Development of an adhesive grasper for Minimally Invasive Surgery

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Master of Science Thesis

Delft University of Technology

BioMechanical Engineering

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Preface

After graduating high school I had to choose between two interests: technology or the medical field. Eventually I opted for the bachelor Mechanical Engineering at Delft University of Technology. Once I obtained my bachelor degree, a master in BioMechanical Engineering allowed me to combine both interests. During my internship I got the opportunity to work with engineers and medical professionals, which gave me insight in the similarities and differences between the world of engineers and medical professionals. It also gave me a peek in the challenging world of MIS instrument design with its innovative and elegant design solutions for problems in the medical field. For me, this proved that I made the right decision to choose BioMechanical Engineering and for my Master Project I continued down this road by electing the design of an adhesive grasper as Master Project. This paper contains the (summarized) result of the Master Project.

I would like to thank Paul for his knowledge and insights in the design of medical instruments, sharp reasoning and clear views on my work, which helped me keeping the right path, Dimitra for the assistance during the experiments, thorough reviewing of my reports, numerous comments and attention to details. I also want to thank Rick for his support during the design phase, my friends for the motivation, support and great time here in Delft, and last but not least my family for the support and motivation.

Martin de Hullu

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***Abstract*—Laparoscopic graspers require a high pinch force to generate sufficient friction force (grip) for tissue manipulation. Excessive or insufficient pinch forces distributed along the small contact area of laparoscopic graspers can cause damage and are one of the reasons why the risk of intraoperative complications during Minimally Invasive Surgery (MIS) procedures in the abdomen is 2-4 % higher compared to open surgery.**

The goal of this research was to develop and evaluate an 5 mm laparoscopic grasper, which has the same functionality (generated friction force, grasping time) as a conventional grasper for use on the intestine but which requires lower pinch force due to the use of adhesives. To lower the pinch force the adhesive component of the friction force was enlarged by introducing a muco-adhesive between tissue and grasper. To lower (local) high pressures a flat surface was used.

Two experiments were conducted to find out in which direction the friction force generated by the adhesive film was the largest and to find the minimum required area of adhesive film to generate a force of 5 N. Next, a design for the tip and a design for the adhesive film feed mechanism was made. To evaluate the design a prototype was created, which was used to investigate whether the proposed tip design was able to generate a friction force of 5 N using a pinch force lower than 3 N.

The prototype of the adhesive grasper was able to generate a friction force of 3.12 ± 0.58 N, while using a pinch force of 2.5 N. The generated friction force did not meet the goal of 5 N, but the concept of lowering the pinch force by introducing an adhesive layer is promising; the pinch force needed by the proposed tip is lower compared to existing graspers and the friction force was independent of the generated pinch force. The friction force can be increased further by developing a new adhesive film or by increasing the contact area.

***Index Terms*—MIS, pinch, pull, force, tissue damage, grasping, muco adhesive film**

I. Introduction

A. Background

The introduction of Minimally Invasive Surgery (MIS) has radically changed medical procedures. For the patient MIS offers numerous benefits: quicker recovery, shorter stay in the hospital, reduced postoperative pain and less scar tissue. For the surgeon however, procedures have become more complicated compared to open surgery. This research focuses on MIS procedures in the abdomen, so called laparoscopic surgery. The risk of intraoperative complications during laparoscopic procedures is 2-4% higher compared to open surgery [1]. One of the reasons of this higher risk at complications is tissue damage by MIS instruments. For laparoscopic procedures involving soft tissue such as gallbladder, intestine, and vascular structures, the risk of tissue damage is almost two times higher compared to open surgery [2]. A study investigating intestinal injury as complication of laparoscopic surgery reported mortality rates as high as 3.6% (*N*=450, [3]). It is estimated that 25% of all gallbladder perforations during laparoscopic cholecystectomy are due to grasper trauma [4]. The studies by Tang, Hanna, and Cuschieri (2005) [5] and Joice, Hanna and Cuschieri (1998) [6] investigating the causes of grasping error during laparoscopic surgery reported that between 57% (*N*=60, surgical trainees, [5]) and 84% (*N*=20, expert surgeons, [6]) of grasper errors is related to insufficient or excessive force. Excessive force causes high pressures in the tissue, resulting in crushing of the intercellular structures and bursting of cells [7], perforation or microperforation of the tissue [8], damage to the vascular network and shearing of cell-to-cell connections [7]. Insufficient force results in tissue slipping out of the grasper. During tissue slip the surface profile of the grasper induces high local pressures in the tissue, which might damage the tissue.

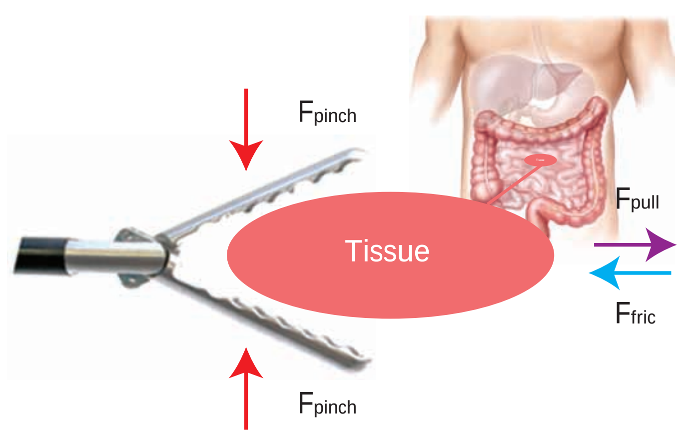


Fig. 1: *Forces on tissue: during safe grasping friction force (F_{fric}) = pull force(F_{pull}) and the generated friction force (F_{fric}) $\leq$ maximum friction force ($F_{fric,max}$)*

To manipulate tissue a surgeon uses pull forces. The pull force (F_{pull}) exerted on the tissue has to be compensated by an equal and opposite friction force (F_{fric}) to avoid tissue slipping out of the grasper (Figure 1). The friction force is limited: if the pull force is higher than the maximal friction force ($F_{fric,max}$) the grasper can generate, tissue will slip out of the grasper.

The maximum friction force is a function of the coefficient of friction (μ), the pinch force (F_{pinch}) , the contact area (A) and adhesive shear coefficient (υ) (Equation 1, [9]). The maximum friction force is subdivided in Coulomb ($F_{coulomb}$) and adhesive ($F_{adhesion}$) friction. During friction between two hard surfaces, Coulomb friction is assumed to be independent of the contact area, because the two surfaces are only in contact at the summit of surface irregularities, resulting in a small real contact area. On the other hand, the softness of the abdominal tissue allows it to adjust to the shape of the grasper jaw, resulting in a larger reel contact area in comparison with two hard surfaces, making area a relevant factor. The adhesive friction is dependent of the contact area because Van der Waal's forces between the two surfaces create adhesive bonds, which can withstand a certain tangential stress.

$$F_{fric} = F_{Coulomb} + F_{Adhesion} = F_{Pinch} \cdot \mu + A \cdot \upsilon \quad (1)$$

In conventional laparoscopic graspers the coefficient of friction (μ) and adhesive shear coefficient (υ) between the wet and slippery tissue and the grasper is low. Consequently, a high pinch force and/or a large area is required to achieve sufficient friction force. The dimensions of the jaws are limited by the size of the trocar and the working area. To further increase the contact area a surface profile can be used. However, the use of a surface profile results in an uneven distribution of the pinch force, which results in unwanted local high pressures, leaving increasing the pinch force for conventional graspers. Safe tissue manipulation is achieved when pinch and pull force are balanced, that is, avoiding slip while preventing damage, as shown graphically by the ”safe grasping area” shown in Figure 2. For safe tissue manipulation the pinch force has to be high enough to prevent tissue slip, which is indicated by the lower boundary of the safe grasping area. When the combination of tension created by the pull force and pressure created by the pinch force becomes too high, tissue damage occurs, which is indicated by the upper boundary of the safe grasping area. Combinations of pinch and pull forces in the area to the right of the crossing point of the slip and damage lines will result in either slip or damage.

B. State of the art: improving grasping safety

Research to address the problem of exerting inadequate grasping forces focuses on three areas:

1) Improving the ergonomics of the used instruments [11], to decrease the disturbance in tactile feedback. This disturbance is caused by the pressure exerted on the fingers and consecutive nerve irritations.

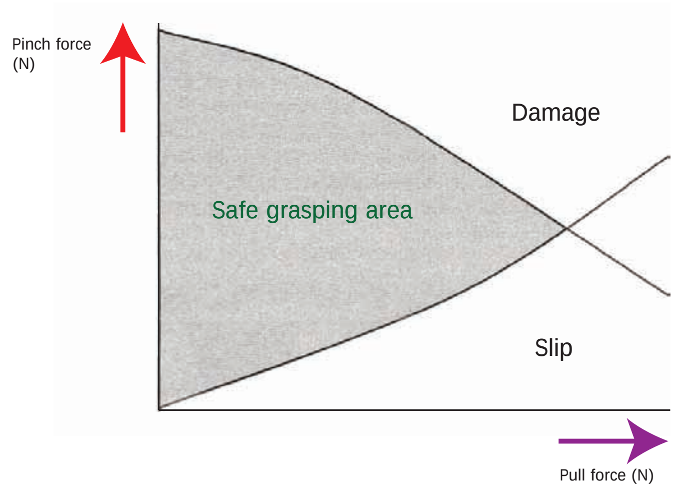


Fig. 2: *A model of the combination of pinch force and pull force leading to slip, damage, or safe grasping of tissue. For safe tissue manipulation the pinch force needs to be high enough to prevent tissue slip, which is indicated by the lower boundary of the safe grasping area. Pull force introduces tension in the tissue, which lowers the maximum allowable pressure on the tissue. Any combination of pull and pinch force above the upper boundary of the safe grasping area will cause damage [10]*

2) Restoring the surgeon's haptic perception, which is done by providing the surgeon with visual or auditory feedback [12] of the applied forces, introducing handles with augmented tactile feedback [13] and developing improved methods to sense forces at the tip of the instrument such as displacement- [14], current- [15], pressure- [16], resistive- [17], capacitive- [18], piezoelectric- [19], vibration- [20], and optical-based [21] sensing.

3) Reducing the high pressures generated at the tip of laparoscopic graspers, which is done by using grasper jaws with curved edges [22], a compliant tip [23] and by optimizing the surface profile of the grasper jaws [10], [24] to lower the pinch force where slip occurs and increase the pinch force where damage occurs, expanding the safe grasping area (Figure 2) with that. Other methods to reduce high pressures are to enclose the tissue using finger like jaws (instead of pinching the tissue) [25] and using a suction cup instead of jaws to hold the tissue. [26].

C. Goal of research

An approach to address the problem of inadequate grasping forces which has not been tried is introducing an adhesive between tissue and grasper. The goal of this research was to develop and evaluate an 5 mm laparoscopic grasper for handling intestine, which has the same functionality (generated friction force, grasping time) as a conventional 5 mm grasper for use on the intestine, but which requires lower pinch force due to the use of adhesives. Introducing an adhesive between tissue and grasper increases the adhesive

component ($F_{adhesion}$) of the friction force (Equation 1). Consequently, a lower pinch force (F_{pinch}) is needed to obtain equal friction force.
According to Visser, Heijnsdijk, Herder and Pistecky, (2002) [10] safe laparoscopic graspers should be able to transmit at least a 5 N pull force to tissue without damaging it. Pinch/pull data of laparoscopic graspers is limited. Only two studies describing pinch and pull forces were found. The lowest found pinch force was 3 N, for a pull force of 5 N, using a jaw with a diamond shaped surface profile of 10 mm $\times$ 10 mm ([10] and [24]). During laparoscopic colectomies, the grasping time varies between less than 1 second (28%) and less than 60 seconds (89%) [27]. To fulfil the goal, the adhesive grasper should generate a friction force of 5 N, using a pinch force lower than 3 N and hold tissue for a period of 60 seconds.

D. Design strategy

To lower the pinch force, a muco-adhesive film is introduced [28] between the tissue and the grasper. Muco-adhesives are polymeric hydrogels that generate physical and chemical bonds with the mucus (layer that covers the intestinal wall). This process is non-reversible. Muco-adhesives are typically used to attach drug delivery systems on the intestinal epithelium, allowing prolonged or controlled drug absorption. The employed adhesive film is thus primarily intended for use on the inside of the intestine, while in this application the grasper interacts with the outer surface. A lower friction force may therefore be expected. Since the adhesive component of the friction force depends on the contact area, the area of muco-adhesives at the tip of the grasper needs to be maximized.
As the adhesive effect of muco-adhesives is strongest at first contact, a laparoscopic grasper functioning by means of muco-adhesives requires a constant feed of fresh muco-adhesives for every grasping action. To achieve that, a muco-adhesive film will be conveyed from the outside world though the shaft to the tip of the grasper.
This research focuses on the design of the tip and adhesive film transfer mechanism. An prototype is constructed to evaluate whether the designed tip is able to generate a friction force of 5 N while using a pinch force lower than 3 N.

E. Outline of report

The design of the adhesive grasper was subdivided in three parts: first, conceptual design solutions to maximize the friction force and lower the peak pressures at the tip of the grasper (Section IIa) and a adhesive film feed mechanism were generated (Section IIb). Next, two exploring experiments were conducted (Section III and IV) to find out in which direction the friction force generated by the adhesive film was the largest, and the minimum required area to generate a pull force of 5 N. The results of these experiments, combined with dimension and force constraints, resulted in a set of boundary conditions, which were used for the final design of the adhesive grasper (Section V). To evaluate the final design, a prototype was build. The goal of the evaluation experiment (Section VI) was to investigate whether the prototype was able to generate a friction force of 5 N while using a pinch force lower than 3 N.

II. Adhesive grasper: conceptual design

In the first part of this section conceptual design solutions for maximizing the adhesive force of the tip, while avoiding high surface pressures were generated. In the second part conceptual design solutions for the adhesive film transfer mechanism (located inside the central shaft) were generated.

A. Tip design

The design of the tip was focused on two areas: maximising the adhesive force by creating a contact area as large as possible and lowering peak pressures. Besides these two areas, the adhesive film must be guided around the jaw(s).

a) Contact area: To bring the adhesive film in contact with the tissue, jaw(s) are needed. A larger jaw area results in a larger area of adhesive film in contact with the tissue, which results in a larger adhesive force. When assuming equal length, an increased number of jaws might result in an increased area of adhesive film in contact with the tissue. The tip may consist of 1, 2 or 3 jaws (Figure 3). A higher number of jaws was considered not viable due to high mechanical complexity. When using three (or more) jaws, tissue can be grasped in multiple ways (Figure 4), which increases the grasping difficulty. For this reason a tip consisting of 3 jaws was considered not viable. When using a single jaw, the adhesive film has to generate detachment or shear force to grasp the tissue. When using 2 jaws the film has to generate shear force to grasp the tissue. The highest detachment and shear force which can be generated by the adhesive film was unknown; therefore experiments were required to determine the number of contact forces needed to generate a friction force of 5 N.
To increase the contact area further, expandable jaws can be used. However, the use of expandable jaws was considered too complex for the first prototype of the adhesive grasper and was thus not used in the final design of the adhesive grasper.

