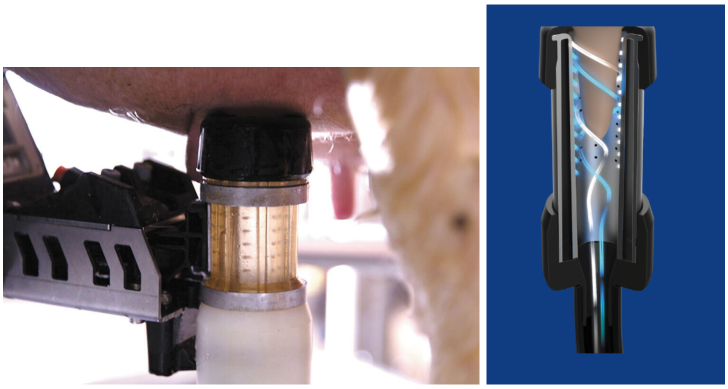


(a) (b)

Figure 4.1: (a) The two counter rotating brushes of the Lely Astronaut A5 clean and stimulate the teat (b) the brushes get disinfected after the pretreatment [40].

### 4.1.2. DeLaval VMS V300

DeLaval has chosen to clean, stimulate and premilk the cow before milking in a separate set of teat cups [11], as can be seen in figure 4.2. This all takes place in a separate system to prevent cross contamination when milking. The teats are washed inside the teat cups with jets of water, air and optionally soap and blow dried before milking.



(a) (b)

Figure 4.2: (a) The cup from the DeLaval VMS V300 cleans, stimulates and premilks the cow (b) a cross section pictures the flowing of the water/soap and air inside the cup [11].

### 4.1.3. GEA DairyRobot R9500

In contrast to its competitors, GEA performs the whole pretreatment process in the same teat cup that's used for milking [30], as can be seen in figure 4.3. The teats are cleaned by injecting water into the cups at intervals, washing them clean. Simultaneously the teats are stimulated by pulsating/vibrating the liner inside the teat cup, which is very similar to the milking technique but with less power.

(a) (b)

Figure 4.3: (a) The GEA DairyRobot R9500 executes the pretreatment and milking process in the same teat cup (b) stimulation of the teat is done by vibrating the liner inside the cup, similar to the milking technique but with less power [30].

## 4.2. Pretreatment literature research

In this chapter, findings from a literature research on the three parts of pretreatment will be discussed. The research has been executed using the Scopus database [18] following the PRISMA method [61] and is divided in three separate search queries, one for each pretreatment stage. The goal of the research was to find information on different methods of cleaning, stimulation and premilking, especially those used in automated milking machines.

### 4.2.1. Cleaning

The search query for the literature research on the cleaning method is: *TITLE-ABS-KEY(cow AND (clean* OR sanit*) AND (teat OR udder) AND (premilking OR pre-milking OR pretreatment OR pre-treatment OR preparation))*. All words in the query are searched for within the title, abstract and keywords of documents in the database, since this proved to give the most relevant articles. A vast amount of literature is available on research in the dairy animal industry and therefore the search query contains multiple words to narrow down the results to just the pretreatment cleaning process for cows, with some connected with the 'OR' operator to find articles that use synonyms or different spelling for the same subjects. The so-called wildcard used in 'clean*' returns variations on the word like 'cleans', 'cleaning' and 'cleansing' to broaden the search. The same goes for 'sanit*' with for example 'sanitize' or 'sanitation'. See figure 4.4 for the amount of results and the selection process. Only a small part of the found literature was considered relevant, since most papers are focused on the importance and effect of cleaning of the teats before milking, but not on the cleaning method itself and why it's effective.

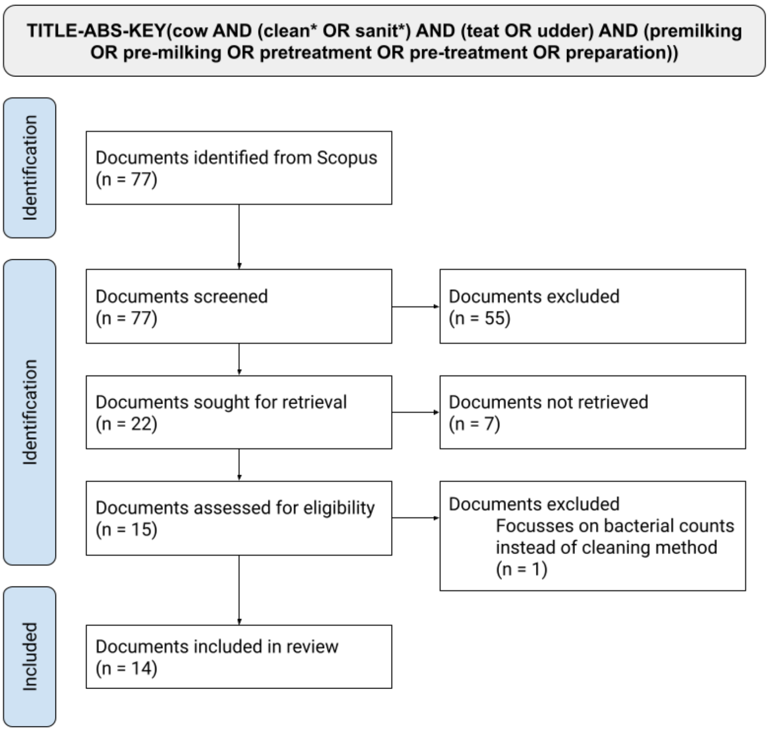



Figure 4.4: Selection process for literature research on cleaning methods based on PRISMA.

For the cleaning of the teats, opinions in literature are divided on what the preferred method is. However, all considered papers agree on one thing: as the final step in the cleaning process the teats have to be dried properly before the milking, which when performed manually should be done with a clean (paper) towel to prevent cross-contamination. Not properly drying the teats before attaching the milking machine can result in slippage of the liner and damage the udders [66]. Before the drying part, some researchers state that washing the teats with a disinfectant is most effective in removing bacteria from the teats [32], while others say the use of only water is sufficient to prevent intramammary infections [44] [54]. Furthermore, other researchers state that the mechanical cleaning motion and its duration are the most important [1] [63] [54]. [66] states that washing or cleaning with a towel both are the most effective as long as a disinfectant is used. Meanwhile, other researchers state that dipping the teats in a disinfectant removes the most bacteria from the teats [29], which could be a commonly used iodophor solution, or a more experimental foam [26] or gel [41]. One paper proposes the use of garlic or cactus extracts as a natural teat-dipping solution alternative after promising test results [58]. One paper was found on a semi-automated teat scrubber manufactured by FutureCow [5] [28]. It consists of three horizontally rotating brushes in a handheld device, with a nozzle spraying them with chloride dioxide for sanitation. First the teats are cleaned with the chloride dioxide, then the brushes centrifuge themselves dry and the teats dried with the dry brushes. This composition of two rotating brushes is one of the most effective ways of cleaning and stimulation mechanically according to [59] (more on stimulation in subsection 4.2.2).

### 4.2.2. Stimulation

For the stimulation stage, the following search query was used: *TITLE-ABS-KEY (cow AND (stimulat* OR prepar*) AND (udder OR teat) AND (oxytocin OR let-down OR eject* OR "milk remov*" OR "removing milk"))*. Similar to the search query for the cleaning stage, the title, abstract and keywords


Figure 4.5: The FutureCow Teatscrubber is used to clean and stimulate the cow's teats after forestripping [28].

are searched, and multiple words are included in the query to narrow down the results to pretreatment stimulation for cows. Again, wildcards and 'OR' operators are used to not exclude relevant articles. In figure 4.6 the amount of results and the selection process is shown.

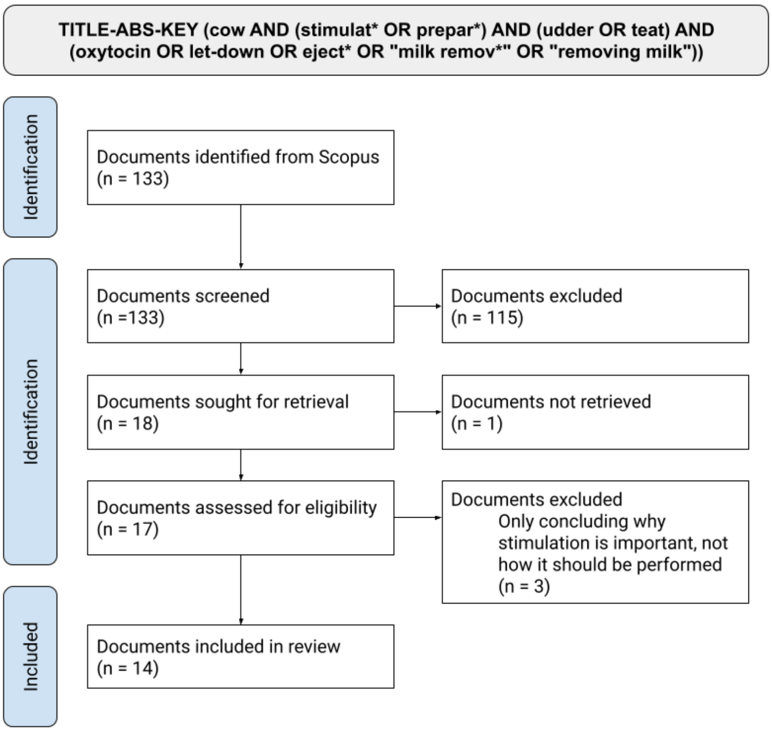



Figure 4.6: Selection process for literature research on stimulation methods based on PRISMA.

The stimulation stage in the pretreatment process overlaps with the cleaning and/or forestroking stage. For example, the washing of the teats using a moist cloth has a stimulating effect [47] [17], as does the manual forestripping of the teats [66] [78]. This is because the milk ejection reflex is activated by tactile stimulation [69]. The use of heat as a stimulus is not sufficient, since using warm or cold water for washing does not make a difference in oxytocin release [17] [47], nor does bathing the udders or spraying the udders with warm water or exposing them to infra-red radiation or warm air [69]. A method that does stimulate the teats sufficiently according to multiple papers is a (reduced) pulsating vacuum applied by the teat cups of a conventional milking machine prior to milking [52] [69] [80] [70]. Furthermore, the horizontally counter-rotating brushes used as a teat cleaning technique explained in section 4.2.1 are also a good stimulus [42] [59] [52] (see figure 4.5).

The stimulation time needed for the milk to be ejected into the cisterns and large ducts depends on the degree of udder filling [9] [81] [46]. The times vary slightly between research papers, but it can be concluded that the time between start of teat stimulation and milk let-down is 20-40 s for well-filled udders [8] [9] [81] [34] and 1.5 - 2 min or more for udders with small amounts of milk [9] [81]. Instead of continuous stimulation, a short stimulation period followed by a latency period is also suitable, as long as the total time is enough for the milk to be fully ejected [46]. This results in 15 s of stimulation and a latency period of up to 45 s for well filled udders, and 30 s of stimulation followed by up to 1 min of latency for less-filled udders.

### 4.2.3. Premilking

To find relevant articles on premilking, the following search query is used: *TITLE-ABS-KEY (cow AND ( foremilking OR fore-milking OR forestripping OR fore-stripping))*. The term forestripping or foremilking is used, since it became apparent that this was the preferred naming in literature instead of premilking, which is often used to refer to the complete pretreatment process before milking. In figure 4.7 the amount of results and the selection process are shown. Similar to the literature research on cleaning methods, most literature is focused on the importance and effects of premilking, but not on different methods that could be used. Therefore, only one article is found that is considered relevant to this research.

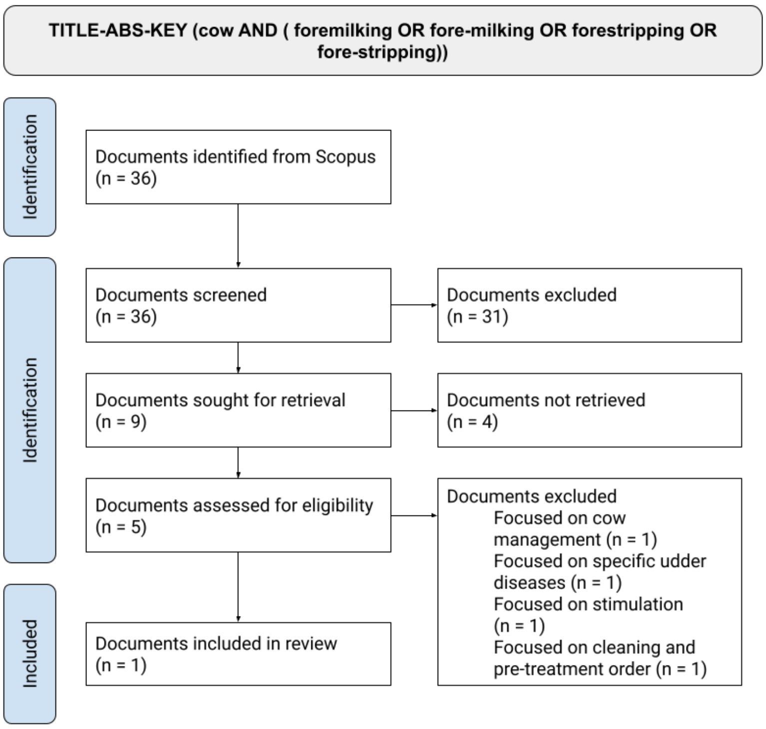



Figure 4.7: Selection process for literature research on premilking methods based on PRISMA.

