Phase switching dynamics for body-powered hand prostheses

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Design of a booster to passively switch between phase dynamics

By

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#4011627

Thesis submitted in partial fulfilment of the requirements for the degree of

Master of Science
in BioMedical Engineering

with specialisation in
Biomechatronics

at the Delft University of Technology,
to be defended on Wednesday September 16, 2020 at 14:30.

Thesis Committee:
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TU Delft

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Introduction

Background

Types of prostheses
There are three main types of prostheses available for below-elbow amputees. Cosmetic prostheses are used for their appearance and are non-functional. Passive prostheses are actuated using external forces and torques, usually provided by the other limb. Active prostheses assist amputees in performing daily activities by allowing users to operate the prosthesis. Currently there are two main control-types for active prostheses: body-powered and externally powered. Body-powered prostheses use bodily motion and forces generated somewhere else on the body to mechanically operate the prosthesis. A Bowden cable is generally used in combination with a harness to actuate the prosthesis either via shoulder or elbow movement (Bajaj et al., 2019). Externally powered prostheses use externally powered actuators to operate the prostheses. They use either electric motors, pneumatic or hydraulic systems (Bajaj et al., 2019).

Motion and Pinching phase
Hand prostheses used by below-elbow amputees require two phases to assist with daily activities. There is the open and closing motion of the hand (Motion Phase) and the phase when the hand is in contact with an object, and the fingers apply a pinching force (Pinching Phase). The motion phase allows people to quickly grasp objects and the pinching phase allows them to apply a pinching force to pick up, push, or pull the object. Each phase requires a different set of dynamics to properly function. In the Motion Phase a small amount of applied force must cause a large translation of the fingers and in the Pinching Phase a small amount of force must result in a large pinching force and a small translation.

Problem statement

Body-powered prostheses can provide fast motion, but a high pinching force is also required to effectively use the protheses for daily activities. Body-powered prostheses are fast during the motion phase but lack the desired pinching force of 30 N (Smit et al., 2015, Hichert, 2017) required for daily activities and have a high operating force of 33-130N to achieve a pinching force of 15 N (Hichert, 2017).

The problem is that body-powered prostheses can achieve motion phase dynamics, but lacks the dynamics required for the pinching phase.

Objective

Design a mechanism that passively switches between the dynamics of the motion phase and pinching phase for body-powered active closing hook prostheses.

The passive switching must be initiated by the force feedback created by the pinching force. In the motion phase a small force input must result in a large output translation and in the pinching phase a small force input must result in a larger force output and a small output translation.

List of symbols

Symbol	Name	Unit	Unit symbol
F	Force	Newton	N
A	Surface area	Square meter	m^2
P	Pressure	Pascal	Pa
l	Length	Meter	m
c	Spring constant	Newton per meter	N/m
s	Travel distance	Meter	m
V	Volume	Cubic meter	m^3
r	Moment arm	Meter	m

Outline

This thesis consists of two chapters. Chapter I is a scientific paper which concludes the most important results of the thesis. Chapter II consists of Appendices A to F. The appendices cover the different stages of the design process. Appendix A presents the initial design aspects of the design requirements, the different concepts, and their evaluation to choose a final concept. Appendix B presents the basic calculations used for the dimensioning of the design. Appendix C presents the manufacturing of the prototype, the manufacturing of the measurement setup and the performance of the prototype. Appendix D discusses necessary improvements to apply to future designs. Appendix E is the MATLAB script used for dimensioning the design. Appendix F are the SolidWorks drawings of the design.

I. Scientific Paper

Phase switching dynamics for body-powered hand prostheses

Randy R. de Jong

Abstract – **Body-powered prosthetic hands used by below-elbow amputees function in two phases. There is the opening and closing motion of the hand (Motion Phase) and the phase when the hand is in contact with an object, and the fingers apply a pinching force (Pinching Phase). Each phase requires a different set of dynamics to properly function. In the Motion Phase, a small amount of applied force must result in a large translation of the fingers, in the Pinching Phase a small amount of force must result in a large pinching force and a small translation.**
The problem is that body-powered prostheses have fast motion given a low force input during the motion phase but cannot achieve a high pinching force with a low force input during the pinching phase.
The goal of the project is to design a mechanism that passively switches between the dynamics of the motion phase and pinching phase for body-powered active closing hook prostheses. In the motion phase a small force input must result in a large output translation and in the pinching phase a small force input must result in a larger force output and a small output translation. In the motion phase a minimum cable force of 10 N is required and in the pinching phase a pinching force of 30 N must be achieved with an input force of 40 N or less
The prototype consists of a hydraulic telemanipulation system with a master (shoulder), operated by the shoulder harness, and slave (hand), operates the hand prosthesis, cylinder connected to each other via a booster mechanism. The booster is inactive in the motion phase and active in the pinching phase.
The results show that in the motion phase an input force of 5 N can perform the full translation of the prosthesis. If the hand is met with resistance the input 5 N input can increase up to 24 N until the pinching phase activates. The translation in the pinching phase is too small to observe any change. The pinching phase activates at a pinching force of 12 N and an input force of 24 N. In the pinching phase the pinching force reaches 35 N with an input force of 32 N input force. The dynamics of the phases show to be unaffected by different object stiffnesses and lowering the activation force of the pinching phase only shifts the pinching phase along the motion phase.
In conclusion the 5 N minimum input force is too low. An input force below 10 N result in inferior control for the user. In the pinching phase an input force of 32 N can reach a pinching force of 35 N, which meets the set requirements of 30 N pinching force with an input force of 40 N or less. A larger translation is required in the pinching phase to compare the translation dynamics between the motion and pinching phase. More research is required to properly define the desired activation force, how much translation is required in the pinching phase, and to find optimal spring properties for the return springs in the hydraulic cylinders.

Introduction

Below-elbow amputees have several options when it comes to choosing prostheses. There are cosmetic prostheses which are used for cosmetic purposes only and are non-functional. There are passive prostheses which are actuated using external forces and torques, usually provided by the other limb. Finally, there are active prostheses (Bajaj et al., 2019). Active prostheses assist amputees in performing daily activities by allowing users to operate the prosthesis.

Hand prostheses used by below-elbow amputees require two phases to assist with daily activities. There is the open and closing motion of the hand (Motion Phase) and the phase when the hand is in contact with an object, and the fingers apply a pinching force (Pinching Phase). The motion phase allows people to quickly grasp objects and the pinching phase allows them to apply a pinching force to pick up, push, or pull the object. Each phase requires a different set of dynamics to properly function. In the Motion Phase a small amount of applied force must cause a large translation of the fingers and in the Pinching Phase a small amount of force must result in a large pinching force and a small translation. Currently there are two main control-types for active prostheses: body-powered and externally powered.

Body-powered prosthetics

Body-powered prostheses use bodily motion and forces generated somewhere else on the body to mechanically operate the prosthesis. A Bowden cable is generally used in combination with a harness (Figure 1) to actuate the prosthesis either via shoulder or elbow movement (Bajaj et al., 2019). The use of body motion to operate the prosthesis allows proprioceptive senses to control the prosthesis with a high operating speed because the reaction forces are perceived via the mechanical linkage. There are two types of terminal devices for body-powered prostheses: hooks and hands. Advantages that body-powered hooks have over hands are low weight and hooks allow for good visibility of the objects. (Biddis and Chau, 2007)

The disadvantages of body-powered prostheses are that the harness is uncomfortable, abrasion of clothes, the socket smells due to respiration, high wear temperature, unattractive appearance and have a low pinching force with high energy expenditure (Kruit and Cool, 1989, Biddiss and Chau, 2007). Disadvantages specific for body-powered hands are difficult to clean and perform maintenance, hands are heavier compared to hooks (Biddis and Chau, 2007).

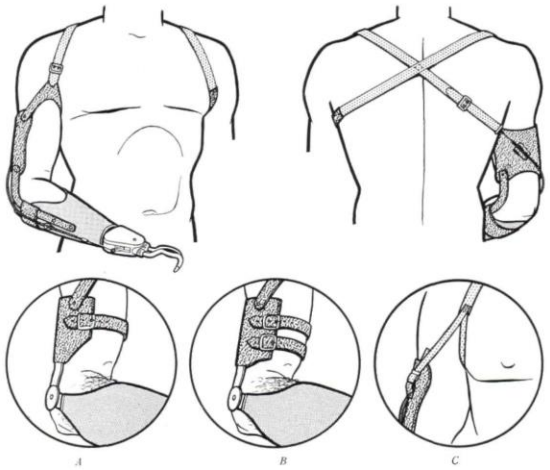

Figure 1: Example of upper extremity prosthetic harness. Copied from Pursley (1955).

Externally powered prosthetics

Externally powered prostheses use externally powered actuators to operate the prostheses. They use either electric motors, pneumatic or hydraulic systems (Bajaj et al., 2019). The actuators allow for the prosthesis to acquire higher pinching forces. The motors allow for feedback by vibrations and motor noise. External powered prostheses have an advantage in appearance compared to body-powered prostheses, lack the uncomfortable harness and there is less muscle fatigue due to EMG control (Biddis and Chau, 2007).

However, actuators also have a set operating speed making them slow compared to body-powered prostheses. The actuators make the prosthesis very heavy and more complex mechanisms require more maintenance and have a higher cost (Biddis and Chau, 2007).

When comparing the achievable pinching force and control methods of body-powered and external powered prosthesis. Proprioceptive feedback gives body-powered prostheses more pinch control and more control over the operating speed. While externally powered prostheses allow for higher pinching force and less muscle fatigue.

Problem definition

Externally powered and body-powered prostheses are both capable of providing either high pinching force or fast motion respectively and both are required to effectively use the protheses for daily activities. Body-powered prostheses are fast during the motion phase but lack the desired pinching force of 30 N (Smit et al., 2015, Hichert, 2017) required for daily activities and have a high operating force of 33-130N to achieve a pinching force of 15 N (Hichert, 2017). Externally powered prostheses can reach a pinching force of 30N, but they are slow in the motion phase and are very heavy due to motor components and a battery (Wright et al., 1995, Stein and Walley, 1983).

The problem is that body-powered prostheses have fast motion given a low force input in the motion phase but cannot achieve a high pinching force with a low force input in the pinching phase. This can be solved by implementing a mechanism that provides shifting between the dynamics of the motion and pinching phases. This will provide low operating force during motion phase and more precision movements and a higher pinching force in the pinching phase.

The goal of the project is to design a mechanism that passively switches between the dynamics of the motion phase and pinching phase for body-powered active closing hook prostheses. The passive switching must be initiated by the force feedback created by the pinching force. In the motion phase a small force input must result in a large output translation and in the pinching phase a small force input must result in a larger force output and a small output translation.

Methods

A design is developed based on design criteria. A prototype of the design is used to validate the design by measuring the performance of the motion and pinching phase. The performance is evaluated based on the goal and the design criteria.

The design requirements are categorised using the 3 C's: Cosmesis, comfort and controllability (Kruit and Kool, 1989). Cosmesis includes the requirements affecting the appearance. The size of the design can influence the appearance. A smaller design can be hidden to make the prosthesis look natural. Comfort includes the requirements that enable the user to comfortably operate the prosthesis. The amount of cable force required to operate the design must be within a comfortable range for the user to prevent muscle fatigue. The weight must be low because the prosthesis is worn for long periods of time. Controllability includes requirements that define the control of the prosthesis. The cable force defines the desired forces for each control phase. Force-Translation defines the desired relation between the force input and the translation for each phase. The pinching force must allow the user to control an object. A universal design allows different prostheses to be controlled.

Cable force (Comfort and Controllability)
Minimum cable force required for operation is 10 N because lower forces result in inferior control (Hichert, 2017). During motion phase the aim for the cable force is 20 N and during pinching phase a force of 40 N at 30 N pinching force (Hichert, 2017). The activation of the pinching phase will be at 5 N applied pinching force.

Force-Translation (Control)
In the motion phase, low force input must result in a large translation. Whereas in the pinching phase a high force input must result in a small translation.

Weight (Comfort)
The aim for the design is to have a maximum weight of 50 g at the wrist.

Size (Cosmesis)
The design must be as small as possible to prevent inconvenience during movement when wearing the design and to make the design less visible.

Prosthetic type (controllability)
The design will be implemented in an TRS active closing hook prosthesis but aims to be universally applicable to active closing body-powered prostheses.

Pinching force (Controllability)
Pinching force required for daily activities is 30 N (Hichert, 2017, Smit et al., 2012, Smit et al., 2015).

Design principle
The concept is based on a bicycle brake booster designed by Van Frankenhuyzen (2007). It utilizes a hydraulic booster mechanism which is placed between the master and slave cylinder. The master cylinder is actuated by the brake handle, which in turn actuates the slave cylinder. The slave cylinder actuates the brake callipers. Once the brake callipers contact the brake disc, the pressure in the system increases. This is caused by the force on the brake handle increasing and the inability of the slave cylinder to translate any further. This increase in pressure activates the booster, which utilizes a piston with different surface areas on each end to increase the hydraulic pressure in two separate chambers of the booster.

The design consists of a master (shoulder) cylinder, actuated by the shoulder harness, and slave (hand) cylinder, actuates the hand prosthesis, connected to each other via a booster mechanism (Figure 2). The booster consists of two chambers. Chamber 1 is connected to chamber 2 via a piston. The shoulder cylinder is connected to both chamber 1 and chamber 2. Chamber 2 connects to the hand cylinder. The springs in the cylinders are used to return the pistons to their initial positions.

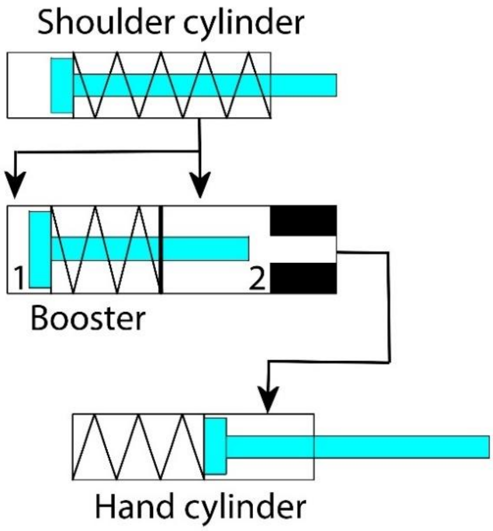

Figure 2: Lay-out of the cylinders and the booster. The shoulder cylinder connects to both the booster chambers. Booster chamber 1 connects to booster chamber 2 via a piston. Booster chamber 2 connects to the hand cylinder. The springs in the shoulder and hand cylinder return the pistons to their initial positions. The spring in the booster has a preload to prevent movement in the motion phase and returns the piston to its initial position.

In the motion phase, the booster is inactive and does not affect the system dynamics. The hand cylinder is controlled by the shoulder cylinder via chamber 2 (Figure 3), while the preload of the spring in chamber 1 prevents the fluid from entering chamber 1 (Figure 2). The fluid flows from the shoulder cylinder into chamber 2 and exists the booster via output D (Figure 5 (2)). The phase switching is set to an input force of 23 N, which corresponds with a pinching force of 5 N at the end of the hook. The pressure in the system is increased by the pinching force preventing motion of the hand cylinder while the user keeps applying additional force to the system via the shoulder cylinder. The rise in pressure creates a force on both side of the piston in the booster, because the pressure is the same the larger surface in chamber 1 has more force applied to it (Figure 4). Once the force in chamber 1 exceeds the spring force and the force in chamber 2, the piston is pushed from chamber 1 into chamber 2 blocking off the connection between the shoulder cylinder and chamber 2 (Figure 5 (3)). In the pinching phase the piston in the booster blocks the connection between the shoulder cylinder and booster chamber 2 (Figure 5 (3)). In this phase the hand cylinder is controlled by the shoulder cylinder via the piston in the booster (Figure 3).

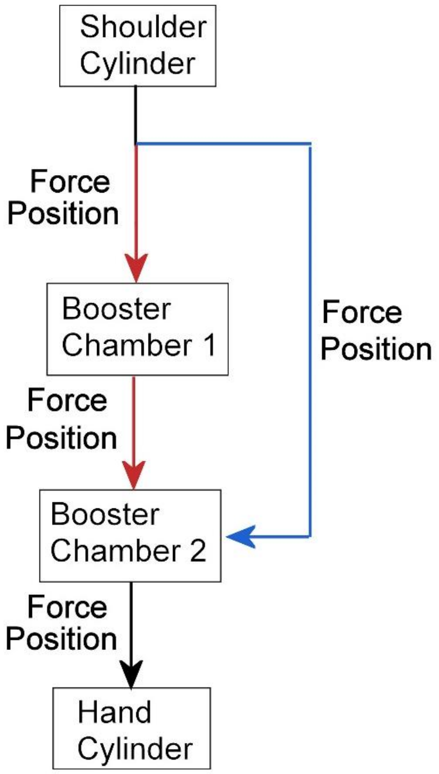

Figure 3: Hydraulic block scheme of design. The system transfers both position and force. The blue lines show the motion phase, the red lines show the pinching phase and the black lines are for both phases.

The booster increases the pinching force by increasing the pressure between chamber 1 and chamber 2. The pressure in chamber 1 works on area $A_{chamber1}$ (Figure 4) which transfers a force to chamber 2. This force creates the pressure in chamber 2 using area $A_{chamber2}$ (Figure 4, equations 1-3). The ratio between $A_{chamber1}$ and $A_{chamber2}$ creates an increase in pressure between the chambers. Chamber 2 connects to the hand cylinder (Figure 5 (3)) meaning the increase in pressure creates an increase in pinching force created by the hand cylinder. The booster also reduces the output translation (Figure 4). The translation of the piston in chamber 1 requires a larger volume than the volume that is displaced by the piston in chamber 2, because of the smaller surface area in chamber 2 (equation 4).

The input force required to operate the system in the motion phase is set to 16 N. The phase switching is set to an input force of 23 N, which corresponds with a pinching force of 5 N at the end of the hook. In the pinching phase the booster is set to amplify the input force to achieve a pinching force of 30 N with an input force of 40 N.

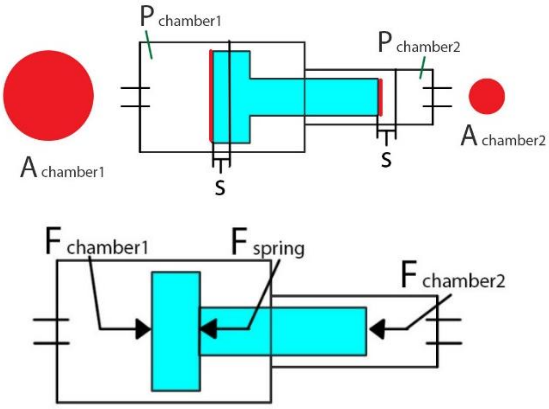

Figure 4: The booster schematic. A) Shows the pressures, surfaces, and translation. B) Shows the forces created by the pressures and surfaces.

$$F_{chamber1} - F_{spring} = F_{chamber2} \quad (1)$$

$$P_{chamber1} * A_{chamber1} - F_{spring} = P_{Chamber2} * A_{chamber2} \quad (2)$$

$$P_{chamber2} = P_{chamber1} * \frac{A_{chamber1}}{A_{chamber2}} - \frac{F_{spring}}{A_{chamber2}} \quad (3)$$

$$s * A_{chamber1} > s * A_{chamber2}$$
$$\Delta V_{chamber1} > \Delta V_{chamber}2 \quad (4)$$

Prototype

The prototype is produced with the intent to make the components with high risk of failure more accessible for troubleshooting and to allow the preloads of the springs to be changed. The booster is partially built out of screw components**.** This allows the booster to be taken apart and analyse what component causes the leakage.

Air pressure is used to substitute the preloads created by the springs (Figure 5 (1)). This way the preloads can be changed by changing the pressure level while keeping the functionality of returning the system to its initial state when the external forces are removed.

Measurements

The input force, output translation and output force (pinching force) are measured during the motion and pinching phase. The relation between the input force and output force (FF relation) and the relation between the input force and output translation (FT relation) are used to evaluate the change in dynamics between the motion and pinching phase and to compare the performance with the design requirements.

Two different test setups are used (Figure 6). The measurements are performed by attaching the shoulder cylinder to a custom-built test bench (Figure 7) (Smit and Plettenburg, 2010). This custom setup is actuated by manually turning a spindle, which creates a translational motion to actuate the shoulder cylinder.

The first setup measures the FF relation. The second setup measures the FT relation. Objects of a different stiffness are simulated using three springs with stiffnesses of 4,26 N/mm, 5.76 N/mm, 8.75 N/mm, and the final situation is a solid object. The stiffnesses of the springs are measured using the test bench. During the measurements, the preload of the booster is set to 9.5 bar and a preload of 2 bar to act as the return spring in the hand cylinder both pressures are supplied by two separate CO2 cylinders. The 2 bar is provided by a CO2 cylinder from SodaStream and the 9.5 bar is provided by a 10 L/7.5 kg CO2 cylinder from Hoekloos in Schiedam refilled with carbon dioxide 2.7.

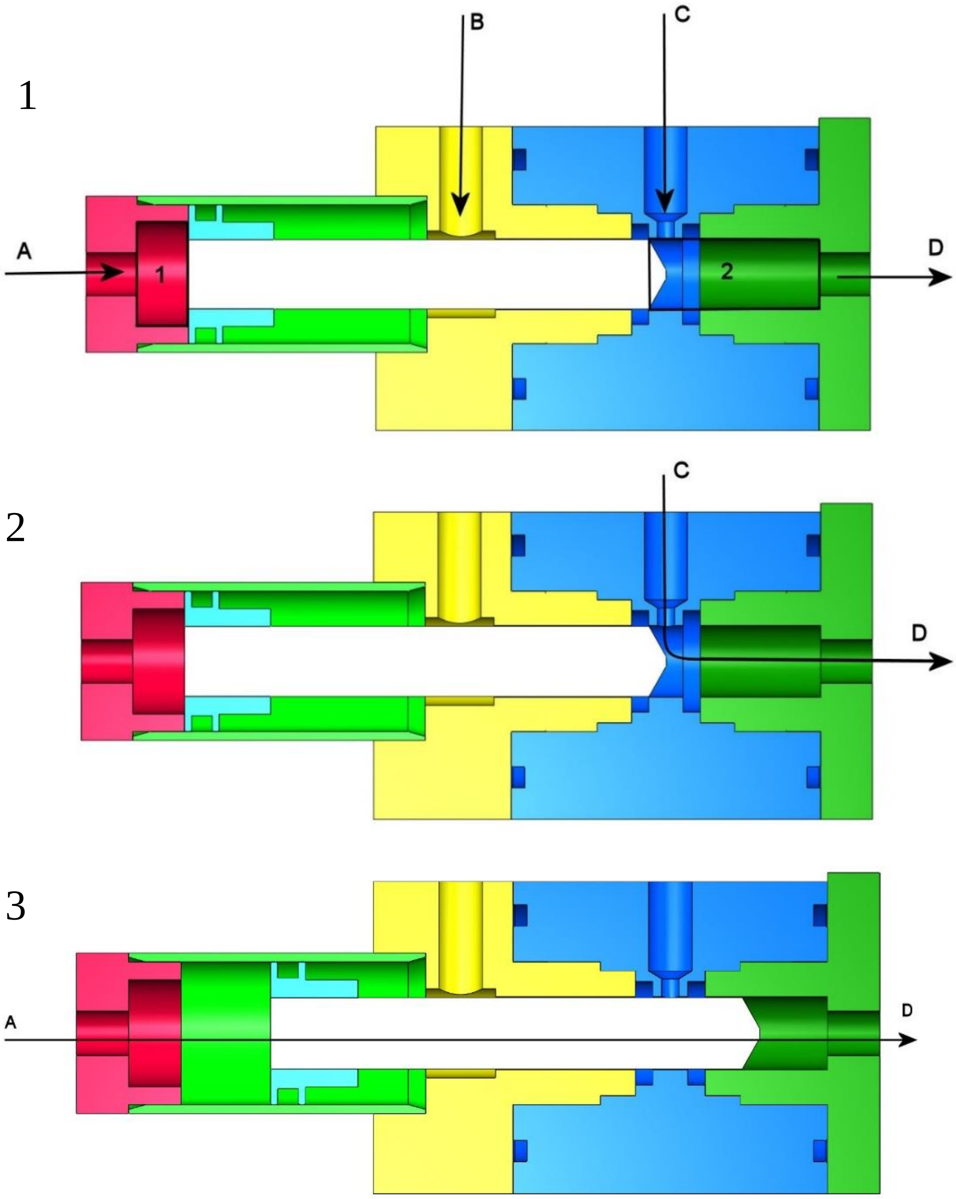

Figure 5: 1) The booster with all inputs, outputs and chambers highlighted. Input A and C are connected to the shoulder cylinder via a T-junction (Figure 2 and Figure 3). Input B is connected to regulated air pressure of 9.5 bar which provides a preload of 34 N instead of a spring. Output D is connected to the hand cylinder. 2) In the motion phase the fluid flows from input C directly out of output D. 3) In the pinching phase input C is blocked off by the piston. The fluid flows via input A into chamber 1 and applying pressure on the piston. The piston transfers this pressure to chamber 2 and out of output D.