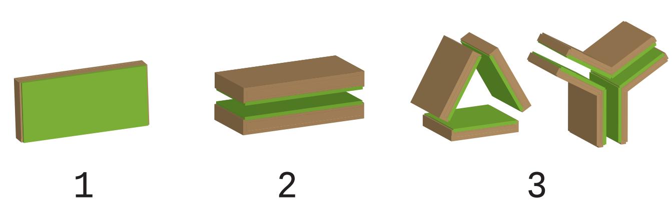


Fig. 3: *Contact area: 1 jaw (left), 2 jaws (middle) and 3 jaws (right). Adhesive film is shown in green.*

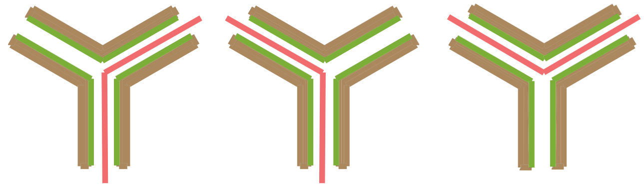


Fig. 4: *When using a tip with 3 jaws, tissue can be grasped in three different ways. Adhesive film shown in green, tissue in pink*

Fig. 6: *Guidance concepts (cross section). Solid shaped guide (left) and solid wide guide (right). Adhesive film shown in green.*

b) Pressure: A surface profile can be applied to the jaw of the adhesive grasper. This enlarges the contact area and therewith the adhesive force. However, the increase in contact area comes at the cost of local peak pressures, which might result in tissue damage. To avoid this, a flat surface profile was used. High pressures are also generated at the edge of the jaw. To reduce these high pressures, the edges of the jaw were rounded [22].

If multiple, movable jaws are used, the distribution of the contact pressure is influenced by the motion mechanism of the jaws. If a single hinge motion mechanism is used, high pressures are exerted near the hinge, while a parallel motion mechanism will result in an equal distributed surface pressure. (Figure 5). However, the mechanism needed for parallel movement of the jaws and guidance of the adhesive film around the jaws is complex and requires considerable space inside the shaft. For these reasons a combination mechanism was selected for use in the final design (Figure 5 right). In the combination mechanism each jaw has a separate hinge, resulting in a motion which is a combination of the conventional single hinge and parallel motion, offering lower surface pressures near the hinges compared to the single hinge mechanism, while not being as highly complex as parallel motion.

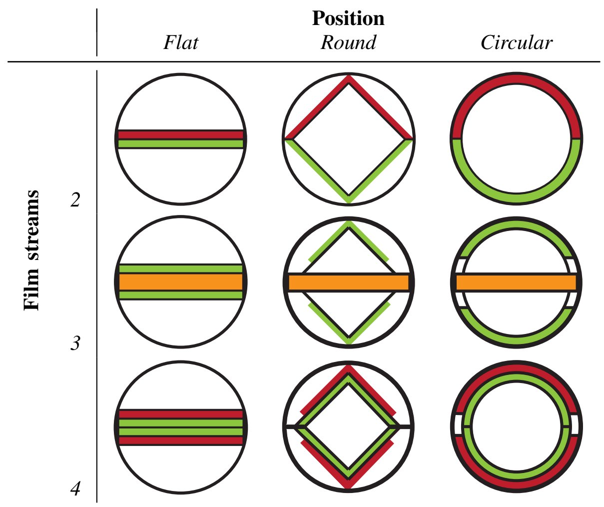
c) Guidance of the adhesive film: Due to the use of a continuous feed of adhesive film, the adhesive film has to be guided around the jaw(s). Also, the adhesive film must be kept on the jaw(s) when the surgeon manipulates tissue. Three types of guidance are considered: none, a shaped guide which limits sideways movements of the film and making the width of the guide larger than the width of the film (Figure 6).

The guide can be solid or using rolls. The use of rolls reduces friction, but comes at the cost of increased complexity of the design. In both considered guidance methods the width of the guide exceeds the width of the adhesive film. Due to maximization of the contact area, the width of the adhesive film will be at least 5 mm. As a result of that, the width of the guide will exceed 5 mm, so a folding mechanism is required, further increasing the complexity of the design. The use of a guide does not contribute to the adhesive force, but does increase the complexity of the design. Therefore, the option no guidance of the adhesive film was selected for the final design.

B. Shaft design

To maximize the adhesive force at the tip, the amount of film transferred through the shaft needs to be maximised because the area of adhesive film at the tip of the instrument is limited by the width of the film which is fed through the shaft of the grasper. Therefore, the width of the film transferred through the shaft needs to be maximised. Three parameters were used for maximisation of the film width: number of film streams, position of the film in the shaft and shape of the film.

TABLE I: *Number of film streams and position in shaft. Fresh film is indicated in green, used film indicated in red, used film put together in orange. Note that not all possible film configurations are show in this table and only flat film is considered.*



a) Film streams: The minimum required number of film steams is 2; (Table I), one fresh (indicated by green) and one used (indicated by red). Increasing the number of film streams increases the area of adhesive film available at the tip but also increases the complexity inside the shaft because more structures are needed to support the film. Furthermore, more film streams result in less available space for other structures inside the shaft such as a hinge and transmission. More film streams also result in an increased risk of used film sticking to the inside of the shaft and creating a blockage of the film feed. More than 4 film streams (2 fresh, 2 used) was considered not viable due to the high complexity (the film streams need structures to shape, support and separate them), friction and required space. Putting the sticky sides of the used film together (Table I, shown in orange) eliminates the problem of blockage of the film feed. For this reason an uneven number of film streams was preferred for use in the final design.

b) Position: When the film is positioned flat inside the shaft, the maximum width of the film is restricted by the

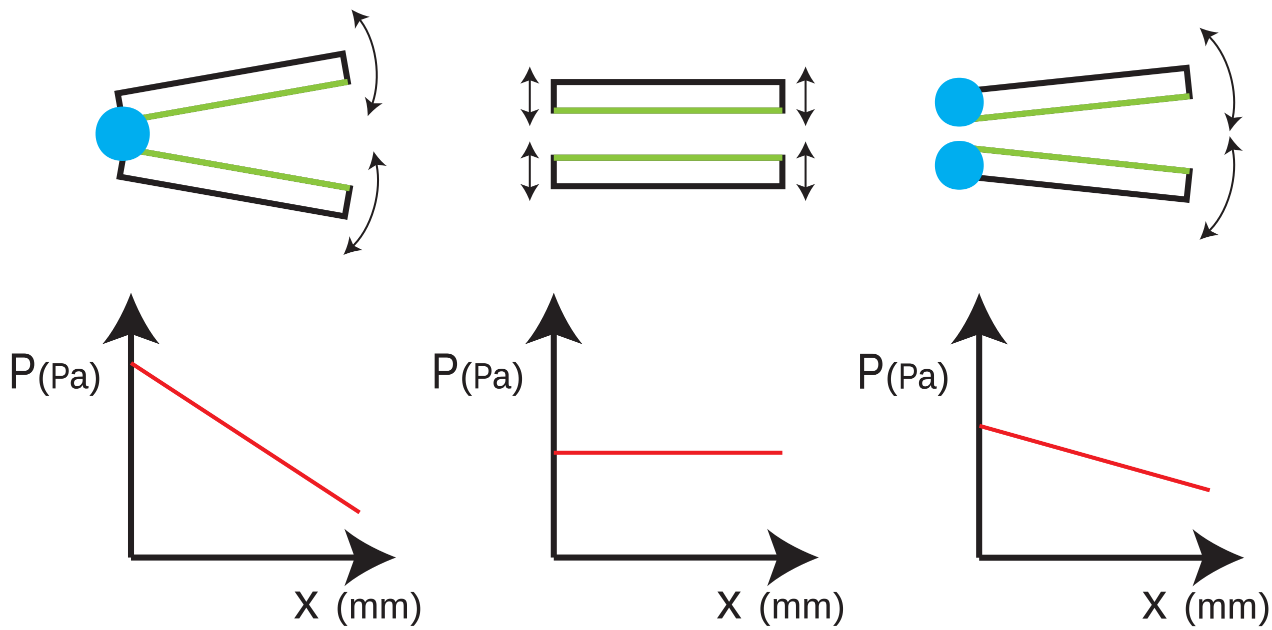


Fig. 5: *Motion concepts and pressure on tissue (theoretical). Single hinge motion(left), parallel motion (middle) and combination motion (right)*

inner diameter of the tube, resulting in a maximum width of approximately 5 mm. When the film is positioned triangular the maximum width is increased to 7.07 mm and when the film is positioned circular the maximum width is increased to 7.85 mm. Using film in a triangular or circular position, increases the complexity and friction because additional structures are needed to obtain the triangular or circular position. Using a triangular or circular position creates a space in the centre of the shaft, which can be used for a transmission. The use of a circular position was preferred for the final design because it offers the largest film width, while leaving a space in the centre of the shaft.

c) Shape: When using flat film in a circular position, the maximum width of the film is 7.85 mm. Folding, crumbling or rolling (Figure 7) increases the maximum width of the film further, but also increases the friction due to the folding and unfolding of the film. Shaping the film requires additional structures inside the shaft. These structures decrease the space available for other structures such as a hinge and transmission, and increase the mechanical complexity of the design. The structures required for crumbling the adhesive film are less complex than the structures required for folding and rolling the adhesive film because the shape of crumbling is arbitrary, while folding and rolling are not. For these reasons crumbling of the adhesive film was preferred to maximise the film width.

Combining the preferred concepts of film streams, position and shape result in the configuration of adhesive film as shown Figure 8. This configuration offers a film width of 7.85 mm, with limited complexity, required space and friction. The fresh adhesive film is supplied in a flat shape and circular position (7.85 mm). The sticky sides of the used adhesive film are put together and returned through the middle of the shaft. The returning film is crumbled to adjust to the maximum width (5 mm) of the shaft.

Fig. 7: *Shaped film: folded (left), rolled (middle) and crumbled (right)*

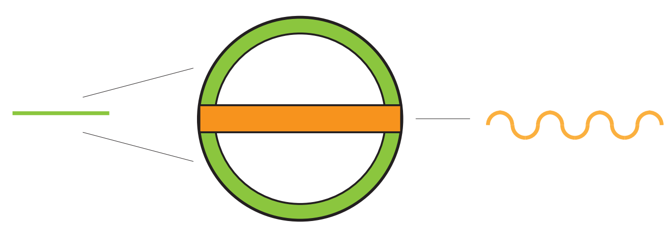


Fig. 8: *Film shape and position central shaft. Fresh adhesive film (green) is supplied in a flat shape and circular position, the sticky sides of the used adhesive film (orange) are put together and returned through the middle of the shaft*

III. Exploring Experiment 1

The conceptual solutions for the tip have resulted in a number of possible designs. From mechanical point of view, the simplest design of the tip would be a single jaw to bring the adhesive film in contact with the tissue (Figure 9). In this case, the adhesive film is mainly loaded in the detachment direction (Figure 10). As a result peeling occurs. During peeling the contact area of the film decreases and the friction force with that. To find out if despite the peeling, an adhesive grasper using a single jaw is viable, an experiment was conducted investigating whether the adhesive films are able to generate a 5 N detachment force for a period of 60 seconds.

A. Goal

To evaluate if an adhesive grasper using a single contact surface with adhesive film was viable, the adhesive film was tested using the following hypothesis: *Adhesive film of 200 mm^2 generates at least 5 N detachment force using a rest time of 15 or 60 seconds.* The hypothesis was tested by placing adhesive film with an area of 200 mm^2 on a piece of intestine and applying and recording a detachment force. The highest recorded force before detachment of tissue and adhesive film occurred was defined as the maximum detachment force. This detachment force was increased in steps of 0.25 N using a rest time of 15 and 60 seconds (Figure 11, Table II) because of the occurrence of peeling. Due to peeling, the use of a continuous increasing detachment force would result in higher (incorrect) maximum detachment forces. Longer rest times than 60 seconds were not considered, because the majority (e.g., 89%, colectomy, N=10, [27]) of grasping periods during laparoscopic surgery were less than 60 seconds. The area of 200 mm^2 (5 mm $\times$ 40 mm) was based on the largest found contact surface dimensions of commonly used laparoscopic graspers ([29] and [30]) for use with the intestine, because the goal of the design of the tip was the maximisation of the friction force.

B. Materials and Methods

Adhesive film (5 mm $\times$ 40 mm) was fixed to a Plexiglas plate. The edges of the plate were slightly rounded to avoid damage of the intestine. The intestine of a pig (obtained from the Academic Medical Centre Amsterdam) was extracted and opened longitudinally. Resected pieces were fixed on a plate, with the outer surface facing upwards. The Plexiglas plate with adhesive film fixed to it was placed on top of the piece of intestine (Figure 12). The Plexiglas plate was connected to the force sensor of a tensile testing machine (Zwick 1484, Zwick GmbH & Co., Germany) using a Dyneema® cord with a tensile spring (C = 500 N/m). A mass of 100 g was placed on top of the Plexiglas plate to ensure a repeatable contact area between adhesive film and intestine. A mass of 100 g corresponds to a pressure (P_{normal}) of 5 kPa. The displacement of the tensile testing machine was transformed to a pull force using a tension spring ($F = C \cdot u$). The strain in the Dyneema® pulling cord was assumed to be negligible. Next, a detachment force was applied to the Plexiglas plate. This detachment force was increased in steps of 0.25 N, while using a rest times of 15 or 60 seconds (Figure 11). The maximum measured force recorded before complete detachment of tissue and adhesive film occurred was defined as the maximum detachment force (Figure 11). Each measurement was conducted on a new piece of intestine. Each measurement was repeated 7 times.