The conventional method of premilking before attachment of the teat cups for milking is done by manually compressing the teats to remove several streams of milk from each udder quarter [78]. This method is also the main method that is used in research on pretreatment, as can be seen in for example [80] [70] [78] [82].

### 4.2.4. Pretreatment sequence

The order in which the three pretreatment stages are discussed in the subsections above is not necessarily the same sequence in which they are performed. As mentioned in 4.2.2, the cleaning of the teats and premilking both work stimulating, which means the stimulation stage is implemented by these stages. Therefore, stimulation is not considered a separate stage and the sequence of pretreatment comes down to whether cleaning or premilking is performed first.

The literature found on the pretreatment techniques describes different sequences used for their experiments. However, all pretreatment methods and sequences end with the drying of the teats. When cleaning is done manually using a damp towel or by washing the udders with water or disinfectant, two researchers [63] [70] perform the premilking before the cleaning, while another [54] first cleans. When the teats are cleaned by dipping them in disinfectant, sequences vary too. Both dipping before [82] [80] and after [5] [78] premilking are used. When using a special teat cup that performs cleaning and premilking, cleaning is performed first [17], but with an automatic teat scrubbing device premilking comes first [5].

One paper is found that investigates what sequence results in the least udder infections [66]. This study concludes that when the cow is cleaned "by wiping with a dry cloth or with a towel soaked with disinfectant", cleaning should follow the premilking. However, when only water is used to wash the teats, premilking should be performed after cleaning. It is thought that the dryness and cleanness of the milker's hands while cleaning and premilking creates this difference. When a milker's hands are both wet and dirty while premilking, there's a higher chance of spreading infections between cows.

## 4.3. Patent study

A patent study has been executed using the worldwide database Espacenet [22]. The following search query has been used: *cl = "A01J7/04" AND (ta any "udder*" OR ta any "teat*" OR ta any "nipple*") AND (ftxt any "dairy" OR ftxt any "cow*" OR ctxt any "milking")*. It was determined that narrowing the search down to a subclass was necessary to obtain a manageable amount of results. Search term 'A01J7/04' refers to the subclass 'For treatment of udders or teats, e.g. for cleaning', which falls under the class A01J7/00 'Accessories for milking machines or devices'. Even though patent 46 is included in the results that is only part of class A01J7 and not subclass A01J7/04, searching through the whole class was considered to give too many results (768). Furthermore, the words 'udder*', 'teat*' or 'nipple*' have to be in the titles or abstract of the patent to narrow the results down to patents concerning this part of the cow. The same goes for the words 'dairy', 'cow*' and 'milking', but these have to be in the description or claims. The '*' refers to the wildcard function, which has to same properties as the wildcard used in the literature research in section 4.2, thus returning variations on the words to include more patents on the same subject. The selection process of the patent research is illustrated in figure 4.8.

The resulting patents are visually organized in figures 4.9 and 4.10. With 46 patents remaining after selection, the patents are divided in the following way: There are two main categories, namely one category with patents that perform the pretreatment inside a teat cup and one that does not. The 'inside teat cup' category is further divided into a group with patents that use a fluid, a group that utilizes a mechanical method and a group with patents that use both. The 'no teat cup' category is also divided into three groups: one with patents utilizing rotators, one concerning the spraying of a fluid and a small group containing other pretreatment methods. The 'rotator' group is further divided into subgroups by the amount of parallel horizontal rotators, and a subgroup with other configurations. In the following chapters, the patents will be discussed per subgroup.

### 4.3.1. Inside teat cup

This category contains all patents that perform the pretreatment inside a teat cup and is illustrated in figure 4.9. It is further divided into groups with patents that use a fluid, patents that use a mechanical method and patents that use both (hybrid).

*Fluid*

This group consists of 5 patents that use a fluid for the pretreatment inside a teat cup. This fluid can be sprayed onto the teat through nozzles inside the cup liner like patents 1 [33] and 2 [62]. Patents 3 [43] and 4 [79] use a flow or vortex of fluid inside the teat cup by rotating the washing cup or have a specially shaped liner, respectively. Patent 5 [10] uses ultrasonic vibration in order to create cavitation in the fluid that helps with the cleaning process. Another notable feature that patent 2 and 3 share is the drying of the teats after washing by blowing air inside the cup. Furthermore, patent 3 describes two teat cups, a big one for washing and a smaller one on the front for dipping the teat in disinfectant. All patents in this group have the function of cleaning the teat, but only 3 and 4 explicitly mention stimulating. None of them are designed for premilking.

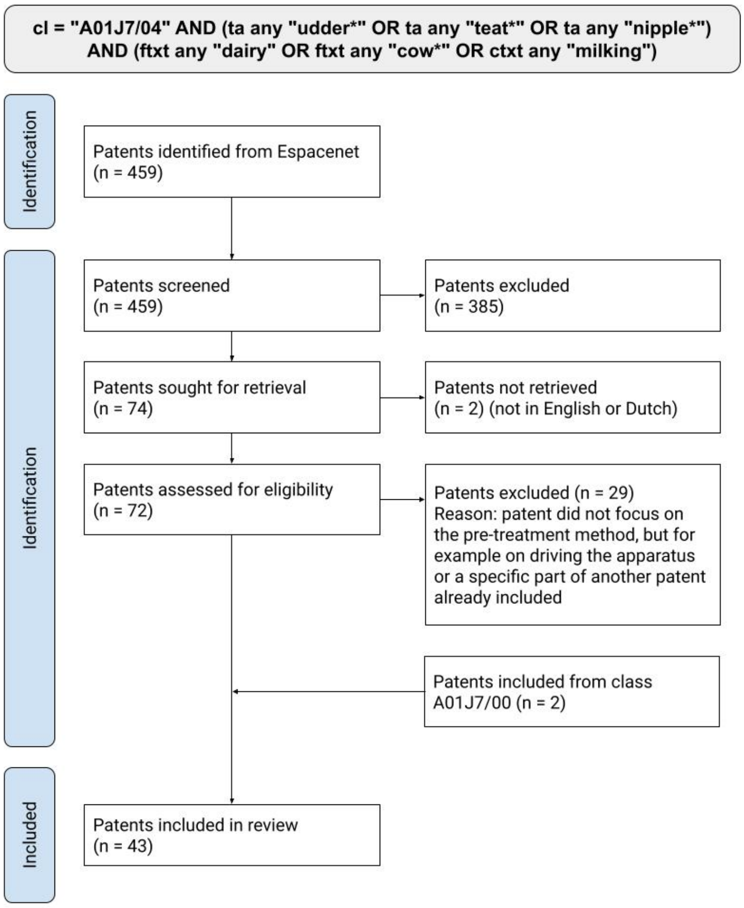



Figure 4.8: Selection process patent research on pretreatment methods based on PRISMA.

*Mechanical*

This group consists of 12 patents that use a mechanical method for the pretreatment inside a teat cup. All patents mention the use of some type of cleaning fluid except for patent 11. Patents 6 to 13, [50] [37] [4] [15] [75] [2] [36] [73] respectively, all utilize some type of cleaning member(s) attached to the inner wall of the teat cup in order to clean the teat. Patents 6 to 10 each have a tubular brush enveloping the teat inside a rotating inner chamber driven by a motor or compressed air. Patent 7 has an inner cup that is adjustable in height and has a flexible opening, so that the cup can be adjusted to different teat sizes. Furthermore, the flexible opening wipes off the washing water when the cup is removed. Patent 8 has two identical cleaning cups, one being wet with disinfectant and one without to dry off the teat after cleaning. Patents 11, 12 and 13 have passive cleaning members on the inside of the teat cup. Patent 11 its cleaning members are elongated and bristle-like, positioned in four perpendicular vertical rows between which the teat is moved back and forth to scrape off dirt. They may be inflatable or stiffenable by fluid pressure or made from an inherently stiff material and may have a certain texture. Patent 12 uses a similar back and forth motion for cleaning the teat, but utilizes multiple stacked rings with inward facing bristles at the opening of the teat cup to scrub the teat and apply germicide. Patent 13 also uses an up and down motion and has a specially shaped liner opening with a structured inside that scrapes the dirt of the teat when it is pulled out of the cup. Patent 14 [6], 15 [83] and 16 [19] use multiple vertical rotating brushes positioned in a circle around the teat. The bottom bristles of the brushes of patent 16 are inclined upward to ensure proper cleaning of the tip of the teat. Patent 17 [84] describes a quite elaborate device, comprising of four teat cups that can be individually aimed toward each teat using cameras. Around each teat cup four rotating massage head are positioned that rotate against the udder surrounding the teat to stimulate the cow. Furthermore, four nozzles spray cleaning fluid at the teats and udders.

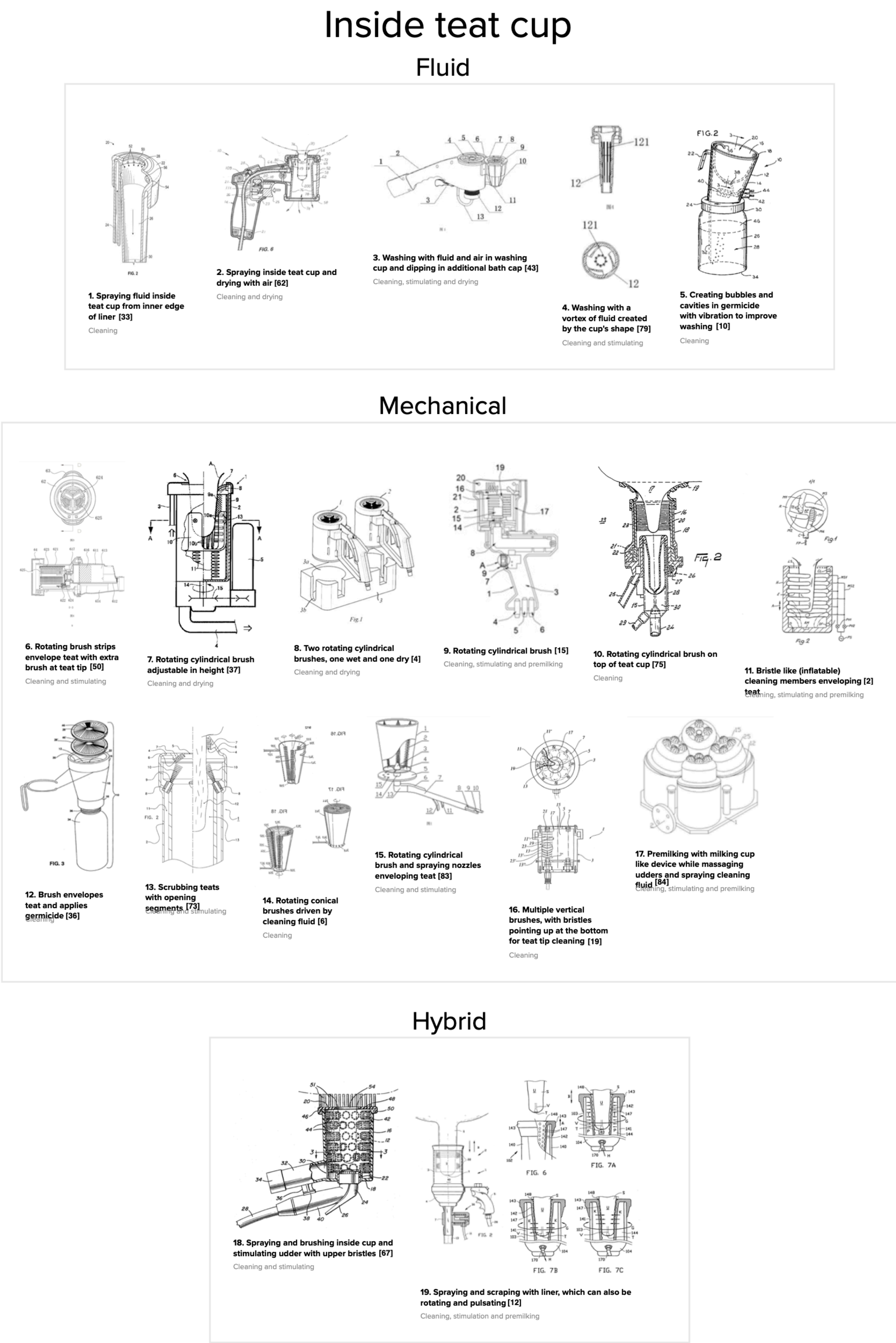



Figure 4.9: Overview of patents that utilize a teat cup for pretreatment of the teats before milking.