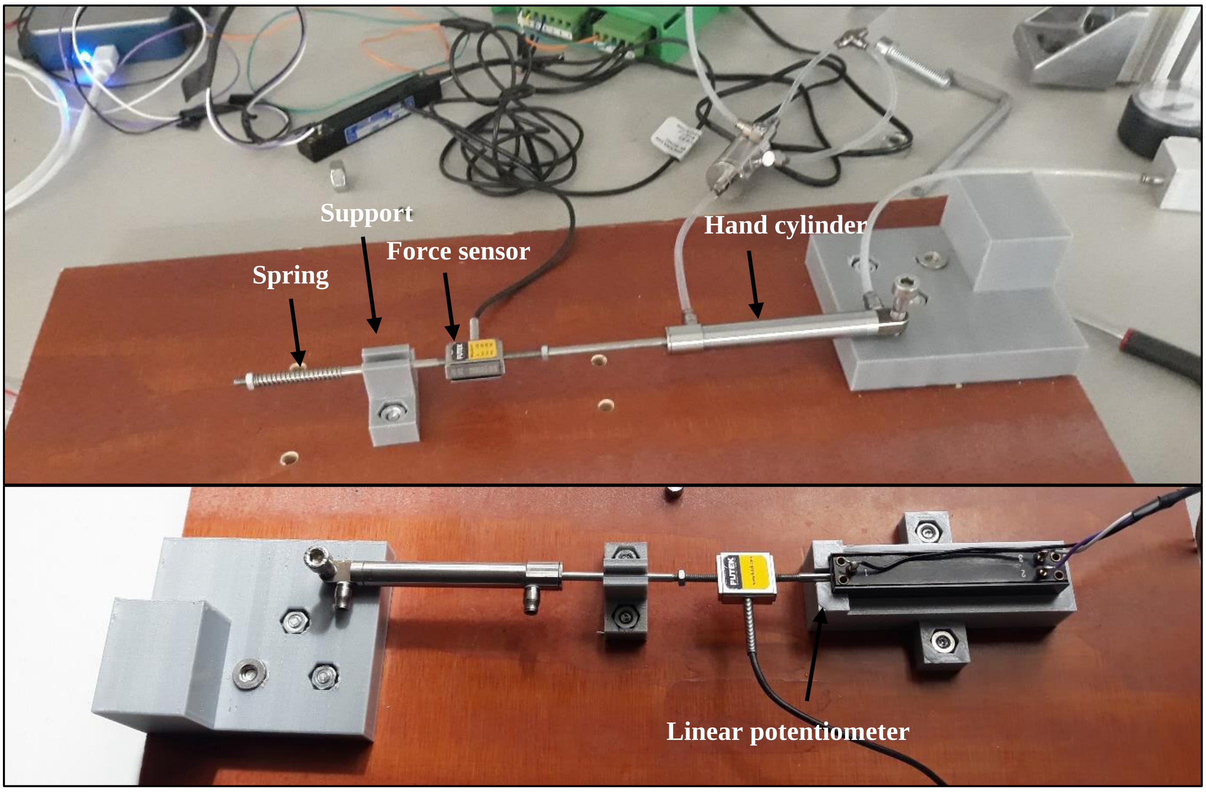

Figure 6: Test setups. On the top the test setup used to measure the output force. The hand cylinder retracts when actuated. The hand cylinder is directly attached to the force sensor. For the measurement without a spring the rod with the spring is replaced with a ck m3x35 screw to assure the screw head contacts the support. On the bottom is the test setup to measure the output translation. The linear potentiometer measures the displacement of the retracting hand cylinder. The force sensor is used as a connection piece and performs no measurement in this setup. The support between the force sensor and the hand cylinder is removed for measurements with springs and the springs are placed around the piston of the hand cylinder.

The preload of the booster is set to two different pressures, 4.5 bar and 9.5 bar, to analyse how the system reacts when the booster activates while an object is not fully compressed and how a lower preload affects the deactivation from pinching phase to motion phase. The different pressures in chamber 2 and input C (Figure 5) will collide during deactivation and this might result in a uncomfortable jerk motion. This measurement is done only with the 8.75 N/mm spring, because the stiffest spring has the highest probability of achieving this effect. All measurements are done up to an input force as high as achievable by the test-bench up to a maximum of 40 N. The input force of

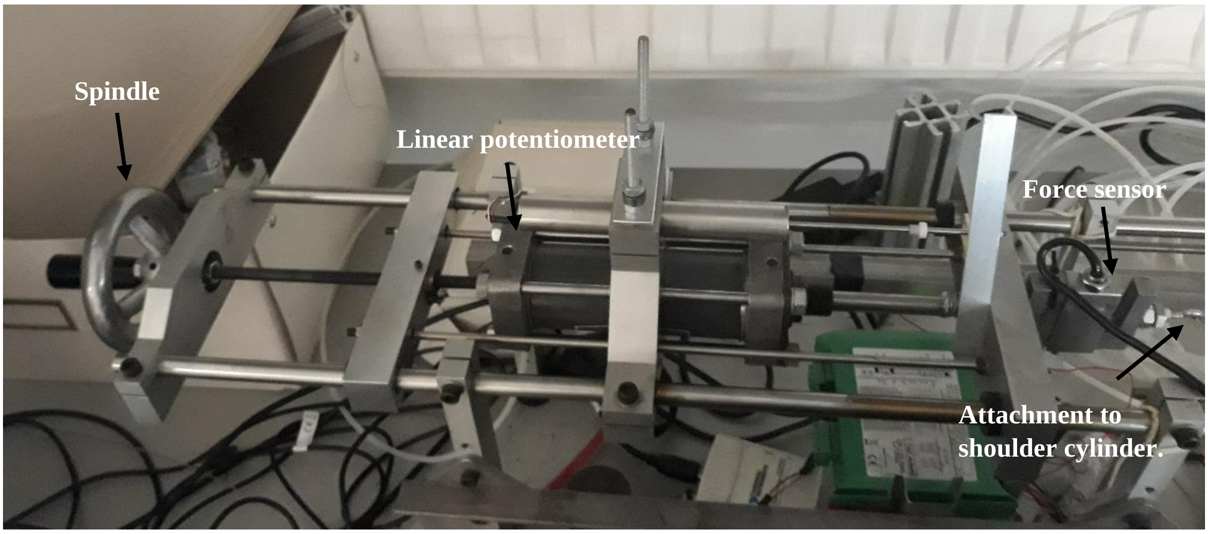

Figure 7: Custom-built test bench including the operating spindle, linear potentiometer, and S-beam force sensor. The test bench is used to measure the input force. The shoulder cylinder is attached to a hook on the force sensor via a cable.

40 N was not achievable for all measurements due to translational limitations of the test bench. The measurements are each repeated three times. After repeating a measurement three times, the hydraulic cables and cylinders were detached and refilled with water to remove air from the system.

The sensors used for the measurements are set up in two separate groups. The first group of sensors is integrated into the test bench and measures the force and translation of the shoulder cylinder (input). The second group of sensors is created separately to measure the force and translation of the hand cylinder (output). Both groups of sensors consist of a linear potentiometer, a force sensor, a signal conditioner, and a USB device to connect the sensors to a laptop. The input force sensor on the test bench is a load cell model B3C-C3-50kg-6B from Zemic and the input linear potentiometer is model LCIT 2000 from Schaevitz. The output force sensor is a 25lbs S-beam load cell from Futek S/N 583662 and the output linear potentiometer is type 13FLP50A from Feteris Components. The force sensors are attached to a Scaime CPJ-CPJ2S analog signal conditioner. The potentiometers and the signal conditioners are attached to a National Instruments low-cost multifunctional DAQ USB device. The sets are each attached to a separate laptop via USB connection of their respective DAQ USB device. One laptop measures the input and the other measures the output. The data is measured using Labview 2013 for the input and Labview 2018 for the output both programs taking samples at an interval of 100 ms. The data is saved in .txt files.

The measured data is analysed using MATLAB R2017a. The data files are imported, the matching input and output data sets for each individual measurement are given matching lengths and plotted. The output forces are divided by 3 to account for the lever of the TRS hook to calculate the pinching force. The manual operation of the test bench and the measurement samples being taken every 100 ms caused every measurement to have a different number of samples. The different sample length for each repeat measurement made it difficult to average them. Plotting the repeat measurements in the same graph showed them to be almost identical. Due to this the three repeat measurements for each stiffness and preload are plotted in the same graph.

Results

Measurements

In the motion phase an input force of 5 N can perform the full translation of the prosthesis (Figure 9D). The different springs show a gradual increase in input force based on the spring stiffness (Figure 9). In the pinching phase the translation is very small (Figure 9). The pinching phase activates with an input force of 24 N, which corresponds with a pinching force of 12 N (Figure 11). The pinching phase reaches its limit at a pinching force of 35 N with an input force of 32 N (Figure 11). In the motion phase the pinching force increases slower compared to the 1:1 relation (Figure 11 at point 1). The pinching force increases faster compared to the 1:1 relation in the pinching phase (Figure 11 at point 2). The different springs do not influence FF relation. The different curves are almost identical (Figure 11). The most noticeable difference is the size of the jump in force during deactivation for the measurement without a spring (Figure 11D at point 5). A lower preload shows no changes in the translation curves (Figure 10), but for the pinching force the lower preload shows a shift of the pinching phase dynamics (Figure 12 at points 2,3,4) along the motion phase dynamics (Figure 12 at points 1,6).

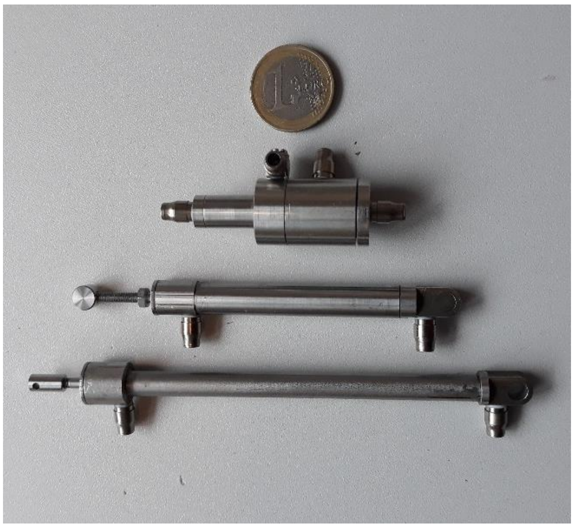

Figure 8: Photo of the prototype with a euro as a scale reference. From top to bottom; the booster, the hand cylinder, and the shoulder cylinder.

Prototype

The prototype is shown in Figure 8**.** The combined weight of the three components is 125 g, the shoulder cylinder is 31 g, the hand cylinder is 27 g and the booster is 67 g. Their lengths are 137 mm retracted and 214 mm when extended for the shoulder cylinder, 106 mm retracted and 143 mm for the hand cylinder, and 65 mm for the booster as shown in Figure 8 including the hydraulic fittings.

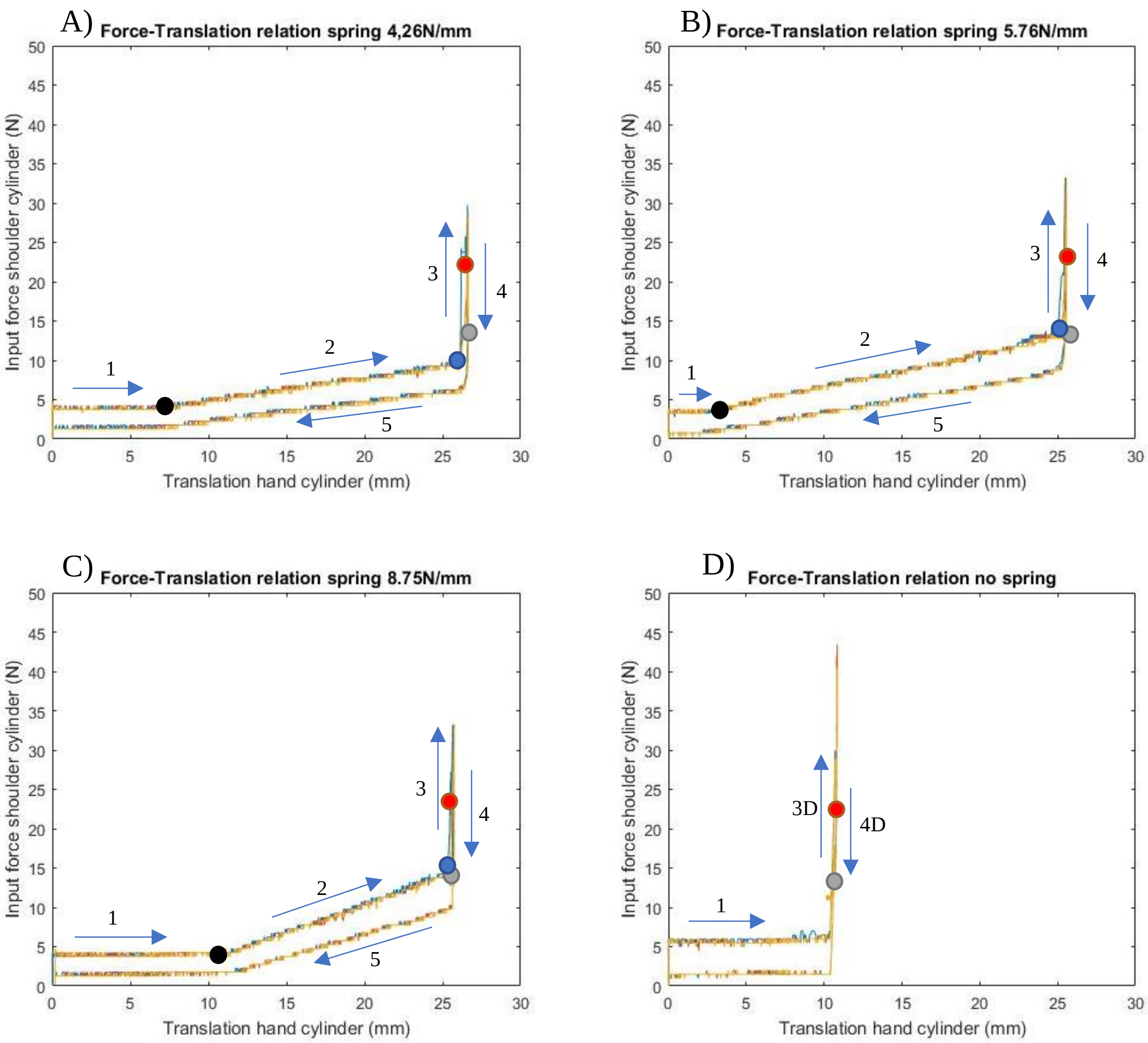

*Figure 9: Input force vs output translation relations with a preload of 9.5 bar for different springs. Explanation based on graph A and D. 1) Initial force input in motion phase (free motion). 2) Force increase during spring compression in motion phase. 3) Force increase with a fully compressed spring. The pinching phase activates at ●. 3D) Force increase while holding a solid object. The pinching phase activates at ●. 4) Force release with a fully compressed spring. The pinching phase deactivates at ●. 4D) Force release while holding a solid object. The pinching phase deactivates at ●. 5) Force release during spring extension in motion phase. ●) Start of spring compression. ●) Fully compressed spring. ●) Motion phase switches to pinching phase. ●) Pinching phase switches to motion phase. The input force for the ● and ● are taken from Figure 11***.**

Discussion

Force-Translation relation

The results of the FT relations (Figure 9) with different stiffnesses show that the free motion in the motion phase (Figure 9 at point 1) requires an input force of 4-5 N. The minor difference in input force during the free motion is presumably caused by a small difference in preload in the hand cylinder. A higher preload requiring a higher input force to initiate the translation. This difference in preload is the result of using an analogue manometer causing a slight pressure difference when reapplying the pressure. The input force of 4-5 N is too low because an input force of below 10 N results in inferior control for the user (Hichert, 2017). The 4-5 N also is less than the predefined 16 N because the absence of the spring stiffness from the return springs. The 16 N is based on the worst-case scenario in which the springs in the shoulder and hand cylinder (Figure 2) are fully compressed. This means that if the shoulder and hand cylinder have springs, the translation of the hand cylinder in the motion phase starts at an input force of 5 N and gradually increases up to 16 N over the distance of 30 mm. The distance of 30 mm is the translation required by the hand cylinder to fully close the hook prosthesis. The spike in input force combined with the small translation (Figure 9 at point 3) make it unclear when the pinching force activates and how the pinching force affects the FT relation.

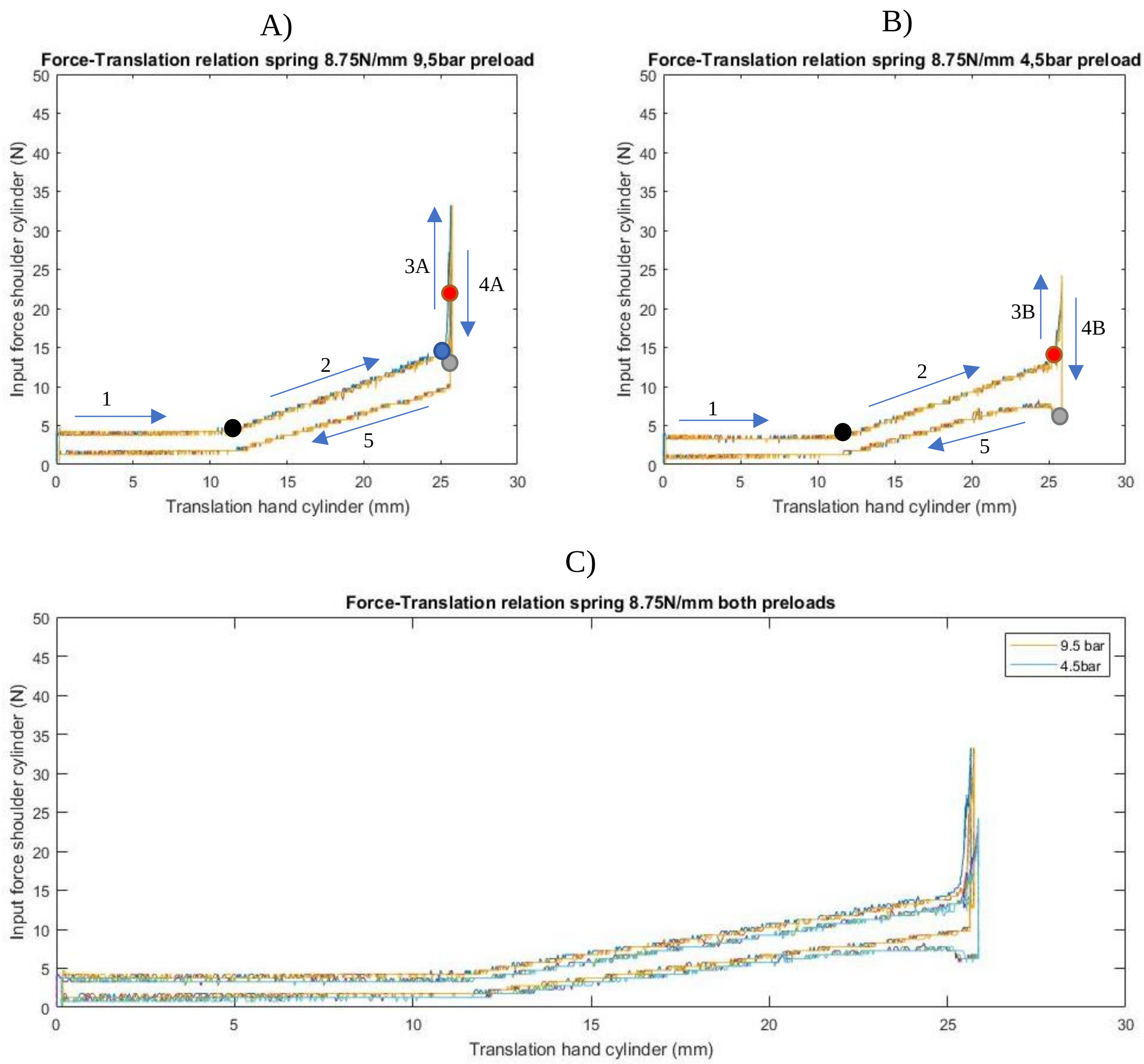

Figure 10: Input force vs output translation relations with an 8.75 N/mm spring and different preloads. Graph A and B show the measurements with different preloads separately and graph C show them in the same graph. Explanation based on graphs A and B. 1) Initial force input in motion phase (free motion). 2) Force increase during spring compression in motion phase. 3A) Force increase with a fully compressed spring. The pinching phase activates at ●. 3B) Force increase in pinching phase. 4A) Force release with a fully compressed spring. The pinching force deactivates at ●. 4B) Force release in pinching phase. 5) Force release during spring extension in motion phase. ●) Start of spring compression. ●) Fully compressed spring. ●) Motion phase switches to pinching phase. ●) Pinching phase switches to motion phase. The input force for the ● and ● are taken from Figure 12. Graph B) It is unclear if the spring fully compressed in the pinching or motion phase because the pinching phase activates close to the full compression of the spring. Graph C) The graphs are almost identical.

The reason being an oversight in the test setup that makes it impossible for the hand cylinder to translate any further once the spring is fully compressed. A solution for future research is using stiffer springs so that the pinching phase activates before the spring is fully compressed. The hand cylinder has a limit of 2 mm translation during the pinching phase. This means that even if the translation were possible, the translation would be too small to assess the FT relation in the pinching phase.

In conclusion free motion in the motion phase requires 5 N input force which is below the 10 N minimum required for appropriate control. In future research a different setup that allows for translation in the pinching phase must be used to measure the FT relation or stiffer springs must be used that activate the pinching phase before being fully compressed. The booster needs to displace more volume in the pinching phase to get a better understanding of the change in FT relation between the motion and pinching phase.