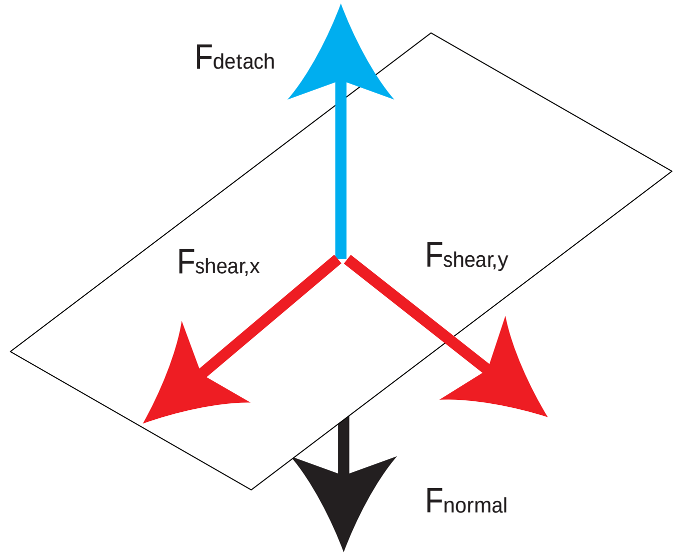


Fig. 10: *Adhesive film: force directions. Adhesive film can generate detachment force and friction force, while for example a normal force can be applied to the film to enlarge the reel contact area*

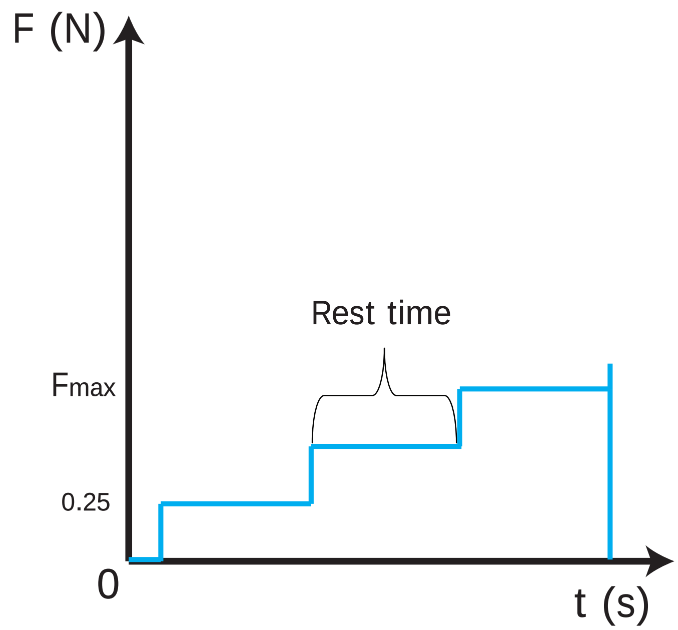


Fig. 11: *Exploring experiment 1: force profile. Detachment force was increased in steps of 0.25 N using a rest time of 15 or 60 seconds to have a reasonable estimate of the maximum detachment force, within an acceptable experiment time. A minimum rest time of 15 seconds was required to observe if peeling occurred. A maximum rest time of 60 seconds was used, as stated in Section I C*

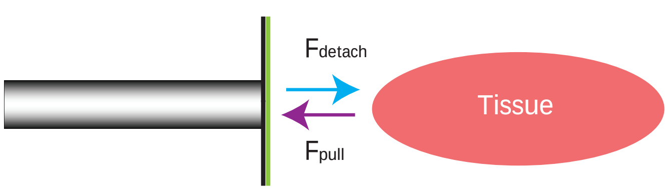
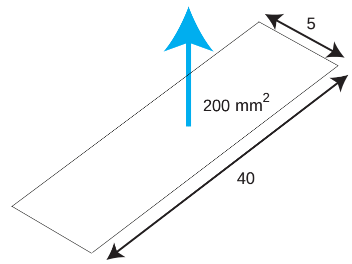


Fig. 9: *Concept of adhesive grasper using a single contact surface (schematic). Adhesive film has to generate detachment force*

TABLE II: *Exploring experiment 1: samples, load and rest time*



F_{normal} (N)	1	1
P_{normal} (kPa)	5	5
Rest time (s)	15	60

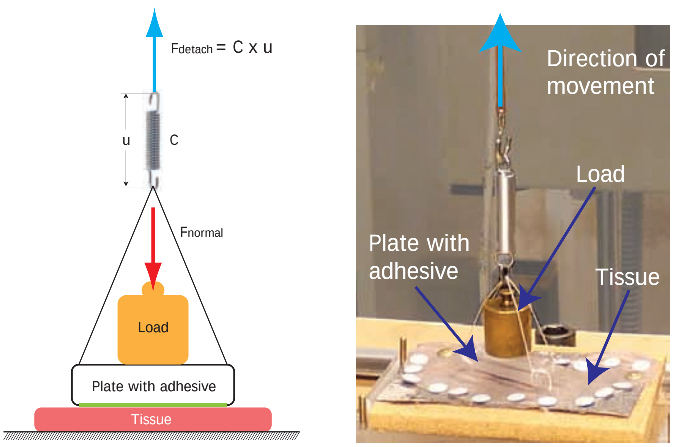


Fig. 12: *Exploring experiment 1: set-up schematic (left), reality (right) to measure the maximum detachment force. Adhesive film (200 mm^2) is fixed to a Plexiglas plate, which is placed on a piece of intestine. A load of 5 kPa is placed on top of the Plexiglas plate. Next a stepwise increasing detachment force is applied and measured*

To find the actual maximum detachment force the force generated by the 100 g mass was subtracted from the measured force. Results for the 15 and 60 seconds rest time were compared using the Student's t-test and differences were regarded as significant when $p < 0.05$. Calculations were performed using MATLAB® (R2009b). The used protocol and measurements results can be found in Appendix A.

C. Results

The results are shown in Figure 13. The average adhesive force was 2.62 ± 0.50 N for rest time of 15 seconds and 1.93 ± 0.11 N for a rest time of 60 seconds. The detachment force for a 15 second rest time was significant lower than the detachment force for a rest time of 60 seconds, $F(2,12) = 3.981$, $p < 0.05$. The variance using a rest time of 15 seconds was larger than the variance using a rest time of 60 seconds.

D. Discussion and conclusion

The hypothesis was falsified: the maximum measured average detachment force for the 15 second rest time was 2.62 ± 0.50 N, which was below the required 5 N stated in the hypothesis. The maximum measured average detachment

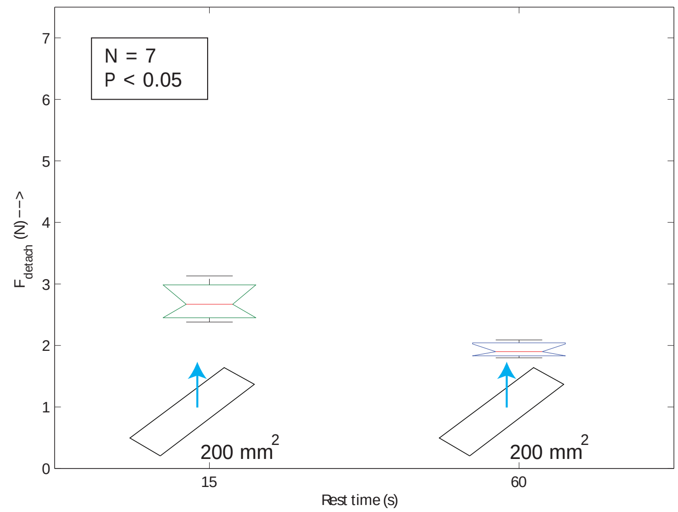


Fig. 13: *Exploring experiment 1: effect of rest time on detachment force, for contact area of 200 mm^2 and P_{normal} 5 kPa. The line in the middle of the box is the median, the upper and lower lines indicate the interquartile range, the whiskers extending indicate the spread*

force for the 60 second rest time was even lower: 1.93 ± 0.11 N. The variance using a rest time of 15 seconds was much larger than the variance using a rest time of 60 seconds. A possible explanation for this is the higher forces present at the 15 seconds rest time. Because of the occurrence of peeling and the low maximum detachment force a tip using a single contact area is considered not viable for use in the final design.

IV. Exploring Experiment 2

As concluded in exploring experiment 1, a single contact area was considered not viable due to the occurrence of peeling, which resulted in a low friction force. When multiple jaws are used, peeling is avoided because the adhesive film generates friction force in the shearing direction (Figure 10). This might result in a higher friction force, which is tested during this experiment.

A. Goal

To evaluate if an adhesive grasper which prevents peeling by using a multiple jaws with adhesive film, is able to generate a shear force of 5 N shear force, as stated in the goal, the adhesive film was tested using the following hypothesis: *Adhesive film (contact area 100 mm^2 and 200 mm^2) generates at least 5 N shear force in x and y direction.* The hypothesis was tested by placing adhesive film with an area of 100 mm^2 (5 mm × 20 mm) or 200 mm^2 (5 mm × 40 mm) on a piece of intestine and applying and recording a shear force in x or y direction (Figure 10), with an applied normal pressure of 5, 15 or 30 kPa. The highest recorded force before shearing of tissue and adhesive film occurred was defined as the maximum shear force. The dimensions of the 100 mm^2 plate were based on the jaw dimensions of common used laparoscopic graspers. The dimensions of the 200 mm^2 plate were based on the largest found jaw dimensions [29]. Three different normal pressures were applied to each area to measure the effect of ploughing [9]. The highest normal pressure of 30 kPa was approximately the same as the normal pressure exerted by the diamond shaped surface profile ([10] and [24]) of 10 mm × 10 mm which was used to determine the minimum pinch force criteria, as stated in goal of research. The lowest surface pressure of 5 kPa was chosen to enable comparison with exploring experiment 1.

B. Materials and Methods:

A Plexiglas plate with adhesive film fixed to it was placed on a piece of intestine. The edges of the Plexiglas plate were slightly rounded to avoid damage to the intestine. Subsequently, a normal pressure of 5, 15 or 30 kPa (Table III) was applied to the movable plate with the piece of intestine (Figure 14). This movable plate was connected to the force sensor of a tensile testing machine (Zwick Type 1484, Zwick GmbH & Co., Germany) using a Dyneema® cord and a pulley (Figure 14). The tensile testing machine pulled the movable plate forward with a constant speed of 0.5 mm/s and recorded the shear force.

The maximum shear force was measured for an area of 100 mm^2 (5 mm × 20 mm) and 200 mm^2 (5 mm × 40 mm), and an applied normal pressure of 5, 15 and 30 kPa. The intestine used in this experiment was obtained and prepared in the same manner as during exploring experiment 1. Each measurement was repeated 7 times.

Before the start of the experiment, the force needed to pull the movable plate forward was measured. The maximum shear force was defined as the highest measured shear force minus the force required to pull the movable plate forward. Each measurement was conducted on a new piece of intestine. Results were compared using the Student's t-test (effect of area and direction) and ANOVA test (effect of normal force). Differences were regarded as significant when $p < 0.05$. Calculations were performed using MATLAB® (R2009b). The used protocol and measurements results can be found in Appendix B.

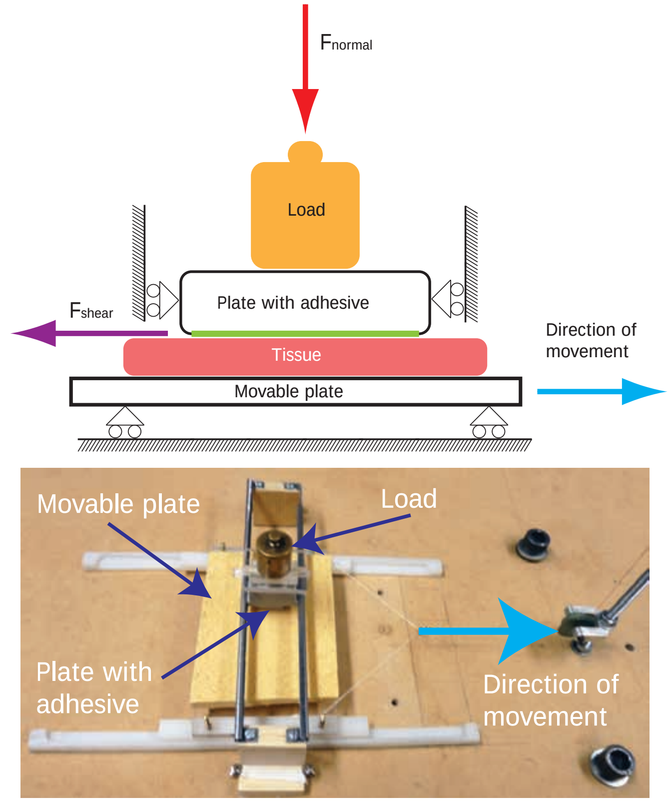


Fig. 14: *Exploring experiment 2: set-up schematic (top), reality (bottom) to measure the maximum $F_{shear,x}$ and $F_{shear,y}$. Adhesive film (100 mm^2 or 200 mm^2) is fixed to a Plexiglas plate, which is placed on a piece of intestine. A load of 5, 15 or 30 kPa is placed on top of the plate with adhesive. Subsequently the movable plate is pulled to the right and the shear force is measured*

C. Results

The results are shown in Figure 15 and Figure 16. For an area of 200 mm^2, the $F_{shear,y}$ was significant higher than $F_{shear,x}$, (Figure 15, t = 2.153, p = 0.037). The variance of $F_{shear,y}$ was slightly larger than the variance of $F_{shear,x}$ for the 200 mm^2 area. The measured $F_{shear,x}$ for the 200 mm^2 area was significant higher than the measured $F_{shear,x}$ for 100 mm^2 area (Figure 16, $F(2,39) = 9.854$, $p < 0.05$). The variance of the 200 mm^2 area was larger than the variance of the 100 mm^2 area. An increased normal force only resulted in a significant higher $F_{shear,y}$, $F(2,22) = 35.447$, $p < 0.05$ for an area of 200 mm^2.

D. Discussion and conclusion

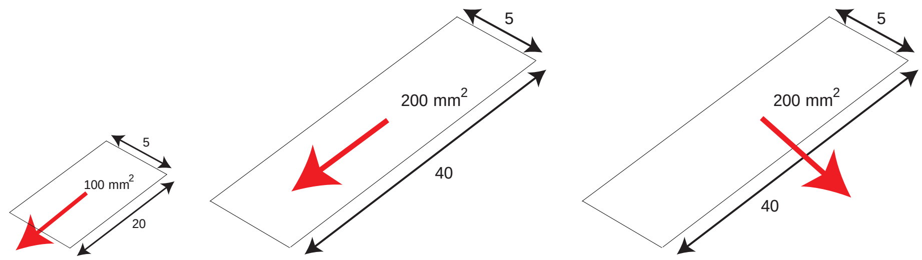
The hypothesis was falsified: only for the y direction, the 200 mm^2 area and a P_{normal} of 30 kPa, the highest measured average shear force was 6.15 ± 0.73 N, which was above the 5 N stated in the hypothesis. For all other cases the measured shear force was lower than 5 N.

The variance of the 200 mm^2 area was larger than the variance of the 100 mm^2 area. A possible explanation is that the influence of the irregularities of the intestine on the maximum shear force was larger for the larger area.

The variance of $F_{shear,y}$ was slightly larger than the variance of $F_{shear,x}$ for the 200 mm^2 area. This difference can be explained by ploughing [9]: with the large edge facing the direction of travel ($F_{shear,y}$), the contribution of ploughing to the maximum shear force is larger compared to the contribution of shearing of the adhesive connections. The large influence of ploughing to the friction force can also be seen in Figure 15: $F_{shear,y}$ was significant higher than $F_{shear,x}$ and an increased normal pressure resulted in a significant higher $F_{shear,y}$. A tip using ploughing could be used to increase the friction force but is not advised due to the introduction of peak pressures in the tissue.

Overall, the found average shear forces during exploring experiment 2 were higher than the found average detachment forces during exploring experiment 1. Consequently a tip which prevents peeling by using multiple jaws is desired.