*Hybrid*
This subgroup consists of two patents that use a combination of spraying fluid and mechanical cleaning members to clean and stimulate the teat. Patent 18 [67] comprises of a teat cup with 'bristle-like blades' projecting inward to the teats and vertically upward from the cup's rim directly. Jets of water are sprayed from the bottom of the cup onto the teat but also the blades in order to create an oscillating motion that improves cleaning and stimulation, also directly at the udder with the upwards facing blades. Patent 19 [12] describes nozzles inside the teat cup aimed at the teat to spray cleaning fluid directly at the teat. The cup liner itself is textured and can rotate around the teat to scrape of dirt. Furthermore, the liner can pulsate like a conventional milking cup in order to premilk the cow.

### 4.3.2. No teat cup
This category contains all patents that don't use a teat cup for the pretreatment process and is illustrated in figure 4.10. It is further divided into three groups: a group containing patents that use a fluid to perform the pretreatment process, a group with patents using a mechanical method and a group with other types of pretreatment methods.

**Fluid**
The patents in this group utilize a fluid in order to perform the pretreatment. Patent 20 [77] consists of a ring which is positioned around the teat, with nozzles spraying cleaning fluid inward onto the teat in order to clean and stimulate it. Patent 21 [53] sprays disinfectant from the rim of a teat cup, slightly upwards with the teat being positioned above the teat cup. Patents 22 [6], 23 [64] and 24 [60] focus on the complete udder, instead of only the teats. The udder is sprayed with cleaning fluid or a mixture of fluid and gas, which has a cleaning and stimulating effect. Patent 24 also dries the cow's udders by blowing air at it. Patent 25 [56] describes a method of spraying electrostatic charged droplets of for example disinfectant on the cow's teats and udders. By charging them the droplets will stick to the target better and therefore reduce waste and contamination of surrounding areas.

**Mechanical**
This group contains the patents that use horizontal rotating cleaning members or rotators to perform the pretreatment. It is further divided into subgroups by the amount of rotators and a subgroup containing other configurations.

*Two parallel horizontal rotators*
In this subgroup, patents use two parallel horizontal rotating cleaning members to perform the pretreatment. Patent 26 [49] comprises of two rotating rollers that can be made from a sponge-like material or a rubber or plastic-like material shaped into a profile with empty spaces for the teat to fall in. This way, all sides of the teat are cleaned in combination with cleaning fluid. Patent 27 [35] uses two rotating brushes and cleaning fluid to clean and stimulate the teats, after which the brushes are rotated dry and used to dry the teats. Patent 28 [27] uses the same method, but also has a pattern of bristles with different properties that makes the teat move back and forth while cleaning and stimulating, improving the effect. Patent 29 [6], 30 [6] and 31 [74] furthermore focus on premilking, with patent 29 using an iris diaphragm that encloses around the base of the teat in order to prevent milk inside the teat from being pushed up instead of down while two rotating rollers squeeze the teat. Patent 30 and 31 use different shapes of cleaning members to improve the premilking function. While patent 30 has cylindrical brushes with expanded cores to increase the pressure on the teat, patent 31 utilizes rollers with non-circular cross-sections to mimic the milking motion. The distance between these special rollers is variable and the shape of the cross-section can be adjusted to switch from cleaning to premilking.

*Three parallel horizontal rotators*
This subgroup consists of patents using three parallel horizontal rotating brushes. All patents use a type of cleaning liquid in combination with the brushes, except for patent 32 [16]. Patents 32, 33 [57], 34 [14] and 35 [13] all use the same method of having two counter rotating brushes and one brush positioned below and in between, focused on cleaning the tip of the teat. Patent 35 mentions drying the brushes by rotating them in order to dry the teat after pretreatment. Patent 36 [7] its third lower roller is positioned slightly off-centre and has an additional 'idle roller' which guides the teats tip to the third roller. Also it mentions drying of the teat by using dry brushes. Patent 37 [38] is very similar to

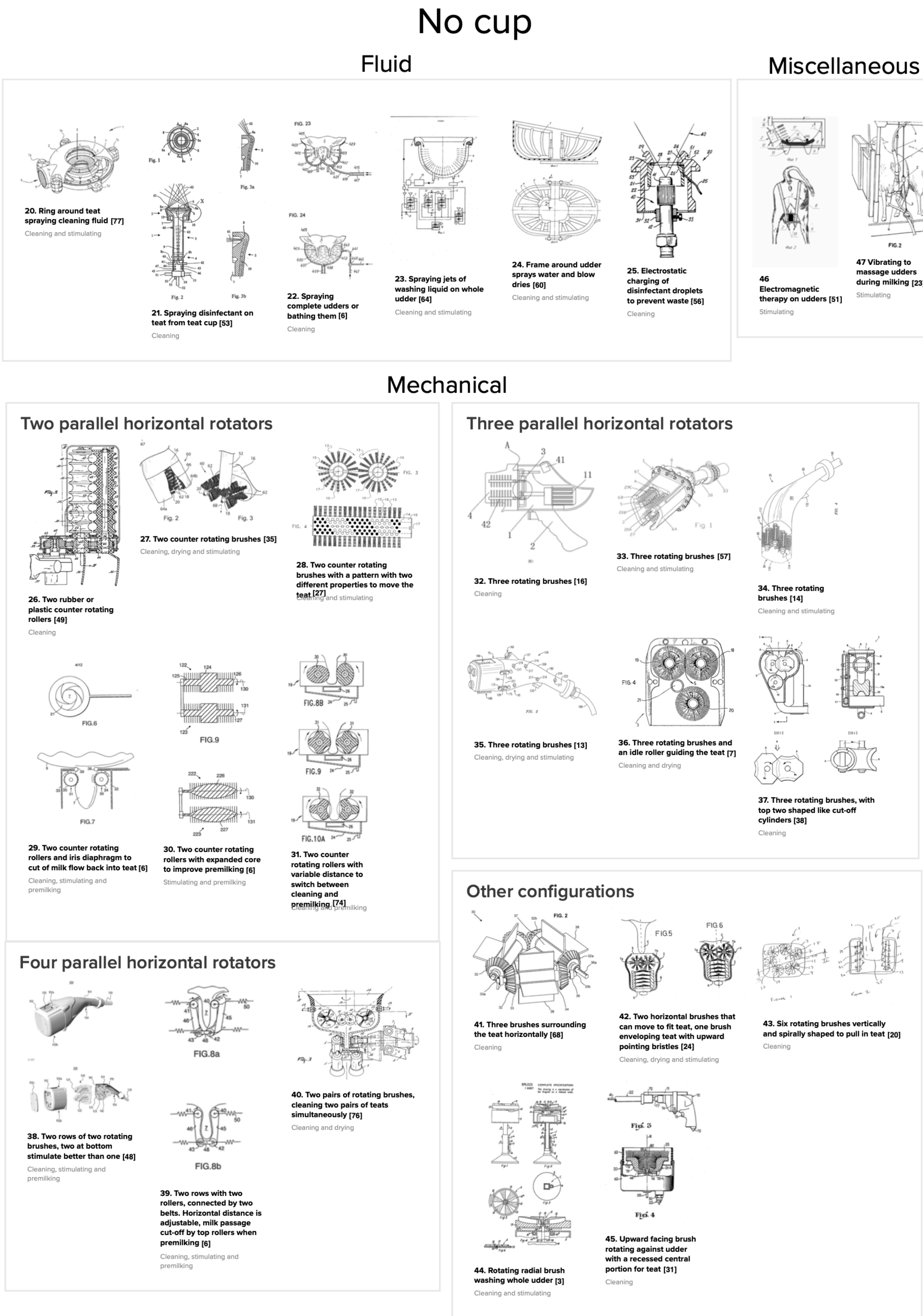



Figure 4.10: Overview of patents that do not utilize a teat cup for pretreatment of the teats before milking.

patent 36, but instead of the idle roller it uses the a part of the housing to guide the teat. Furthermore, instead of two cylindrical brushes, patent 37 uses two cylindrical shaped brushes with the axis positioned through the side and with 'four semi-circular arc action parts' to ensure that the teat is scraped from base to tip.

*Four parallel horizontal rotators*

This subgroup contains three patents that use four parallel horizontal rotators. Patent 38 [48] is very similar to patents 32 to 35, except for having one extra brush in the bottom row. It is claimed that having two brushes below the top pair instead of one has a better stimulating effect on the teat. Patent 39 [6] also uses two rows of two rotators, but these are connected with two belts that are pressed against the teat and can have a texture to improve performance. The horizontal distance between the rollers is adjustable and the top two rollers can cut-off the milk passage to the udders while premilking. Patent 40 [76] has a different configuration: it comprises of two counter rotating pairs of one big and one small brush positioned in a horizontal plane. Each pair of brushes cleans two teats, so the method cleans all four teats at once. After cleaning, the teats are blow-dried.

*Other configurations*

This subgroup is a collection of patents utilizing rotating brushes in varying configurations that do not fit in the other subgroups. Patent 41 [68] uses three brushes rotating in the horizontal plane and their rotational axes forming an equilateral triangle. The brushes comprise four paddles, extending radially outward from the rotational axes and made from a resilient plastic or rubber material. It is claimed that the teat being scraped from three directions instead of two improves the cleaning performance. Patent 42 [24] consists of two counter rotating brushes through which the teat enters the device, but with an extra vertical rotating cup-like brush below that envelops the teat. The bristles of this cup-like brush are pointed slightly upward to ensure proper cleaning of the tip of the teat. The distance between the two horizontal brushes can be adjusted to fit different teat sizes. Patent 43 [20] utilizes six vertical rotating brushes that are positioned in a circle around where the teat enters the device. The brushes have a spirally shaped cleaning surface which ensures the teat to be pulled downwards into the device, stretching the skin to remove the dirt in the skin's creases. Patents 44 [3] and 45 [31] both utilize one large disc-shaped brush that cleans both the teats and the udders. The brush used in patent 44 is positioned on top of an in height adjustable foot that is positioned below the cow's udders and makes an reciprocating rotating motion around the vertical axis. Patent 45's brush does not cover the whole udder at once, but has a recessed central portion, which ensures that not only the udders but also each individual teat can be cleaned thoroughly. This brush is positioned on a curved handle which enables the operator to position it under the udder.

### 4.3.3. Miscellaneous

This group contains two patents that do not use a teat cup, nor do they use a fluid or a mechanical method for the pretreatment. Patent 46 [51] comprises a harness that is applied around the cow's udders, which houses a high-frequency electromagnetic pulse generator. This type of electromagnetic therapy is meant to stimulate the cow's udders and prevent or treat udder diseases and is claimed to be an effective and environmentally friendly alternative to drug treatment for for example mastitis. Patent 47 [23] describes a device for stimulating the udders before and during the milking process by massaging the udders. Two hooks that are attached to the device are positioned around the back teats of the cow, keeping it in place while it vibrates and massages the udders.

# 5
# Results

The first part of this paper explained a cow's milking process with a focus on the pretreatment process and its advantages and challenges. In the second part, the state of the art pretreatment techniques were given by studying the flagship automatic milking systems made by the three biggest manufacturers at the moment. Furthermore, a literature research and a patent study provided a comprehensive overview of current and experimental pretreatment techniques. In total, 29 papers and 43 patents are incorporated in this study.

### 5.0.1. Milking process

The pretreatment can be separated in three stages: cleaning, stimulation and premilking. Cleaning is necessary to avoid contaminating the milk and prevent the cow from getting mastitis [8] and is required by EU law [71]. Stimulation makes sure the cow's milk ejection reflex is activated before attachment of the milk machine, in order to remove the milk as quick as possible. This results in the least machine-on time, which is better for the teat tissue [47] [82]. Premilking makes sure the first squirts of milk of each quarter are kept separated, since these contain the most bacteria and can contaminate the bulk milk [66] [78] [72]. During premilking the cow is also checked for mastitis and it is required by EU law [71]. After milking, a post-treatment can be performed by spraying or dipping a disinfectant or protecting agent on the teats to prevent mastitis.

### 5.0.2. Current pretreatment techniques

The three biggest manufacturers of automatic milking systems are Lely, DeLaval and GEA. Each company uses a different pretreatment technique in their newest systems. The Lely Astronaut A5 [40] uses two horizontally counter-rotating brushes that clean and stimulate the cow's teats and the premilking is performed by the milking system. The advantage of using this technique is that when the teat is not aligned perfectly, it will automatically be pushed to the center by the brushes. Furthermore, Lely claims that the mechanical motion of a brush cleans and stimulates better than other options using teat cups. A disadvantage of this method compared to competitors is that it does not perform premilking, because the premilking is then performed by the milking system while the premilk has to be kept separate from the bulk milk to prevent contamination.