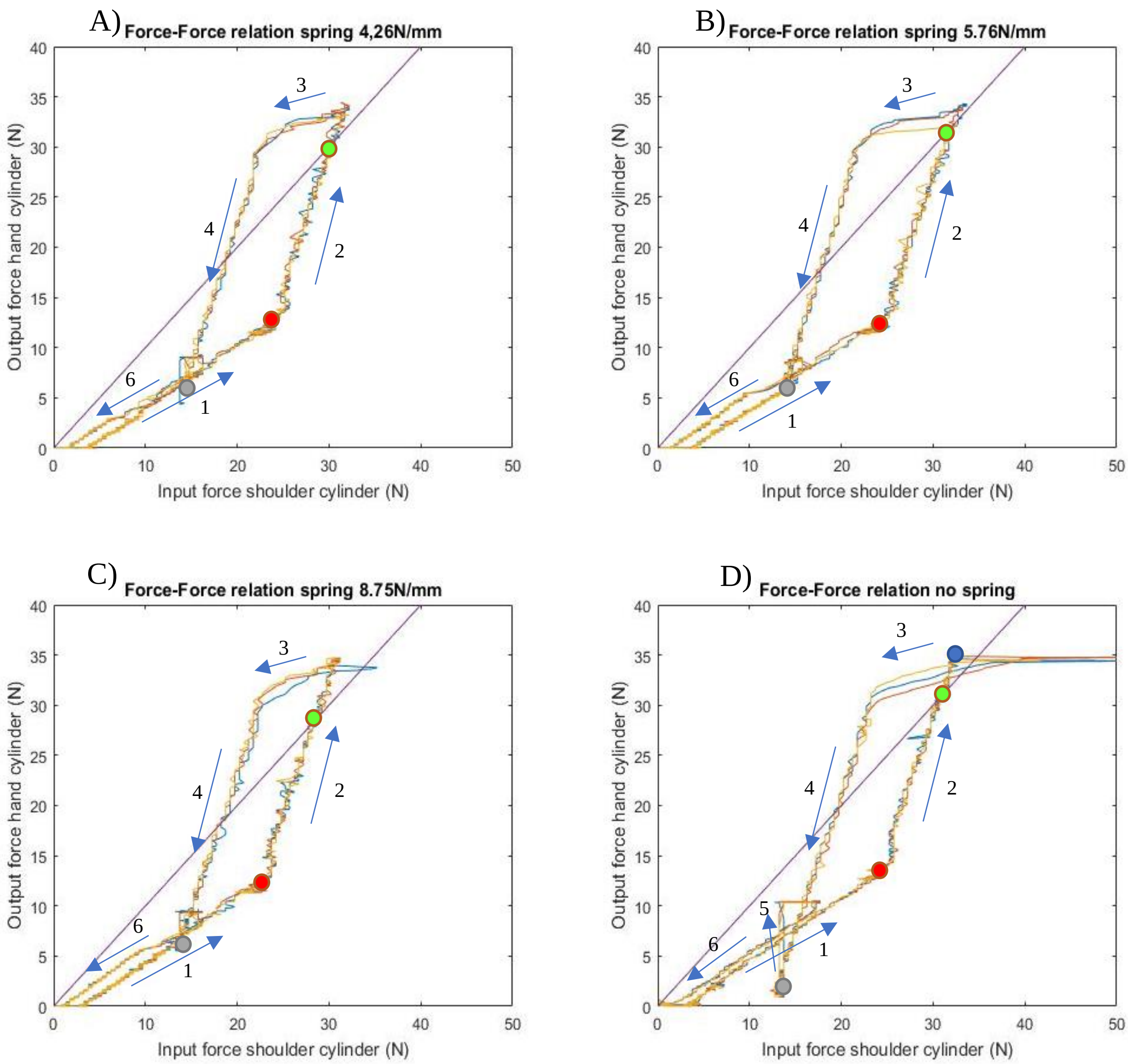

Figure 11: Input force vs output force (Pinching force) relations with a booster preload of 9.5 bar for different springs. The diagonal line shows the 1:1 relation between the input and output force. Explanation based on graph D. 1) Pinching force increase in the motion phase. 2) Pinching force increase in the pinching phase. 3) Release of input force. 4) Release of input force in the pinching phase. 5) deactivation of the booster. 6) Release of input force in the motion phase. ●) Motion phase switches to pinching phase. ●) Pinching phase switches to motion phase. ●) The moment the system crosses the 1:1 relation between the input and output force. ●) The maximum achievable output force. The graphs are overall almost identical. The biggest difference is size of the jump during the deactivation of the booster (5) this occurs in all graphs but is the largest in graph D.

The lower preload of 4.5 bar shows (Figure 10B) that the pinching phase activates close to full compression of the spring. The comparison (Figure 10C) shows that both preloads achieve the same translation, but the preload of 4.5 bar achieves this with a lower input force. In the pinching phase the hand cylinder has a limit of 2 mm translation meaning that if the preload is taken below 4.5 bar the total translation will shorten. The shorter total translation might cause issues with more compliant objects. Further research must be conducted to analyse how much translation is desired in the pinching phase.

In conclusion research is required to analyse how much translation is required in the pinching phase to perform daily activities.

Force-force relation

The results of the FF relations (Figure 11) with different stiffnesses and their repeat measurements are almost identical. This shows that as expected the system functions consistently and that the springs did not affect the pinching force (output force) dynamics. In the motion phase the measurements (Figure 11 at point 1) show a lower increase compared to the 1:1 relation, because in this phase the goal is to achieve translation instead of pinching force. The motion phase switches to the

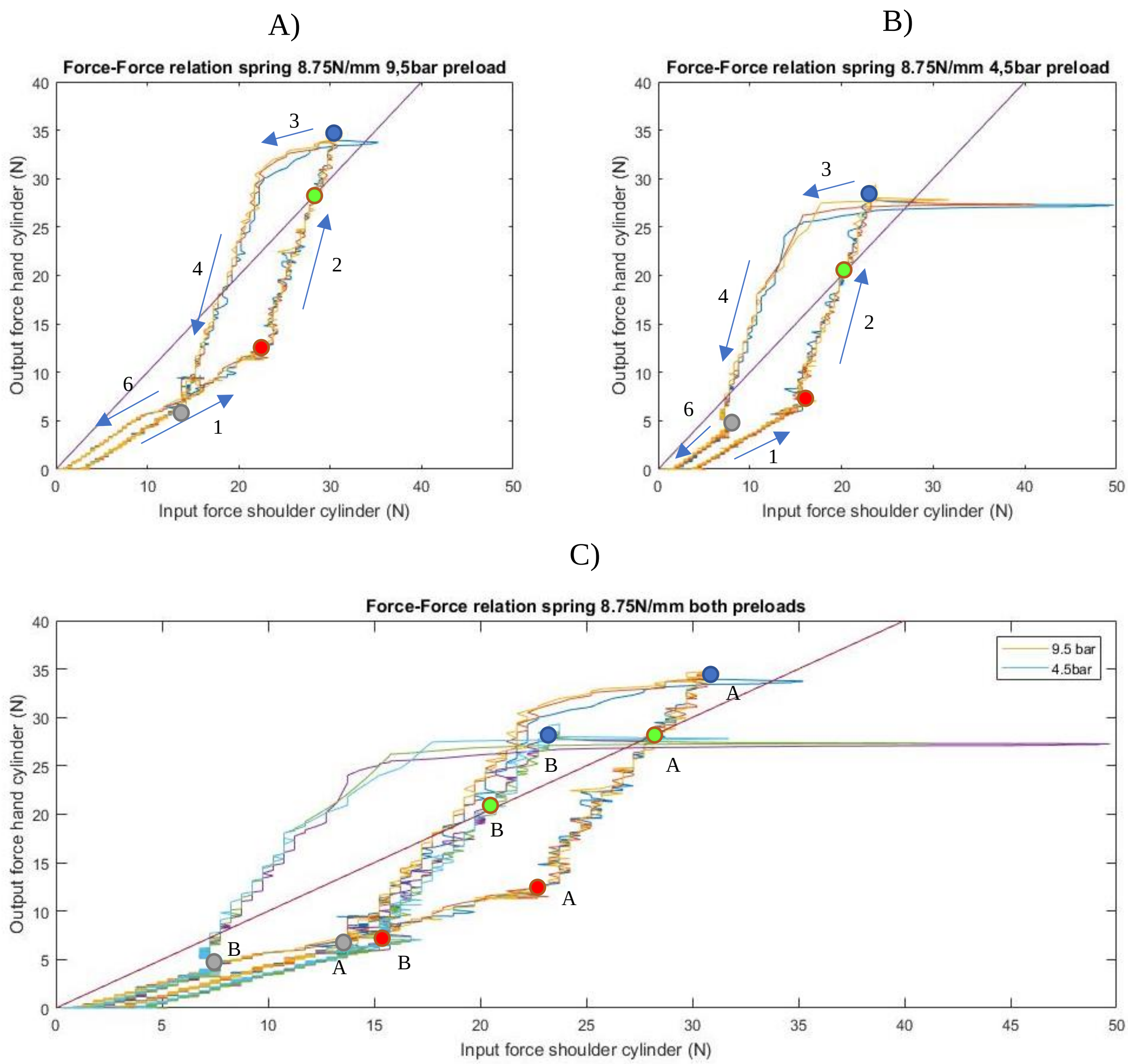

Figure 12: Input force vs output force (Pinching force) relations with an 8.75 N/mm spring with different preloads. The diagonal line shows the 1:1 relation between the input and output force. Graph A and B show the measurements for the different preloads separately and graph C shows them combined. Explanation based on graph A. 1) Pinching force increase in the motion phase. 2) Pinching force increase in the pinching phase. 3) Release of input force. 4) Release of input force in the pinching phase. 6) Release of input force in the motion phase. ( ) Motion phase switches to pinching phase. ( ) Pinching phase switches to motion phase. ( ) The moment the system crosses the 1:1 relation between the input and output force. ( ) The maximum achievable output force. Graph A and B) Comparing the switching from pinching to motion phase ( ) graph A shows a jump in force that is absent in graph B. Graph C) The dots are labelled to indicate their corresponding graph. The different activation points and maximum output forces show that the booster increases the output force by 23 N with a 7,5 N input force increase.

pinching phase (booster activation) at an input force of 24 N and an output force of 12 N (Figure 11). The 24 N is close to the 23 N defined as the input force for the booster activation. The output force of 12 N is higher than the intended activation at 5 N output force. The reason for the higher output force at the booster activation is caused by the lack of spring stiffnesses which were accounted for when defining the activation forces of 5 N. In the pinching phase the measurements (Figure 11 at point 2) show a larger increase compared to the 1:1 relation, because in this phase the goal is to achieve a high pinch force with a low force input. The highest achievable pinching force in the pinching phase is 35 N with an input force of 31 N. The plateau in Figure 11D is the best representation of this. The plateau is a result of the piston in the booster reaching its translational limit causing the input force to increase without increasing the output force. It is important to keep in mind that the prototype does not implement spring stiffnesses meaning that the pinching force will be lower if springs are implemented in the cylinders. Deactivation of the booster (Figure 11D at point 5) creates a jump in force. It is not fully understood what causes this and why the size of the jump is different between the stiffnesses (Figure 11). It is assumed that they are caused by the collision of the different pressures between chamber 2 (Figure 5 (1,3)) and entrance c upon reconnection when the booster deactivates. It is beneficial for future research to investigate if the jump during the deactivation is uncomfortable for the user.

In conclusion the force dynamics in the motion and pinching phase are unaffected by object stiffness. The pinching phase activates at the predefined input force, but not the predefined output force. In the pinching phase the FF relation is better than 1:1 and capable of 35 N pinching force with a 32 N input force. Further research must investigate if the force jump in force during deactivation is uncomfortable for users.

The predefined value of 5 N pinching force as the activation force in this paper is a random value, because no sources on this subject were found. It is beneficial for future research to investigate the most comfortable activation force using human subjects and different activation forces. The functioning of the pinching phase is unaffected by the lowering activation force (Figure 12). As expected, the pinching phase shifts to the right along the motion phase. In the pinching phase the pinching force is increased by 23 N with a 7.5 N input force increase. The maximum pinching force is lower with a 4.5 bar preload (Figure 12B) because the translational limit of the booster's piston. Meaning that a lower activation force can require a longer booster to achieve a pinching force of 30 N. The deactivation of the booster with a 4.5 bar preload (Figure 12B at ●) shows a smoother transition compared to the measurements with a 9.5 bar preload (Figure 11). It is assumed that the transition is smoother because it occurs at lower forces meaning the pressure difference between chamber 2 (Figure 5 (1,3)) and entrance c upon reconnecting is also lower when the booster deactivates.

In conclusion research must be done to define a comfortable activation force which allows the performance of daily activities. The pinching phase dynamics are unaffected by the activation force. A lower activation force requires a larger translation of the booster's piston to achieve the same pinching force.

Prototype

The main issue with the design is the use of return springs. The length and force of the spring varies based on the position of the hook's finger. This causes the activation force of the booster to be dependent on the object size. The measurements (Figure 11) show the booster activates at a pinching force of 12 N without spring stiffnesses. The pinching force for booster activation of 5 N defined in the requirements is with the springs fully compressed. This means that in the system with springs implemented (Figure 2) the booster activates with a pinching force of 12 N with a fully open hook and activates with a pinching force of 5 N with a fully closed hook. Another issue caused by the spring in the booster is that it requires a specific preload. The preload must prevent the booster from activating until the pinching force is achieved and once active a low spring stiffness is required to achieve translation of the piston with minimal increase of input force. In the pinching phase the value of F_{spring} (Figure 4) is the preload plus the added force caused by compression. If the stiffness is too high the spring can negate the force increase of the booster (equation 3). To prevent this the spring requires a high preload, but low stiffness and a small length to achieve a compact design. The preload is the value of F_{spring} (Figure 4) in the motion phase. The preload must be larger than $F_{chamber1}$ (figure 4, equation 1) to keep the booster inactive in the motion phase. The size of $A_{chamber1}$ and $P_{chamber1}$ (Figure 4**,** equation 2) directly affect the preload. Indirectly the length of the shoulder cylinder affects the preload. The shoulder and hand cylinder must have the same volume for the shoulder cylinder to fully translate the hand cylinder because of this a shorter shoulder cylinder also increases its diameter to keep the same volume. This relates to a higher force input to achieve a pinching force of 30 N. The booster must negate this increase in input force by either increasing $A_{chamber1}$ or decreasing $A_{chamber2}$ (equation 3). There is a physical limit to how small $A_{chamber2}$ can become meaning $A_{chamber1}$ must become larger, which increases the preload. Building a simulation of the system can benefit in trying different spring variables.

The booster prototype is heavier and larger in size than optimally possible to allow disassembly of the prototype. This allowed the booster to be easily disassembled in case of malfunction to find the cause of the malfunction. The booster (Figure 5**,** Figure 8**)** weighs 67 g. By removing the excess material this can be reduced to 16 g. While the hand cylinder weighs 27 g and the shoulder cylinder weighs 31 g.

Lengths of the cylinders will increase if springs replace the pressurised gas used in the prototype, because the spring requires space to house their compressed state.

In conclusion research must be done to find the optimal springs or find a different method to apply the preloads. The weight of the booster and hand cylinder at the wrist are 94 g which is higher than the maximum of 50 g in the requirements. The length of the cylinders will increase if the springs are implemented.

For future improvements it is possible to integrate the booster into the hand cylinder creating a single mechanism. Unlike with the prototype which has the two separate components connected via hydraulic wires. A single mechanism will remove the hydraulic tube connecting them and make the design more compact. A similar design is implemented in a bicycle break made by Brake Force One (Levy, 2014).

To summarize the conclusions:

- The force required for translation in the motion phase must be increased to a minimum of 10 N.
- Force dynamics in the motion and pinching phase are unaffected by object stiffness.
- The pinching phase activates at the predefined input force, but not output force and the pinching phase can achieve a 35 N pinching force with a 32 N input force.
- The pinching phase dynamics are unaffected by the activation force, but a lower activation force requires a larger translation of the booster's piston to achieve the same pinching force.
- To measure the FT relation a different setup must be used to allow translation in the pinching phase or stiffer springs to activate the pinching phase before the springs are fully compressed.
- More displacement is required in the pinching phase to analyse the FT relation between the motion and pinching phase.
- Further research is necessary on how much displacement is required in the pinching phase to perform daily activities.
- Further research is necessary to learn if the force jump during the booster's deactivation is uncomfortable for the user.
- Further research is necessary on what activation force is required for daily activities.
- Further research is necessary to find the optimal springs for the system.

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II. Appendices

A. Design methodology

The goal of the project is to design a mechanism that passively switches between the dynamics of the motion phase and pinching phase for body-powered active closing hook prostheses. The passive switching must be initiated by the force feedback created by the pinching force. In the motion phase a small force input must result in a large output translation and in the pinching phase a small force input must result in a larger force output and a small output translation.

A literature review on brake boosters for cars and bicycles resulted in three pre-existing designs that can be downscaled to a size that allows them to be implement in prostheses. Of these three results one actuates based on the force feedback instead of the travel distance of the input (in this scenario the travel distance of the brake pedal). Because of this the usable design concept from the literature review is the design of the brake booster by Jan van Frankenhuyzen (Van Frankenhuyzen, 2007).

Design requirements

Using the upcoming design requirements and brainstorming other concepts are realised.

Cable force
Minimum cable force required for operation is 10 N because breathing and friction losses influences the controllability at lower forces (Hichert, 2017). During motion phase the aim for the cable force is between 10 N and 20 N and during pinching phase a force of 40 N or less at 30 N pinching force. The 20 N is chosen as it is 10% of the maximum force that 23 participants of experiments performed by Hichert (2017) could achieve to minimizing muscle fatigue. The 40 N at 30 N assumes that the maximum pinching force is only used for small periods of time making it more reasonable to apply a higher force (Hichert, 2017). The activation of the pinching phase is set at 5 N applied pinching force.

Weight
Body-powered hand prosthesis weigh 395-447 g while hooks way 87-242 g (Smit et al., 2012). The perceived weight by the user is much higher than the weight of the prosthesis (Figure 13). Based on this the design must weigh a fraction of this weight because it is used in addition to the hand. The aim for the design is to have a maximum weight of 50 g at the wrist.

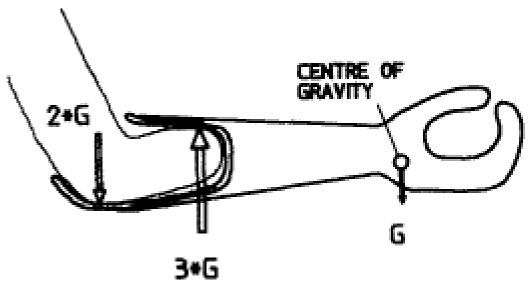

Figure 13: The weight of the prosthesis generates a force on the stump which is three times as high. Copied from Kuit and Cool (1989)

Size
The design must be as small as possible to prevent inconvenience during movement when wearing the design and to make the design less visible.

Prosthetic type
The design will be designed to be implemented in a TRS active closing hook prosthesis but aims to be universally applicable to active closing body-powered prostheses.

Pinching force
Pinching force required for daily activities is 30 N (Hichert, 2017, Smit et al., 2012, Smit et al., 2015).

Conceptual design

Pulley system

The pulley system (Figure 14) utilises the Bowden cable and a pulley configuration combined with a spring to switch between the motion and pinching phase. Once the pinching force (Figure 18) overcomes the spring stiffness the spring extends. This allows the pulley attached to it to move and boost the pinching force through the cable configuration. The pulley that initiates the boost is attached at a larger distance from the pivot allowing the force increase to be combined with an increasing in moment.

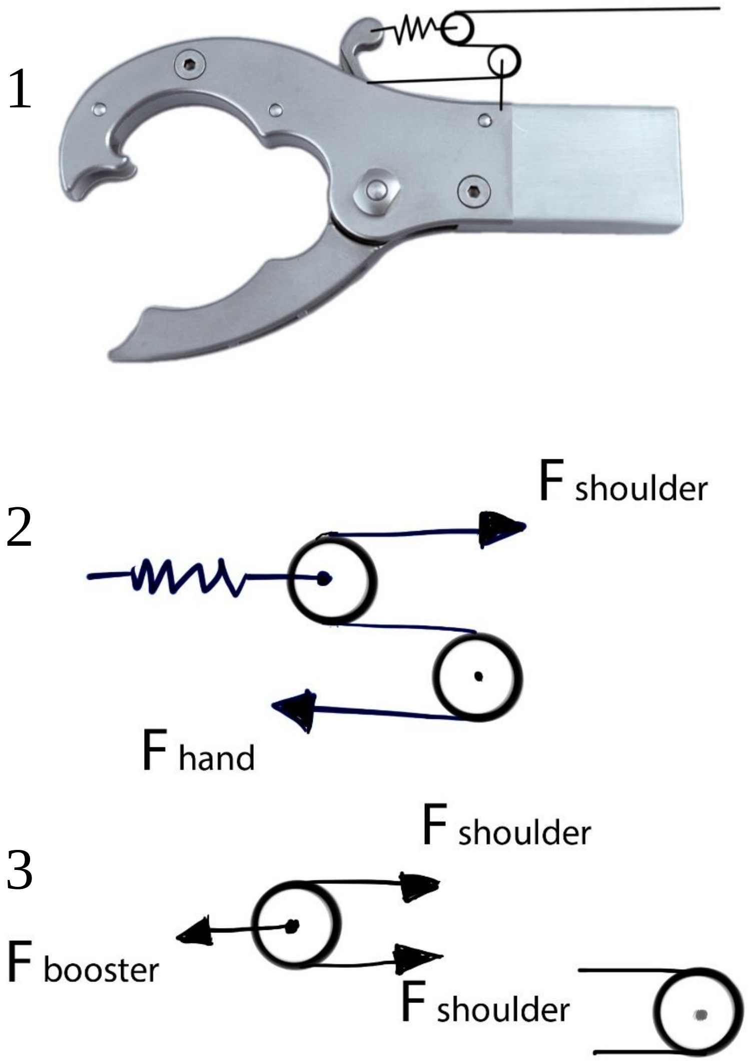

Figure 14: Pulley system drawings. 1) Simple method of attaching the design to the prosthesis. The spring is attached further from the pivot to allow the boost force to utilize a larger moment. 2) In the motion phase both pulleys remain stationary and the relation between the shoulder and hand force are 1:1. 3) In the pinching phase the pinching force prevents the cable from moving any further. The spring attached to the first pulley will extend with an increase of shoulder force and create a boosting force which is twice as large as the force generated by the shoulder and the booster force is attached at a larger distance from the pivot creating a larger moment.

Spring activation
A spring is attached to the end of the Bowden cable. The spring is used to activate a hydraulic boosting mechanism. In the motion phase the Bowden cable operates the prosthesis. The cable force increases to create a pinching force causing the spring to extend or compress. The extension or compression of the spring initiates the pinching phase by actuating a hydraulic booster through a lever (Figure 15). The hydraulic booster increases the force by using a piston to create a pressure and applying the pressure on a piston with a larger surface area to increase the output force. The booster can be designed as a single cylinder with a different size of surface area on each side or two cylinder which are positioned in parallel and attached to each other with a direct connection. The booster can also be 2 separate cylinders. How the booster is attached to the prosthesis depends on the design and would most likely require a frame to support the booster when exerting a force on the hook.

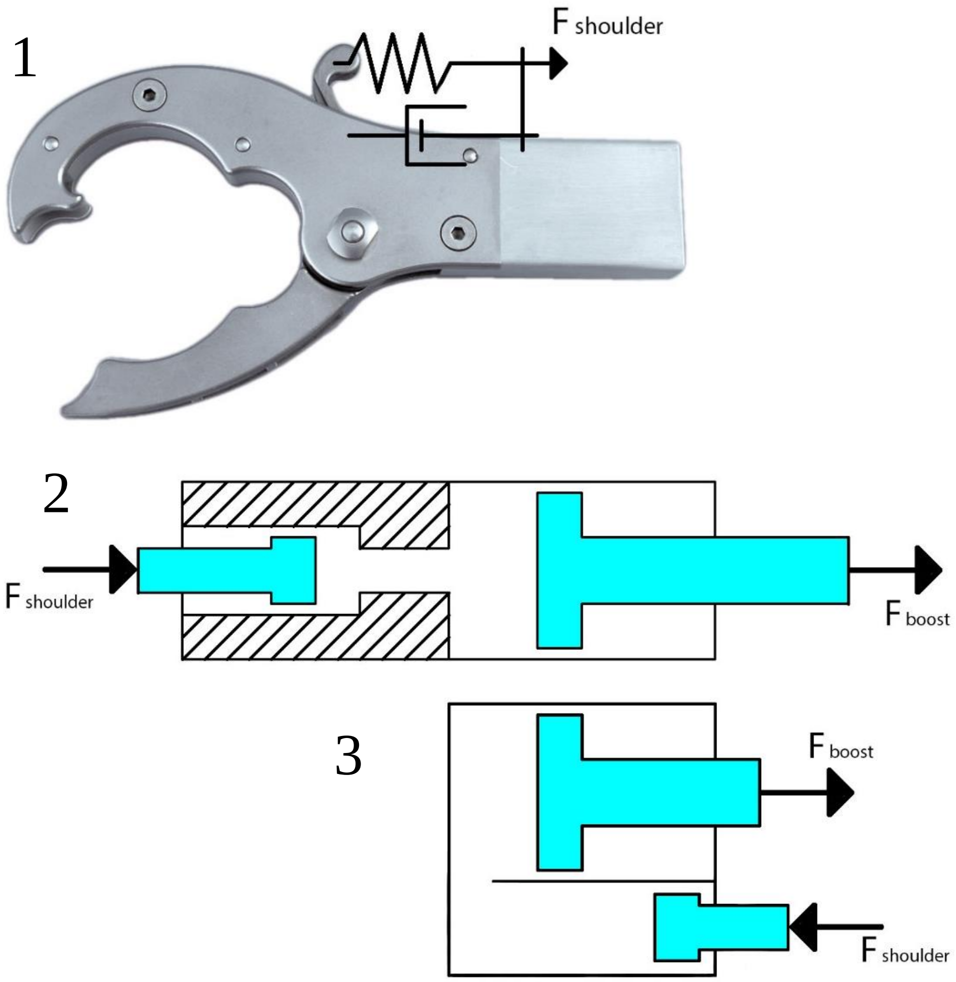

Figure 15: 1) A simple method of attachment. The attachement can change based on the design of the booster. 2) A single cylinder booster design that transfers the force in the same direction. 3) A booster consistig of two cylinders attached to eachother to change the direction of the force.