TABLE III: *Exploring experiment 2: samples, load and direction*



F_{normal} (N)	0.5	1.5	3.0	1.0	3.0	6.0	1.0	3.0	6.0
P_{normal} (kPa)	5	15	30	5	15	30	5	15	30

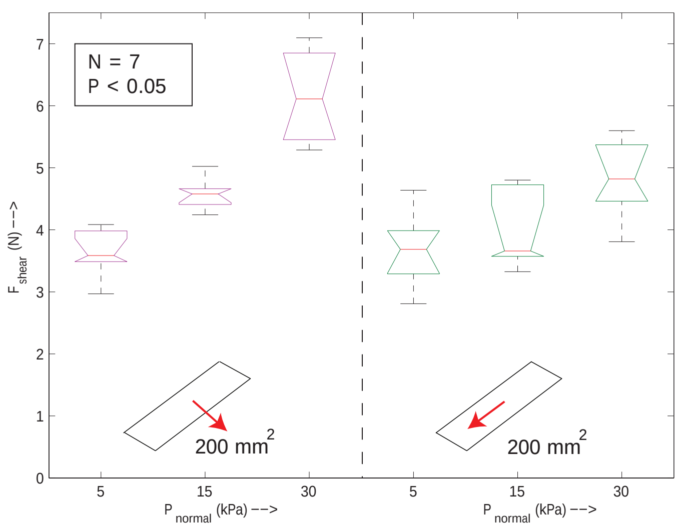


Fig. 15: *Exploring experiment 2: effect of direction of displacement, for a contact area of 200 mm² and P_{normal} of 5, 15 or 30 kPa. The line in the middle of the box is the median, the upper and lower lines indicate the interquartile range, the whiskers extending indicate the spread*

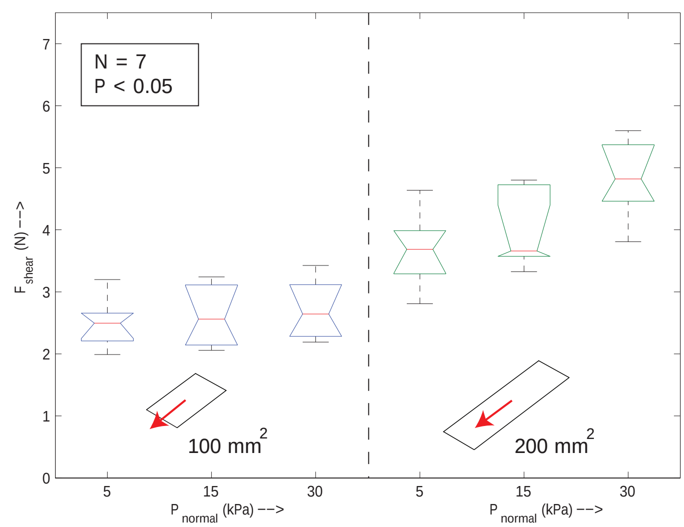


Fig. 16: *Exploring experiment 2: effect of size of contact area, for a contact area of 100 mm² and 200 mm² and P_{normal} of 5, 15 or 30 kPa. The line in the middle of the box is the median, the upper and lower lines indicate the interquartile range, the whiskers extending indicate the spread*

V. Adhesive grasper: final design

The exploring experiments were conducted to investigate how to maximize the friction force of the available adhesive film. The conclusions of these experiments resulted in boundary conditions for the tip. Boundary conditions for the shaft were not defined because the film width was already maximised in the conceptual design. Boundary conditions for a handle were not defined, because a handle is not required for the initial evaluation of the adhesive grasper.

Tip:

- Use multiple jaws to avoid peeling during grasping
- Contact area at least 200 mm²

A. Final design

a) Tip: In the final design two rectangular jaws were used. The main advantage of using two jaws is that peeling was avoided. Another advantage is that surgeons are already accustomed to grasping using two jaws. The jaws were chosen to be flat with rounded edges to avoid (local) high pressures in the tissue and tearing of the adhesive film. Because of the flat jaws, the effect of ploughing is small which will result in a lower friction force (as found in exploring experiment 2) and the friction force is virtually a function of the contact area (Equation 1). The thickness of the jaws was set at 1 mm. As a result, the tip of the instrument does not deform due to the exerted forces during manipulation of tissue . With a thickness of 1 mm, the width of the jaws is limited to 4.45 mm due to the dimensions of trocar (5 mm diameter). The length of the jaws was set at 30 mm, resulting in a total contact area of 4.45 mm × 30 mm × 2 = 267 mm². The length of the jaws was slightly larger than the length of the conventional grasper jaws (most used 20 mm, largest found 40 mm, [29] and [30]). To connect the jaws to the grasper a cut was made at the back. One of the jaws is shown in Figure 17.
Due to the use of two jaws, motion of these jaws is required to adjust the distance between them to the thickness of the tissue. As stated in Section IIa, the chosen concept of motion was the compliant concept, because it offered lower surface pressures near the hinges compared to the motion generated

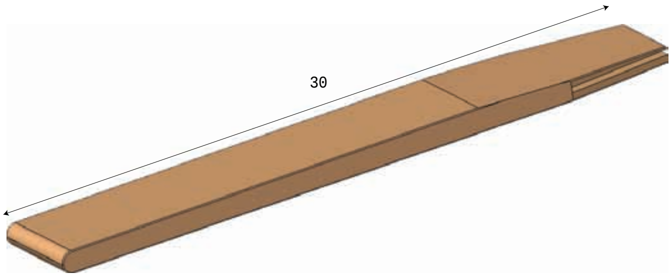


Fig. 17: *Adhesive grasper: jaw. Two flat, rigid, rectangular jaws with rounded edges are chosen to prevent high surface pressures. The jaws are connected to the instrument by the cut in the back. The top of the jaw is sloping to allow actuation using a hollow tube*

by a single hinge, while not being as highly complex as parallel motion.

b) Shaft design: To realise the film configuration as shown in Figure 8 three concentrically tubes were used, as shown in Figure 18 and Figure 19). The outer tube (outer diameter 5 mm, wall thickness 0.25 mm) shields the fresh adhesive film from the environment, preventing premature activation, while the inner tube (outer diameter 3.5 mm, wall thickness 0.25 mm) is used to separate, shape and position the fresh and used film. To actuate the tip another tube was added (middle tube). A tube was chosen to actuate the tip because it leaves a large space inside the shaft and does not interfere with the film configuration. This middle tube slides across the inner tube. The wall thickness of the middle tube has to be sufficient to actuate the tip without deforming. A small wall thickness was preferred, on the other hand, to minimize the folding of the used adhesive film. A tube with outer diameter of 4 mm and wall thickness of 0.25 mm was chosen, to meet both requirements. As a consequence of this, the distance between the outer and middle tube is 0.25 mm. This enables irregular thickness of the adhesive film, which has an average thickness of approximately 0.15 mm. To fix the distance between the outer and inner tube, a plug was used. A window in the wall of the middle tube (Figure 23) allows this tube to slide around the plug. The plug is glued to the inner and outer tube. The use of a plug limits the maximum width of the fresh adhesive film to 6.85 mm. The used adhesive film has to crumble from 6.85 to 3 mm, which generates a considerable amount of friction. The inner tube was left open to not further increase friction.

The hinge is located at the tip of the grasper, where crumbling of the used adhesive film occurs, which requires space and will generate adhesive residue. To avoid contamination and to maximise the available space for adhesive film, material hinges were used to provide the combination motion. The material hinges were formed by the inner tube. The end of the inner tube is sawed in, made flat and bend upwards (Figure 21), creating a material hinge and mounting point for the jaws. The jaws were glued to the inner tube. In the default position the grasper is in open position. To close the grasper the middle tube is pushed forward, across the open jaws, which forces the jaws to close (Figure 20). When the middle tube is pulled back, the jaws are opening again due to the elasticity of the material hinge.

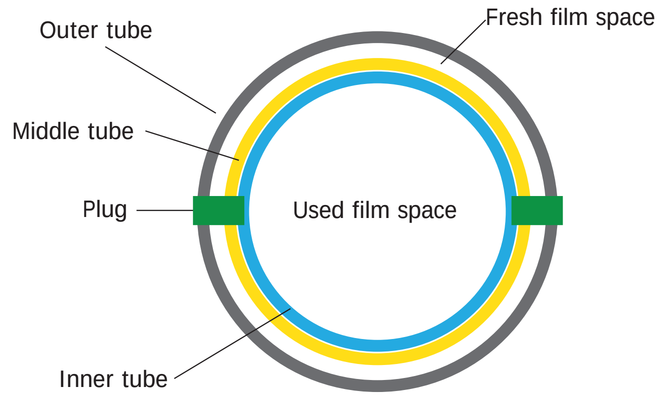


Fig. 18: *Central shaft: cross section without middle tube (left) and with middle tube (right). Inner and outer tube are fixed using a plug. The middle tube slides across the inner tube to actuate the jaws. Fresh adhesive film is located between middle and outer tube, used adhesive film is located inside the inner tube*

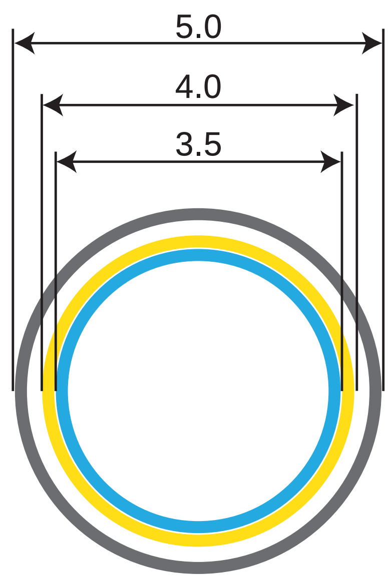


Fig. 19: *Central shaft: cross section dimensions. For the outer tube (grey) a tube with 5mm outside diameter was used. For the outer tube (yellow) a tube with 4 mm outside diameter was used. For the inner tube (blue) a tube with 3.5 mm outside diameter was used. All tubes have a wall thickness of 0.25 mm. The distance between outer and middle tube is 0.25 mm*

The complete final design is shown in Figure 22 and an exploded view in Figure 23.

B. Prototype design

For the prototype, the length of the shaft was shortened to approximately 100 mm instead of 300 mm. This was due to length restrictions of the available adhesive film. Because of the short length, the plugs to fix the distance between inner and outer tube were not required. The outer tube was secured in an aluminium block by a screw, the middle tube was glued in an aluminium block and the inner tube was clamped in

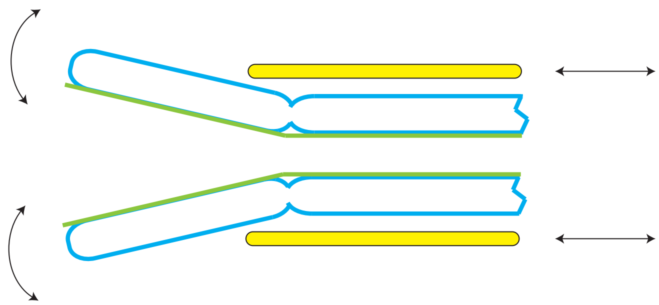


Fig. 20: *Adhesive grasper: actuation schematic (left) and render (right). In the starting position the grasper is in open position. Pushing the middle tube (yellow) pushed forward across the inner tube (blue) forces the jaws to close*

Fig. 21: *Adhesive grasper: inner tube hinge. The end of the inner tube is sawed in, made flat and bend upwards, creating a material hinge and mounting point for the jaws. The round hole on the left is a relief cut for the material hinge. The square hole on the right is for the plug*

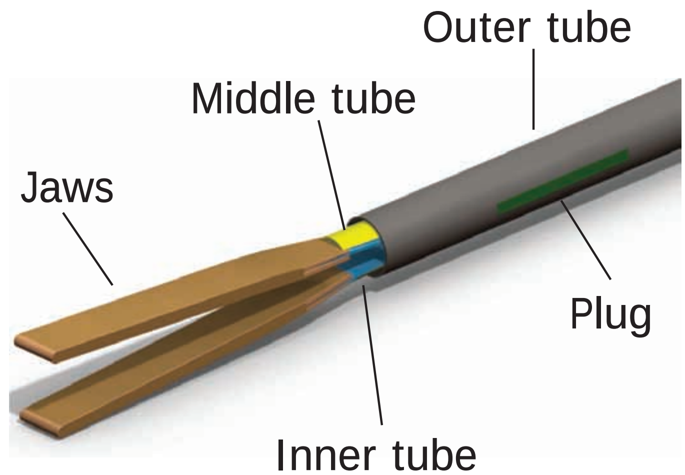


Fig. 22: *Adhesive grasper: tip detail (without adhesive film)*

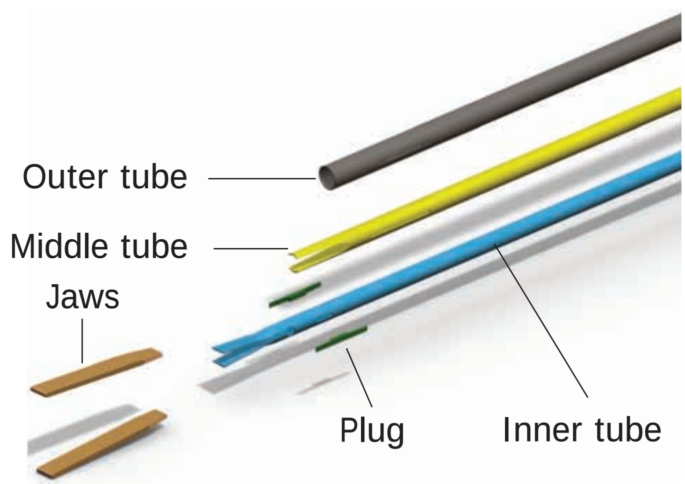


Fig. 23: *Adhesive grasper: exploded view(tubes shortened)*

an aluminium block. These fixation methods allows for the prototype to be taken apart to clean or to load with adhesive film. The distance between the block securing the outer tube and the block clamping the inner tube was fixed using two rails. The block fixing the middle tube is able to slide across the rails. The prototype of the adhesive grasper is shown in Figure 24, and an exploded view in Figure 25. Construction drawings of the prototype can be found in Appendix D.

a) Outer tube: For the prototype of the adhesive grasper a standard stainless steel tube with outer diameter of 5 mm and wall thickness of 0.25 mm was used (Figure 19). Stainless steel was used because of the resistance against corrosion and high stiffness. Due to the absence of the plug to fix the distance between inner and outer tube, the windows in the side of the tube were omitted. All edges in contact with the adhesive film were rounded to prevent tearing of the film.

b) Middle tube: A standard stainless steel tube with outer diameter of 4 mm and wall thickness of 0.25 mm was used (Figure 19). Stainless steel was used because of the resistance against corrosion and high stiffness. Due to the absence of the plug, the windows in the side of the tube were omitted. All edges in contact with the adhesive film were rounded to prevent tearing of the film.

c) Inner tube: A standard stainless steel tube with outer diameter of 3.5 mm and wall thickness of 0.5 mm was used (Figure 19). Stainless steel was used because of the resistance against corrosion and high stiffness. Due to the absence of the plug, the windows in the side of the tube were omitted. All edges in contact with the adhesive film were rounded to prevent tearing of the film.

d) Tip: The tip of the grasper consists of two stainless steel jaws of 30 mm $\times$ 4.45 mm $\times$ 1 mm. The top of the jaws is skewed to enable the middle tube to slide over it. The jaws were glued to the inner tube.

e) Blocks: The blocks securing the tubes were made from aluminium for easy machining and low cost. The block securing the outer tube (20 mm $\times$ 20 mm $\times$ 10 mm) has holes for the outer tube, rails and a screw. The block securing the middle tube (20 mm $\times$ 20 mm $\times$ 10 mm) has a hole