The DeLaval VMS V300 [11] utilizes an extra teat cup for cleaning, stimulating and premilking. The advantage of this system using teat cups for the pretreatment is that it also involves premilking and that it is executed by a separate milking system to keep the premilk separate. A disadvantage is however a teat cup has to be applied twice per teat.

Finally, GEA performs all three pretreatment stages and the milking process in the same teat cup of the DairyRobot R9500 [30]. An advantage of this system is that it only needs to attach a teat cup once per teat. However, a disadvantage is that extra measures have to be taken to keep the pretreatment waste separate from the bulk milk and to prevent cross-contamination, because everything takes place in one system.

### 5.0.3. Pretreatment literature research

The literature research is executed using the Scopus database [18] and divided in three separate search queries, one for each stage of the pretreatment. This way the search queries could be more specific, giving less results but more relevant papers.

For the cleaning stage, opinions in literature are divided on what the preferred method is. The methods found are washing the teats with water [32] or disinfectant [44] [54], mechanically cleaning [1] [63] [54] in combination with a disinfectant using a towel [66], an (automatic) teat scrubber using horizontally rotating brushes [28] [5] [59], or dipping the teats in a disinfecting iodophor solution [29], a special foam [26] or gel [41] [58]. However, all papers agree that the teats should be properly dried before milking, to prevent the liners from the milking machine to slip and damage the udders. Potentially all previously mentioned cleaning methods are effective, but what method is preferred depends on the context, like the milking system, herd size or laws the milker has to follow.

The stimulation stage overlaps with the cleaning and/or premilking stage, since these two stages can also work stimulating [47] [17] [66] [78]. Tactile stimulation activates the milk ejection reflex [69], which horizontally rotating brushes can perform effectively [28] [42] [59] [52]. Applying a pulsating vacuum through teat cups like a milking machine also works stimulating [52] [69] [70] [80]. Heating the udders with warm water or air does not have a stimulating effect [17] [47] [69]. This suggests that mechanical or tactile stimulation is the most effective, where the teats are physically 'touched'.

The stimulation time needed for milk to be ejected so it can be removed, depends on the udder filling [9] [81] [46]. The stimulation time should be between 20-40 s for well-filled udders [8] [9] [81] [34] and 1.5 - 2 min or more for udders with small amounts of milk [9] [81]. Stimulating for 15 s followed by a latency period of up to 45 s for well-filled udders, and 30 s of stimulation and 1 min of latency for less-filled udders also works [46].

Premilking is done manually in the research found in literature [80] [70] [78] [82], by compressing the teats and removing several streams of milk per udder quarter. It is evident that the found literature is not focused on different premilking techniques and that manual premilking is considered standard.

The sequence in which the three pretreatment stages are performed differs throughout the found literature. Manually cleaning the teats with a towel or washing them is performed before [54] or after [70] [63] the premilking stage. Dipping the teats in disinfectant also takes place both before [82] [80] or after premilking [5] [78]. When using a special teat cup that performs both cleaning and premilking, cleaning is performed first [17], but with an automatic teat scrubbing device premilking comes first [5]. However, all pretreatment methods end with the drying of the teats. One paper [66] suggested when a milker's hands are both wet and dirty while premilking, there's a higher chance of spreading infections between cows. Therefore, when cleaning is done by washing with only water, premilking should be performed before cleaning. When wiping with a dry cloth or washing with disinfectant, premilking should be performed after cleaning. This difference found in pretreatment sequences suggests that there is no pretreatment sequence that works for all pretreatment methods and is highly dependent on the method and context.

### 5.0.4. Patent study

The patents study is executed using the Espacenet database [22]. The results are divided into two main categories, one with patents utilizing a teat cup and one without. These categories are further divided into groups based on the working principle using a fluid or a mechanical motion, a hybrid of fluid and mechanical, or 'Miscellaneous'. The 'Mechanical' group of the 'No teat cup' category is further divided into subgroups based on the amount of parallel horizontal rotators.

In table 5.1 an overview of the results of the patent study is given. Most patents, 31 in total, use brushing as (one of) their main technique(s) and 14 of these brushing techniques are applied by parallel horizontal rollers (PHR). For brushing, 2 and 3 rollers are both used 6 times, while 4 rollers are only used 2 times. This means brushing with 2 or 3 PHR is the most common technique used in the found patents.

Spraying is the second most used main technique and is used 10 times. Compressing the teats is the main technique only 6 times and is combined with spraying or brushing 3 times. Drying is implemented in 9 patents and always combined with other techniques, most likely because drying is only the end of the cleaning stage. Washing is the least implemented main technique, which is used only 3 times.

Except for drying, only 4 patents combine multiple techniques. The use of a type of fluid is mentioned

Table 5.1: An overview of the results of the patent study. TC = teat cup, Sp = spraying, W = washing, B = brushing, C = compressing, D = drying, #T = number of teats pretreated at once, VCB = vertical cylindrical brush, ICB = inward cylindrical brush, #PHR = number of parallel horizontal rotators, SICB = stationary inward cylindrical brush, C = cleaning, St = stimulating, P = premilking and Tot = total number of patents containing this aspect.

| | | Main technique | | | | | | | Rotating | | | | | PT Stage | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **#** | **TC** | **Sp** | **W** | **B** | **C** | **D** | **Other** | **#T** | **VCB** | **ICB** | **#PHR** | **Other** | **SICB** | **C** | **St** | **P** |
| 1 | X | X | | | | | | 1 | | | | | | X | | |
| 2 | X | X | | | | X | | 1 | | | | | | X | | |
| 20 | | X | | | | | | 1 | | | | | | X | X | |
| 21 | | X | | | | | | 1 | | | | | | X | | |
| 22 | | X | | | | | | 4 | | | | | | X | | |
| 23 | | X | | | | | | 4 | | | | | | X | X | |
| 24 | | X | | | | | | 4 | | | | | | X | X | |
| 25 | | X | | | | | | N/S | | | | | | X | | |
| 18 | X | X | | X | | | | 1 | | | | | X | X | X | |
| 19 | X | X | | X | X | | | 1 | | | | | X | X | X | X |
| 3 | X | | X | | | X | | 1 | | | | | | X | X | |
| 4 | X | | X | | | | | 1 | | | | | | X | X | |
| 5 | X | | X | | | | Vibr. | 1 | | | | | | X | | |
| 6 | X | | | X | | | | 1 | | X | | | | X | X | |
| 7 | X | | | X | | X | | 1 | | X | | | | X | | |
| 8 | X | | | X | | X | | 1 | | X | | | | X | | |
| 9 | X | | | X | | | | 1 | | X | | | | X | X | X |
| 10 | X | | | X | | | | 1 | | X | | | | X | | |
| 11 | X | | | X | | | | 1 | | | | | X | X | X | X |
| 12 | X | | | X | | | | 1 | | | | | X | X | | |
| 13 | X | | | X | | | | 1 | | | | | X | X | X | |
| 14 | X | | | X | | | | 1 | X | | | | | X | | |
| 15 | X | | | X | | | | 1 | X | | | | | X | X | |
| 16 | X | | | X | | | | 1 | X | | | | | X | | |
| 26 | | | | X | | | | 1 | | | 2 | | | X | | |
| 27 | | | | X | | X | | 1 | | | 2 | | | X | X | |
| 28 | | | | X | | | | 1 | | | 2 | | | X | X | |
| 32 | | | | X | | | | 1 | | | 3 | | | X | | |
| 33 | | | | X | | | | 1 | | | 3 | | | X | X | |
| 34 | | | | X | | | | 1 | | | 3 | | | X | X | |
| 35 | | | | X | | X | | 1 | | | 3 | | | X | X | |
| 36 | | | | X | | X | | 1 | | | 3 | | | X | | |
| 37 | | | | X | | | | 1 | | | 3 | | | X | | |
| 38 | | | | X | | | | 1 | | | 4 | | | X | X | X |
| 40 | | | | X | | X | | 4 | | | 4 | | | X | | |
| 41 | | | | X | | | | 1 | | | | 3 brush triangle | | X | | |
| 42 | | | | X | | X | | 1 | | X | 2 | | | X | X | |
| 43 | | | | X | | | | 1 | X | | | | | X | | |
| 44 | | | | X | | | | 4 | | | | Hor. disk brush | | X | X | |
| 45 | | | | X | | | | 4 | | | | Hor. disk brush | | X | | |
| 29 | | | | X | X | | | 1 | | | 2 | | | X | X | X |
| 30 | | | | X | X | | | 1 | | | 2 | | | | X | X |
| 17 | X | | | | X | | Massage | 4 | | | | 4 RMH per teat | | X | X | X |
| 31 | | | | | X | | | 1 | | | 2 | | | X | | X |
| 39 | | | | | X | | | 1 | | | 4 | | | X | X | X |
| 46 | | | | | | | EMT | 4 | | | | | | | X | |
| 47 | | | | | | | Vibr. | 4 | | | | | | | X | |
| Tot | 19 | 10 | 3 | 31 | 6 | 9 | | | 4 | 6 | 16 | | 5 | 44 | 26 | 9 |

in almost every patent and it can be assumed that all brushing patents use it in order to clean properly, but using fluid for wetting a brush is not considered to be spraying or washing in this study. Patent 19 combines the most techniques, namely spraying, brushing and compressing, and covers all three pretreatment stages. A potential argument for why techniques are not often combined is that it makes the device unnecessarily more complex when using one technique also suffices.

Patent 17 is considered to be the most complex. It comprises 4 teat cups that can be aimed individually at the teats using cameras positioned inside the teat cups. 4 nozzles apply cleaning fluid to the udders while the teats are premilking by the compressing teat cups and the 4 massage heads positioned at the top of the teat cup stimulate the udders by rotating.

The table shows that 19 out of 47 patents use a teat cup. Teats cups are mostly used for brushing, 13 times in total, and use rotating vertical cylindrical brushes (VCB) 3 times, while rotating and static inward cylindrical brushes (ICB and SICB) are used with a teat cup 5 times each. It should be noted with the SICB that although the devices that use one do not actively move the brush, the whole device can be moved manually by the milker to create a scrubbing or scraping motion.

# 6 Discussion

It is clear that most patents only pretreat one teat at a time. 9 out of the 47 patents treat 4 teats simultaneously and none do 2 or 3 teats. Pretreating 3 teats seems illogical, but what is remarkable is that no patent mentions pretreating 2 teats at once, since this in theory could speed up the process. The patents pretreating 4 teats at once are using varying techniques, so it is not clearly linked to a specific technique.

Regarding the pretreatment stages, it should be considered that when a patent does not mention a specific stage, it could still have that effect on the teats. For example, only 3 patents do not mention cleaning the teats: patents 30, 46 and 47. Patents 46 and 47 use an unconventional method for stimulating the udders using respectively electromagnetic therapy (EMT) or vibrations. Based on the findings in this study, it is assumed that without a mechanical motion or the spraying of fluids patents 46 and 47 two patents do not have a cleaning or premilking effect, but maybe do have a stimulating effect. However, patent 30 uses 2 specially shaped PHR with bristles to stimulate and premilk, which although not mentioned in the patent most likely also cleans the teats. The same goes for patents that do not mention stimulating effects, but do clean using brushes or textured rotators, or spray fluid. These techniques likely will also have a stimulating effect, like other patents using similar techniques do mention. 26 of the 47 patents claim to work stimulating, but more patents could have a stimulating effect. It is however important that the teats are properly stimulated, as explained in section 3.2, and when the focus is not on the stimulating stage its effect might not be sufficient and therefore not mentioned.

It can be seen that the premilking stage is only implemented in patents that use brushing and/or compressing as (one of) their main technique(s). This suggests that spraying or washing the udders is not suited for premilking. Only 9 patents claim to perform premilking and 7 of them also perform the cleaning and stimulation stage. It seems that the focus of the found patents is more on cleaning and stimulating and premilking is done manually or by the milking system.

## 6.1. Implications and limitations

It should be noted that for the literature research and the patent study only one database is used each, Scopus [18] and Espacenet [22], respectively. Although these databases are substantial, potentially more results can be found when using additional databases. Furthermore, although the search queries used in these databases are based on a balance between most relevant results and the amount of results, some relevant papers or patents might have not been found. An example of this is patent 46 from the patent study that does not fall in the subclass A01J7/04 that was searched in but class A01J7/00, but is still included in the study. There might be more patents like this, but including the complete class would result in almost double the amount of results (roughly 800) and after briefly scanning them it was decided that the class was not relevant enough. Furthermore, most literature on pretreatment is focused on conventional (manual) pretreatment methods and not automated systems. A potential explanation for this is that the majority of literature found dates from before automated milking systems became commercially available. However, most results from the patent study are focused on automated pretreatment systems and therefore helps showing a complete picture of existing pretreatment techniques. Finally, it is not possible to tell from a patent if the described device actually works the way it is intended to. This makes it hard to conclude what pretreatment technique works best, but seeing multiple patents based on the same technique gives cause to believe it's an effective one.