Hydraulic brake booster
This design works the same as the design described in Van Frankenhuyzen, 2007. The design consists of a master (shoulder) cylinder, actuated by the shoulder harness, and slave (hand) cylinder, actuates the hand prosthesis, connected to each other via a booster mechanism (Figure 16). The booster consists of two chambers. Chamber 1 is connected to chamber 2 via a piston. The shoulder cylinder is connected to both chamber 1 and chamber 2. Chamber 2 connects to the hand cylinder. The springs in the cylinders are used to return the pistons to their initial positions. The spring in chamber 1 has a preload to prevent fluid from entering in the motion phase. In the motion phase the shoulder cylinder actuates the hand cylinder without interference from the booster.

A pinching force will increase the pressure in the system. The rise in pressure creates a force on both side of the piston in the booster, because the pressure is the same the larger surface in chamber 1 has more force applied to it (Figure 17, equation 5). Once the force in chamber 1 exceeds the spring force and the force in chamber 2 the piston is pushed from chamber 1 into chamber 2 blocking off the connection between the shoulder cylinder and chamber 2 (Figure 16).

In the pinching phase the piston in the booster blocks the connection between the shoulder cylinder and booster chamber 2 (Figure 16). In this phase the hand cylinder is controlled by the shoulder cylinder via the piston in the booster. The increase in pinching force is created by using the size of the surface areas on the booster's piston to increase the pressure in chamber 2 and thus also in the hand cylinder (Figure 17, equations 5-7).

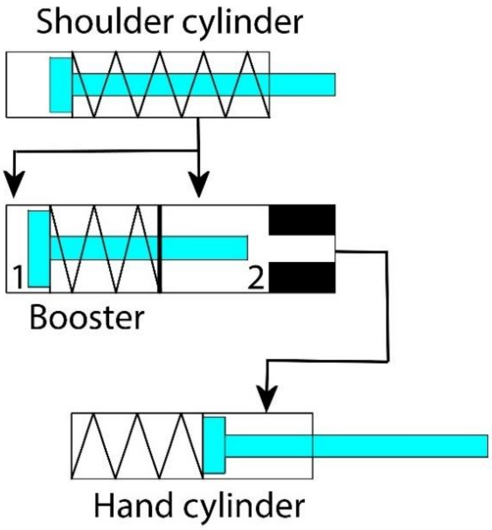

Figure 16: Lay-out of the cylinders and the booster. The shoulder cylinder connects to both the booster chambers. Booster chamber 1 connects to booster chamber 2 via a piston. Booster chamber 2 connects to the hand cylinder. The springs in the shoulder and hand cylinder return the pistons to their initial positions. The spring in the booster has a preload to prevent movement in the motion phase and returns the piston to its initial position.

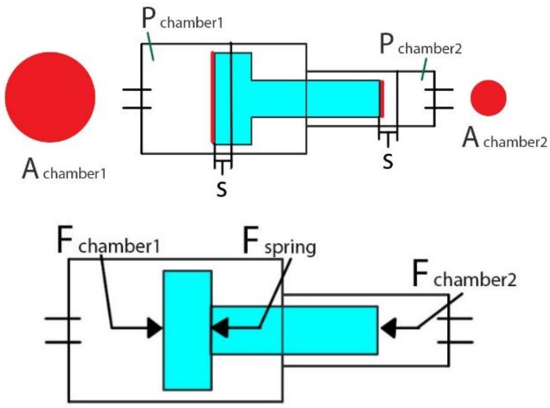

Figure 17: The booster schematic. A) Shows the pressures, surfaces, and translation. B) Shows the forces created by the pressures and surfaces.

$$F_{chamber1} - F_{spring} = F_{chamber2} \quad (5)$$

$$P_{chamber1} * A_{chamber1} - F_{spring} = P_{Chamber2} * A_{chamber2} \quad (6)$$

$$P_{chamber2} = P_{chamber1} * \frac{A_{chamber1}}{A_{chamber2}} - \frac{F_{spring}}{A_{chamber2}} \quad (7)$$

Assessment

The concepts are assessed based on the design requirements and graded from 1 to 4 with 1 being the worst and 4 being the best fit (Table 1). The requirements are weighted to signify their importance. The cable force and the pinching force are the most important because the goal of the design is to improve the pinching force while keeping the cable force in a comfortable range for the user. The size and the weight are moderately important because these define user comfort. The prosthetic type is the least important because the first concern in this early stage is the functionality. Making the design universally applicable can be added in a later design. The concept with the highest score is the concept that shows the most promise.

Table 1: Concept assessment. The weight of the requirements shows the importance of the criteria 1 being less important and 3 being more important. The concepts are graded from 1 to 4 with 1 being the worst and 4 being the best fit. The grades are added to a total score with the highest score showing the most promising concept.

	Weight of the requirements	Pulley system	Spring activated brake booster	Bicycle brake booster
Cable force	3	1	2	4
Weight	2	3	2	3
Size	2	2	2	2
Prosthetic type	1	3	1	3
Pinching force	3	3	3	3
Total		25	24	36

Pulley system

Cable force, grade 1

The pulleys will be positioned close to the prosthetic and the Bowden cable has high energy loss (Smit et al., 2012) due to the long cable making a lot of turns and the friction from the pulleys add more energy loss (Ju, F. & Choo, Y.S. (2005), Peng, Y., et al. (2017)). This energy loss results requiring higher input forces. Assuming a pinching force of 30 N and measuring the prosthesis resulting in $r_{finger} = 90\,mm$ and $r_{lever} = 60\,mm$ (Figure 18). The booster force shows to be 45 N (equation 8-9) making the shoulder force 22.5 N (Figure 14 (3)), however this is without the spring forces and frictional forces of the pulleys and the return spring of the system. The grade is based on the amount of friction and energy losses in the concept.

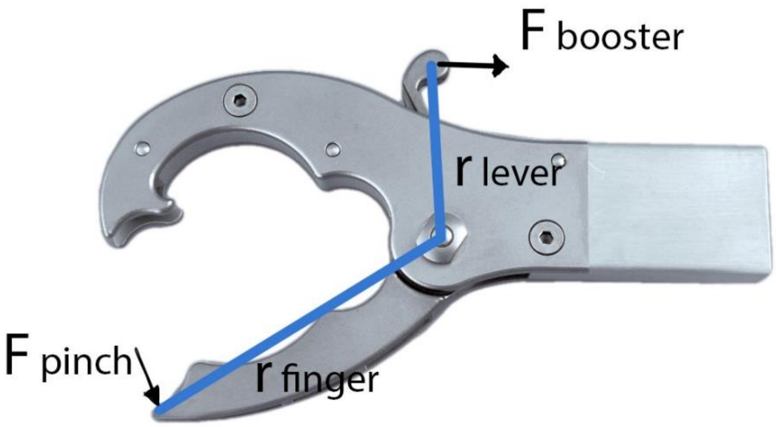

Figure 18: Free body diagram for pulley system in the pinching phase. Showing forces and moment arms.

$$F_{pinch} * r_{finger} = F_{booster} * r_{lever} \tag{8}$$

$$F_{booster} = 30 * \frac{90}{60} = 45\,N \tag{9}$$

Weight, grade 3

The pulleys must be attached to a frame. The frame must resist relatively high forces, meaning the frame must be robust adding to the weight. The frame is the heaviest component of this concept because the other components are the pulleys and the spring. The grade is based on the frame being most of the weight.

Size, grade 2

The overall size of the system is determined by the optimal configuration of the pulleys and the size of the required pulleys. The pulleys must be metal to prevent them from wearing out easily. The outer diameter of several small pulley wheels found online are 13 mm (Carl Stahl Sava Industries, last consulted on 07/2020). Meaning that using 3 pulleys will make the system at least 40-45 mm wide and 40 mm long assuming the moving pulley moves 10 mm. The reason behind the grade is because the size can increase rapidly if more pulleys are required.

Prosthetic type, grade 3
The concept is attached between the Bowden cable and the prosthesis because of this the concept can easily be implemented on different type of prostheses. Minor alteration might apply to attach the concept to the different prostheses. The grade is based on the concept requiring minor alteration to use the concept on other prostheses.

Pinching force, grade 3
The pinching force can be achieved with a configuration of pulleys because pulleys can increase the force output, however depending on the configuration the size can increase. The use of the Bowden cable during the motion phase means that a high cable force is required before the booster activates (Smit, 2010). Because of this the amount of force between the activation and reaching the comfortable limit of 40 N is small (Hichert, 2017). This causes a lower accuracy for the force control during the pinching phase. The grade is based on that pulleys being capable of increasing the output force.

Spring activated
Cable force, grade 2
This concept uses a Bowden cable meaning the energy loss of the Bowden cable is an issue (Smit et al., 2012). The spring will add to the force on the cable in the pinching phase. The moment arm of the lever can increase the force transferred to the hydraulic cylinder used to create the pinching force. The grade is based on that the losses from the Bowden cable are present in the motion phase but in the pinching phase the force increase from the booster can be achieved without adding much friction.

Weight, grade 2
The spring, the hydraulic cylinder(s) and the frame of the cylinders make up most of the weight for this concept. Based on Festo catalogues, pneumatic cylinders with a 6 mm bore diameter and 25 mm stroke weighs 24 g (Festo, 2019) and a cylinder with an 8 mm bore diameter with 0 mm stroke weighs 20.1 g adding 2.4 g for every 10mm added stroke length (Festo, 2020). The weight and size of the frame is dependent on the design of the booster because the design defines how the booster will be attached to the prosthesis. For the comparison, the weight of the frame is assumed to be equal to the weight of the frame for the pulley system. The grade is based on the frame having a similar weight as the frame from the pulley system but that the system also utilizes hydraulic cylinders which are heavier than the pulleys.

Size, grade 2
The cylinder can be relatively small, but the frame to which it should be attached will increase the size of the system. This makes the size highly dependable on how the mechanism will be attached to the prosthesis. The grade is based on that the size dependent on the implementation of the booster. The cylinders of the booster also require the same stroke length because of this the ratio of the surface areas will affect the length difference of the cylinders. This limits the size to the required force increase of the booster.

Prosthetic type, grade 1
The system requires a spring and lever to be attached to the cable and the prosthesis. This can require some minor alterations to the prosthesis design. The attachment of the cylinder and its frame will most likely require alterations to the prosthesis' design. The grade is based on that more extensive alteration are required to use the concept on other prostheses.

Pinching force, grade 3
The use of the Bowden cable during the motion phase means that a high cable force is required before the booster activates (Smit, 2010). Because of this the amount of force between the activation and reaching the comfortable limit of 40 N is small (Hichert, 2017). This causes a lower accuracy for the force control during the pinching phase. The reason for this grade is that given the right ratio of the surface areas in the booster the pinching force can be achieved.

Bicycle brake booster
Cable force, grade 4
The cable force can easily be lowered by replacing the cable with a hydraulic system. This is done by altering the ratio of the slave and master cylinder surface areas during the motion phase and the ratio of the surface area of the two sides of the rod in the booster. The grade is based on the cable force in the motion and pinching phase can be separately defined by altering the surface areas of the shoulder and hand cylinders in the motion phase and the surface areas of the ends on the booster's piston.

Weight, grade 3
The weight of the cylinders can be reduced by using lightweight polymers if the forces will allow this. The cylinders can be positioned at different location and thus spreading out the weight distribution. Based on Festo catalogues, pneumatic cylinders with a 6 mm bore diameter and 25 mm stroke weighs 24 g (Festo, 2019) and a cylinder with an 8 mm bore diameter with 0 mm stroke weighs 20.1 g adding 2.4 g for every 10 mm added stroke length (Festo, 2020). The grade is based on allowing the cylinders to be placed at different locations and the possibility to use lighter materials.

Size, grade 2
The size of the concept is limited by the smallest possible surface area of the cylinders and the ratio. The smallest cylinder in the Festo catalogues has a bore diameter of 2.5 mm, however the stroke length is also limited by the diameter (Festo, 2019). The grade is based on that a very small diameter can be used but the stroke volume between the shoulder and hand cylinder must be equal. This limits the size to the translation required by the hand cylinder to open and close the prosthesis.

Prosthetic type, grade 3
The concept can be implemented instead of the Bowden cable in combination with a shoulder harness. Minor alteration might apply to attach the concept to the different prostheses and harnesses. The grade is based on the concept requiring minor alteration to use the concept on other prostheses.

Pinching force, grade 3
The pinching force is theoretically limited by the ratio applied to the booster rod surface areas. Meaning it can realize the required pinching force. The grade is based on a high achievable pinching force and hydraulics having relatively low friction.

Final concept

The hydraulic brake booster shows to be the most promising concept (Table 1). The concept can reduce the cable force, while increasing the pinching force. The feedback activation can be controlled and implemented by utilizing the pressure level. The weight can be low, and the size can be small, but it is also possible to space the weight out over different parts of the harness. This way the perceived weight can be minimized. The shoulder and hand cylinder are simplistic cylinders (Figure 19). The shoulder cylinder which is controlled via the harness through shoulder motion and the hand cylinder which is operated via the shoulder cylinder. The hand cylinder opens and closes the prosthesis. The different colours are used to give a clear view on how the different components connect. The booster (Figure 21) is positioned between the shoulder and hand cylinder (Figure 16).

In the motion phase the hand cylinder is controlled by the shoulder cylinder via chamber 2 (Figure 20), while the preload of the spring in chamber 1 prevents the fluid from entering chamber 1 (Figure 16). The fluid flows from the shoulder cylinder into chamber 2 and exists the booster via output D (Figure 22 (2)). The pinching force increases the pressure in the system by preventing motion of the hand cylinder while the user keeps applying additional force to the system via the shoulder cylinder. The rise in pressure creates a force on both side of the piston in the booster, because the pressure is the same the larger surface in chamber 1 has more force applied to it (Figure 17). Once the force in chamber 1 exceeds the spring force and the force in chamber 2 the piston is pushed from chamber 1 into chamber 2 blocking off the connection between the shoulder cylinder and chamber 2 (Figure 22 (3)). In the pinching phase the piston in the booster blocks the connection between the shoulder cylinder and booster chamber 2 (Figure 22 (3)). In this phase the hand cylinder is controlled by the shoulder cylinder via the piston in the booster (Figure 20).

The booster increases the pinching force by increasing the pressure between chamber 1 and chamber 2. The pressure in chamber 1 works on area $A_{chamber1}$ (Figure 17) which transfers a force to chamber 2. This force creates the pressure in chamber 2 using area $A_{chamber2}$ (Figure 17, equations 5-7). The ratio between $A_{chamber1}$ and $A_{chamber2}$ creates an increase in pressure between the chambers. Chamber 2 connects to the hand cylinder (Figure 22 (3)) meaning the increase in pressure creates an increase in pinching force created by the hand cylinder.

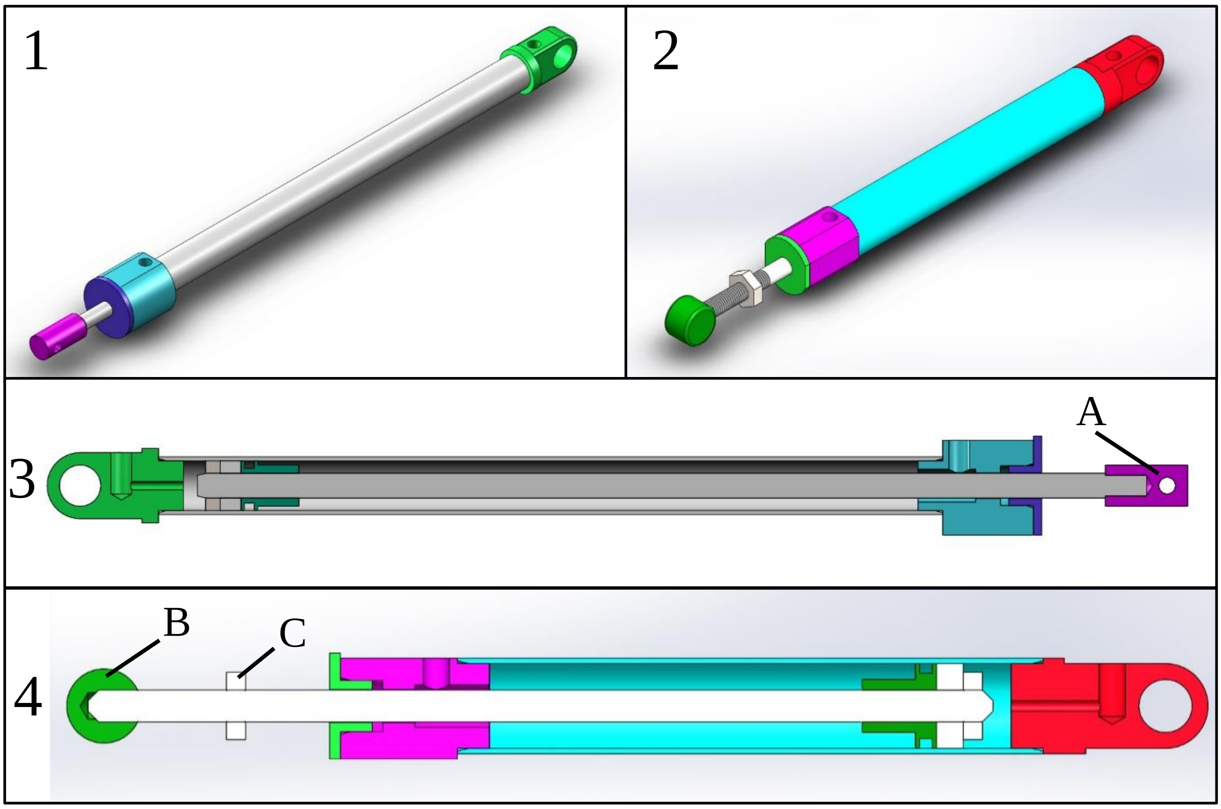

Figure 19: 1) The shoulder cylinder. 2) The hand cylinder. 3) Shows a section view of the shoulder cylinder. A) Attachment for the cable connecting the cylinder to the shoulder harness. 4) Shows a section view of the hand cylinder. The lever by which the prosthesis is controlled is positioned between component B and nut C. B) Component used to pull the hook closed. C) This nut is used to push the prosthesis open when the force on the shoulder cylinder is released and the system returns to its initial state.

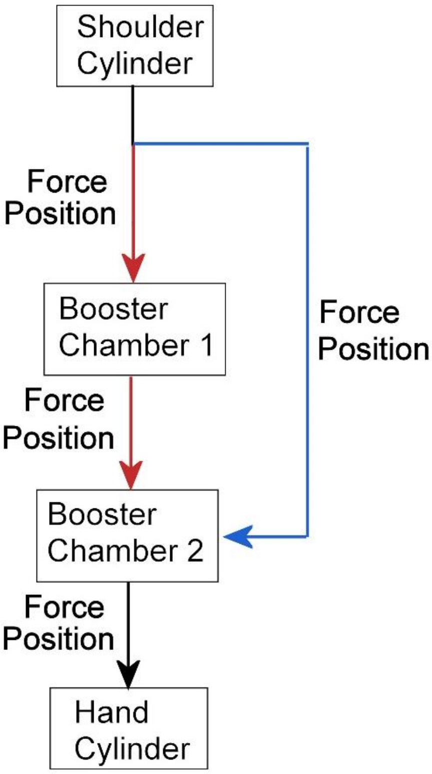

Figure 20: Hydraulic block scheme of design. The system transfers both position and force. The blue lines show the motion phase, the red lines show the pinching phase and the black lines are for both phases.

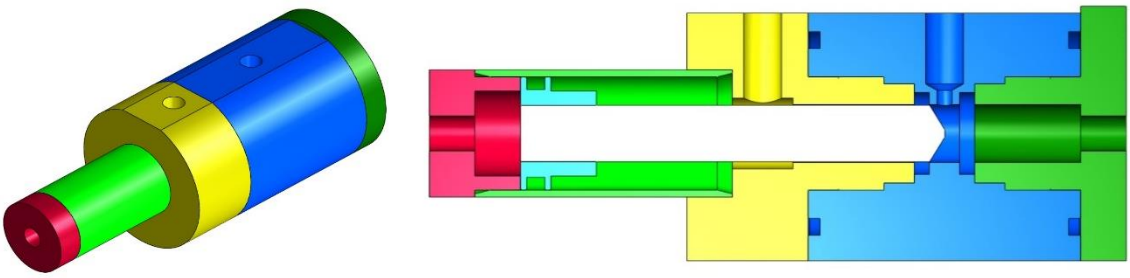

Figure 21: The booster cylinder and the section view of the booster cylinder.

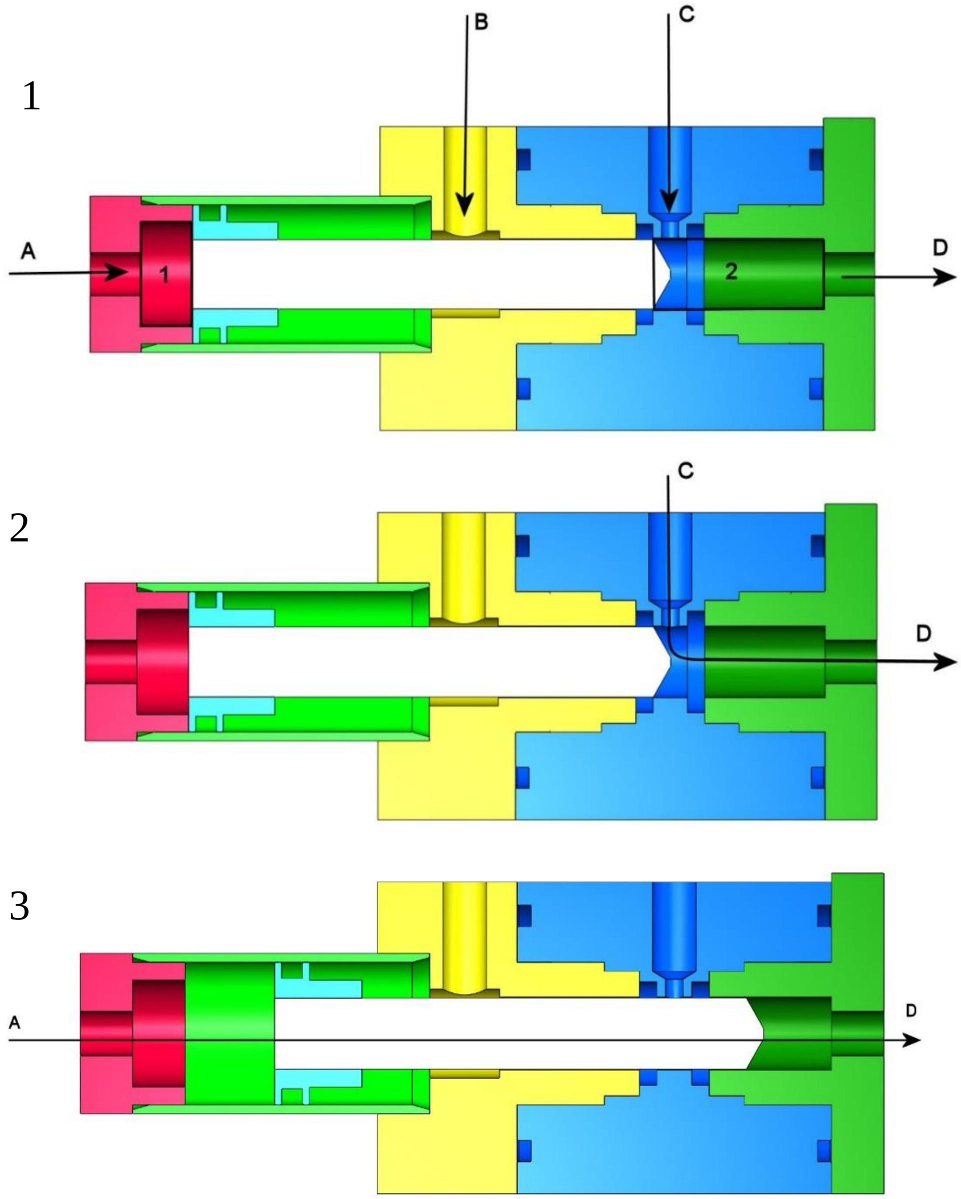

Figure 22: 1) The booster with all inputs, outputs and chambers highlighted. Input A and C are connected to the shoulder cylinder via a T-junction (Figure 2 and Figure 3). Input B is connected to regulated air pressure of 9.5 bar which provides a preload of 34 N instead of a spring. Output D is connected to the hand cylinder. 2) In the motion phase the fluid flows from input C directly out of output D. 3) In the pinching phase input C is blocked off by the piston. The fluid flows via input A into chamber 1 and applying pressure on the piston. The piston transfers this pressure to chamber 2 and out of output D.