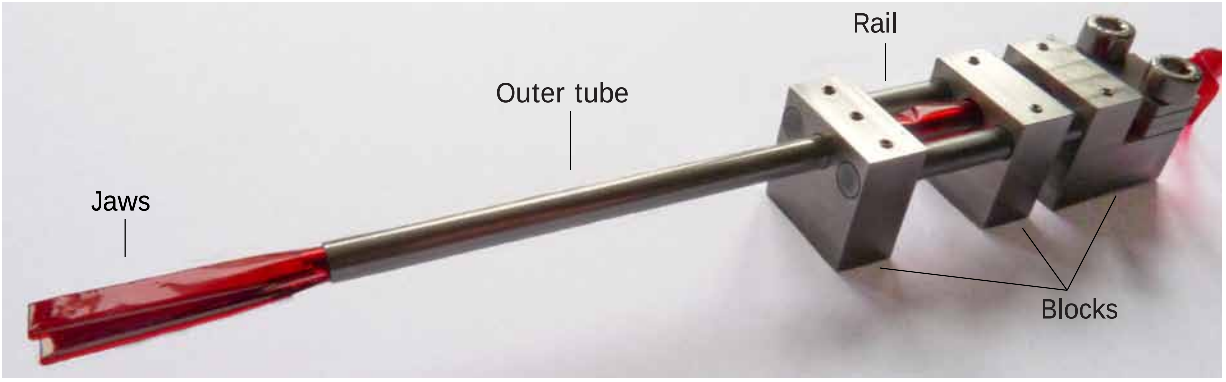


Fig. 24: *Adhesive grasper: prototype*

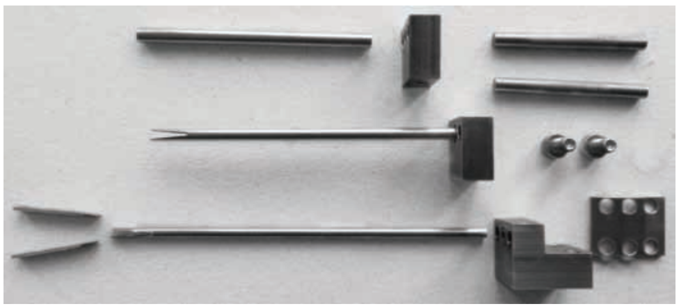


Fig. 25: *Adhesive grasper: exploded view*

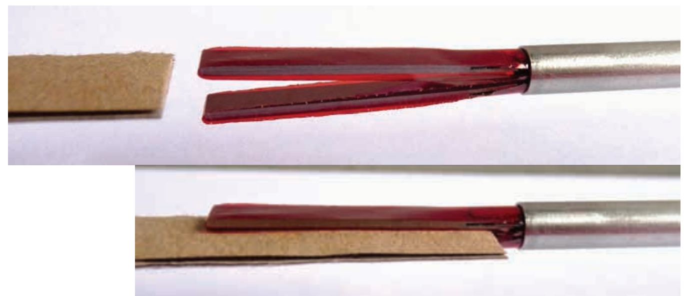


Fig. 26: *Adhesive grasper: grasping. Tissue is positioned between the jaws of the grasper and the jaws are closed. The tissue is released by opening the jaws after which the tissue will release. After release of the tissue, the adhesive film is refreshed*

for the middle tube, two semi-circular holes for the adhesive film and two holes for the rails. The block clamping the inner tube (20 mm × 25 mm × 10 mm) has a hole for the inner tube, two semi-circular holes around it for the adhesive film and two holes for the rails. At the back of the block three stainless steel plates are located, which can be used to secure the adhesive film.

Figure 26 shows how the adhesive grasper works. In the default position the jaws of the grasper are open. Tissue is positioned between the jaws of the grasper and the jaws are closed by pushing the middle tube forward. The tissue is released by pulling back the middle tube, which increases the distance between the jaws after which the tissue will release. The release of tissue can be accelerated by pulling the fresh film back between the outer and middle tube. After release of the tissue, the used film is put together, crumbled and pulled inside the inner tube, and replaced with fresh adhesive film.

VI. Evaluation experiment

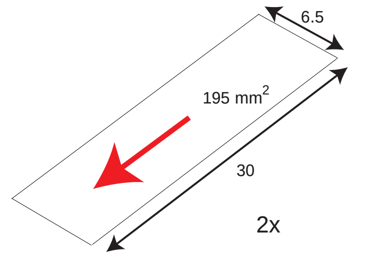
A. Goal

The goal of this research was to develop and evaluate an 5 mm laparoscopic grasper for handling intestine, which is able to generate a friction force of 5 N, using a pinch force lower than 3 N and hold tissue for a period of 60 seconds. To evaluate this goal the prototype of the adhesive grasper was tested using the following hypothesis: *The adhesive grasper prototype generates a friction force of 5 N, using a pinch force lower than 3 N.* The hypothesis was tested by grasping a piece of intestine with the prototype of the adhesive grasper while applying a pinch force of 0.1, 1.0, 2.5 or 7.5 N (Figure IV) and measuring the pull force. The lowest pinch force of 0.1 N was chosen to have a repeatable lowest value for the pinch force, while the pinch force of 7.5 N results in an approximate equal average surface pressure as induced by the surface profile of [10] and [24] used to determine the 3 N pinch force criteria. Besides testing of the hypothesis, the experiment was also used to test the functioning of the design of the adhesive grasper (e.g. adhesive film feed and hinge).

B. Materials and Methods

The prototype was loaded with adhesive film with a width of 6.5 mm (resulting in a contact area of 2 × 6.5 mm × 30 mm = 390 mm^2). The intestine of a pig (obtained from the Academic Medical Centre Amsterdam) was extracted and resected laterally. One side of the resected piece was clamped between two Plexiglas plates, the other end was extending 30 mm. Sandpaper was used between the Plexiglas plates and the intestine piece to prevent movement. The extending end of the intestine piece was positioned between the jaws of the prototype and the jaws were closed. When closed, a height adjustable support was used to support the lower jaw to prevent downward motion. A mass was placed on top of the upper jaw to simulate pinch force. The Plexiglas plates holding the intestine were connected to the force sensor of a tensile testing machine (Zwick Type 1484, Zwick GmbH & Co., Germany) using a Dyneema® cord and a pulley

TABLE IV: *Evaluation experiment: load and direction*



F_{pinch} (N)	0.1	1.0	2.5	7.5
P_{normal} (kPa)	0.51	5.13	12.82	38.46

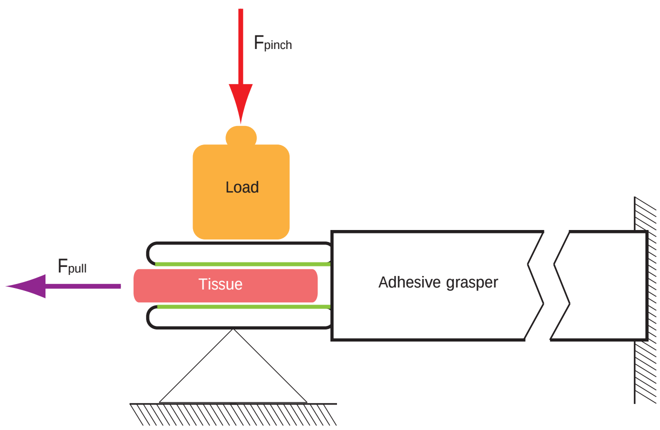


Fig. 27: *Evaluation experiment: set-up (schematic) to measure the maximum pull force. The prototype of the adhesive grasper is loaded with adhesive film (resulting in a contact area of 390 mm^2). Subsequently a pinch force of 0.1, 1, 2.5 or 7.5 N is applied and the tissue is pulled to the left, while the pull force is measured*

(Figure 27). The tensile testing machine pulled the Plexiglas plates with an increasing force of 1 N/s, while recording the pull force. An increasing force of 1 N/s was used to enable comparison with [10] and [24]. The maximum pull force was defined as the highest measured pull force.
Each measurement (Table IV) was repeated 5 times. For each measurement a fresh piece of intestine was used. All experiments were executed within 24 hours of removal of the intestine. Measurements were compared using the ANOVA test. Differences were regarded significant if $p < 0.05$. Calculations were performed using MATLAB® (R2009b).

C. Results

The results are shown in Figure 28. The highest average pull force was 3.12 ± 0.58 N for a pinch force of 2.5 N and the lowest average pull force was 2.17 ± 0.59 N for a pinch force of 0.1 N. The ANOVA test showed no significant difference between the found pull forces, $t = 2.4$, $p = 0.077$.

D. Discussion and conclusion

The hypothesis was falsified: the maximum found pull force was 3.12 ± 0.58 N, which was below the 5 N stated

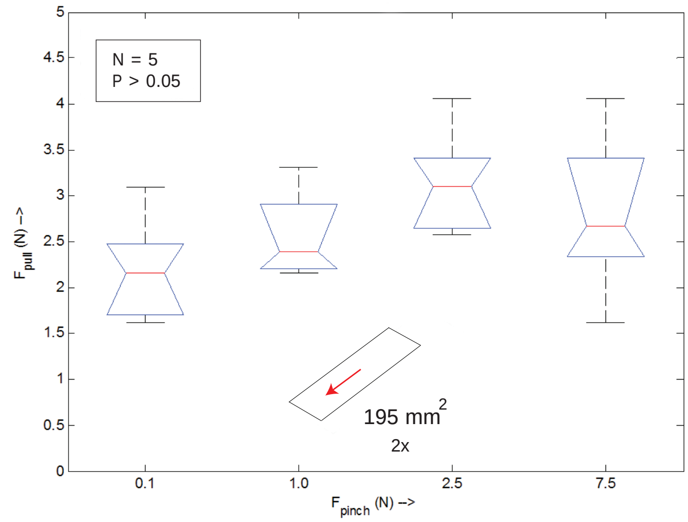


Fig. 28: *Evaluation experiment: effect of pinch force on pull force for a contact area of 390 mm^2 and applied pinch force of 0.1, 1.0, 2.5 and 7.5 N. The line in the middle of the box is the median, the upper and lower lines indicate the interquartile range, the whiskers extending indicate the spread*

in the hypothesis. The generated friction force in this experiment was in fact lower than the generated friction force in exploring experiment 2, despite a larger contact area during this experiment. A possible explanation is the absence of ploughing. Extrapolating and comparing the results of this experiment and [10] and [24] indicates that the adhesive grasper requires a substantial lower pinch force while having a smaller contact area. The increased pinch force did not result in a significant higher pull force, which indicates that the friction force generated by the adhesive grasper is independent from the pinch force. During the experiment the adhesive film feed got stuck frequently. Due to the high stiffness of the film and large change in width of the film (from 6.5 to approximately 3 mm) crumbling induced a lot of friction. The crumbling of the film resulted in cloths of residue accumulating at the point where fresh film exits and used film enters the shaft, blocking the film feed. A large change in film width using crumbling is thus not recommended. Also, the opening angle of the contact surface was limited. This resulted in just enough distance between the jaws to grasp a flat colon fragment. To increase the usability of the grasper, the distance between the jaws needs to be increased in future versions of the adhesive grasper.

VII. Discussion and Conclusion

The goal of this research was to develop and evaluate an 5 mm laparoscopic grasper, which has the same functionality (generated friction force, time) as a conventional 5 mm grasper for use on the intestine but requiring lower pinch force due to the use of adhesives. Tissue damage due to insufficient forces was eliminated by minimizing the peak pressures in the tissue due to the use of a flat surface profile. Tissue damage due to excessive force was eliminated by introducing an adhesive between tissue and grasper. Adding an adhesive increased the adhesive component ($F_{adhesion}$) of the friction force, resulting in a lower pinch force (F_{pinch}) to obtain the same friction force. To minimize the pressure in the tissue during grasping, the contact area of muco-adhesives at the tip of the grasper was maximized. As a result, the friction force was almost a function of the adhesive force.

During the evaluation experiment, the prototype of the adhesive grasper was able to generate a friction force of 3.12 ± 0.58 N, using a pinch force of 2.5 N. The friction force generated by the tip of the instrument was independent of the applied pinch force. The maximum friction force generated by the adhesive grasper did not meet the goal of 5 N however, the required pinch force was substantially lower and for procedures involving dissection of the intestine an average pull force of 2.5 N is required [31], which could be generated.

Despite a larger contact area, the friction force generated by the prototype of the adhesive grasper was lower than the friction force generated during exploring experiment 2. A possible explanation can be found in the design of the tip of the adhesive grasper: flat jaws were used, minimising the effect of ploughing. The difference between the friction force generated in exploring experiment 2 and the evaluation experiment indicates that the contribution of ploughing to the friction force was substantial. During the evaluation experiment the adhesive film was only tested in the x shear direction, while the effect of ploughing in the y shear direction is larger, probably resulting in a higher friction force. Testing of the prototype in the y shear direction would reveal if the proposed guide is able to keep the adhesive film on the jaws. Only simple (rectangular) shapes of the tip of the grasper were considered, while exploring experiment 2 indicated that ploughing results in an increased friction force. To further increase the friction force of the adhesive grasper another shape (e.g. a T shape) of the tip is recommended, which increases the frontal edge and contact area and results in a higher friction force. Another possibility to increase the friction force is to develop an adhesive film which is intended for use on the outside of organs.

To improve usability, friction between film and grasper must be decreased. Also, a lot of friction and residue was generated by the large amount of crumbling of the used adhesive film. Due to the stiffness of the adhesive film, only small changes of the shape of the used film (e.g. crumbling, folding etc.) are recommended.

This research has showed that the use of an adhesive grasper in MIS is promising; the friction force generated by the proposed tip design was independent of the applied pinch force, and the pinch force was substantially lower, and (local) high pressures in the tissue were avoided, which may reduce errors due to excessive or insufficient force and increase grasping safety with that.