## 6.2. Recommendations

This research based on literature and patents is meant as a basis for further research on improving existing pretreatment techniques or inventing new ones. However, since the information found on what techniques actually work are more like general guidelines, actual experiments should be carried out to be able to evaluate what methods are most effective and what parameters should be used. Furthermore, since there is no main pretreatment technique that is clearly superior to its alternatives, it could very well be that there are techniques that have not yet been explored that are good alternatives or even more effective. This research on pretreatment techniques and overview of existing methods and devices should therefore serve as inspiration for inventing new ones.

# 7 Conclusion

The goal of this paper was to explain why proper execution of the three pretreatment stages (cleaning, stimulation and premilking) is important before the milking of a cow and more importantly to give a comprehensive overview of existing or experimental pretreatment techniques that could be used in an automatic milking system. This goal is achieved by presenting general information on the milking process, the state of art of automatic pretreatment systems, a literature research divided in three separate research for each pretreatment stage giving insight in what makes a technique effective, and a patent study presenting patents for different sorts of pretreatment methods to show what techniques exist.

The results in this paper suggest that there is no superior pretreatment technique, but multiple effective methods that are preferred in different contexts. However, it can be seen that rotating horizontal parallel brushes and spraying of the teats with a fluid are the two most popular techniques. These methods are potentially preferred because of the tactile stimulation from the brushes and the fact that the spraying can be performed inside a modified teat cup. It is clear that each method has its own trade-offs, like the rotating brushes not covering the premilking stage, or when spraying inside a teat cup that teat cups have to be applied twice or cleaned properly to avoid contamination and mastitis. Therefore, what pretreatment technique is best suited for a specific system is largely based on the context in which it will be used.

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# B

# Concepts Methods

As mentioned in chapter 2, a morphological chart is used to design the first three concepts that are tested. Solutions are drawn up for four problems: cleaning, stimulation, premilking and catching. The first three problems are the three pretreatment stages that the concept has to perform (premilking is desired, not required) and catching concerns the way the device makes sure that the teat is in the right position. The colours indicate what solutions are chosen for each concept.

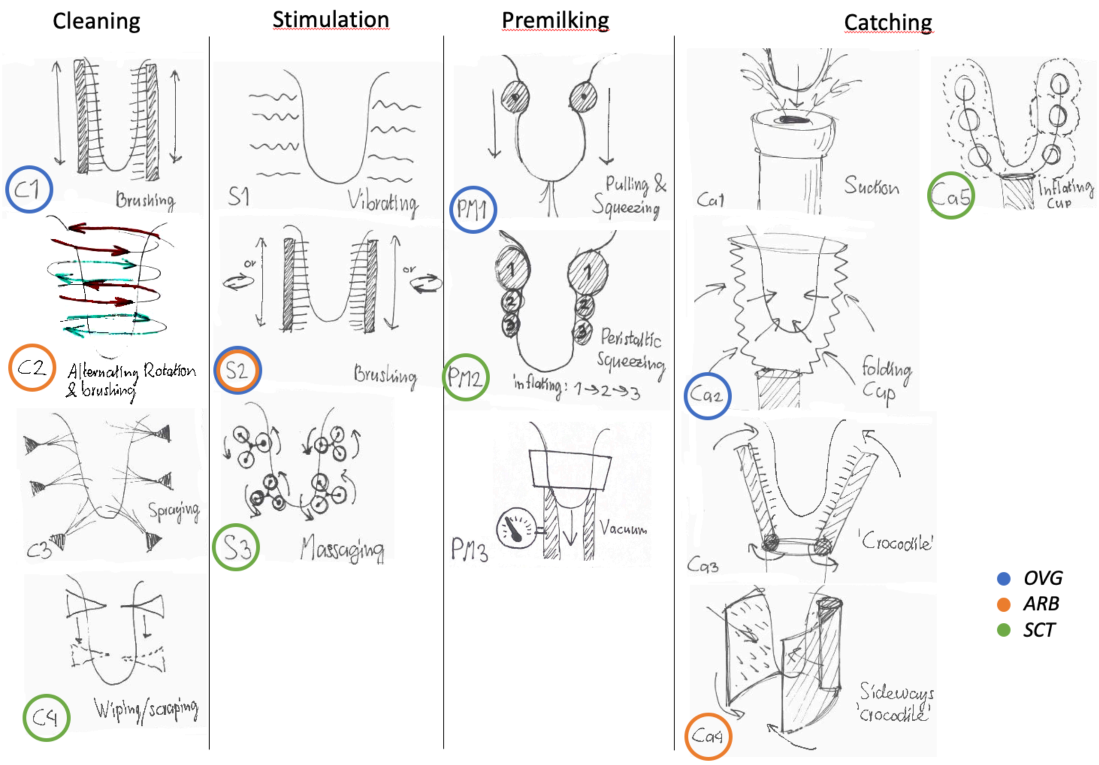
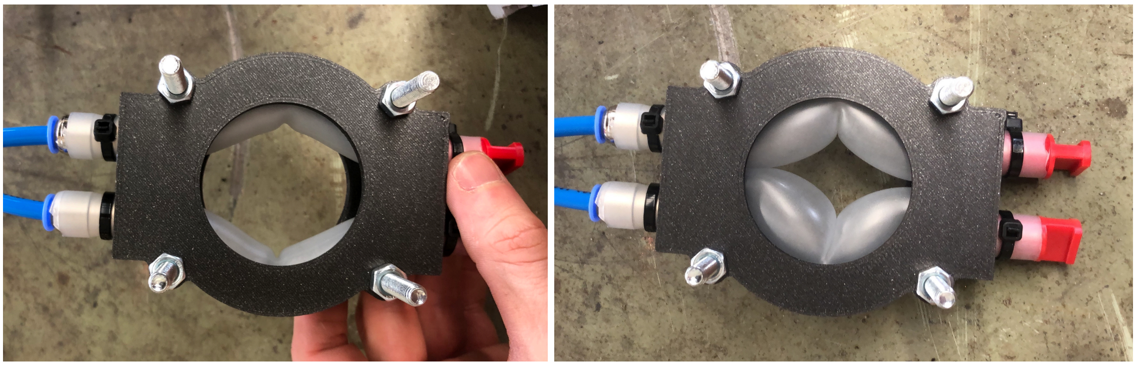



Figure B.1: Morphological chart used to choose the three concepts further developed for the first tests. The colours indicate what solutions were chosen for each concept.

# C

# Stepwise Compressing Tubes prototyping

The SCT first prototype had a large circular 50 mm diameter opening for the teat, but it was found that the two tubes would have to be inflated too far to properly compress the teat. Furthermore, to make the tubes follow the circular shape of the opening a thin rigid tube was inserted into the silicon tubes that pushed it outward into the circular shape. However, having the silicon tubes bent in such an arc resulted in them buckling and inflating unevenly, as can be seen figure C.1.



(a) (b)

Figure C.1: The first Stepwise Compressing Tubes prototype. (a) Non-inflated with the silicon tubes pushed into a circle-like arc. (b) Inflated, showing the buckling of the tubes causing them to inflate unevenly.

To solve this problem, it was considered to use three tubes per step in a triangular formation, pushing onto the teat from three directions instead of two. This would make for an larger opening for the teat without having to guide the silicon tubes and less risk of the tubes to buckle. However, the triangular composition would result in the tubes or the tube connectors to collide and therefore does not fit. Therefore, the final prototype has a more ellipse shaped opening of 50 mm by 38 mm and the tubes running straight, as can be seen in figure 2.8. This resulted in the tubes having to be inflated less to squeeze the teat.

# D

# Concepts Cleaning Test

This appendix shows the footage of the cleaning tests not shown in section 2.4.2.

**Lely Brushes**

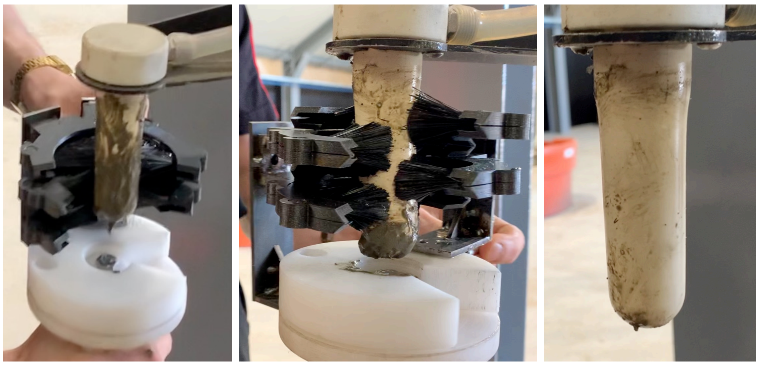
(a) (b) (c)

Figure D.1: The test-teat covered in wet mud (a), the test teat inserted between the rotating Lely pretreatment brushes (b), the cleaning result (c).

(a) (b) (c)

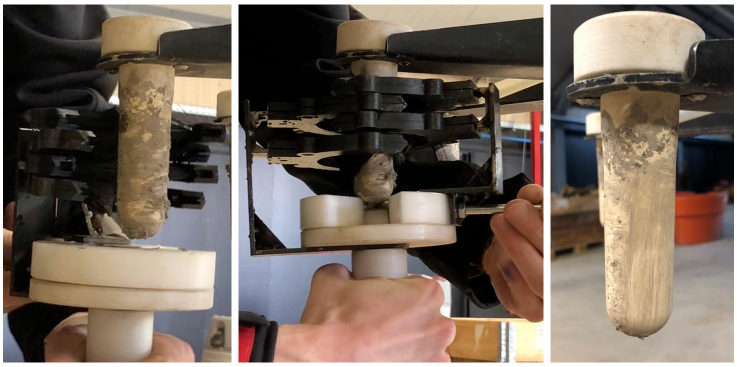
Figure D.2: The test-teat covered in dry mud (a), the test teat inserted between the rotating Lely pretreatment brushes (b), the cleaning result (c).

### Alternating Rotating Brushes



(a) (b) (c)

Figure D.3: The test-teat covered in wet mud (a), the ARB rotating around the test-teat (b), the cleaning result (c).



(a) (b) (c)

Figure D.4: The test-teat covered in dry mud (a), the ARB rotating around the test-teat (b), the cleaning result (c).

### Origami Vacuum Gripper

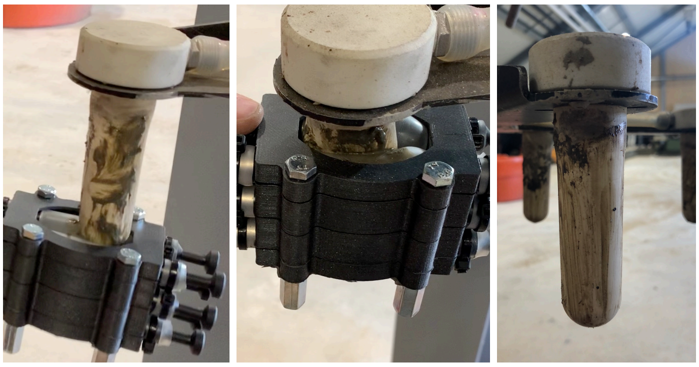
(a) (b) (c)

Figure D.5: The test-teat covered in wet mud (a), the OVG gripping and brushing the test-teat (b), the cleaning result (c).

(a) (b) (c)

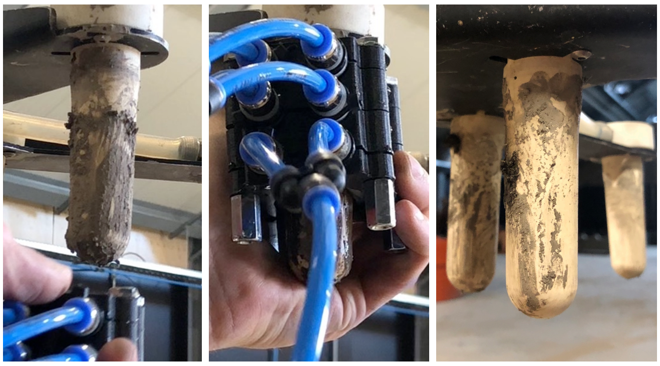
Figure D.6: The test-teat covered in dry mud (a), the OVG gripping and brushing the test-teat (b), the cleaning result (c).

### Stepwise Compressing Tubes



(a) (b) (c)

Figure D.7: The test-teat covered in wet mud (a), the SCT squeezing and scraping clean the test-teat (b), the cleaning result (c).