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B. Dimensioning

The dimensioning of the concept is done by iterative calculations until the actuation and pinching forces match with the design requirements. This Appendix discusses the basic calculations to show the basic relations between the forces and surface areas. The complete calculations including the spring and friction forces are present in the MATLAB script in Appendix E. The MATLAB script is used for the iterative process. Three different scenarios are calculated. The forces during the motion phase, the forces at the switching from motion to pinching phase (activation) and the forces during pinching phase. The forces during motion and pinching phase are used to match the design criteria, while the forces at the switching point are used to determine a preload for the booster. The pinching force is defined as the force at the end of the finger of the hook prosthesis (Figure 23) and the actuation force is the force applied to the piston of the shoulder cylinder ($F_{shoulder}$, Figure 24). The desired pinching force for each phase is used to calculate the activation force.

The length of the finger to the pivot of the prosthetic (r_{finger}) and the lever to which the Bowden cable is attached (r_{lever}) are measured to determine the relation between F_{pinch} and F_{hand} (Figure 23**,** Equations 10-11). The hand cylinder is attached at 30 mm from the pivot instead of the 60 mm at which the Bowden cable is attached.

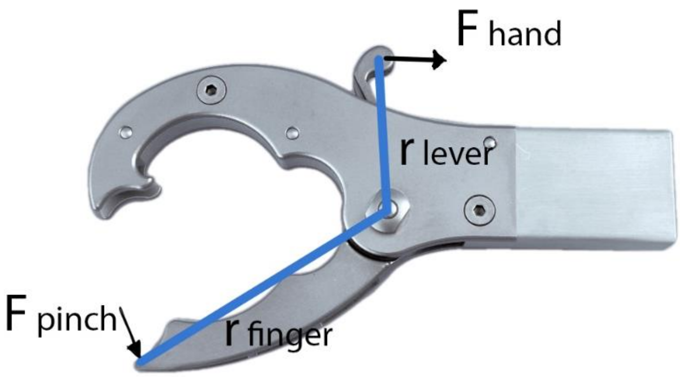

Figure 23: Freebody diagram of the finger. Showing the forces and moment arms.

$$F_{pinch} * r_{finger} = F_{hand} * r_{lever} \quad (10)$$

$$F_{hand} = F_{pinch} * \frac{r_{finger}}{r_{lever}} \quad (11)$$

Motion phase

The function of the booster is to create a larger force in the hand cylinder while keeping the actuation force below 40 N. To achieve this goal, before implementing the booster, the output force can be increased by giving the hand cylinder a larger diameter than the shoulder cylinder (Figure 24, equations 12-16).

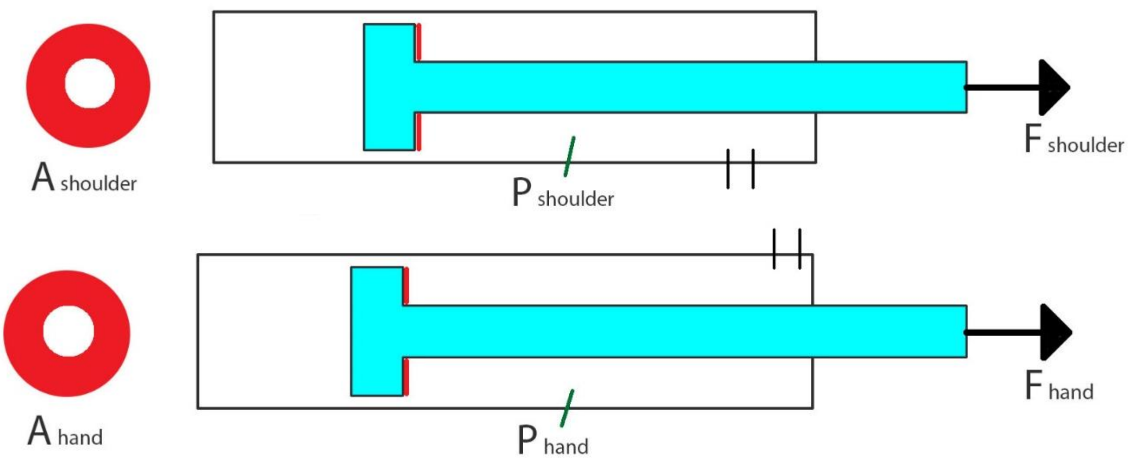

Figure 24: schematics of shoulder and hand cylinder showing forces, pressures, and surface areas.

$$\frac{F_{shoulder}}{A_{shoulder}} = P_{shoulder} = P_{hand} = \frac{F_{hand}}{A_{hand}} \quad (12)$$

$$F_{shoulder} = \frac{A_{shoulder}}{A_{hand}} * F_{hand} \quad (13)$$

In the motion phase the shoulder and hand cylinder have the same pressure because they are connected. This results in a force relation based on the ratio of the surface areas (equation 13). To ensure that force provided by the hand cylinder is larger than the force applied to the shoulder cylinder the A_{hand} must be larger than $A_{shoulder}$ (equation 14-16).

$$F_{shoulder} < F_{hand} \quad (14)$$

$$\frac{A_{shoulder}}{A_{hand}} < 1 \quad (15)$$

$$A_{shoulder} < A_{hand} \quad (16)$$

The volume of the shoulder and hand cylinder must be the same to allow for their full range of motion. The hand cylinder is placed closer to the pivot of the finger to reduce the length of the cylinder. The larger force required to compensate for the shorter moment arm can be provided by the ratio of A_{hand} and $A_{shoulder}$. The shoulder cylinder will have a smaller diameter than the hand cylinder (equations 14-16). A smaller diameter means that the shoulder cylinder must be longer than the hand cylinder to assure the same volume. This is beneficial for the control. The shoulder cylinder will have a larger translation to control the small translation of the hand cylinder allowing for more precision control by the user.

Activation phase
The activation feedback force for the pinching phase is defined as 5 N of pinching force at the tip of the finger. The 5 N is chosen as an experiment considering no literature is found on when the motion phase switches to the pinching phase. The force must not be to low that any minor contact will activate the pinching phase. If the activation force is too high the booster must be stronger because the is actuation force is closer to the comfortable limit. A force of 5 N is applied on the end of the finger to calculate the pressure in the cylinders. This pressure defines the activation between the motion and pinching phase. The preload for the spring in the booster is calculated by using the pressure at the activation and multiplying it by the large surface area ($A_{chamber1}$) of the booster's piston (Figure 25 ,equations 17-19). The size of $A_{chamber1}$ is directly linked to the preload (equation 19). The size of $A_{shoulder}$ and A_{hand} are indirectly linked to the preload (equation 20). In the prototype air pressure is used to simulate the preload of the spring. This way the activation feedback force of 5 N can be experimented with by changing the air pressure and thus the preload.

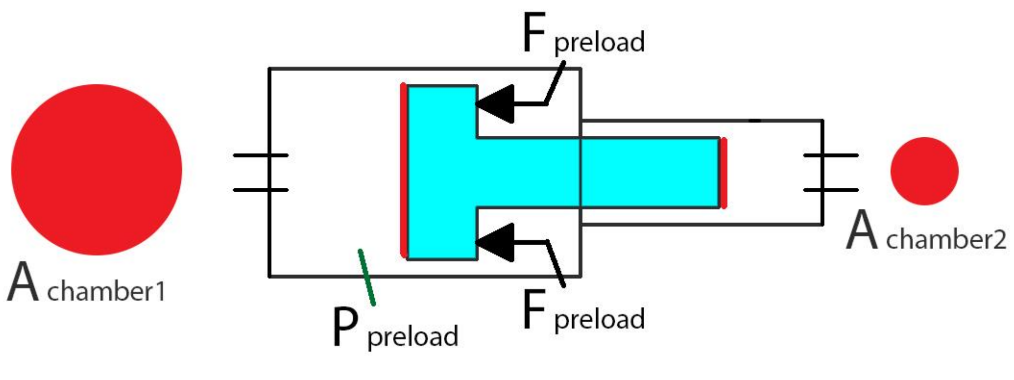

Figure 25: Booster schematic showing the preload, pressure, and surface areas.

$$\frac{F_{hand}}{A_{hand}} = P_{hand} \quad (17)$$

$$P_{hand} = P_{shoulder} = P_{preload} \quad (18)$$

$$P_{preload} * A_{chamber1} = F_{preload} \quad (19)$$

$$F_{hand} * \frac{A_{chamber1}}{A_{hand}} = F_{shoulder} * \frac{A_{chamber1}}{A_{shoulder}} = F_{preload} \quad (20)$$

Pinching phase

The pressure is calculated with the desired pinching force of 30 N applied to the tip of the finger. The actuation force is calculated with an inactive booster (equation 13). The ratio of the booster's piston surfaces is acquired by using the actuation force limit of 40 N. The ratio reduces the actuation force required to achieve the pinching force of 30 N (Figure 26, equation 21-28). Comparing equation 28 and equation 13 it shows that the booster introduces another ratio in the pinching phase to reduce the actuation force required for a 30 N pinching force. The booster's performance can be increased by either reducing the size of $A_{chamber2}$ or by increasing the size of $A_{chamber1}$. There is a limit to how small $A_{chamber2}$ can become meaning that eventually $A_{chamber1}$ must became larger to further increase the boosting effect. Increasing the size of $A_{chamber1}$ comes combined with an increase in preload (equation 19**).** A higher preload comes with either a longer or stiffer spring. The stiffer spring will influence the force build up during the pinching phase and a longer spring will increase the size and weight of the design.

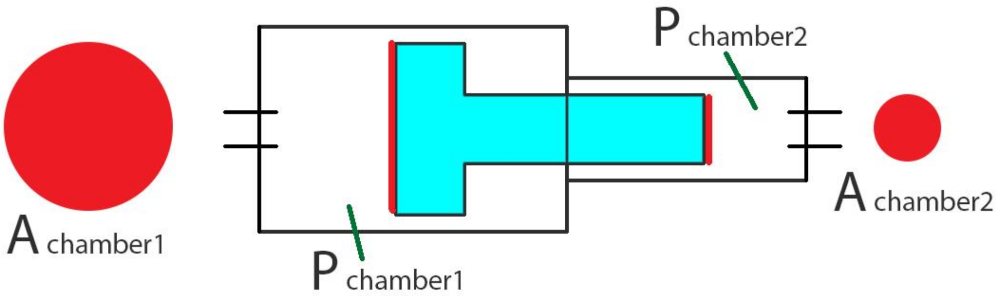

Figure 26: Booster schematic showing the pressures and surface areas.

$$\frac{F_{hand}}{A_{hand}} = P_{hand} \tag{21}$$

$$P_{hand} = P_{chamber2} \tag{22}$$

$$P_{chamber2} * A_{chamber2} = P_{chamber1} * A_{chamber1} \tag{23}$$

$$P_{chamber2} * \frac{A_{chamber2}}{A_{chamber1}} = P_{chamber1} \tag{24}$$

$$P_{chamber1} = P_{shoulder} \tag{25}$$

$$F_{shoulder} = P_{shoulder} * A_{shoulder} \tag{26}$$

$$P_{hand} * \frac{A_{chamber2}}{A_{chamber1}} = P_{shoulder} \tag{27}$$

$$F_{hand} * \frac{A_{chamber2}}{A_{chamber1}} * \frac{A_{shoulder}}{A_{hand}} = F_{shoulder} \tag{28}$$

Spring force

The design uses springs to return the cylinders to their initial position. This causes the forces to fluctuate based on the orientation of the finger, for example when the finger is open the springs are close to their natural length and thus have a smaller force impact on the system but when the finger is completely closed the springs are elongated or compressed and have a larger force impact on the system. Due to these properties of the springs the forces in each phase have been calculated for their extreme positions. This means that the pinching force at which the booster activates is 11 N when the hook is completely open and the 5 N pinching force that is calculated is when the hook is fully closed.

Friction force

The hydraulic system uses O-rings to prevent the system from leaking (Figure 27). Two red and black circles depict a single O-ring. The friction is calculated for each O-ring separately and is calculated based on methods provided by Parker (last consulted on 07/2020), Suisse, B. E. (2007). All the O-rings are 70/75 Sh and have a cross sectional width of 1 mm with an 8% compression. The hardness of 70/75 Sh is chosen because it comes with lower frictions and is the lowest recommended for dynamic systems by Parker (2018).

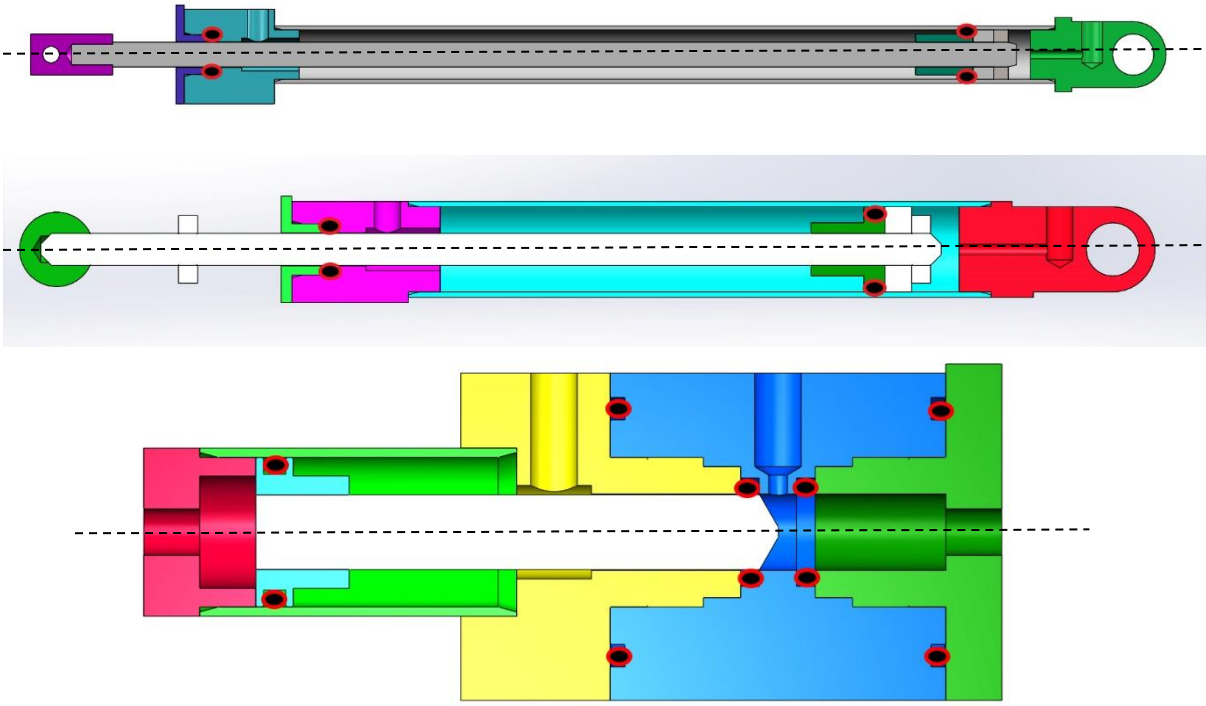

Figure 27: O-ring positions in the cylinders and booster. The red and black circles show the cross sections of the O-rings. Two circles create a single O-ring around the longitudinal axis of the cylinders portrayed as a dashed line.

References

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C. Prototype Performance

The design is altered to simplify the manufacturing and create ways to troubleshoot specific parts of the design (Figure 28).

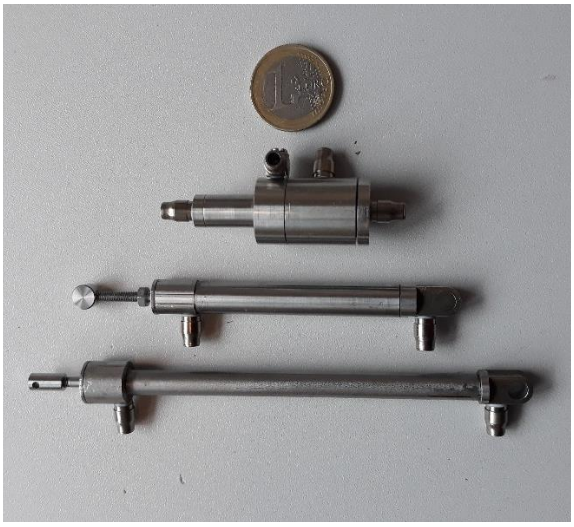


Figure 28: Photo of the prototype with a euro as a scale reference. From top to bottom; the booster, the hand cylinder, and the shoulder cylinder.

Springs are replaced by air pressure in the prototype because the system is experimental and changing the pressure allows to try different preloads without having to switch springs. By using air pressure, the spring preload can be altered without having to disassemble and reassemble the prototype. This causes the cylinders to be shorter, because when using the springs there needs to be room to house the spring in its compressed state.

The booster is partially designed to allow easy access to parts with a higher risk of failure. This is done by adding screw components allowing these parts to be screwed together. The rest of the booster is glued together using Loctite (Figure 29). The screw thread makes components longer compared to if the components were glued together.

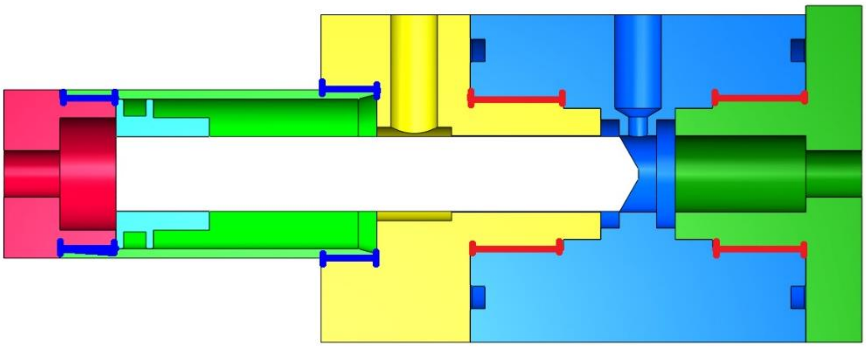


Figure 29: The booster showing glued parts with blue lines and screw parts with red lines.

For manufacturing purposes, the design is of the second booster chamber has a cylindrical shape with excess material making the booster heavier than it could be. Leaving the shape cylindrical reduced the manufacturing time. Based on the Solidworks model (Figure 30) the weight of the prototype can be reduced from 67 g to 16 g by removing the excess material and by gluing all components together instead of screwing some together.

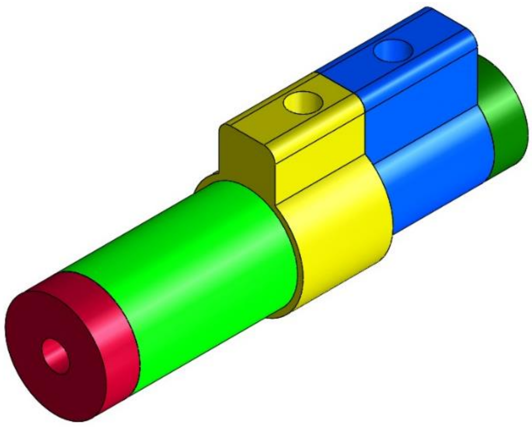


Figure 30: Booster without excess material.

During the manufacturing, a minor error has been made in dimensioning the second booster chamber (Figure 22). The volume of this chamber was meant to be equal to the volume required to translate the hand cylinder 5 mm. The volume of the second chamber was matched to this requirement, but the diameter of the hand cylinder was changed without reassessing the volume of the second chamber. This allows for a 2 mm translation instead of a 5 mm translation in the pinching phase.

The shoulder and hand cylinder are standard cylinders. This provided a high level of certainty that they would not fail and are therefore glued together using Loctite.

The prototype is attached to a hook prosthesis from TRS prosthetics. The moving finger of the prosthesis is removed just as the bearing components (Figure 32 (4)) between the plates and the finger. The finger is replaced with an aluminium replica of the finger (Figure 32 (1-2)). This replica is a leftover from a previous project. The finger is reduced in thickness to fit in the prosthesis and a groove is made in the handle to attach the hand cylinder to the finger (Figure 32 (3)). The groove is 30mm long and 3mm wide allowing the tilting motion of the hand cylinder makes during the closing of the prosthesis.

Three components (Figure 31) of the test setup are 3D printed using an Ultimaker and PE. The first is a block which can be attached to a wooden plank using nuts and bolts. The block has a bolt to which the hand cylinder can be attached (Figure 31, Figure 33) and the end of the block has an opening for the TRS hook prosthesis to be attached. The second is a housing to put the linear potentiometer in and bolt it to the plank. The third is a support piece (Figure 31, Figure 33) which supports the rod and also acts as an object for the hand cylinder to exert force on.

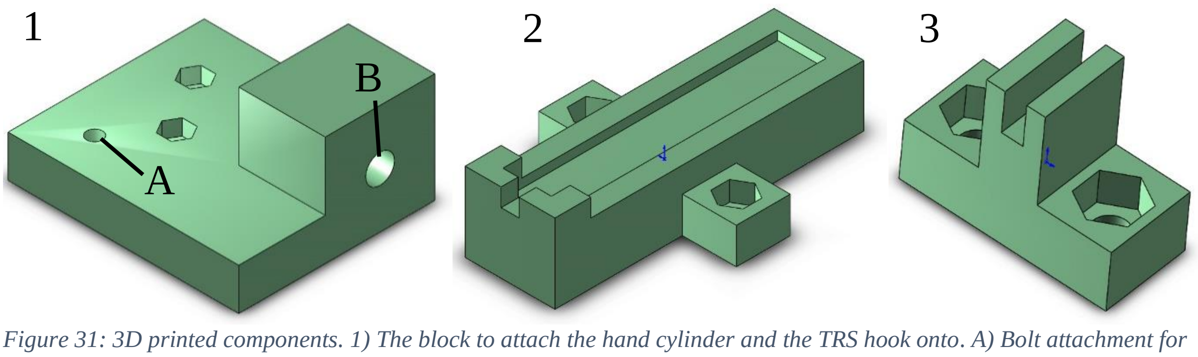


Figure 31: 3D printed components. 1) The block to attach the hand cylinder and the TRS hook onto. A) Bolt attachment for the hand cylinder. B) Attachment for the TRS hook. 2) The housing for the linear potentiometer. 3) The support piece.