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Appendix A

Exploring Experiment 1

A.1 Protocol

1. Clean, open (longitudinally) and resect intestine
2. Prepare adhesive film sections (5 mm x 40 mm)
3. Bring the platform of tensile testing machine to its starting position (if needed)
4. Fix intestine fragment on pad, outside upwards
5. Fix adhesive film section to Plexiglas plate
6. Place Plexiglas plate with adhesive film on top of intestine fragment
7. Connect Plexiglas plate to Dyneema® pull wire
8. Place 100 g mass on top of Plexiglas plate with adhesive film
9. Start measurement
10. When measurement completed: store maximum detachment force
11. Disconnect Plexiglas plate from Dyneema® pull wire
12. Remove 100 g mass from Plexiglas plate
13. Remove Plexiglas plate with adhesive film from intestine
14. Remove intestine fragment from pad
15. Remove adhesive film section from Plexiglas plate
16. Repeat measurement from step 3 onward until sufficient measurements are conducted

A.2 Results

Table A.1: *Exploring experiment 1: results*

	Rest time (s)	
	15	**60**
F_{detach} (N)	2.38	1.9
	1.64	1.8
	3.13	1.81
	2.66	2.09
	2.79	2.06
	2.67	1.99
	3.05	1.9

Appendix B

Exploring Experiment 2

B.1 Protocol

1. Clean, open (longitudinally) and resect intestine
2. Prepare adhesive film sections (5 mm x 20 mm and 5 mm x 40 mm)
3. Bring the platform of tensile testing machine to its starting position (if needed)
4. Fix intestine fragment on movable plate, outside upwards
5. Connect movable plate to Dyneema® pull wire
6. Fix adhesive film section (5 mm x 20 mm or 5 mm x 40 mm) to Plexiglas plate
7. Place Plexiglas plate with adhesive film on top of intestine fragment
8. Apply normal pressure (5, 15 or 30 kPa) to Plexiglas plate
9. Start measurement
10. When measurement completed: store maximum shear force
11. Disconnect movable plate from Dyneema® pull wire
12. Remove normal pressure from Plexiglas plate
13. Remove Plexiglas plate with adhesive film from intestine
14. Remove intestine fragment from movable pad
15. Remove adhesive film section from Plexiglas plate
16. Repeat measurement from step 3 onward until sufficient measurements are conducted

B.2 Results

Table B.1: *Exploring experiment 2 : results $F_{shear,x}$, A=100 mm^2*

	$\mathbf{P_{normal}}$ (kPa)		
	5	**15**	**30**
$\mathbf{F_{shear,x}}$ (N)	2.58	3.242	2.732
	2.559	2.057	2.19
	2.434	2.405	2.642
	2.429	3.175	3.245
	3.199	2.718	3.425
	1.99	3.048	2.557
	2.736	2.228	

Table B.2: *Exploring experiment 2 : results $F_{shear,x}$, A=200 mm^2*

	$\mathbf{P_{normal}}$ (kPa)		
	5	**15**	**30**
$\mathbf{F_{shear,x}}$ (N)	4.033	3.657	4.82
	3.677	4.726	4.66
	2.808	4.802	5.507
	3.694	3.572	5.599
	4.637	3.325	4.965
	3.621	3.659	4.395
	3.942		

Table B.3: *Exploring experiment 2 : results $F_{shear,y}$, A=200 mm^2*

	$\mathbf{P_{normal}}$ (kPa)		
	5	**15**	**30**
$\mathbf{F_{shear,y}}$ (N)	2.969	4.597	7.095
	3.651	5.023	7.013
	4.084	4.558	5.859
	3.88	4.401	6.357
	3.519	4.663	5.288
	3.48	4.417	6.11
	3.495	4.242	5.317
		4.66	

Appendix C

Evaluation Experiment

C.1 Protocol

1. Clean and separate intestine in lateral fragments
2. Bring the platform of tensile testing machine to its starting position (if needed)
3. Fix intestine fragment between Plexiglas plates
4. Connect Plexiglas plates with intestine fragment to Dyneema® pull wire
5. Refresh adhesive film
6. Open grasper
7. Position intestine fragment between jaws (30 mm)
8. Check position intestine fragment
9. Close jaws
10. Apply support lower contact surface
11. Apply pinch force to upper contact surface (F_{pinch} = 0.1, 1.0, 2.5, 5.0, 7.5 N)
12. Start measurement
13. When measurement completed: store maximum force
14. Remove pinch force from upper contact surface
15. Remove support lower contact surface
16. Open grasper
17. Remove intestine fragment from between jaws
18. Disconnect Plexiglas plates with intestine fragment from pull wire

19. Remove intestine fragment from Plexiglas plates
20. Repeat measurement from step 3 onward until sufficient measurements are conducted

C.2 Results

Table C.1: *Evaluation experiment: results*

	$\mathbf{F_{pinch}}$ (N)				
	0	**0.1**	**1**	**2.5**	**7.5**
$\mathbf{F_{pull}}$ (N)	2.3696	3.095	2.5136	3.1994	1.6199
	3.904	2.2652	3.3083	4.0552	3.1958
	3.7042	2.1527	2.2652	6.756	4.0552
	2.3768	1.6199	2.1527	2.5775	2.6756
	3.1454	1.7288		3.0977	2.5775
	3.4999				
	5.0164				
	4.1821				
	2.8448				
	3.7483				

Appendix D

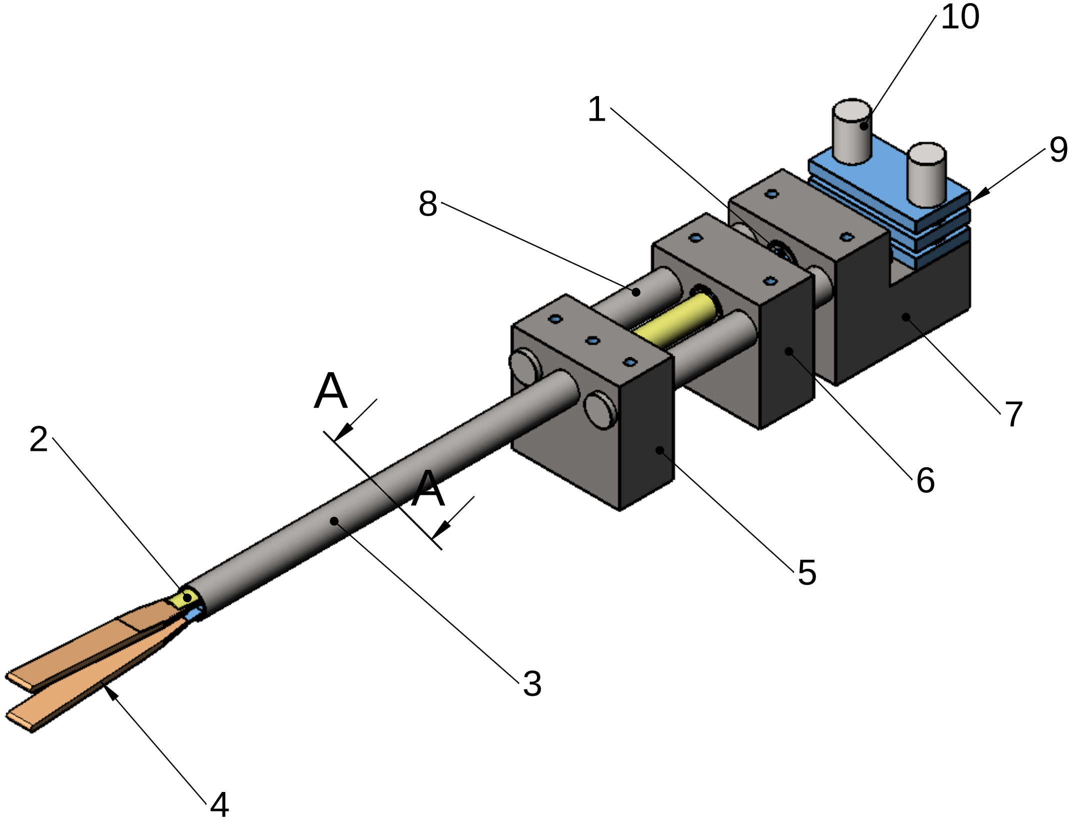
Construction drawings prototype

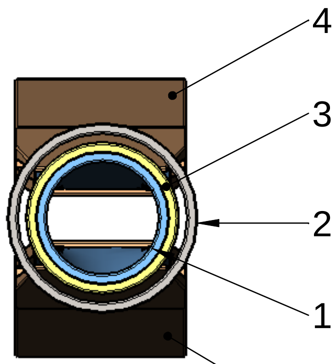
D.1 Bill of materials

Table D.1: *Prototype: bill of materials*

Drawing number	Name	Material	Quantity
1/10	InnerTube	Stainless steel AISI 304	1
2/10	ControlTube	Stainless steel AISI 304	1
3/10	OuterTube	Stainless steel AISI 304	1
4/10	Jaws	Stainless steel AISI 304	2
5/10	Block1	Aluminium 7075	1
6/10	Block2	Aluminium 7075	1
7/10	Block3	Aluminium 7075	1
8/10	Rail	Stainless steel AISI 304	2
9/10	Plate	Stainless steel AISI 304	3
10/10	Stud	Stainless steel AISI 304	2

D.2 Drawings

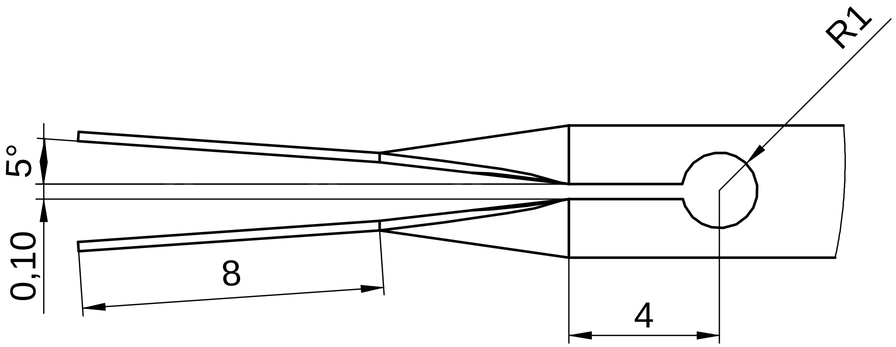




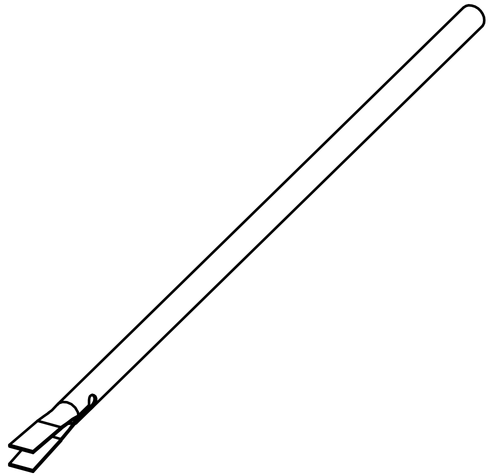
A-A (5:1)

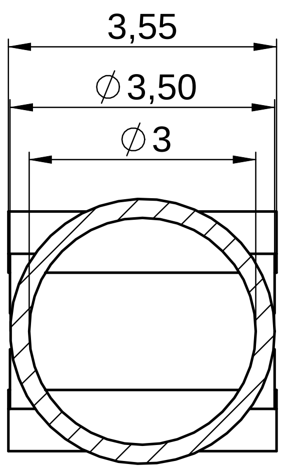
Number	Name	Quantity
1	InnerTube_V7	1
2	MiddleTube_V3	1
3	OuterTube_V7	1
4	Jaws_V8	2
5	Block1_V2	1
6	Block2_V2	1
7	Block3_V2	1
8	Rail_V1	2
9	Plate_V2	3
10	Stud_V1	2

TU Delft Mechanical Engineering	name: Setup_V3	date: 12-11-2010	dimensions: mm
	scale: 1:1	group: MISIT	format: A4
	designed by: MdH		drawing number: 0/10



A (5 : 1)





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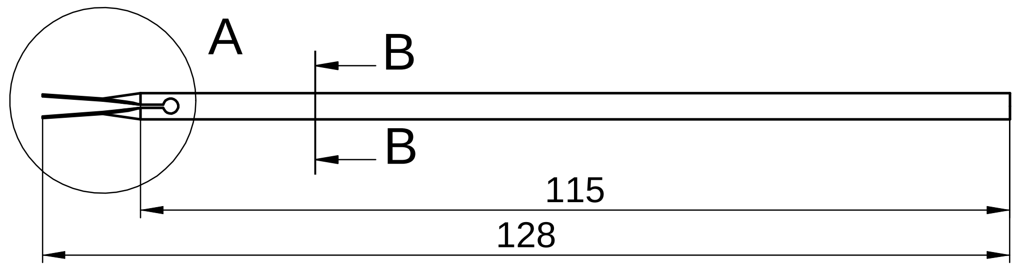
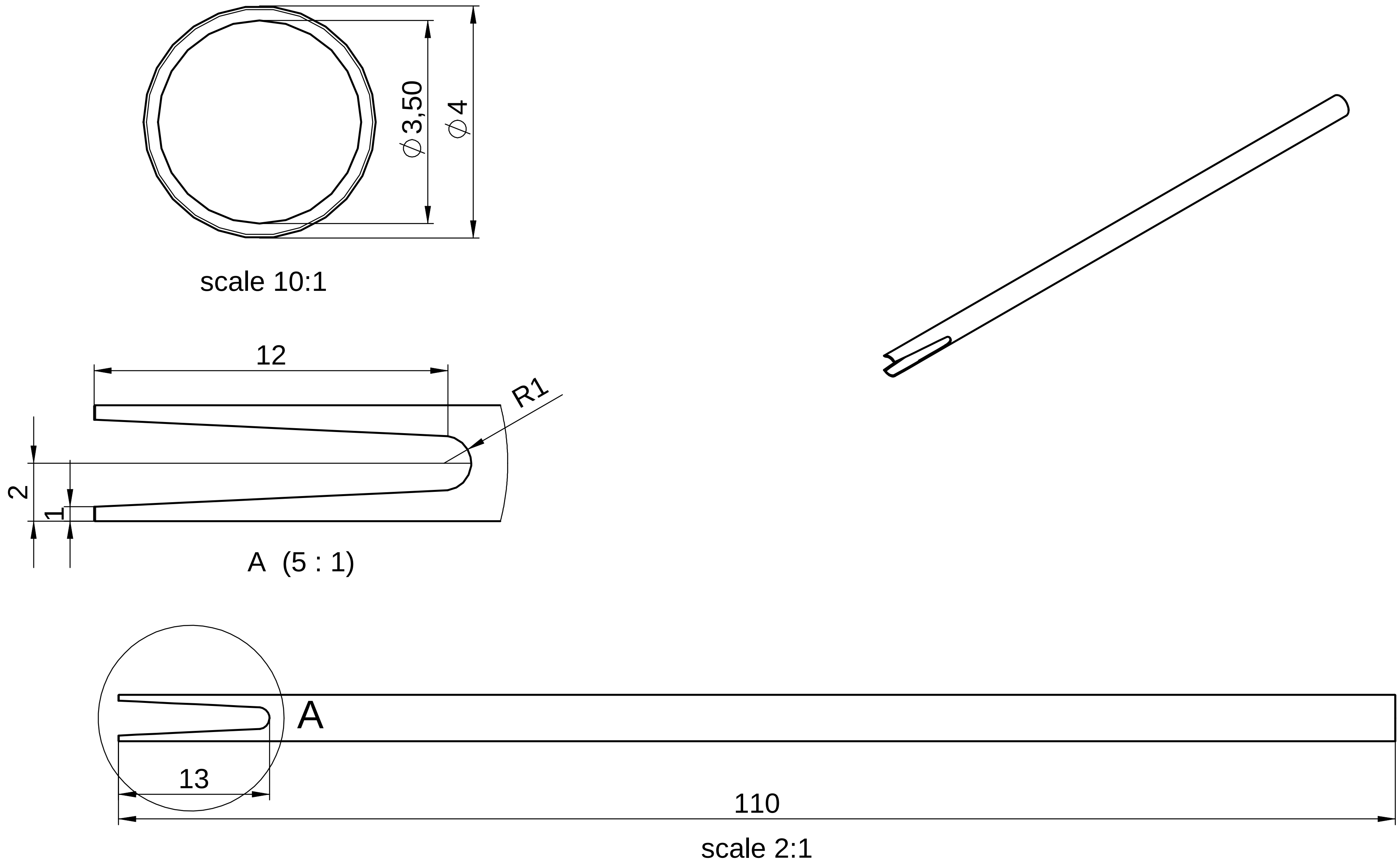
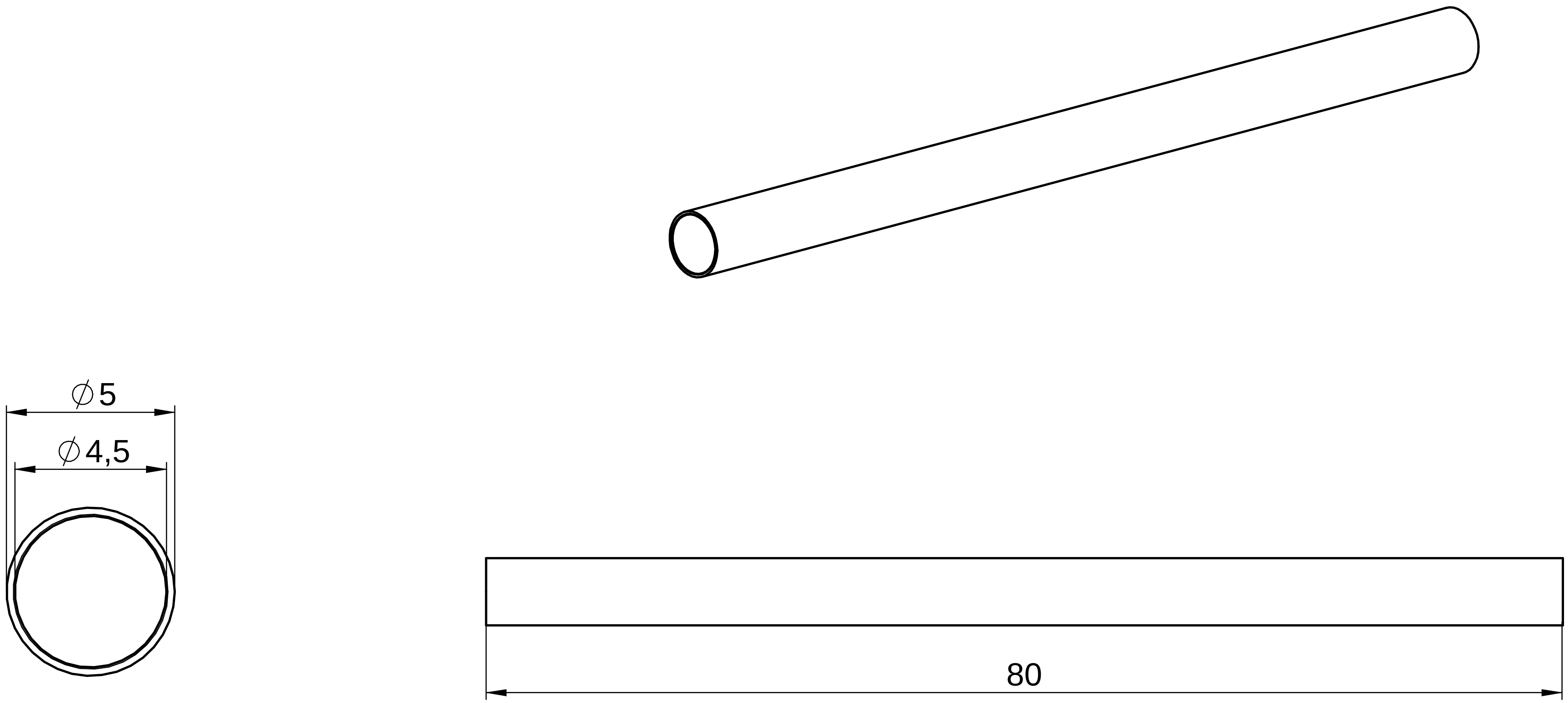