(a) (b) (c)

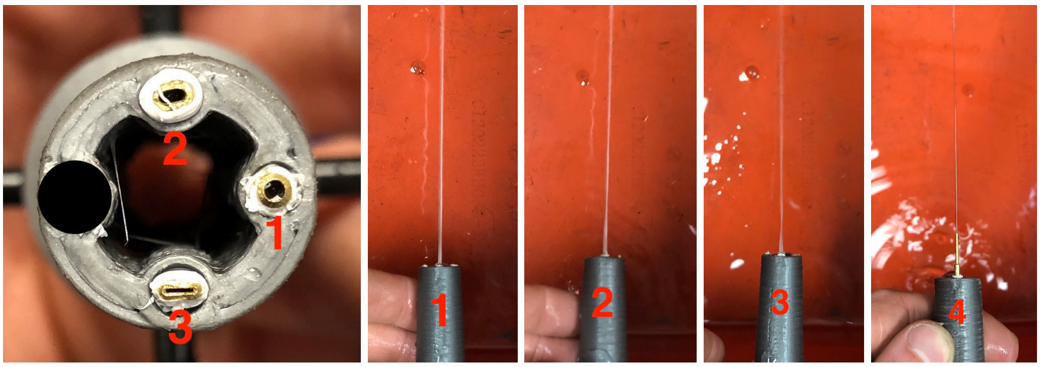
Figure D.8: The test-teat covered in dry mud (a), the SCT squeezing and scraping clean the test-teat (b), the cleaning result (c).

# E

# Spraying System

For the spraying of the teat, several methods were tested. As explained in section 3.3, the water tubes are connected to the side of the connector, which has four canals that guide the water to the bottom of the gripper. The initial idea was to fit small nozzles at the end of these canals to create one wide spray of water that would have a better cleaning effect than four separate thin streams. There were no nozzles available on the internet that would fit in this thin wall of the connector. Therefore, when designing the connector, it was decided that giving the canals a diameter of 2 mm would allow thin brass tubes with different inner diameters and lengths to be inserted to guide the water like a nozzle would.

The following configurations of nozzles were tested (see figure E.1): inserting a 1.1 mm inner diameter tube and flatten the end to try and create a more flat spread spraying pattern. This is tested in three gradations, from not flattened at all to the most flat to still let water through. The other (fifth) configuration is inserting an 0.6 inner diameter tube inside the 1.1 mm tube and see if its thin enough to widen the spray.

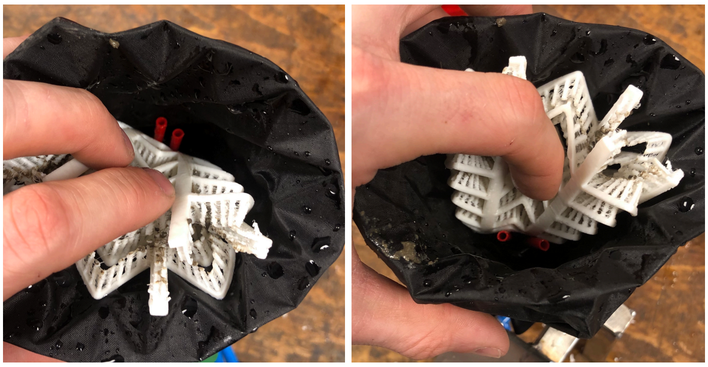



(a) (b) (c) (d) (e)

Figure E.1: (a) The three gradations of flattened 1.1 mm brass tube, ranging from not flat (1), half flat (2) to flat (3), shown while spraying in (b) to (d). (e) shows the fourth configuration, which is the thinner 0.6 mm tube inserted into the 1.1 mm tube spraying.

It was clear that even with the flattened end or thinner tube, no wider spraying effect can be created. Instead, a smaller single stream with a higher velocity was created.

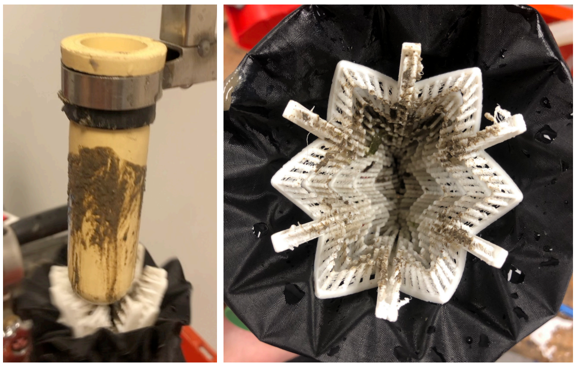
Another method that is tested to spray the teats and clean the brush liner, is spraying from behind the brush liner. Thin flexible tubes are attached to the connector's canals and positioned behind the brush liner, as can be seen in figure E.2. Ideally these four tubes would be positioned at equal distances in four quarters, spreading the water evenly. However, this was not possible due to the location of the flaps securing the brush liner, so for the test the four tubes were positioned in two groups at 2 sides of the brush liner, which was considered adequate for the testing of this concept.



(a) (b)

Figure E.2: The four spraying tubes positioned in pairs behind the brush liner on two sides ((a) and (b)).

As can be seen in figure E.3, the cleaning result is not sufficient. Although the sides of the brush liner where the spraying tubes were behind were rinsed almost free of dirt, not enough water reached the test-teat through the brush liner and is therefore not rinsed clean. Furthermore, positioning the tubes behind the brush liner pushes it slightly up, decreasing the pressure the gripper can apply higher up the test-teat and therefore it's cleaning capabilities in that area.



(a) (b)

Figure E.3: The cleaning result of the test-teat (a) and the state of the brush liner after cleaning (b).

Based on these results, it is decided to test spraying with the 1.1 mm tubes in the connector, since these would have a higher flow rate than the thinner tubes, and the extra velocity is not needed. The idea was that the higher flow rate would fill the gripper with more water and therefore compensate for the fact that it's four separate streams of water. The tubes are made roughly 40 mm longer as can be seen in figure E.4, in order to reach to the bottom of the brush liner and avoid getting accidentally blocked by the skeleton's skin.

(a) (b) (c) (d)

Figure E.4: The final connector spraying system (a), the dirty test-teat before testing (b), water rinsing the test-teat with the gripper open (c) and the cleaning result (d).

As can be seen in figure E.4, the spraying system with 1.1 mm tubes gave promising results. It was found that spraying the water with the test-teat inside the gripper, but with the gripper still open, gave the best results. This gave enough room for the water to rinse the test-teat clean, but while being confined inside the gripper.

# F

# Airtight Skin

Prior to building actual skins for the skeleton, five samples were ordered to see what exact type of fabric was the most suitable for this purpose, shown in figure F.1. The thinnest and second thinnest materials were chosen to experiment further with, the 70 g/qm (black) and 170 g/qm (yellow) fabrics. The fabric has the TPU coating on only one side, which is why small strips of the same material were used as seams that are welded onto the edges of the pieces that needed to be joined.


(a)

Figure F.1: The five samples that were ordered to see what fabric was suited for the airtight skin.

The initial idea for the airtight skin around the origami skeleton was to make two conical shapes and welding them together at one side, creating a shape that would be similar to a balloon around the skeleton with a hole in the middle that fit at the bottom of the gripper (see figure F.2). The small opening at the inside is made longer with a narrow 'tube' that's welded onto it, that can be clamped in the connector.

(a) (b)

Figure F.2: The first prototype of the airtight skin, consisting of two conical pieces welded together at the top, with an added narrow tube (yellow) at the inside bottom to be clamped in the connector. Inside out (a), and top view of welds (b)

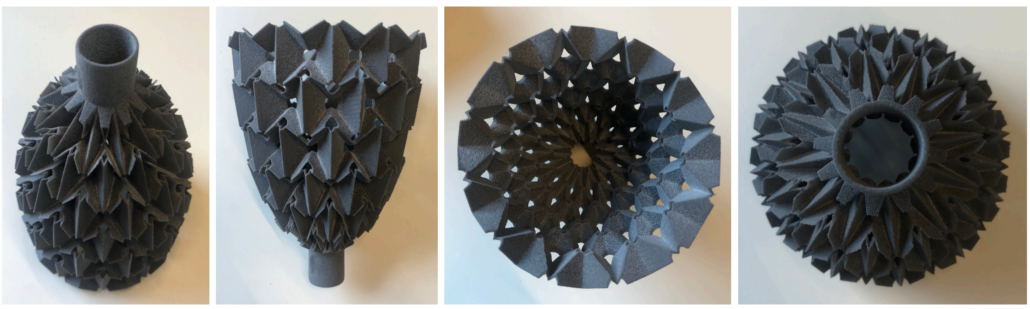
Although the skeleton did fit, the welds at the top of the skin are sticking out and would press into the cows udder while pretreating. The whole skin could be used inside out, but this would result in the TPU coating being on the outside, exposing the welds. Therefore, a different design is chosen that exists simple of one big cone that is folded over the skeleton, which is discussed in chapter 3.4.

# G

# Test 3D Prints

**Origami Gripper Skeleton** Like mentioned in section 3.2, two options were tested to get a most flexible as possible origami skeleton: make test 3D prints to see what thickness works with the MJF printing technique, and print a skeleton with 0.8 mm walls (which was recommended by Materialise, the company that made the models [12]) with gaps at the vertices of the folds to reduce the stiffness.

The wall thicknesses that were tested were 0.2 mm, 0.4 mm, 0.6 mm and 0.8 mm (see figure G.2). It turned out that all thicknesses were printed with a sufficient quality, and therefore the thinnest (0.2 mm) was chosen for the final design. These models are shown in figures G.3, G.4 and G.5. The quality of these three 3D prints was not as good as expected, but good enough for the gripping force test. Like the service employee of Materialize (the company that made the models) explained, the bigger surfaces are harder too 3D print with the thin walls. This is apparent when comparing the three models, as the 20 mm model has the best printing quality while the 40 mm model shows deformed edges and gaps that had to be repaired (see figure G.6).



(a) (b) (c) (d)

Figure G.1: The 0.8 mm wall thickness MJF 3D printed skeleton (30 mm sides) featuring holes at its vertices to decrease its folding stiffness.

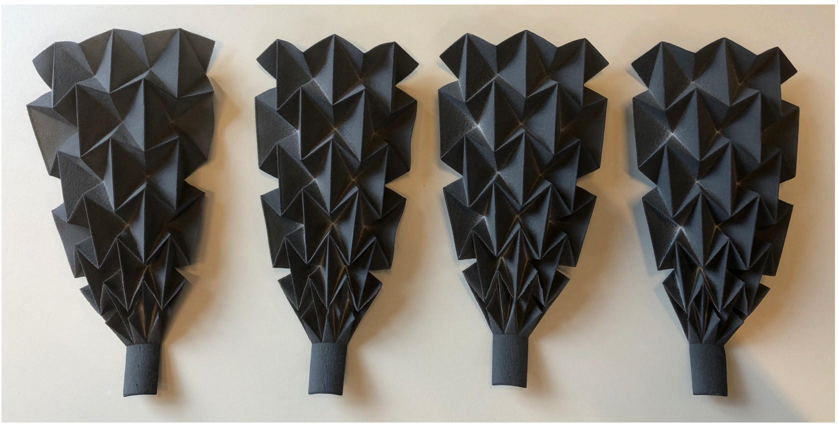
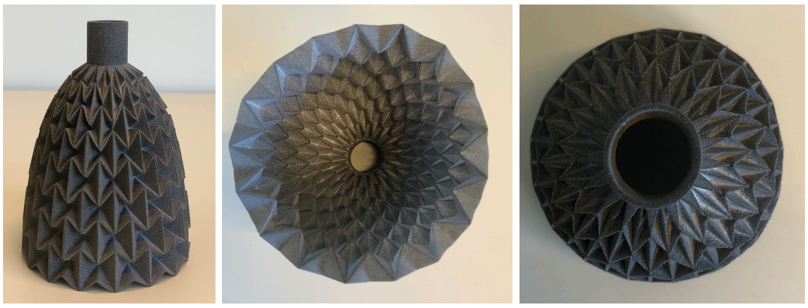
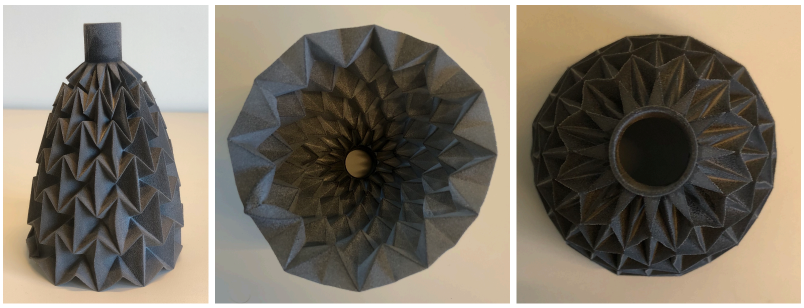