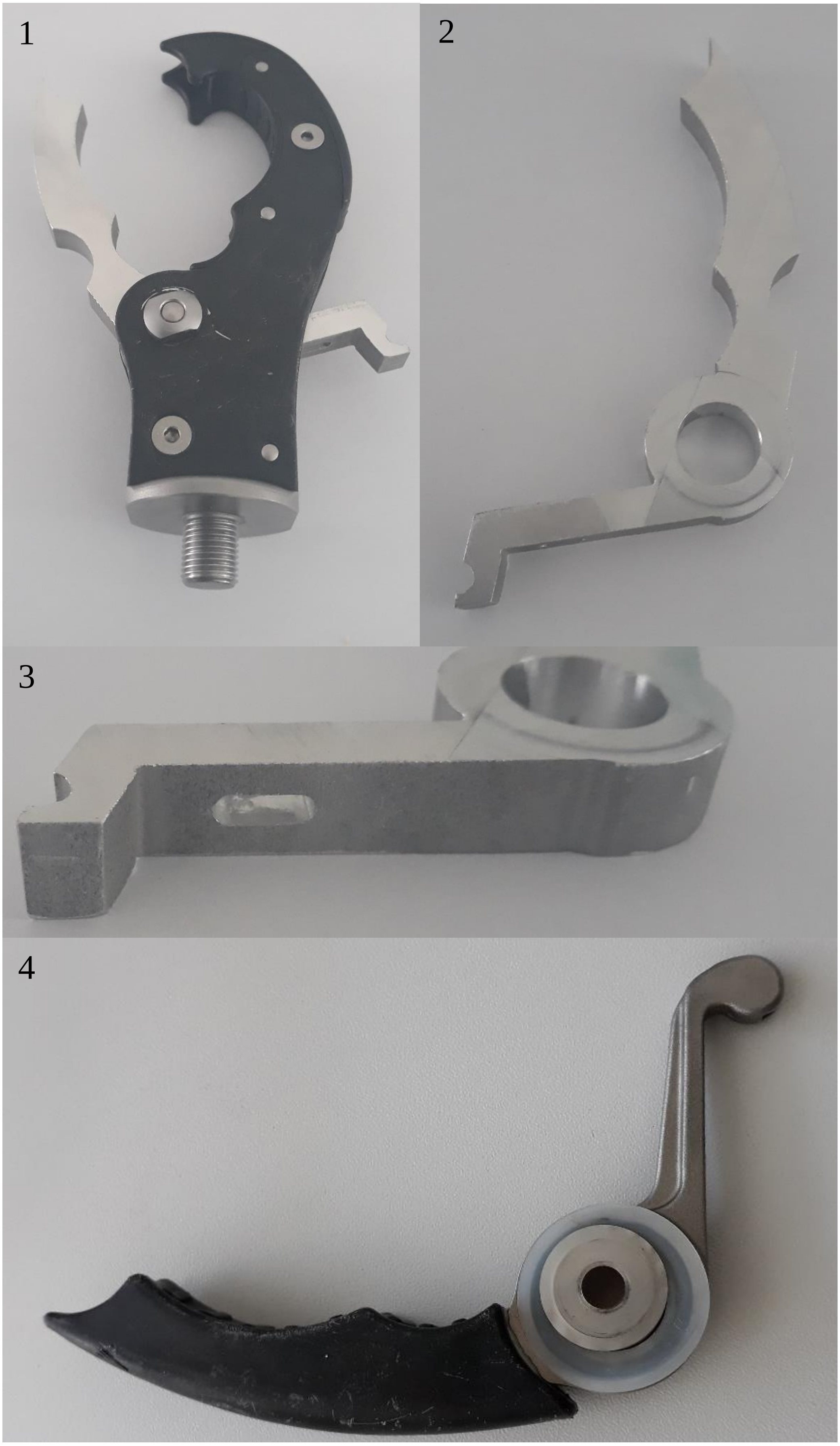


Figure 32: 1) TRS hook with the aluminium replica of the finger. 2) Aluminium replica of the finger. 3) Groove in the aluminium replica. 4) The original TRS finger with bearing components.

Measurements

The input force, output translation and output force (pinching force) are measured during the motion and pinching phase. The relation between the input force and output force (FF relation) and the relation between the input force and output translation (FT relation) are used to evaluate the change in dynamics between the motion and pinching phase and to compare the performance with the design requirements.

The initial plan included measurement with the TRS prosthesis which is why it can be attached to the setup via the block. It showed to be complicated to attach the linear potentiometer to the hook to measure the direct translation of the hook. The issue is that the hand cylinder rotates around the bolt when the prosthesis closes meaning the potentiometer must also make a rotation around the same axis to allow the translation to be measure. This issue resulted in most measurements utilizing the hook to be scrapped and instead directly measure the performance of the boosting system (Figure 33**)**. It was still planned to use the hook to measure the direct pinching force that would be achievable. However due to leakage and the results of the other measurements it was opted to discard this measurement. The results of the FF measurements show very promising results and the TRS hook would only function as a lever with the measured results as an input and the lever proportions would divide the FF relation results by 3 to show the actual pinching force. The leakage was at the end of the hand cylinder were the rod exits the cylinder. The O-ring was already replaced once, but the second leakage presumably occurred due to screw thread having to be pushed through the O-ring to replace it and damaging it during the replacement. Meaning that it is likely that the system would leak even after replacement of the O-ring.

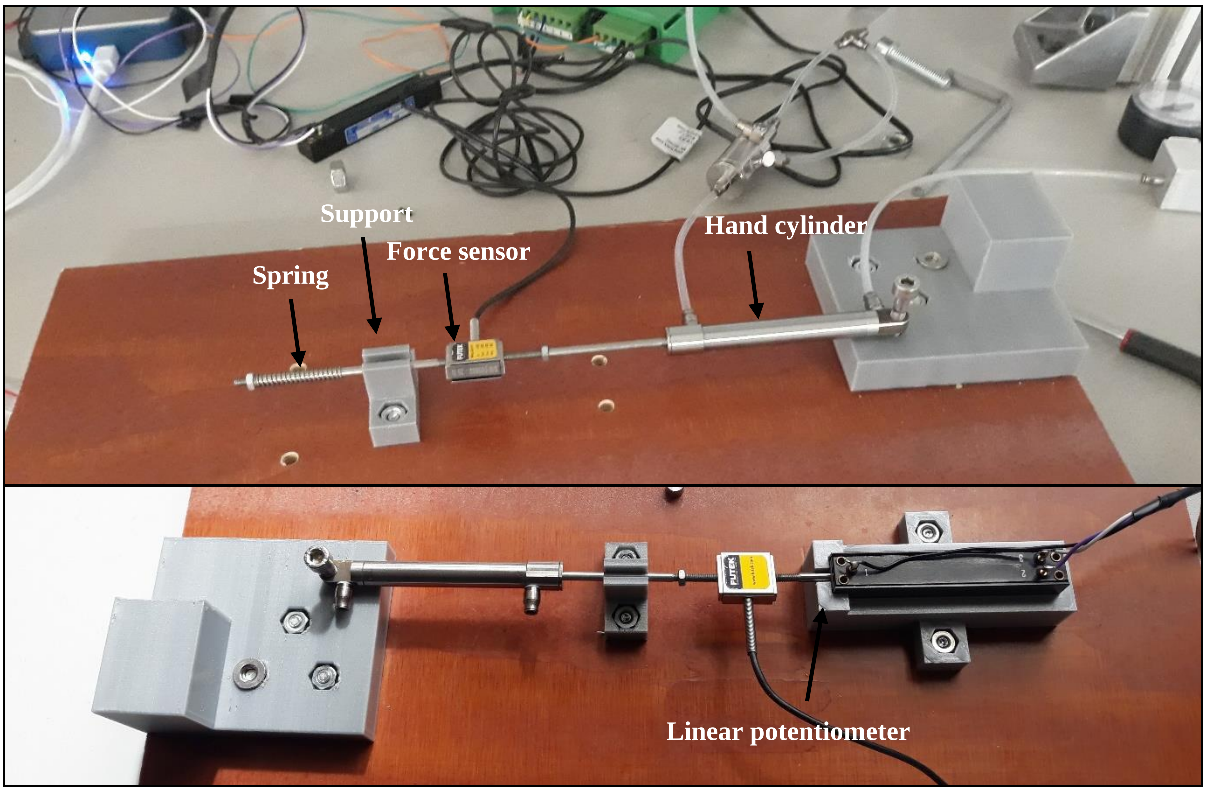


Figure 33: Test setups. On the top the test setup used to measure the output force. The hand cylinder retracts when actuated. The hand cylinder is directly attached to the force sensor. For the measurement without a spring the rod with the spring is replaced with a ck m3x35 screw to assure the screw head contacts the support. On the bottom is the test setup to measure the output translation. The linear potentiometer measures the displacement of the retracting hand cylinder. The force sensor is used as a connection piece and performs no measurement in this setup. The support between the force sensor and the hand cylinder is removed for measurements with springs and the springs are placed around the piston of the hand cylinder.

The shoulder cylinder is attached to a custom-built test bench (Figure 34) (Smit and Plettenburg, 2010). The main issue with this test bench is that the maximum translation it can achieve is smaller than the maximum translation of the shoulder cylinder, because of this it is not always possible to achieve the maximum input force of 40 N.

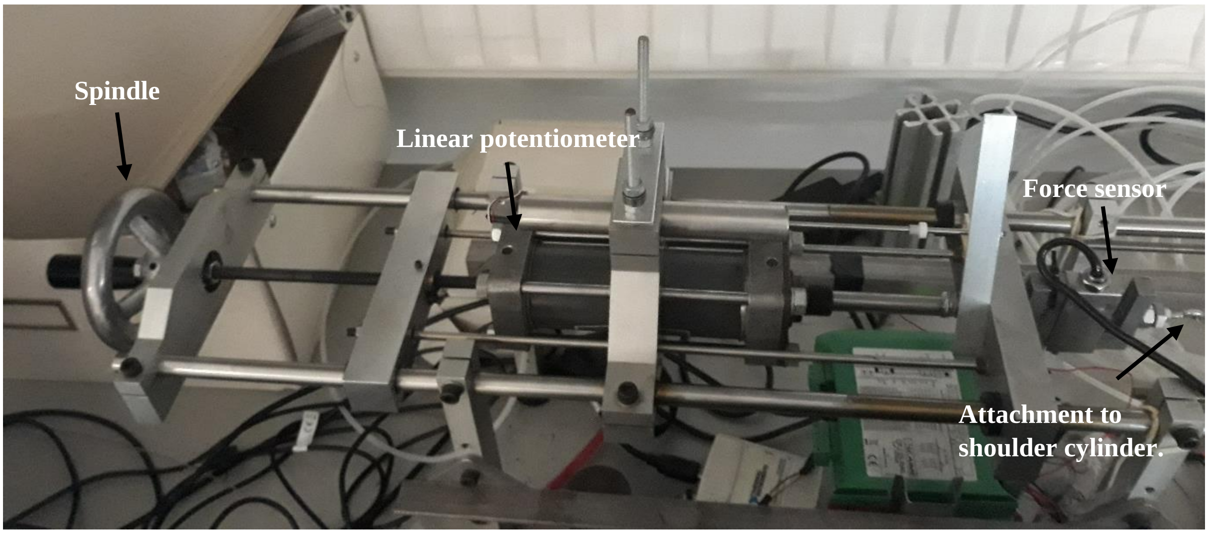


Figure 34: Custom-built test bench including the operating spindle, linear potentiometer, and S-beam force sensor. The test bench is used to measure the input force. The shoulder cylinder is attached to a hook on the force sensor via a cable.

An issue during the measurements was that after a few repeats some air got into the system and the system had to be taken apart to remove the air. This caused some minor difference in air pressure between the measurements because analogue manometers are used and after removing the air the pressures had to be reapplied.

Results

The results for both the FF relations and the FT relations (Figure 35, Figure 36) show some minor differences between different stiffnesses. The minor difference in the FT relations occurs in the input force during the free motion (Figure 35, at point 1). This difference is presumably caused by a small difference in preload in the hand cylinder. A higher preload requiring a higher input force to initiate the translation. This difference in preload is the result of using an analogue manometer. After removing air from the system by reassembling the system the pressure must be reapplied. A minor noticeable difference in the FF relations is the drop in input force during the release of input force (Figure 36 at point 3). It is unclear what precisely causes this but presumably, this difference is caused by the same difference in preload in the hand cylinder or booster caused by the analogue manometer.

Smit & Plettenburg (2010) analysed FF and FT relations of several voluntary closing hand and hook prostheses using bowden cables. Their results can not be compared to the results of the booster to draw a concrete conlusion, because the measurements of the booster didn't use the TRS hook and the pinching force is not directly measured. The output force (Figure 36) is divided by 3 to compensate for the ratio of the moment arms (Figure 21) and show the pinching force. The results of Smit & Plettenburg (2010) can be used as reference to hypothesize. If the pinching force of the prosthesis connected to the booster corresponds with the theoretical pinching force (Figure 36) that is divided by 3. In that case the booster can greatly improve the achievable pinching force of the prosthesis.

The FT relation analysed by Smit & Plettenburg (2010) consists of the translation of the cable which is attached at 60 mm from the pivot while the hand cylinder is attached at 30 mm. Meaning they will have a higher translation. Smit & Plettenburg (2010) analyse the full translation while the graphs in Figure 35 do not analyse the full translation. The lack of spring stiffness in Figure 35 makes it difficult to compare the FT relation with Smit & Plettenburg (2010), because their measurements include the spring stiffness of the returnsping.

Improving the measurement setups (Figure 33) to allow measurements with the prosthesis and implementing spring stiffnesses makes the results directly comparable with Smit & Plettenburg (2010). This will give an accurate representation on the functionality of the design compared to the bowden cable.

References

Smit, G., & Plettenburg, D. H. (2010). Efficiency of voluntary closing hand and hook prostheses. *Prosthetics and orthotics international*, *34*(4), 411-427.

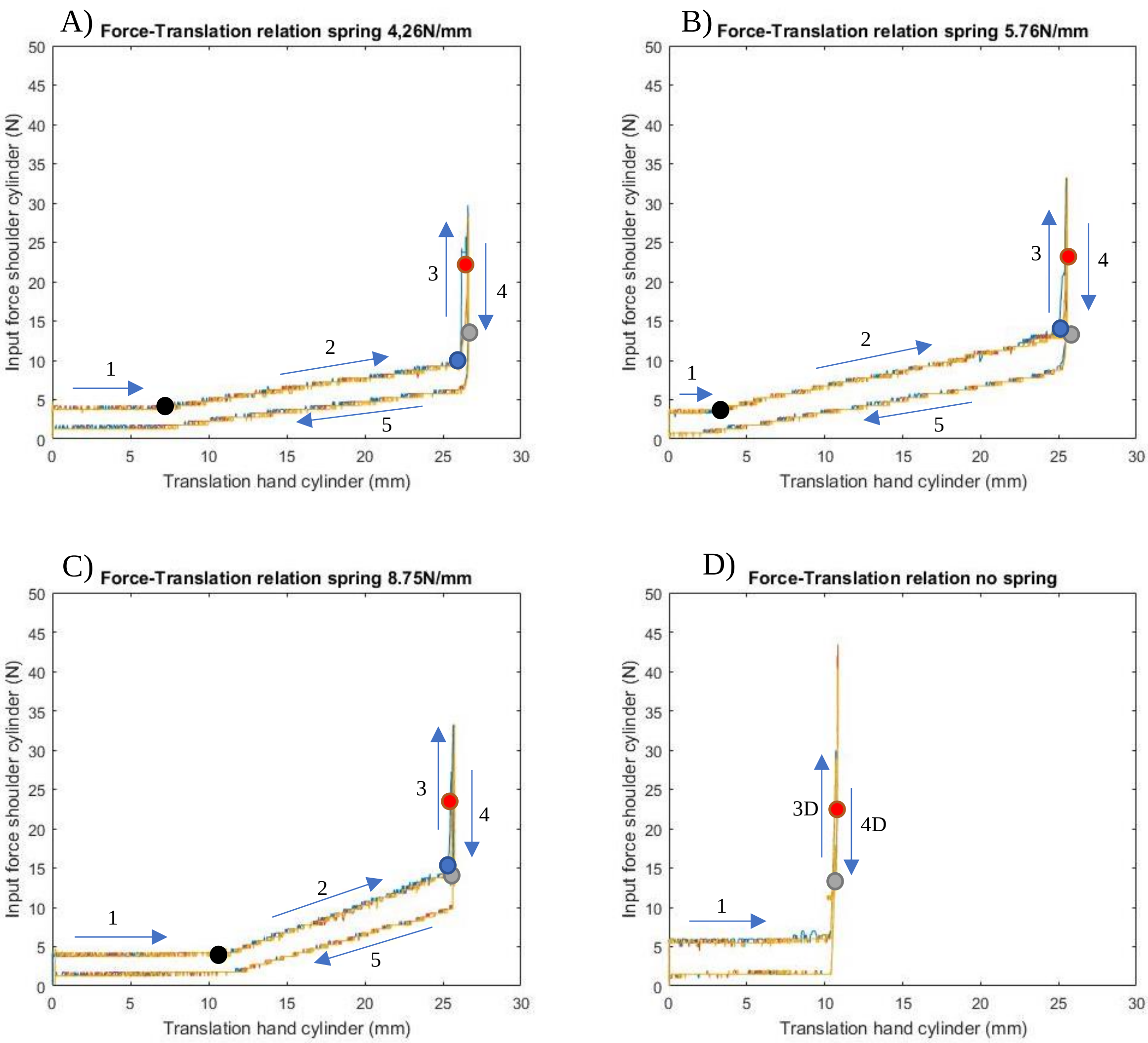


*Figure 35: Input force vs output translation relations with a preload of 9.5 bar for different springs. Explanation based on graph A and D. 1) Initial force input in motion phase (free motion). 2) Force increase during spring compression in motion phase. 3) Force increase with a fully compressed spring. The pinching phase activates at ●. 3D) Force increase while holding a solid object. The pinching phase activates at ●. 4) Force release with a fully compressed spring. The pinching phase deactivates at ●. 4D) Force release while holding a solid object. The pinching phase deactivates at ●. 5) Force release during spring extension in motion phase. ●) Start of spring compression. ●) Fully compressed spring. ●) Motion phase switches to pinching phase. ●) Pinching phase switches to motion phase. The input force for the ● and ● are taken from Figure 11***.***

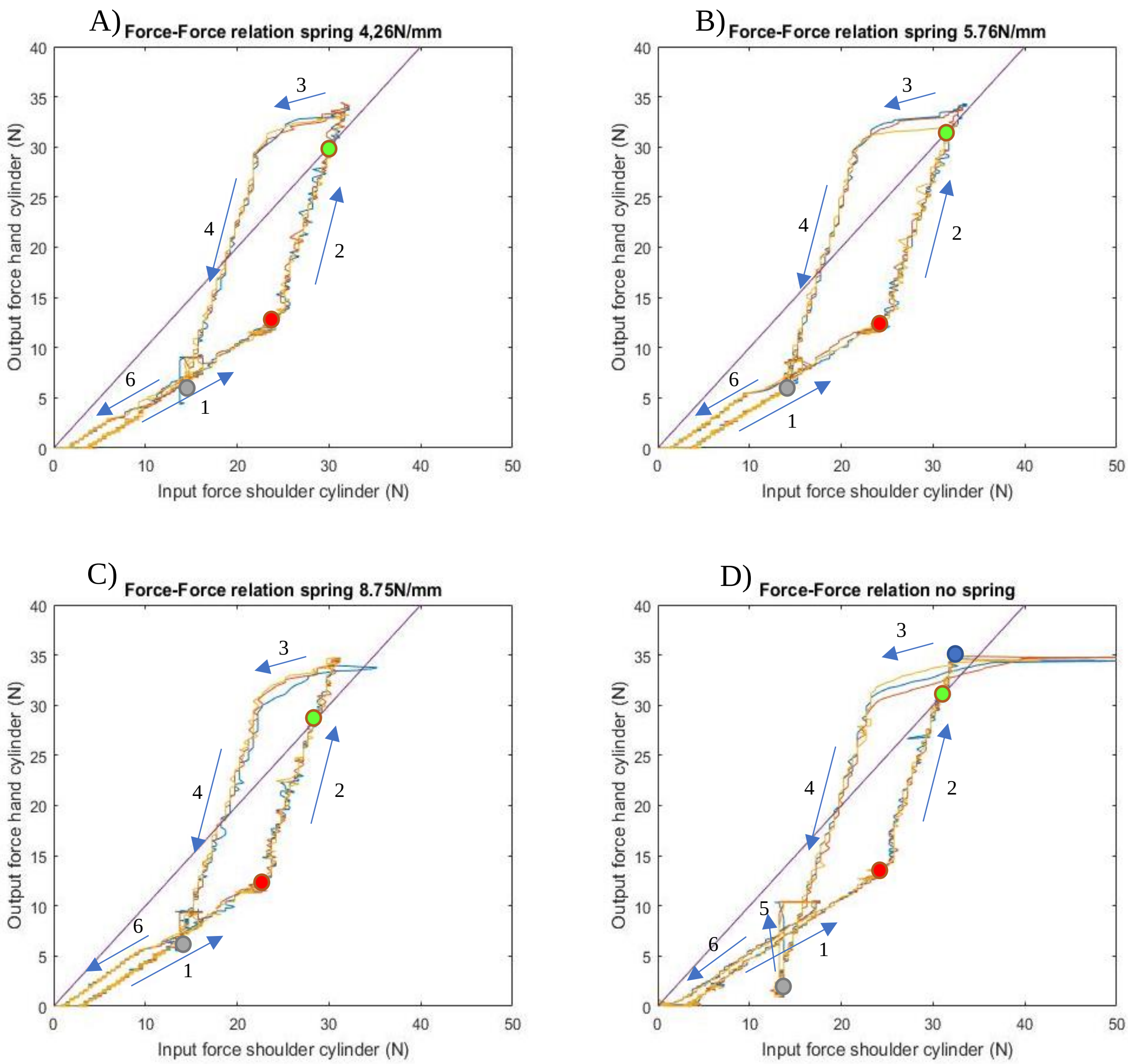


Figure 36: Input force vs output force (Pinching force) relations with a booster preload of 9.5 bar for different springs. The diagonal line shows the 1:1 relation between the input and output force. Explanation based on graph D. 1) Pinching force increase in the motion phase. 2) Pinching force increase in the pinching phase. 3) Release of input force. 4) Release of input force in the pinching phase. 5) deactivation of the booster. 6) Release of input force in the motion phase. ●) Motion phase switches to pinching phase. ●) Pinching phase switches to motion phase. ●) The moment the system crosses the 1:1 relation between the input and output force. ●) The maximum achievable output force. The graphs are overall almost identical. The biggest difference is size of the jump during the deactivation of the booster (5) this occurs in all graphs but is the largest in graph D.

D. Future Work

There are two main aspects that need to be considered for future work. The refinement of the design criteria and some points of optimisation.

The design criteria that need refinement are the activation force and the amount of translation required during the pinching phase. The activation point in this thesis is chosen as an experiment. It is required to do further research on what the activation force should be. For this the requirements must be defined, based on what the pinching phase should be used on. Must the booster only provide an increase in pinching force or also a certain amount of translation and if so, how much translation is required in the pinching phase for daily activities. For example, squeezing a lemon would require more translation in the pinching phase compared to firmly holding a broom stick. A larger translation during the pinching force will also help giving a better understanding on the force-translation relation during the pinching phase. This could be done by having subjects try the system with different activation force and ask them for feedback on which is preferable.

The results show that on the return path a skip occurs. It would be beneficial if subjects that try the different activation forces also give feedback on how this skip is perceived.

The optimisations for the current design are mainly focused on finding the best fit for the springs and looking into integrating the booster into one of the cylinders to make the overall design more compact.

An assessment is required to analyse which spring dimensions and stiffnesses would be the best fit for this system. The springs should be as small as possible when compressed to minimize the extra length required in the cylinders. At the same time the springs constants need to be as low as possible to prevent the forces on the system to increase, while still being able to apply the required preload. This is especially problematic with the spring in the booster because it has a high preload. The best method to assess the springs might be to simulate the system to plot FT and FF graphs to compare different springs properties.

As shown by brake force one it is possible to integrate the booster into the slave cylinder and maybe even the master cylinder. This will make the system more compact and if combined with the master cylinder can reduce the weight on the wrist.