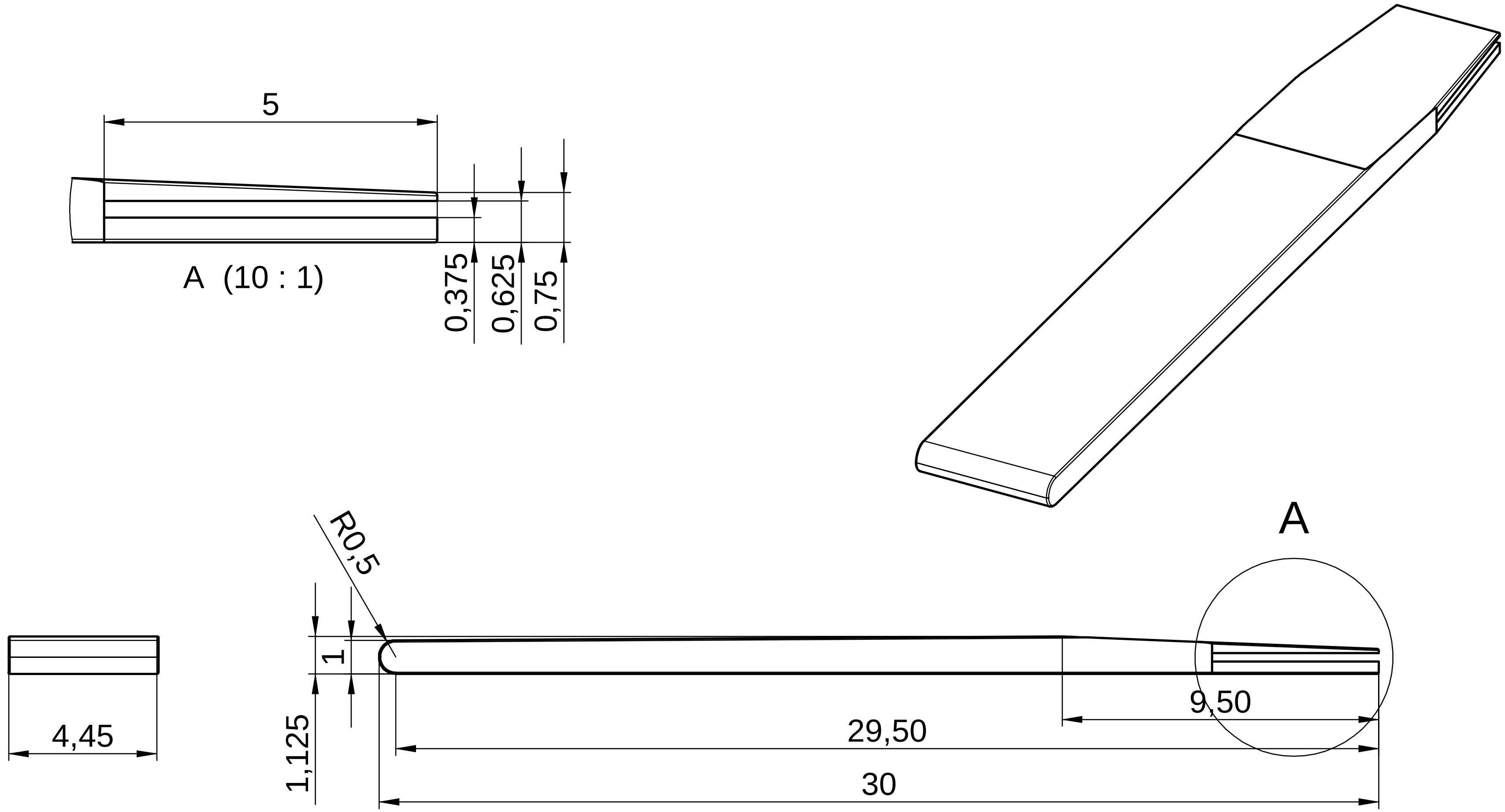
TU Delft Mechanical Engineering	name: InnerTube_V7		date: 12-11-2010		dimensions: mm
	tolerance: ISO 2768 f	material: SS AISI 304	scale: 1:1	group: MISIT	
			designed by: MdH	quantity: 1	format: A4
					drawing number: 1/10



TU Delft	name: MiddleTube_V3			date: 12-11-2010		dimensions: mm
			scale: 1:1	group: MISIT	quantity: 1	format: A4	drawing number: 2/10
Mechanical Engineering	tolerance: ISO 2768 f	material: SS AISI 304	designed by: MdH			



TU Delft Mechanical Engineering	name: OuterTube_V6			date: 12-11-2010		dimensions: mm
			scale: 2:1	group: MISIT	quantity: 1	format: A4	drawing number: 3/10
	tolerance: ISO 2768 f	material: SS AISI 304	designed by: MdH				



TU Delft Mechanical Engineering	name: Jaws_V9			date: 12-11-2010		dimensions: mm
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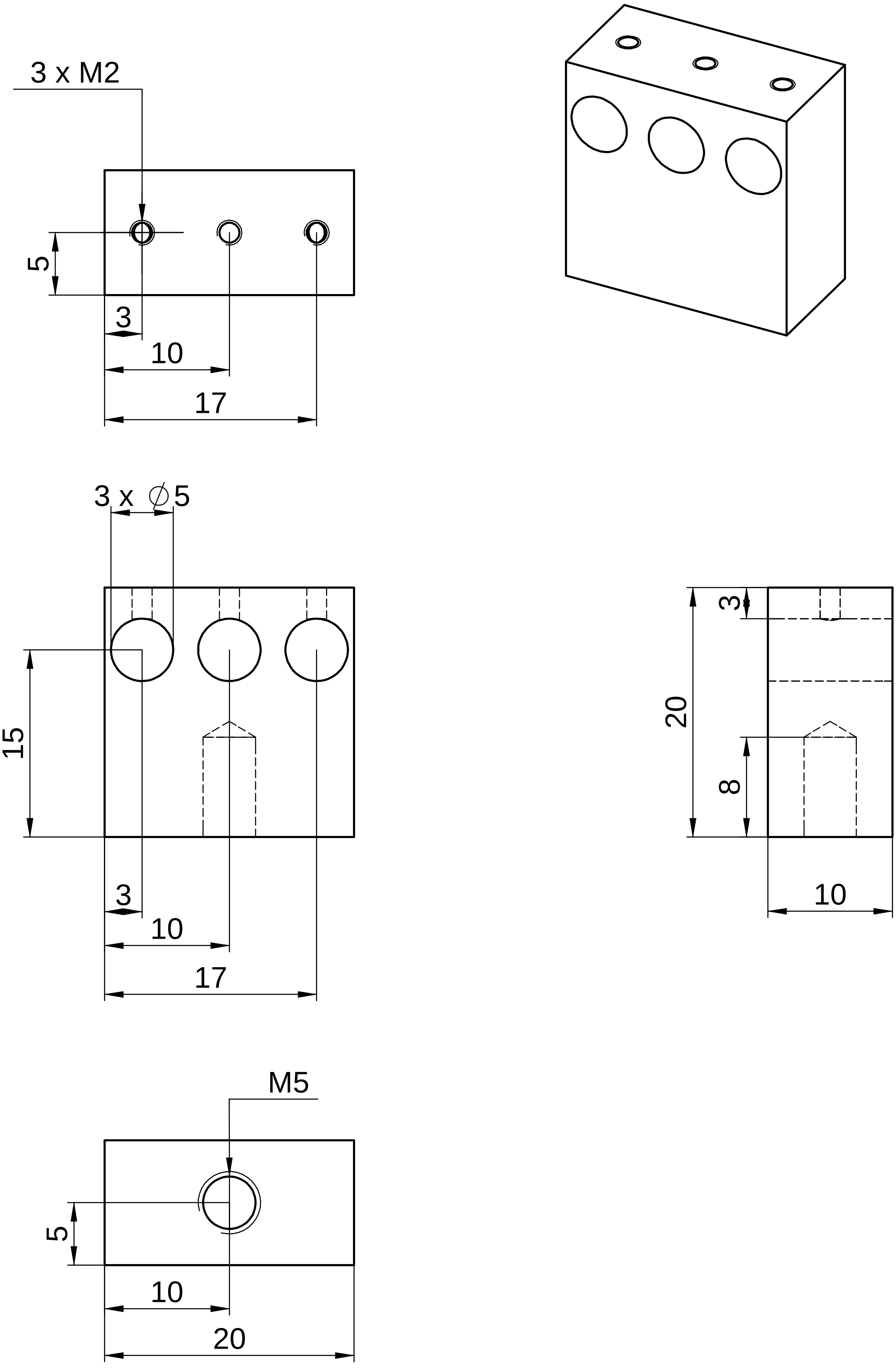
	tolerance: ISO 2768 f	material: SS AISI 304	designed by: MdH			



name	Block1_V2	quantity	1		dimensions mm
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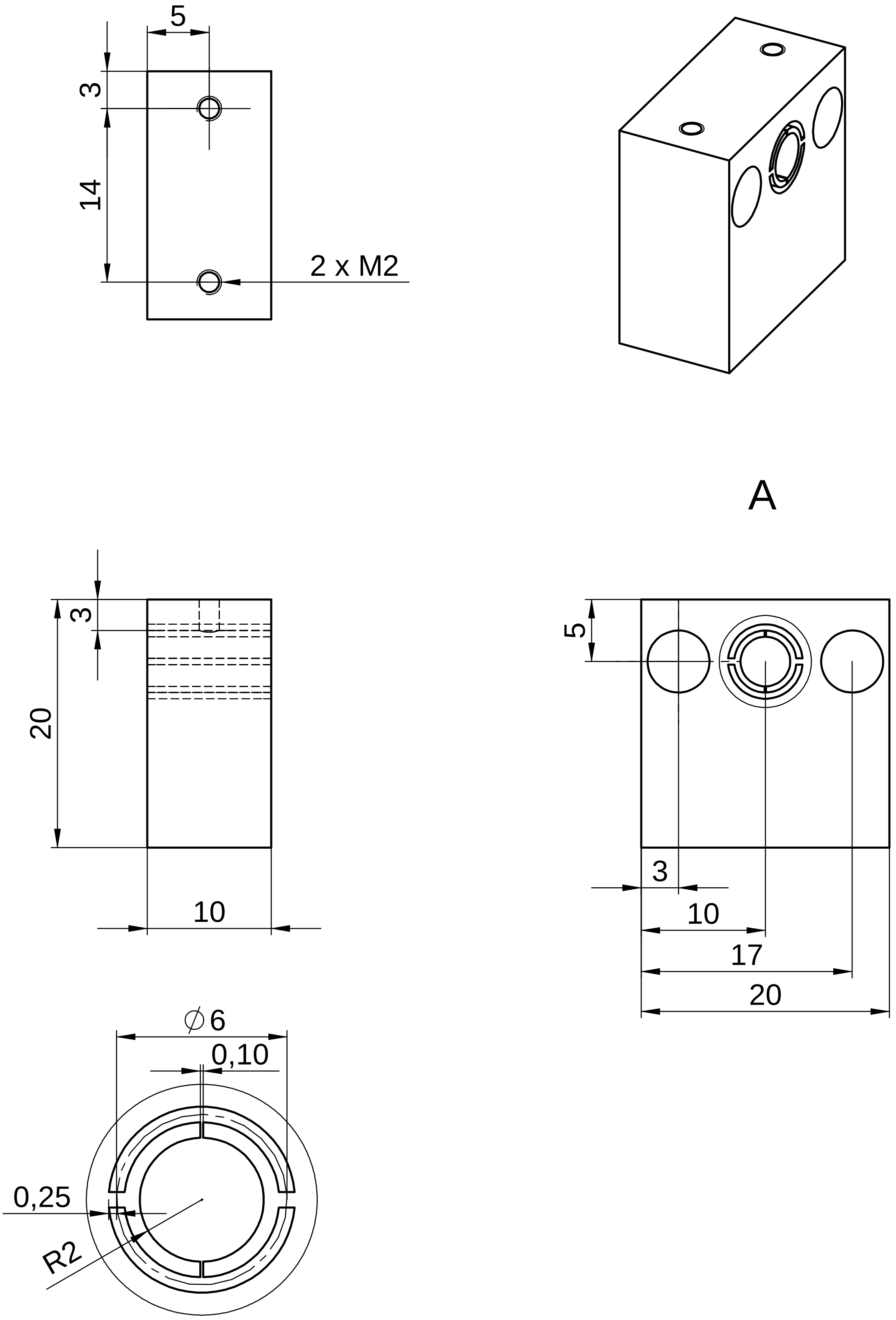
	designed by MdH	tolerance ISO 2768 m	material Al 7075		group MISIT