Figure G.2: Four 3D test-prints to see what wall thickness still has acceptable quality, ranging from 0.2 mm to 0.8 mm, left to right



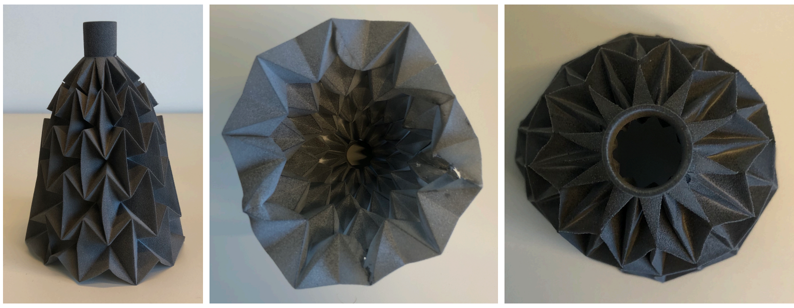
(a) (b) (c)

Figure G.3: 20 mm model, Multi Jet Fusion 0.2 mm wall thickness



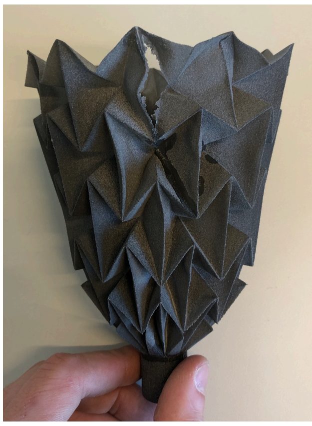
(a) (b) (c)

Figure G.4: 30 mm model, Multi Jet Fusion 0.2 mm wall thickness



(a) (b) (c)

Figure G.5: 40 mm model, Multi Jet Fusion 0.2 mm wall thickness



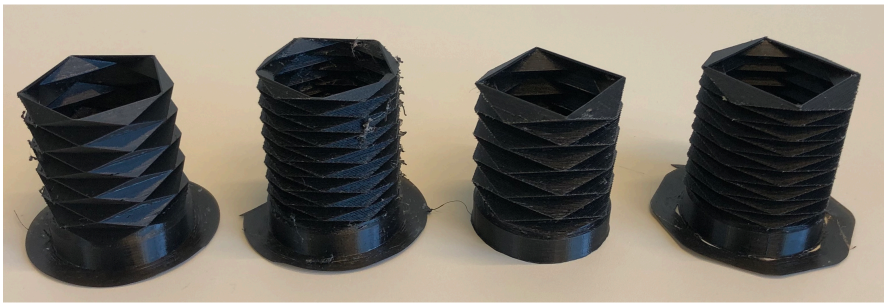
(a)

Figure G.6: 40 mm model gaps in walls, repaired with glue where possible.

**Yoshimura Linear Spring**

In figures G.7 and G.8 the second and third iteration of the Yoshimura structure are shown, respectively.

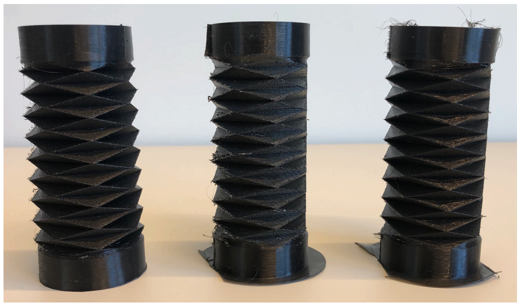
(a)



(b)

Figure G.7: The second iteration of Yoshimura springs.

(a)



(b)

Figure G.8: The third iteration of Yoshimura springs.

# H Gripping Force Test Data

Only the last five repetitions of the gripping force tests are used, since the pressure declines for the first five repetitions and then stagnates. Figures H.1 and H.2 show the mean pressures in kPa inside the test-teat over time for different gripper pressures, the 30 mm and 40 mm gripper model and the large and small test-teat.

| **Large test-teat** | | **30 mm** | | **-20 kPa** | | | |
|---|---|---|---|---|---|---|---|
| test # & time | 0s | 5s | 10s | 15s | 20s | 25s | |
| 1 | 9,6 | 8,6 | 8,3 | 8,1 | 8,1 | 8,1 | |
| 2 | 9,4 | 8,3 | 8,1 | 7,9 | 7,9 | 7,7 | |
| 3 | 9,4 | 8,3 | 7,9 | 7,7 | 7,7 | 7,7 | |
| 4 | 9 | 7,9 | 7,7 | 7,7 | 7,5 | 7,5 | |
| 5 | 8,6 | 7,9 | 7,7 | 7,7 | 7,6 | 7,6 | |
| 6 | 8,8 | 8,1 | 7,9 | 7,7 | 7,7 | 7,7 | |
| 7 | 8,8 | 7,9 | 7,9 | 7,7 | 7,7 | 7,7 | |
| 8 | 8,8 | 7,9 | 7,7 | 7,7 | 7,5 | 7,5 | |
| 9 | 9 | 7,9 | 7,7 | 7,6 | 7,5 | 7,5 | |
| 10 | 9 | 7,9 | 7,7 | 7,6 | 7,5 | 7,5 | *Average* |
| **Mean last 5** | **8,88** | **7,94** | **7,78** | **7,66** | **7,58** | **7,58** | **7,9** |

| **Large test-teat** | | **30 mm** | | **-25 kPa** | | | |
|---|---|---|---|---|---|---|---|
| test # & time | 0s | 5s | 10s | 15s | 20s | 25s | |
| 1 | 11,5 | 10,1 | 9,8 | 9,6 | 9,4 | 9,4 | |
| 2 | 10,7 | 9,8 | 9,4 | 9,4 | 9,2 | 9,2 | |
| 3 | 10,5 | 9,6 | 9,4 | 9 | 9 | 9 | |
| 4 | 10,3 | 9,4 | 9,2 | 9 | 9 | 8,9 | |
| 5 | 10,3 | 9,4 | 9 | 9 | 8,8 | 8,8 | |
| 6 | 10,1 | 9,4 | 9 | 8,8 | 8,8 | 8,8 | |
| 7 | 10,1 | 9,2 | 9 | 8,8 | 8,6 | 8,6 | |
| 8 | 10 | 9,1 | 8,8 | 8,8 | 8,6 | 8,6 | |
| 9 | 9,9 | 9 | 8,8 | 8,6 | 8,6 | 8,5 | |
| 10 | 9,8 | 9 | 8,8 | 8,7 | 8,6 | 8,6 | *Average* |
| **Mean last 5** | **9,98** | **9,14** | **8,88** | **8,74** | **8,64** | **8,62** | **9,0** |

| **Large test-teat** | | **30 mm** | | **-30 kPa** | | | |
|---|---|---|---|---|---|---|---|
| test # & time | 0s | 5s | 10s | 15s | 20s | 25s | |
| 1 | 12,8 | 11,2 | 10,8 | 10,7 | 10,5 | 10,5 | |
| 2 | 12 | 10,9 | 10,6 | 10,5 | 10,4 | 10,3 | |
| 3 | 12,2 | 10,7 | 10,5 | 10,3 | 10,3 | 10,2 | |
| 4 | 11,9 | 10,5 | 10,3 | 10,3 | 10,1 | 10,1 | |
| 5 | 11,6 | 10,5 | 10,3 | 10,1 | 10,1 | 10,1 | |
| 6 | 11,6 | 10,5 | 10,3 | 10,1 | 10,1 | 10,1 | |
| 7 | 11,7 | 10,5 | 10,3 | 10,1 | 10 | 9,9 | |
| 8 | 11,4 | 10,3 | 10,1 | 10,1 | 10 | 9,9 | |
| 9 | 11,4 | 10,3 | 10,1 | 10,1 | 10 | 9,9 | |
| 10 | 11,4 | 10,2 | 10,1 | 9,9 | 10,1 | 9,9 | *Average* |
| **Mean last 5** | **11,5** | **10,36** | **10,18** | **10,06** | **10,04** | **9,94** | **10,3** |

| **Large test-teat** | | **30 mm** | | **-35 kPa** | | | |
|---|---|---|---|---|---|---|---|
| test # & time | 0s | 5s | 10s | 15s | 20s | 25s | |
| 1 | 13,3 | 12,3 | 12 | 11,8 | 11,6 | 11,4 | |
| 2 | 12,7 | 12 | 11,6 | 11,5 | 11,4 | 11,3 | |
| 3 | 12,6 | 11,8 | 11,5 | 11,3 | 11,2 | 11,2 | |
| 4 | 12,5 | 11,8 | 11,4 | 11,4 | 11,3 | 11,2 | |
| 5 | 12,5 | 11,8 | 11,4 | 11,3 | 11,2 | 11,1 | |
| 6 | 12,4 | 11,5 | 11,4 | 11,2 | 11,1 | 11 | |
| 7 | 12,3 | 11,6 | 11,4 | 11,2 | 11,1 | 11 | |
| 8 | 12,3 | 11,6 | 11,3 | 11,2 | 11,1 | 11 | |
| 9 | 12,3 | 11,6 | 11,3 | 11,1 | 11 | 11 | |
| 10 | 12,2 | 11,5 | 11,3 | 11,1 | 11 | 10,9 | *Average* |
| **Mean last 5** | **12,3** | **11,56** | **11,34** | **11,16** | **11,06** | **10,98** | **11,4** |

| **Large test-teat** | | **30 mm** | | **-40 kPa** | | | |
|---|---|---|---|---|---|---|---|
| test # & time | 0s | 5s | 10s | 15s | 20s | 25s | |
| 1 | 14,2 | 12,7 | 12,2 | 12 | 11,8 | 11,8 | |
| 2 | 13 | 12,2 | 11,8 | 11,7 | 11,5 | 11,6 | |
| 3 | 13,5 | 12 | 11,8 | 11,4 | 11,4 | 11,4 | |
| 4 | 13,1 | 11,9 | 11,6 | 11,4 | 11,3 | 11,3 | |
| 5 | 13 | 12 | 11,6 | 11,4 | 11,4 | 11,2 | |
| 6 | 13 | 11,8 | 11,5 | 11,4 | 11,3 | 11,3 | |
| 7 | 13,2 | 11,8 | 11,5 | 11,4 | 11,2 | 11,2 | |
| 8 | 13,1 | 11,8 | 11,5 | 11,3 | 11,2 | 11,1 | |
| 9 | 13,1 | 11,7 | 11,4 | 11,2 | 11,1 | 11 | |
| 10 | 13 | 11,7 | 11,4 | 11,3 | 11,2 | 11 | *Average* |
| **Mean last 5** | **13,08** | **11,76** | **11,46** | **11,32** | **11,2** | **11,12** | **11,7** |

| **Small test-teat** | | **30 mm** | | **-30 kPa** | | | |
|---|---|---|---|---|---|---|---|
| test # & time | 0s | 5s | 10s | 15s | 20s | 25s | |
| 1 | 10,5 | 9,4 | 9 | 8,8 | 8,5 | 8,1 | |
| 2 | 10,1 | 9,1 | 8,8 | 8,6 | 8,4 | 8,3 | |
| 3 | 10,3 | 9,3 | 8,8 | 8,6 | 8,5 | 8,3 | |
| 4 | 10,3 | 9 | 8,8 | 8,6 | 8,4 | 8,3 | |
| 5 | 10,1 | 9 | 8,6 | 8,3 | 8,1 | 7,9 | |
| 6 | 10 | 8,8 | 8,3 | 8,1 | 8,1 | 7,9 | |
| 7 | 9,5 | 8,6 | 8,3 | 8,1 | 7,9 | 7,7 | |
| 8 | 9,4 | 8,6 | 8,3 | 8,1 | 7,9 | 7,9 | |
| 9 | 9,4 | 8,7 | 8,3 | 8,1 | 8,1 | 7,9 | |
| 10 | 9,4 | 8,8 | 8,3 | 8,1 | 8 | 7,9 | *Average* |
| **Mean last 5** | **9,54** | **8,7** | **8,3** | **8,1** | **8** | **7,86** | **8,4** |

| **Large test-teat** | | **40 mm** | | **-20 kPa** | | | |
|---|---|---|---|---|---|---|---|
| test # & time | 0s | 5s | 10s | 15s | 20s | 25s | |
| 1 | 9,2 | 8,1 | 7,7 | 7,7 | 7,5 | 7,5 | |
| 2 | 8,8 | 7,9 | 7,7 | 7,5 | 7,5 | 7,5 | |
| 3 | 8,6 | 7,9 | 7,5 | 7,5 | 7,4 | 7,4 | |
| 4 | 8,6 | 7,9 | 7,7 | 7,5 | 7,5 | 7,3 | |
| 5 | 8,6 | 7,7 | 7,5 | 7,5 | 7,4 | 7,3 | |
| 6 | 8,6 | 7,7 | 7,5 | 7,4 | 7,4 | 7,2 | |
| 7 | 8,5 | 7,9 | 7,5 | 7,3 | 7,2 | 7 | |
| 8 | 8,4 | 7,7 | 7,5 | 7,3 | 7,3 | 7,2 | |
| 9 | 8,1 | 7,5 | 7,2 | 7,2 | 7 | 7 | |
| 10 | 8,3 | 7,5 | 7,3 | 7,2 | 7 | 7 | *Average* |
| **Mean last 5** | **8,38** | **7,66** | **7,4** | **7,28** | **7,18** | **7,08** | **7,5** |