E. Matlab script

```
%============================================%
%Randy de Jong                                %
%Studentnumber 4011627                        %
%TU Delft                                     %
%Deptartment of Biomedical Engineering        %
%============================================%

%% Dimensions final design

%O-ring friction equations based on [source]
% F_friction = [Fc * L]+[Fh*A]
% Fc = Friction factor due to compression based on a graph from [source]
% L = pi*Dc                  || Length of seal rubbing surface
% Dc = Cylinder bore diameter
% Fh = Friction factor due to fluid pressure based on graph from [source]
% A = [pi/4]*[Dc^2-Dp^2]     || Projected area of seal
% Dp = Dc+2*ds[1-[a/100]] or Dc-2*ds[1-[a/100]]   ||Piston groove diameter the first equations denotes an stationary o-ring
diameter the
% ds =o-ring cross section width
% a = [[D0-Dc]/D0]*100       || Radial o-ring squeeze percentage
% D0 = outer o-ring diameter

%% Dimensions
clear all;
clc;

%Hook
r_pinch = 0.09;                                   %meter          ||  Length of finger
s_closing = 0.09;                                 %meter          ||  Maximum travel distance of finger
r_handle = 0.03;                                  %meter          || Length of handle pulled on by system
s_handle = r_handle;                              %meter          || Maximum travel distance handle
c_hand = 0.3*1000;                                %Newton/meter || Spring stiffness hand cylinder
A_hand = ((0.004^2)*pi)-((0.0015^2)*pi);          %meter^2        || Surface area pressed against by fluid
to close hand
% A_hand = ((0.002^2)*pi)-((0.0005^2)*pi);        %meter^2        || Other dimension for surface area
pressed against by fluid to close hand
spring_preload = 1;                               %Newton         || Preload of spring
V_hand = A_hand*s_handle;                         %meter^3        || Volume of the hydraulic fluid in the
cylinder

%booster
A_in = (0.004^2)*pi;                              %meter^2        || Big surface area of rod
A_out = (0.002^2)*pi;                             %meter^2        || Small surface area of rod
% A_in = (0.0015^2)*pi;                           %meter^2        || Iterative purposes
% A_out = (0.0005^2)*pi;                          %meter^2        || Iterative purposes
c_booster = 0.8*1000;                             %Newton/meter  || Spring stiffness booster spring
s_booster = 0.005;                                %meter          || Travel distance booster rod

%Shoulder
c_shoulder = 0.10*1000;                           %Newton/meter || Spring stiffness shoulder cylinder
A_shoulder = ((0.003^2)*pi)-((0.0015^2)*pi);      %meter^2        || Surface area pressed against by fluid
to close hand = (surface area of the piston)-(surface area of the rod)
% A_shoulder = ((0.0015^2)*pi)-((0.0005^2)*pi);   %meter^2        || Iterative purposes
s_shoulder = V_hand/A_shoulder                    %meter          || Length of shoulder cylinder required
to match the volume of the hand cylinder

%% Motion phase
%seal frictions piston hand
L_ph = 0.006*pi;                                  %meter          || Length of seal rubbing surface
fc_ph = 100;                                      %Newton/meter || Friction factor due to compression
fh_ph = 90000;                                    %Pascal         || Friction factor due to fluid pressure
Ag_ph = (pi/4)*(0.006^2-0.00416^2);               %meter^2        || Projected area of seal
F_sfph = (L_ph*fc_ph)+(fh_ph*Ag_ph);              %Newton         || Frictional force caused by the o-ring

%seal friction rod hand/shoulder
L_r = 0.001*pi;                                   %meter          || Length of seal rubbing surface
fc_r = 100;                                       %Newton/meter || Friction factor due to compression
```

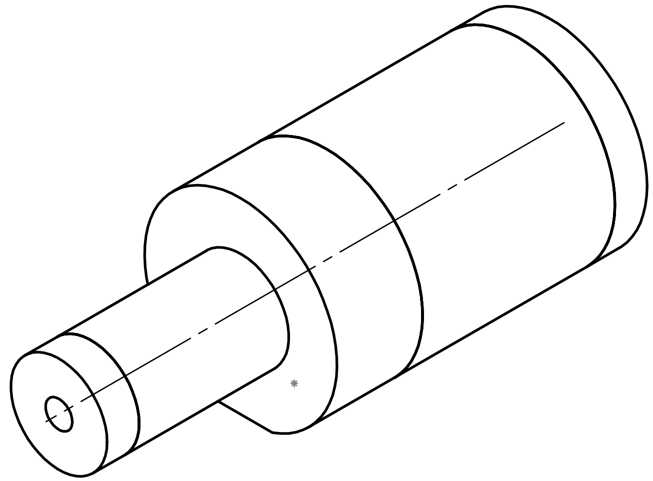
```
fh_r = 90000;                                         %Pascal          || Friction factor due to fluid pressure
Ag_r = (pi/4)*(0.00384^2-0.002^2);                    %meter^2         || Projected area of seal
F_sfr = (L_r*fc_r)+(fh_r*Ag_r);                       %Newton          || Frictional force caused by the o-ring

%seal friction piston shoulder
L_ps = 0.004*pi;                                      %meter           || Length of seal rubbing surface
fc_ps = 100;                                          %Newton/meter    || Friction factor due to compression
fh_ps = 90000;                                        %Pascal          || Friction factor due to fluid pressure
Ag_ps = (pi/4)*(0.004^2-0.00216^2);                   %meter^2         || Projected area of seal
F_sfps = (L_ps*fc_ps)+(fh_ps*Ag_ps);                  %Newton          || Frictional force caused by the o-ring

%Equations hand
F_hand = spring_preload+(c_hand*s_handle)+F_sfph+F_sfr;    %Newton     || Amount of force the hand cylinder
must apply to the prosthesis
P_hand = F_hand/A_hand;                               %Pascal          || Pressure in the hand cylinder

%No equations booster due to booster inactivity

%equations shoulder
P_shoulder = P_hand                                                    %Pascal  || Direct connection
between hand and shoulder cylinder meaning they are the same.
F_shoulder = (P_shoulder*A_shoulder)+(c_shoulder*s_shoulder)+F_sfr+F_sfps    %Newton || Force required to
operate the hook prosthetic during motion phase.

%% Activation phase
%seal frictions piston hand
L_ph = 0.006*pi;                                      %meter           || Length of seal rubbing surface
fc_ph = 100;                                          %Newton/meter    || Friction factor due to compression
fh_ph = 90000;                                        %Pascal          || Friction factor due to fluid pressure
Ag_ph = (pi/4)*(0.006^2-0.00416^2);                   %meter^2         || Projected area of seal
F_sfph = (L_ph*fc_ph)+(fh_ph*Ag_ph);                  %Newton          || Frictional force caused by the o-ring

%seal friction rod hand/shoulder
L_r = 0.001*pi;                                       %meter           || Length of seal rubbing surface
fc_r = 100;                                           %Newton/meter    || Friction factor due to compression
fh_r = 90000;                                         %Pascal          || Friction factor due to fluid pressure
Ag_r = (pi/4)*(0.00384^2-0.002^2);                    %meter^2         || Projected area of seal
F_sfr = (L_r*fc_r)+(fh_r*Ag_r);                       %Newton          || Frictional force caused by the o-ring

%seal friction piston shoulder
L_ps = 0.004*pi;                                      %meter           || Length of seal rubbing surface
fc_ps = 100;                                          %Newton/meter    || Friction factor due to compression
fh_ps = 90000;                                        %Pascal          || Friction factor due to fluid pressure
Ag_ps = (pi/4)*(0.004^2-0.00216^2);                   %meter^2         || Projected area of seal
F_sfps = (L_ps*fc_ps)+(fh_ps*Ag_ps);                  %Newton          || Frictional force caused by the o-ring

%variables
F_pinch = 5;                                          %Newton          || Pinching force working on the tip of
the finger
F_spring = (s_handle*c_hand)+spring_preload;          %Newton          || The force applied by the return
spring in the hand cylinder in the worst case scenario of the hook prosthetic being completely closed.
F_hand = (F_pinch*r_pinch)/r_handle;                  %Newton          || Force applied by the hand cylinder to
acquire the beforementioned pinching force

F_handle = F_hand+F_spring+F_sfph+F_sfr;              %Newton          || Total amount of force applied by the
hand cylinder
P_hand = F_handle/A_hand;                             %Pascal          || Pressure in the hand cylinder

%equations shoulder
P_shoulder = P_hand;                                                   %Pascal   || Pressure in the
shoulder cylinder
F_shoulder = (P_shoulder*A_shoulder)+(c_shoulder*s_shoulder)+F_sfr+F_sfps    %Newton  || Force applied on
the shoulder cylinder

%preload of the booster
P_switch = P_shoulder                                 %Pascal          || Pressure at which the booster
must activate
preload_booster = P_switch*A_in                       %Newton          || Preload the booster requires to
activate with the pinching force in this scenario.
```

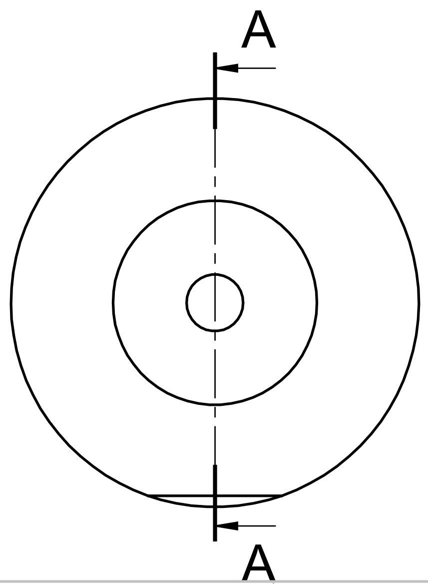
```
%% Pinching phase
%seal frictions piston hand
L_ph = 0.006*pi;                                %meter         || Length of seal rubbing surface
fc_ph = 100;                                    %Newton/meter  || Friction factor due to compression
fh_ph = 90000;                                  %Pascal        || Friction factor due to fluid pressure
Ag_ph = (pi/4)*(0.006^2-0.00416^2);             %meter^2       || Projected area of seal
F_sfph = (L_ph*fc_ph)+(fh_ph*Ag_ph);            %Newton        || Frictional force caused by the o-
ring

%seal friction rod hand/shoulder
L_r = 0.001*pi;                                 %meter         || Length of seal rubbing surface
fc_r = 100;                                     %Newton/meter  || Friction factor due to compression
fh_r = 90000;                                   %Pascal        || Friction factor due to fluid pressure
Ag_r = (pi/4)*(0.00384^2-0.002^2);              %meter^2       || Projected area of seal
F_sfr = (L_r*fc_r)+(fh_r*Ag_r);                 %Newton        || Frictional force caused by the o-ring

%seal friction piston shoulder/booster in
L_ps = 0.004*pi;                                %meter         || Length of seal rubbing surface
fc_ps = 100;                                    %Newton/meter  || Friction factor due to compression
fh_ps = 90000;                                  %Pascal        || Friction factor due to fluid pressure
Ag_ps = (pi/4)*(0.004^2-0.00216^2);             %meter^2       || Projected area of seal
F_sfps = (L_ps*fc_ps)+(fh_ps*Ag_ps);            %Newton        || Frictional force caused by the o-ring

%seal friction booster out
L_ps = 0.002*pi;                                %meter         || Length of seal rubbing surface
fc_ps = 100;                                    %Newton/meter  || Friction factor due to compression
fh_ps = 90000;                                  %Pascal        || Friction factor due to fluid pressure
Ag_ps = (pi/4)*(0.00384^2-0.002^2);             %meter^2       || Projected area of seal
F_sfbo = (L_ps*fc_ps)+(fh_ps*Ag_ps);            %Newton        || Frictional force caused by the o-ring

%equations hand cylinder
F_pinch = 30;                                   %Newton     || Pinching force working on the tip of
the finger
F_spring = s_handle*c_hand+spring_preload;      %Newton     || The force applied by the return spring
in the hand cylinder in the worst case scenario of the hook prosthetic being completely closed.
F_hand = (F_pinch*r_pinch)/r_handle;            %Newton     || Force applied by the hand cylinder to
acquire the beforementioned pinching force

F_handle = F_hand+F_spring+F_sfph+F_sfr;        %Newton     || Total amount of force applied by the
hand cylinder
P_hand = F_handle/A_hand;                       %Pascal     || Pressure in the hand cylinder

%equations booster while active
P_out = P_hand                                                      %Pascal    || Pressure in booster
chamber 2
F_booster = P_out*A_out;                                            %Newton    || Force applied on the
booster rod by the fluid pressure
F_in = F_booster+preload_booster+s_booster*c_booster+F_sfbo+F_sfps+F_sfbo;   %Newton    || Total force applied on
the booster rod
P_in = F_in/A_in                                                    %Pascal    || Pressure in booster
chamber 1

%equations shoulder cylinder
P_shoulder = P_in;                                                       %Pascal   || Pressure in the
shoulder cylinder
F_shoulder = (P_shoulder*A_shoulder)+(c_shoulder*s_shoulder)+F_sfr+F_sfps    %Newton  || Force applied on the
shoulder cylinder
```

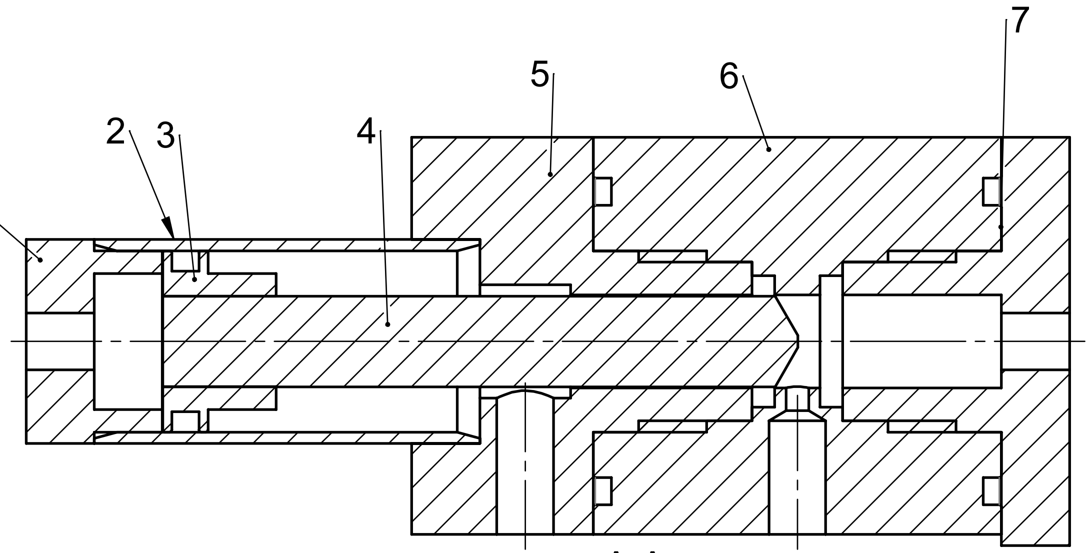
F. Technical Drawings

Booster drawings

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Booster big end		1
2	Booster big cylinder		1
3	Booster pin shaft head		1
4	Booster pin shaft		1
5	Booster middle connect		1
6	Booster small cylinder		1
7	Booster small end		1



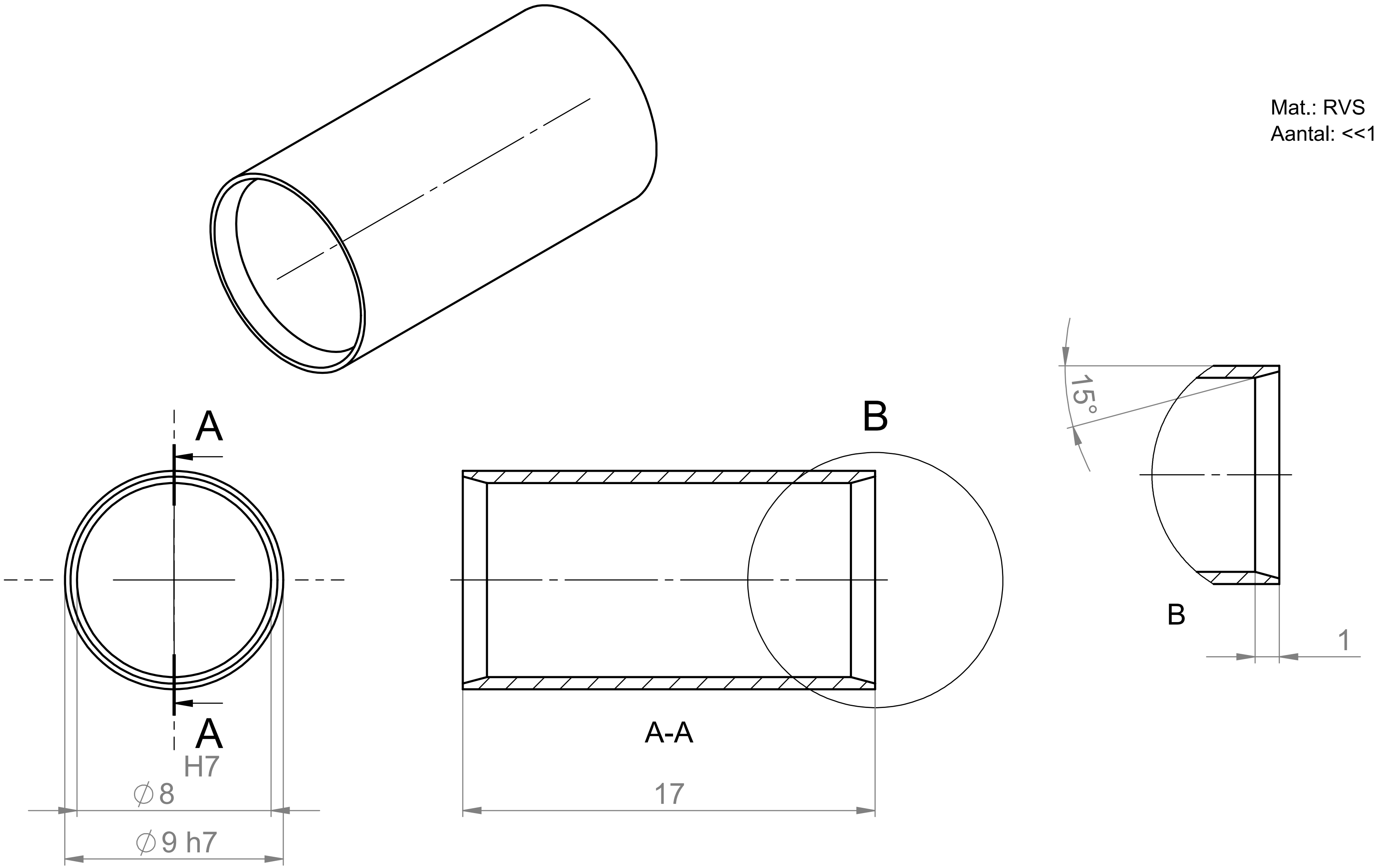




A-A

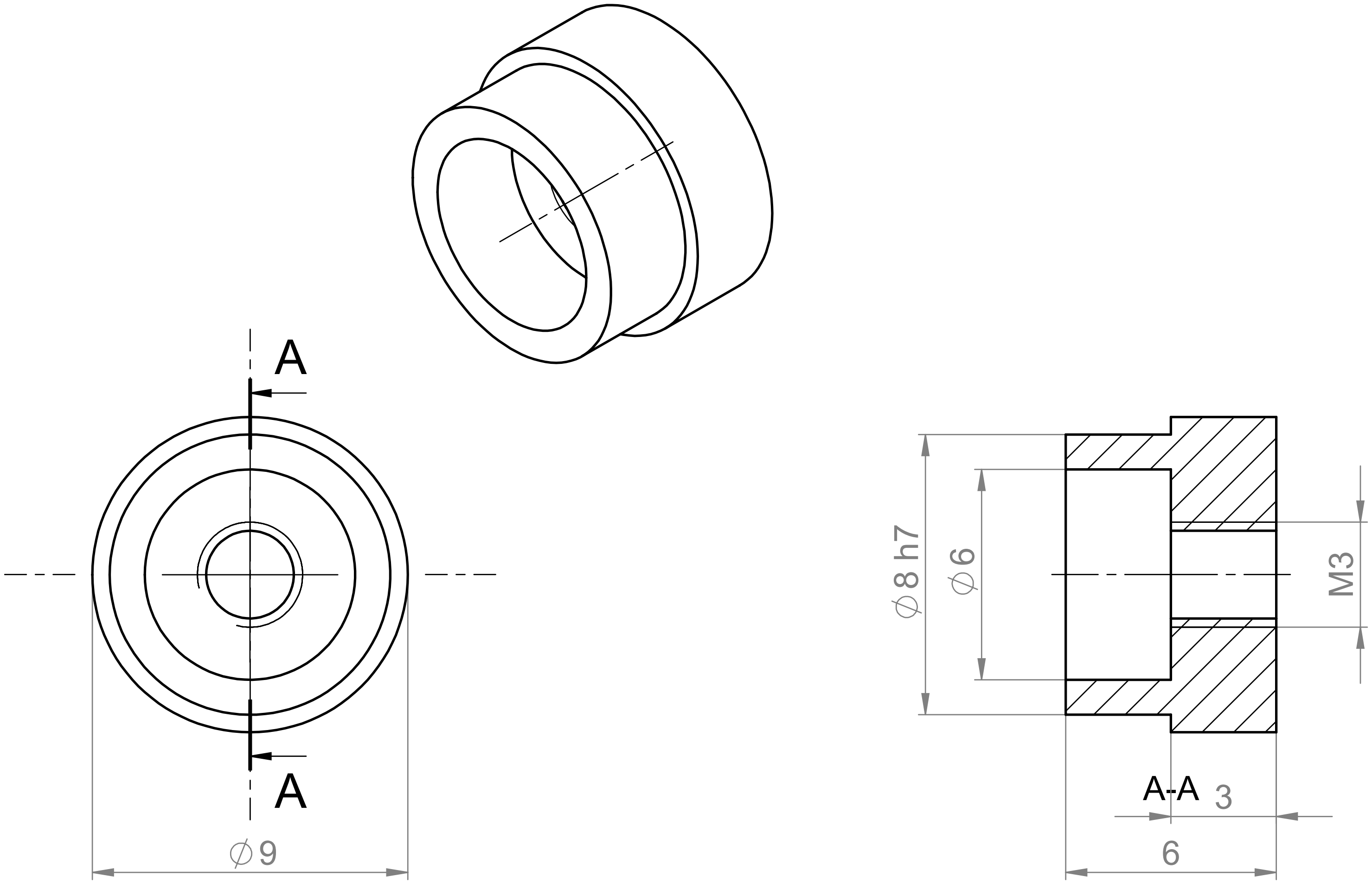
TU Delft Industrial Design Engineering	benaming: Booster assambly	datum: 23/07/2020	schaal: 3:1	maateenheid: mm
		getekend: <<(achter)namen & studienummers>>	groep: <<dagdeel>>	gewicht: 61 gram
			formaat: A4	tekening nr. / opmerkingen: <<tekeningnummer>>