A (5 : 1)

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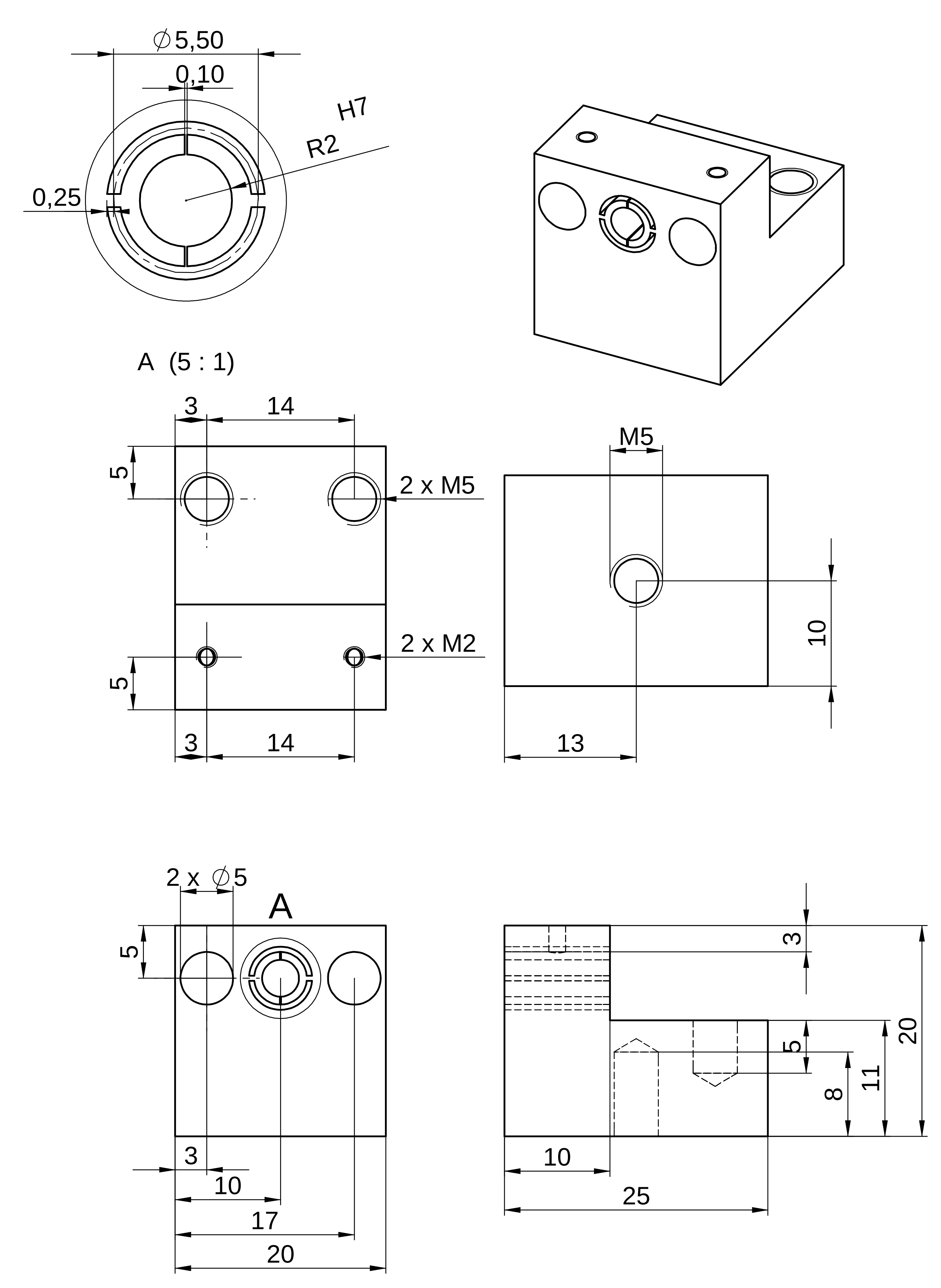

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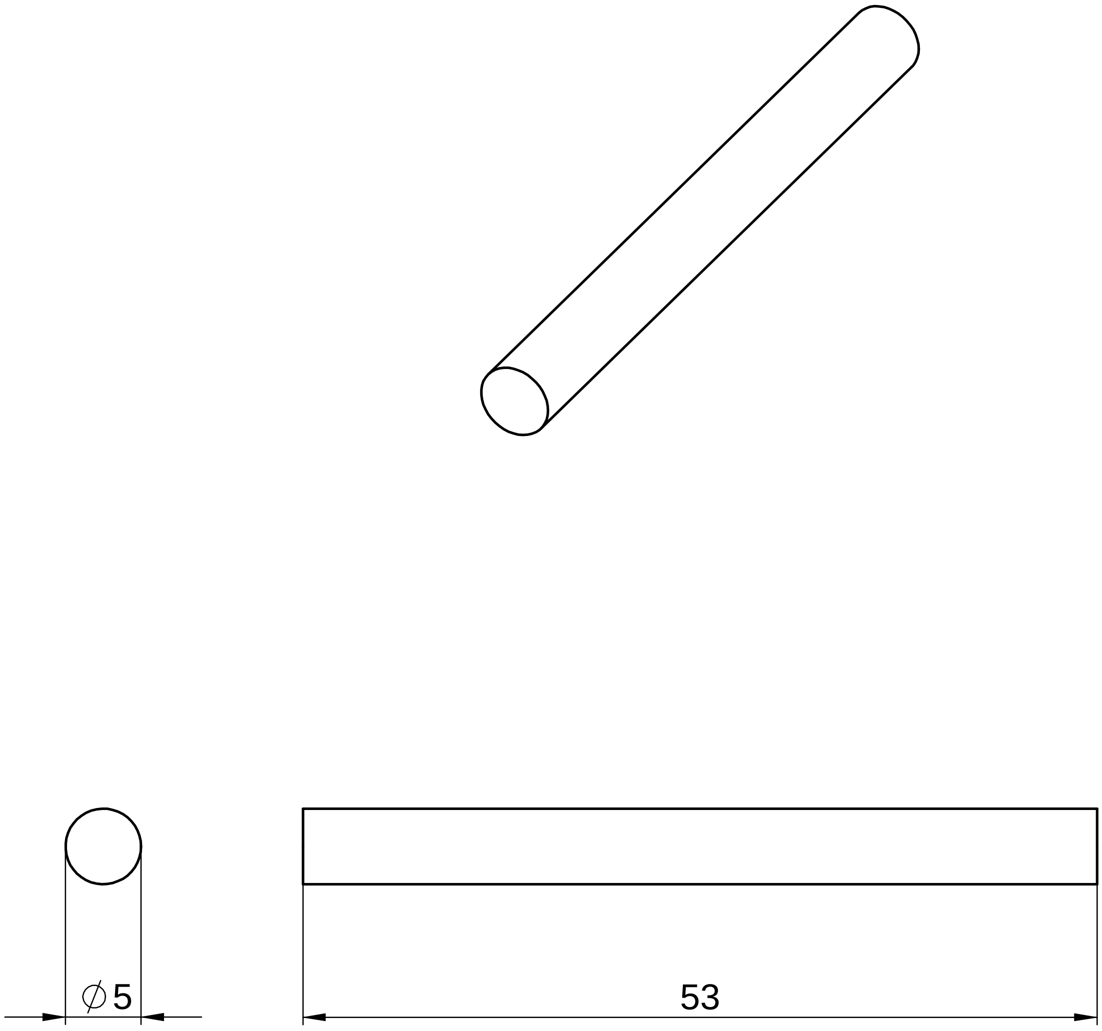

name	Rail_V1	quantity	2	dimensions	mm
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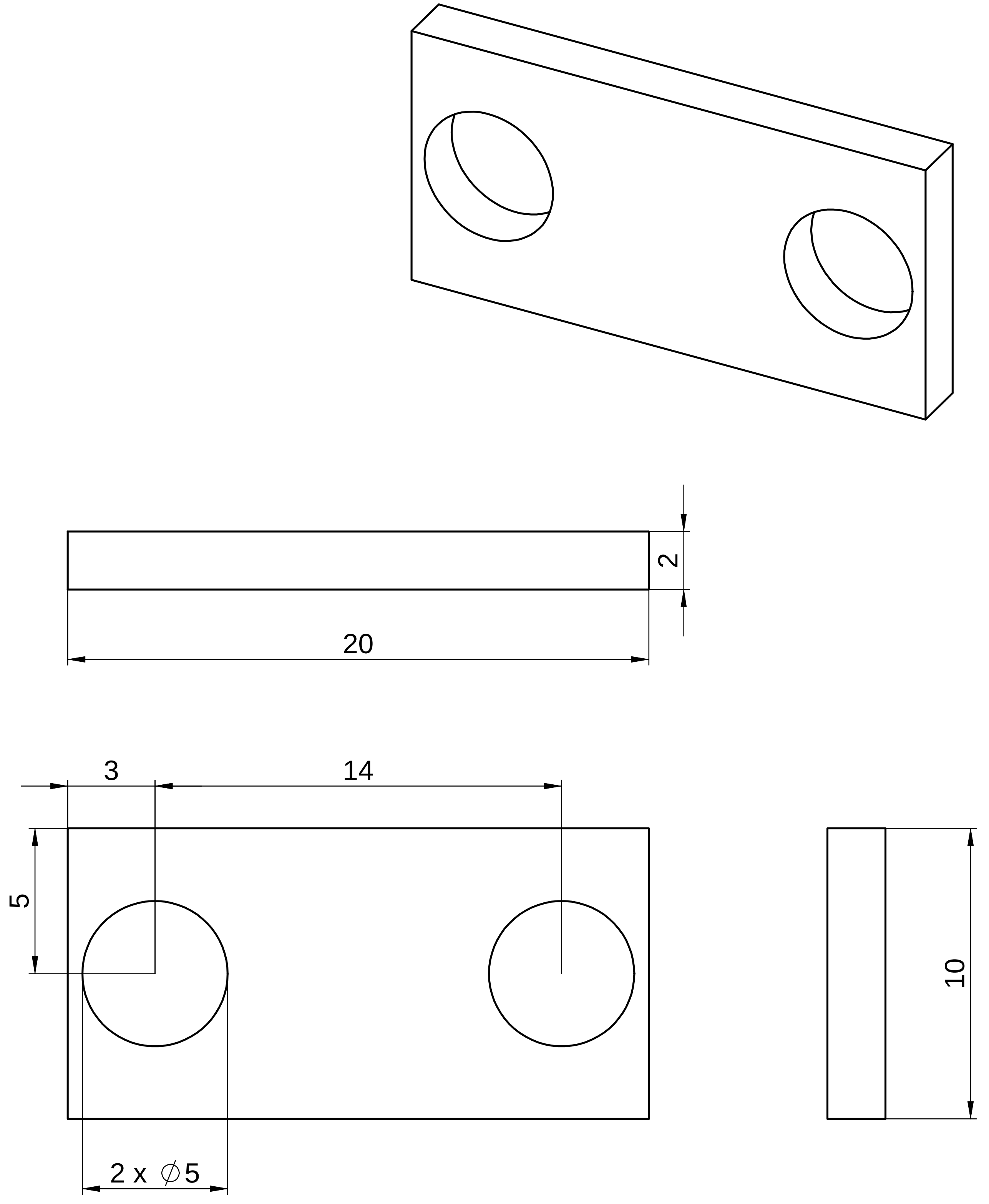

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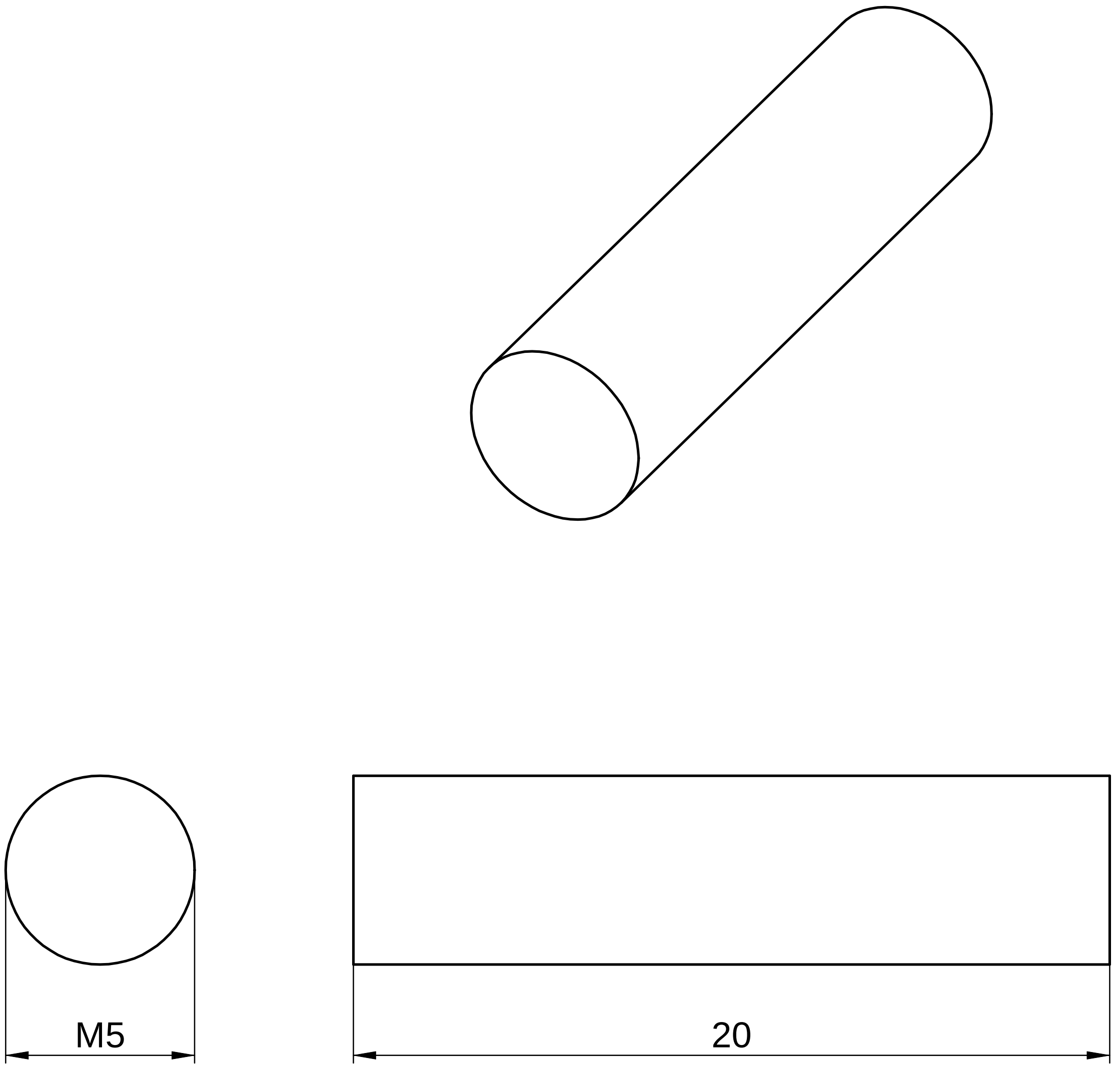

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