| **Large test-teat** | | **40 mm** | | **-25 kPa** | | | |
|---|---|---|---|---|---|---|---|
| test # & time | 0s | 5s | 10s | 15s | 20s | 25s | |
| 1 | 11,4 | 9,8 | 9,4 | 9 | 8,9 | 8,8 | |
| 2 | 10,4 | 9,2 | 8,8 | 8,6 | 8,4 | 8,4 | |
| 3 | 10,3 | 9,2 | 8,8 | 8,6 | 8,5 | 8,3 | |
| 4 | 9,9 | 8,8 | 8,6 | 8,5 | 8,3 | 8,3 | |
| 5 | 10,1 | 8,8 | 8,6 | 8,5 | 8,3 | 8,3 | |
| 6 | 9,8 | 8,8 | 8,5 | 8,3 | 8,3 | 8,2 | |
| 7 | 9,6 | 8,8 | 8,3 | 8,3 | 8,3 | 8,1 | |
| 8 | 9,6 | 8,6 | 8,3 | 8,3 | 8,2 | 8,1 | |
| 9 | 9,8 | 8,8 | 8,4 | 8,3 | 8,3 | 8,1 | |
| 10 | 9,6 | 8,6 | 8,3 | 8,3 | 8,2 | 8,1 | *Average* |
| **Mean last 5** | **9,68** | **8,72** | **8,36** | **8,3** | **8,26** | **8,12** | **8,6** |

| **Large test-teat** | | **40 mm** | | **-30 kPa** | | | |
|---|---|---|---|---|---|---|---|
| test # & time | 0s | 5s | 10s | 15s | 20s | 25s | |
| 1 | 10,9 | 9,9 | 9,6 | 9,4 | 9,2 | 9,1 | |
| 2 | 10,5 | 9,6 | 9,4 | 9,2 | 9 | 9 | |
| 3 | 10,3 | 9,4 | 9,2 | 9 | 9 | 8,8 | |
| 4 | 10,1 | 9,1 | 9 | 8,8 | 8,8 | 8,7 | |
| 5 | 10,1 | 9 | 8,8 | 8,7 | 8,6 | 8,6 | |
| 6 | 9,9 | 9 | 8,8 | 8,6 | 8,5 | 8,4 | |
| 7 | 9,9 | 9 | 8,6 | 8,6 | 8,5 | 8,3 | |
| 8 | 9,8 | 9 | 8,6 | 8,5 | 8,4 | 8,3 | |
| 9 | 9,7 | 9 | 8,6 | 8,5 | 8,3 | 8,3 | |
| 10 | 9,7 | 9 | 8,6 | 8,3 | 8,3 | 8,3 | *Average* |
| **Mean last 5** | **9,8** | **9** | **8,64** | **8,5** | **8,4** | **8,32** | **8,8** |

| **Large test-teat** | | **40 mm** | | **-35 kPa** | | | |
|---|---|---|---|---|---|---|---|
| test # & time | 0s | 5s | 10s | 15s | 20s | 25s | |
| 1 | 10,5 | 9,8 | 9,4 | 9 | 9 | 8,8 | |
| 2 | 10,3 | 9,6 | 9 | 8,9 | 8,8 | 8,6 | |
| 3 | 10,1 | 9,4 | 9 | 8,8 | 8,6 | 8,6 | |
| 4 | 10,1 | 9,4 | 9 | 8,8 | 8,6 | 8,5 | |
| 5 | 9,8 | 9 | 8,8 | 8,6 | 8,6 | 8,4 | |
| 6 | 9,9 | 9 | 8,8 | 8,6 | 8,5 | 8,3 | |
| 7 | 10,1 | 9 | 8,8 | 8,6 | 8,6 | 8,5 | |
| 8 | 9,9 | 9 | 8,8 | 8,6 | 8,5 | 8,3 | |
| 9 | 9,8 | 9 | 8,6 | 8,6 | 8,5 | 8,3 | |
| 10 | 9,8 | 9 | 8,6 | 8,6 | 8,3 | 8,3 | *Average* |
| **Mean last 5** | **9,9** | **9** | **8,72** | **8,6** | **8,48** | **8,34** | **8,8** |

| **Large test-teat** | | **40 mm** | | **-40 kPa** | | | |
|---|---|---|---|---|---|---|---|
| test # & time | 0s | 5s | 10s | 15s | 20s | 25s | |
| 1 | 12,7 | 11,3 | 10,9 | 10,5 | 10,5 | 10,3 | |
| 2 | 12,2 | 10,9 | 10,6 | 10,3 | 10,3 | 10,1 | |
| 3 | 12 | 10,9 | 10,5 | 10,3 | 10,1 | 10,1 | |
| 4 | 11,9 | 10,7 | 10,3 | 10,1 | 10,1 | 10 | |
| 5 | 12,1 | 10,9 | 10,5 | 10,1 | 10,1 | 9,9 | |
| 6 | 12 | 10,7 | 10,3 | 10,1 | 10,1 | 9,9 | |
| 7 | 11,8 | 10,7 | 10,3 | 10,1 | 10,1 | 9,9 | |
| 8 | 12 | 10,9 | 10,5 | 10,1 | 10,1 | 9,9 | |
| 9 | 11,8 | 10,5 | 10,3 | 10,1 | 9,9 | 9,8 | |
| 10 | 11,8 | 10,7 | 10,1 | 10 | 9,8 | 9,7 | *Average* |
| **Mean last 5** | **11,88** | **10,7** | **10,3** | **10,08** | **10** | **9,84** | **10,5** |

| **Small test-teat** | | **40 mm** | | **-30 kPa** | | | |
|---|---|---|---|---|---|---|---|
| test # & time | 0s | 5s | 10s | 15s | 20s | 25s | |
| 1 | 9 | 7,5 | 7 | 6,9 | 6,6 | 6,6 | |
| 2 | 8,1 | 7,2 | 6,8 | 6,6 | 6,5 | 6,5 | |
| 3 | 7,9 | 7 | 6,6 | 6,5 | 6,4 | 6,3 | |
| 4 | 7,9 | 7 | 6,6 | 6,4 | 6,4 | 6,2 | |
| 5 | 7,7 | 6,9 | 6,6 | 6,2 | 6,2 | 6,1 | |
| 6 | 7,7 | 6,6 | 6,6 | 6,2 | 6,2 | 6,1 | |
| 7 | 7,7 | 6,8 | 6,6 | 6,2 | 6,2 | 6,2 | |
| 8 | 7,5 | 6,8 | 6,4 | 6,2 | 6,2 | 6,2 | |
| 9 | 7,7 | 6,8 | 6,5 | 6,4 | 6,2 | 6,2 | |
| 10 | 7,7 | 6,7 | 6,4 | 6,4 | 6,2 | 6,2 | *Average* |
| **Mean last 5** | **7,66** | **6,74** | **6,5** | **6,28** | **6,2** | **6,18** | **6,6** |

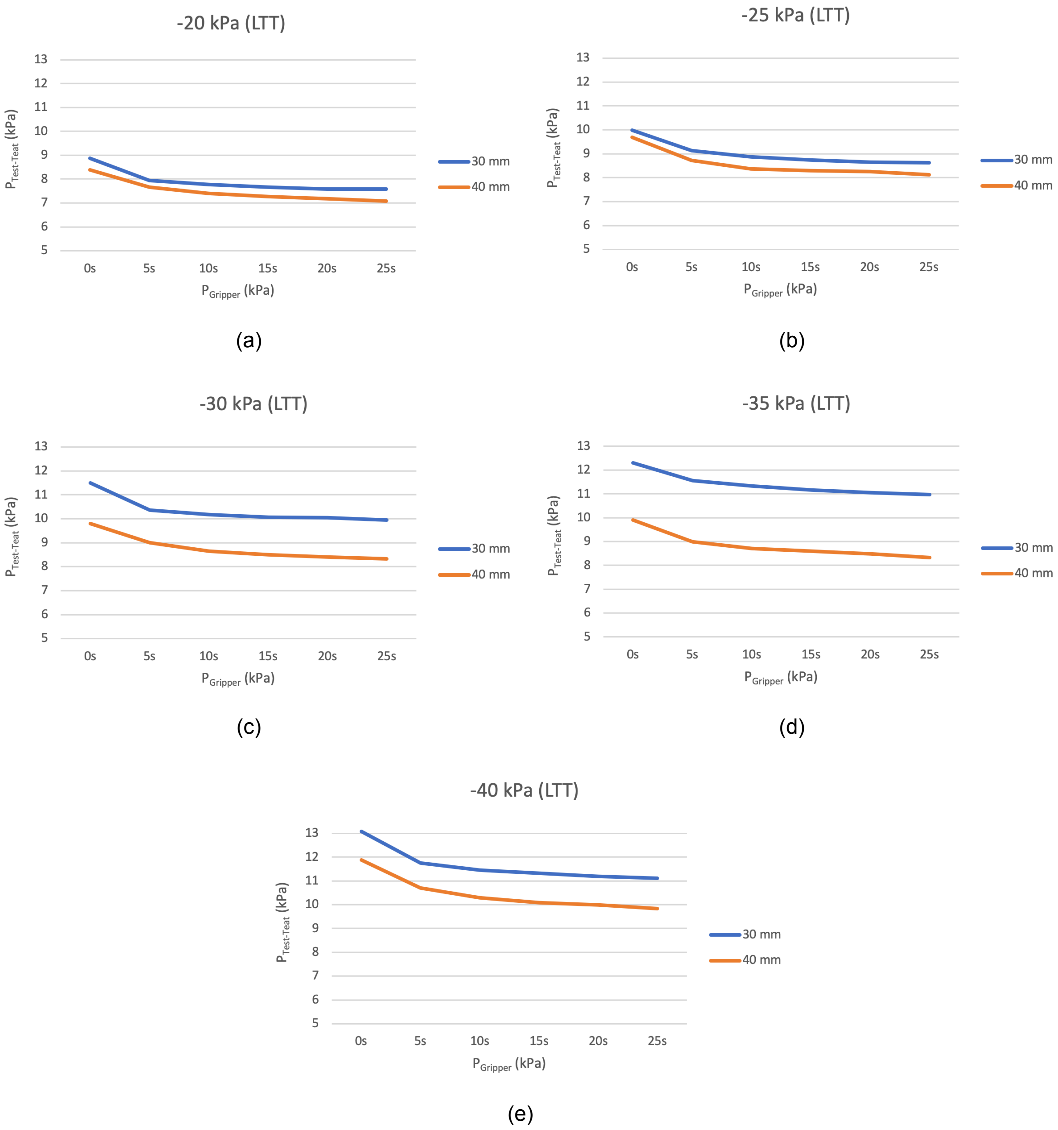



Figure H.1: Average pressure inside the large test-teat over time, both the 30 mm and the 40 mm skeleton and a pressure inside the skeleton ranging from -20 kPa to -40 kPa bar in steps of 5 kPa.

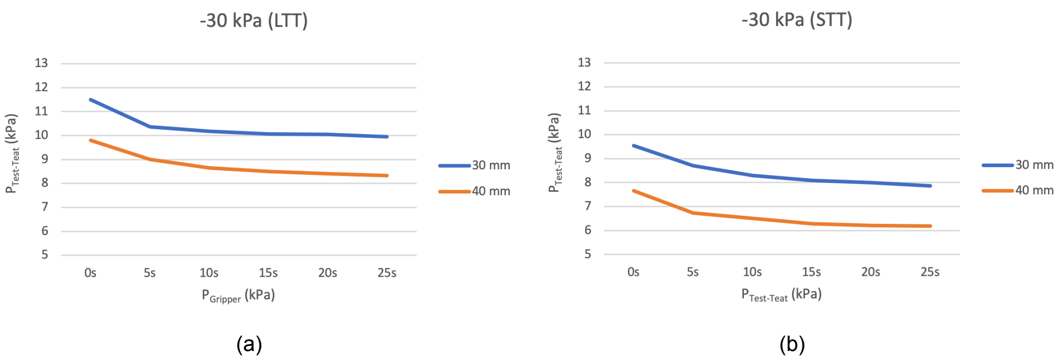



Figure H.2: Average pressure inside the small test-teat over time for both the 30 mm and the 40 mm skeleton and a pressure inside the skeleton of -30 kPa.

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