Mat.: RVS
Aantal: <<1>>

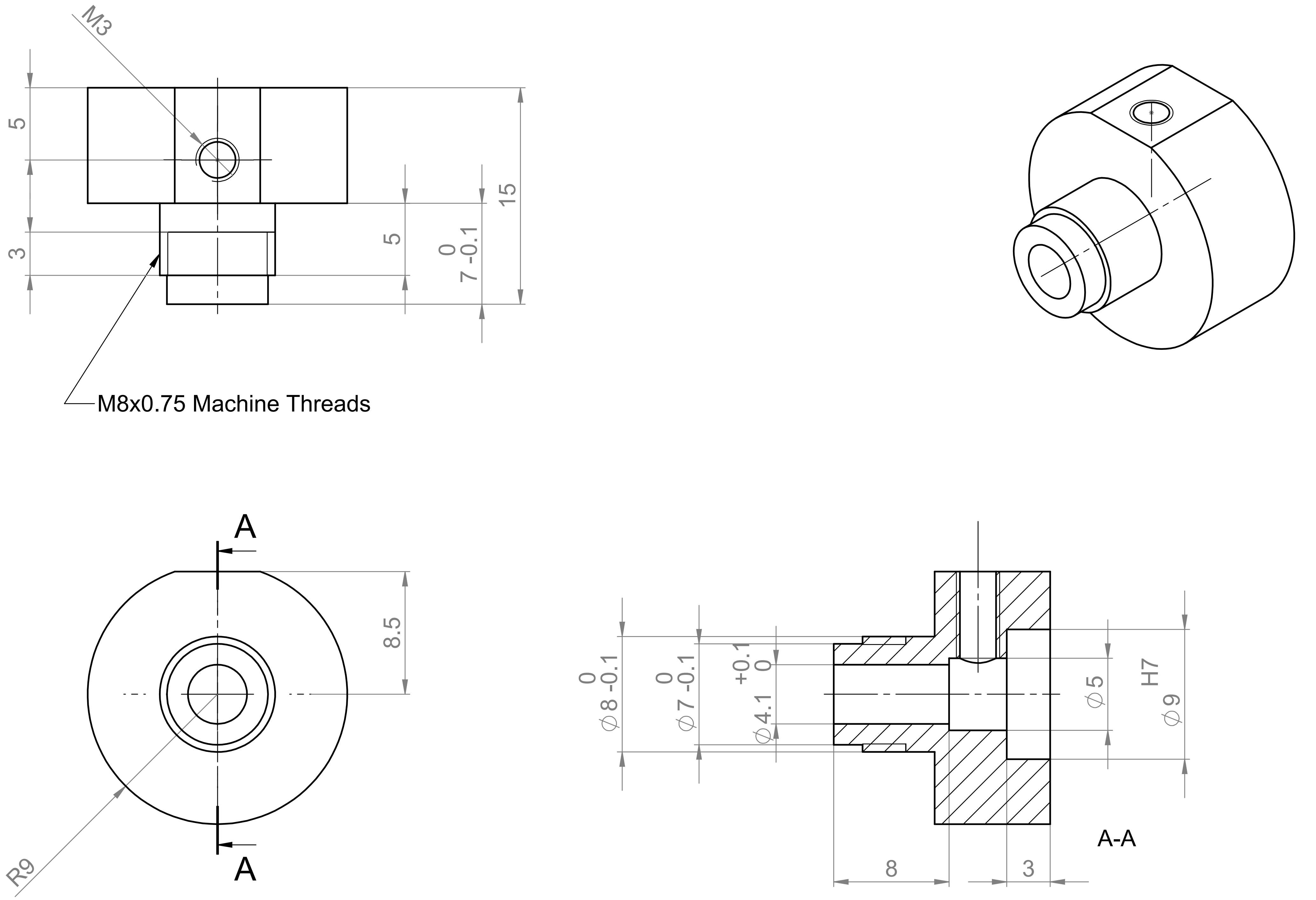


TU Delft	benaming	datum 23/07/2020		schaal 4:1	maateenheid mm
Industrial Design Engineering	Booster big cylinder	getekend	groep <<dagdeel>>	formaat A4	gewicht 2 gram
		<<(achter)namen & studienummers>>			tekening nr. / opmerkingen <<tekeningnummer>>

Mat.: RVS
Aantal: <<1 >>



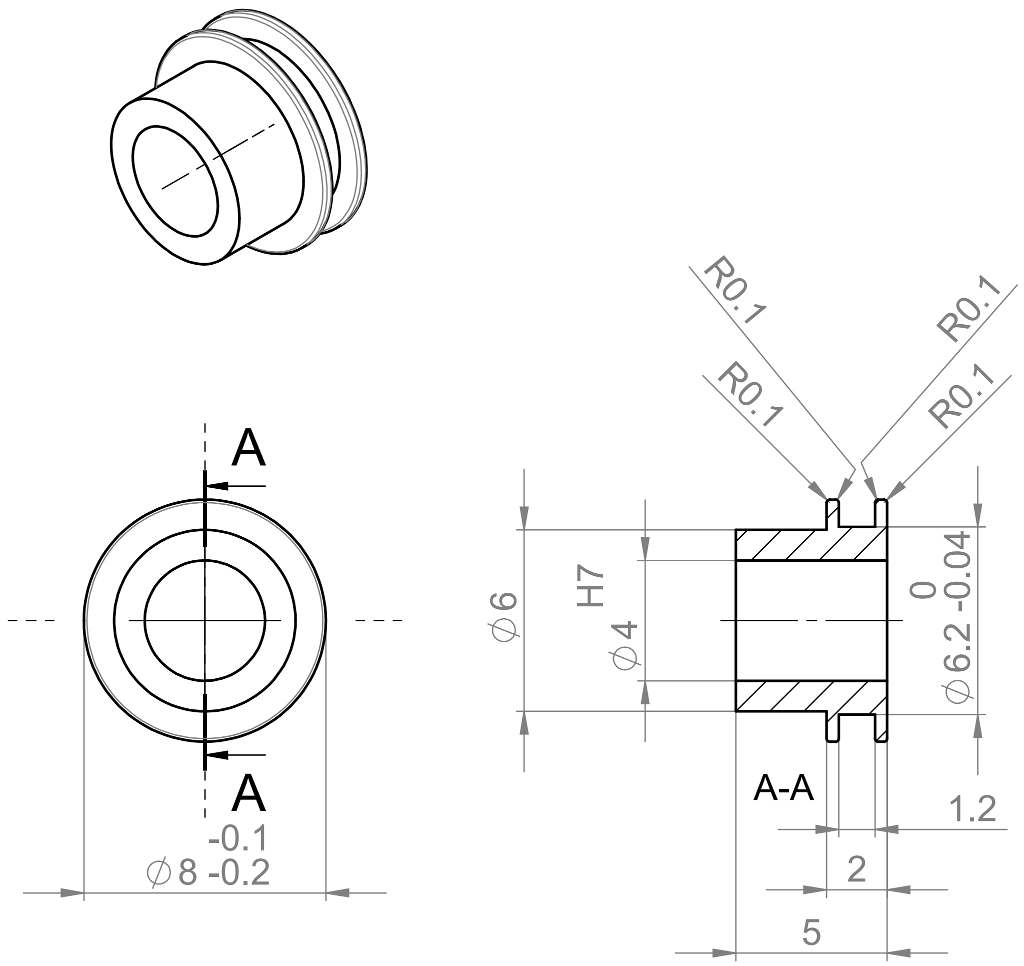
TU Delft Industrial Design Engineering	benaming Booster big end	datum 23/07/2020		schaal 5:1	maateenheid mm
		getekend	groep <<dagdeel>>	formaat A4	gewicht 2 gram
		<<(achter)namen & studienummers>>			tekening nr. / opmerkingen <<tekeningnummer>>



Mat.: RVS
Aantal: <<1>>

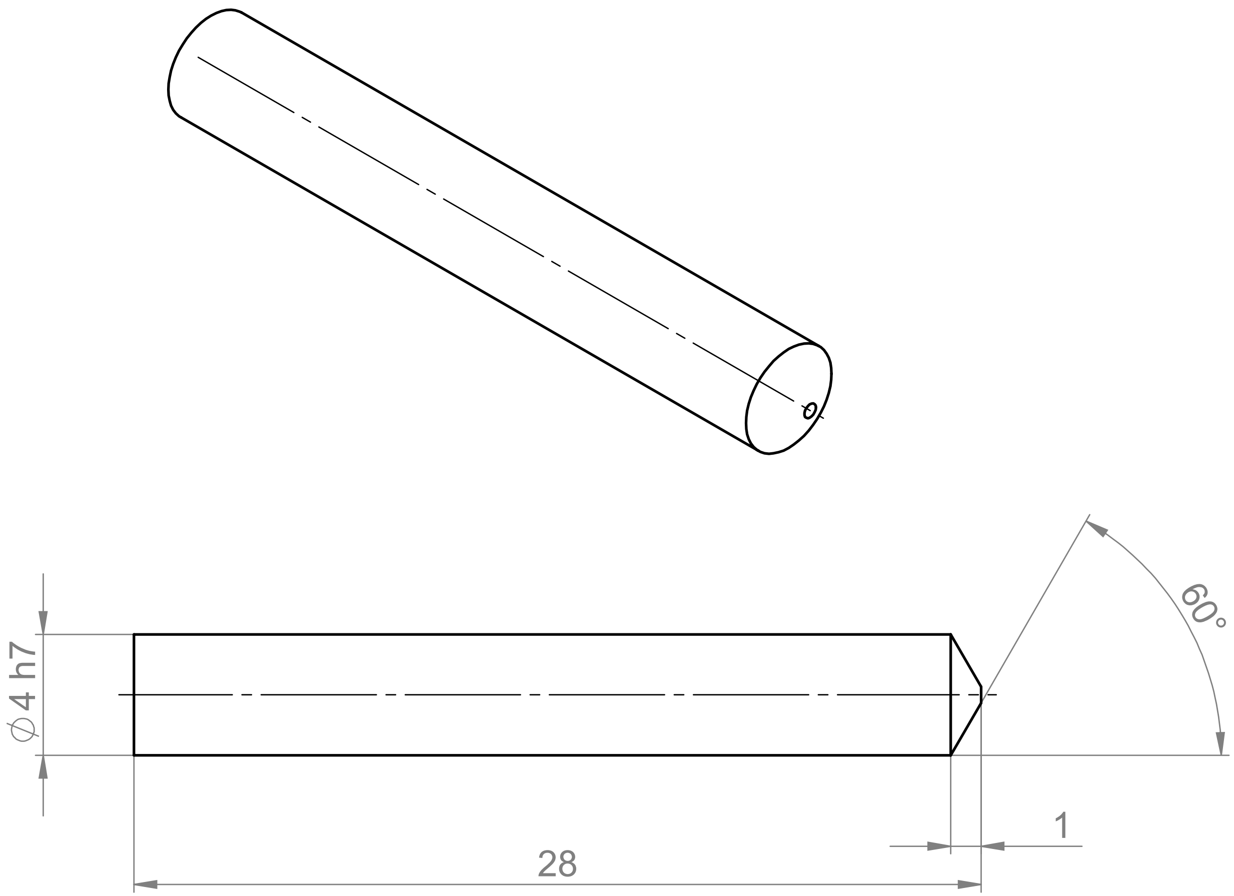
schaal 3:1		datum 23/07/2020	opmerkingen <<opmerkingen>>
maateenheid mm	gewicht 16 gram		
getekend <<(achter)namen & studienummers>>		groep <<dagdeel groep>>	
benaming Booster middle connect			
TU Delft Industrial Design Engineering		formaat A3	tekeningnummer <<tekeningnr>>

Mat.: RVS
Aantal: <<1>>

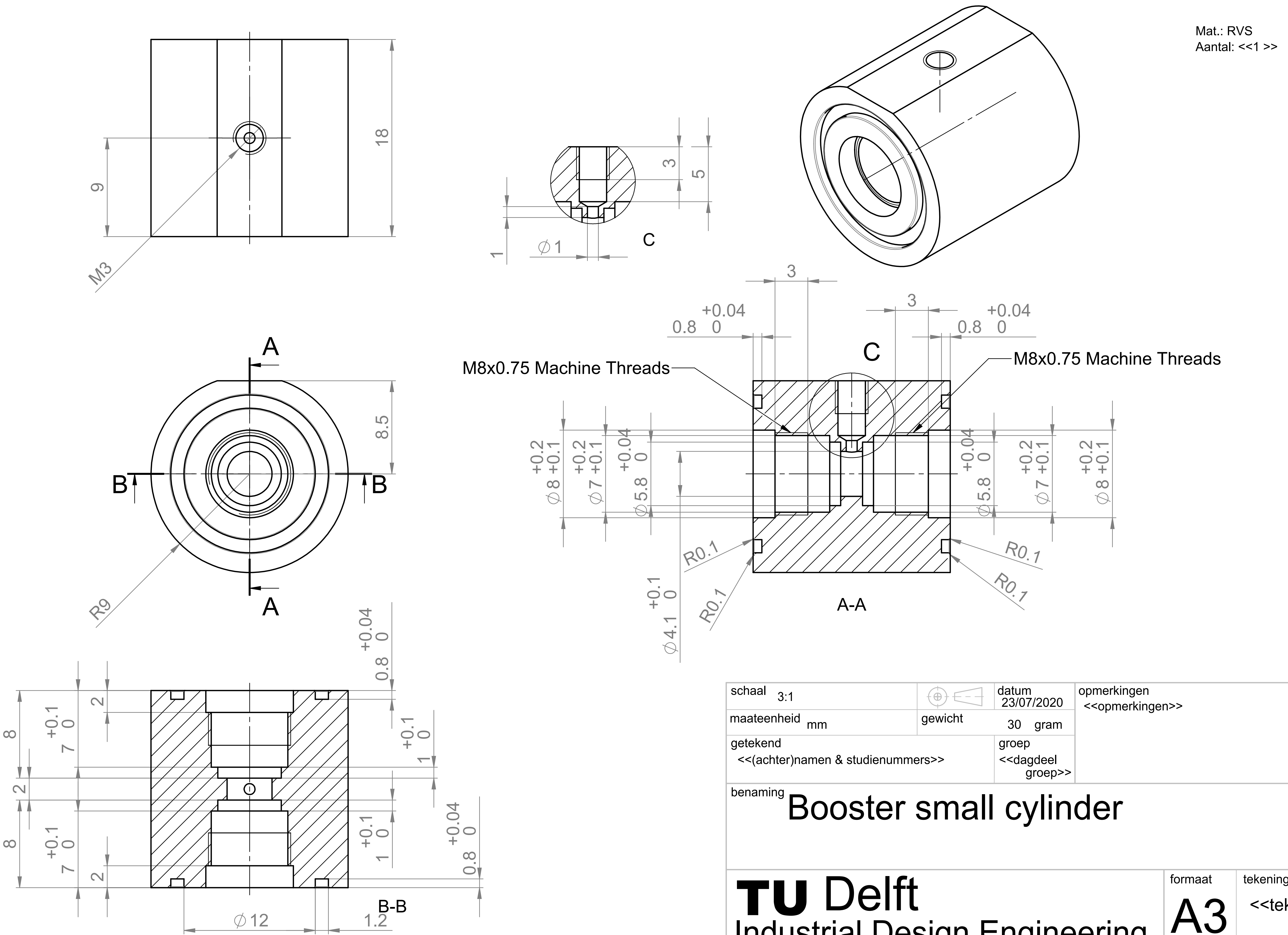


TU Delft Industrial Design Engineering	benaming: Booster pin shaft head	datum: 23/07/2020	schaal: 4:1	maateenheid: mm
		getekend: <<(achter)namen & studienummers>>	groep: <<dagdeel>>	gewicht: 1 gram
			formaat: A4	tekening nr. / opmerkingen: <<tekeningnummer>>

Mat.: RVS
Aantal: << 1>>



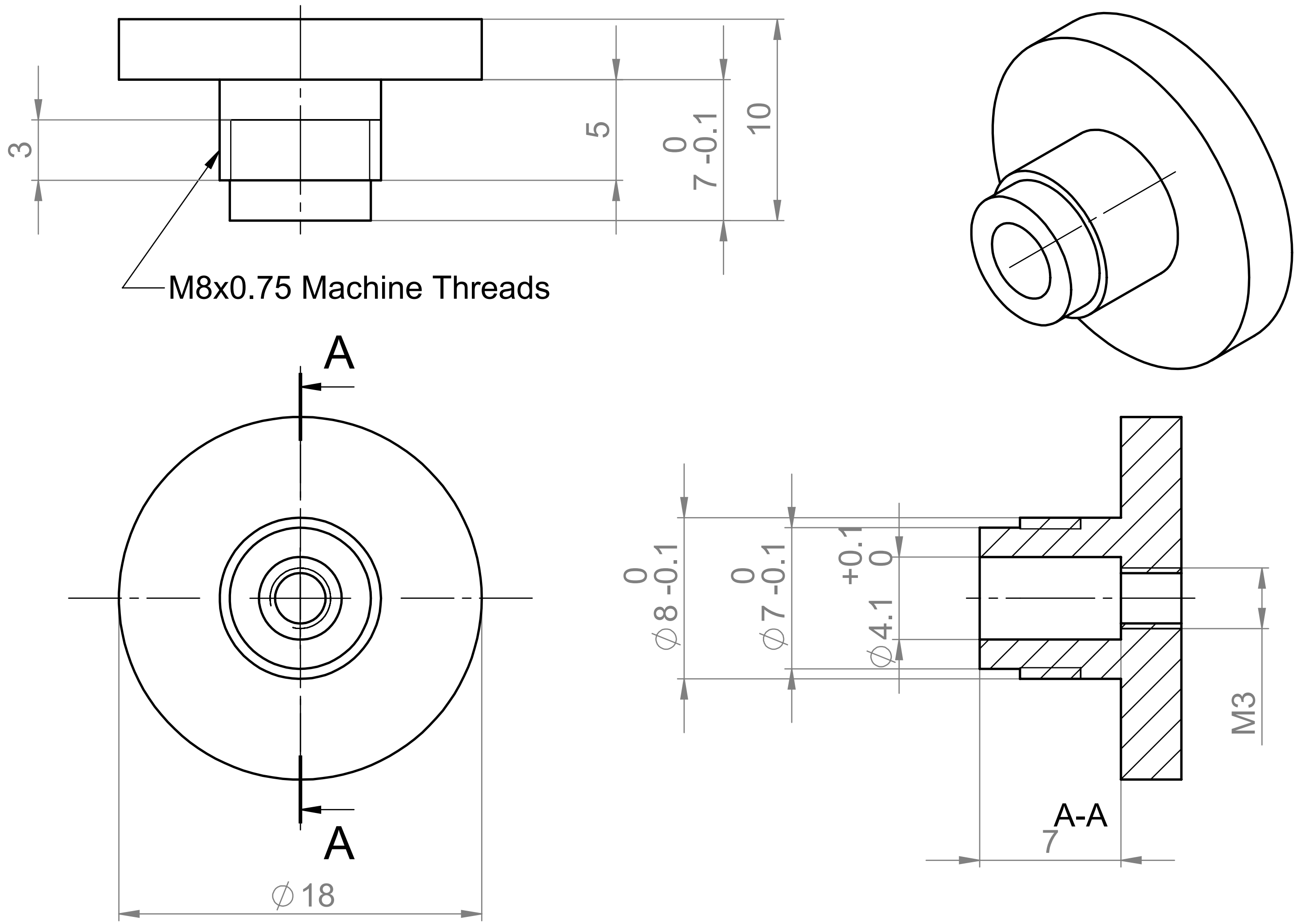
TU Delft Industrial Design Engineering	benaming Booster pin shaft	datum 23/07/2020		schaal 4:1	maateenheid mm
		getekend	groep <<dagdeel>>	formaat A4	gewicht 3 gram
		<<(achter)namen & studienummers>>			tekening nr. / opmerkingen <<tekeningnummer>>



schaal 3:1		datum 23/07/2020	opmerkingen <<opmerkingen>>
maateenheid mm	gewicht 30 gram		
getekend <<(achter)namen & studienummers>>		groep <<dagdeel groep>>	

benaming **Booster small cylinder**

TU Delft Industrial Design Engineering	formaat A3	tekeningnummer <<tekeningnr>>

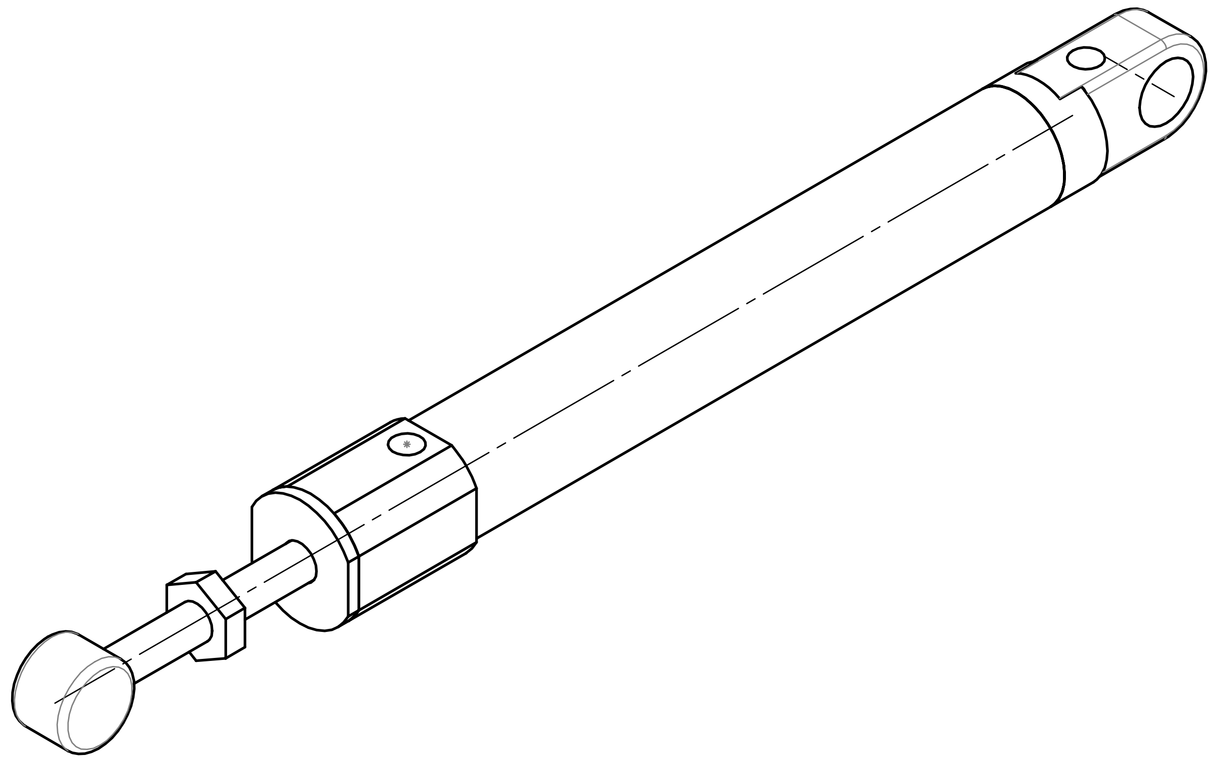


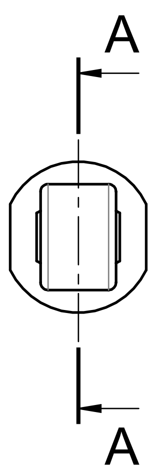
Mat.: RVS
Aantal: <<1 >>

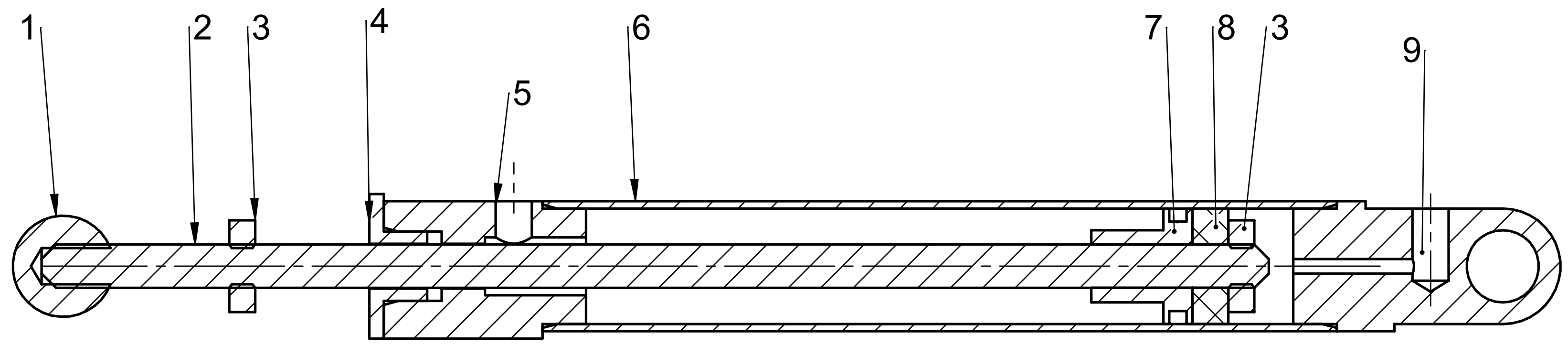
TU Delft Industrial Design Engineering	benaming Booster small end	datum 23/07/2020		schaal 3:1	maateenheid mm
		getekend	groep <<dagdeel>>	formaat A4	gewicht 8 gram
		<<(achter)namen & studienummers>>			tekening nr. / opmerkingen <<tekeningnummer>>

Hand cylinder drawings

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Hand prosthesis end attachment		1
2	Hand plunger rod		1
3	ISO - 4036 - M3 - N		2
4	Hand cylinder outer seal end		1
5	Hand cylinder inner seal end		1
6	Hand cylinder		1
7	Hand plunger head		1
8	Hand teflon ring		1
9	Hand cylinder end		1







A-A

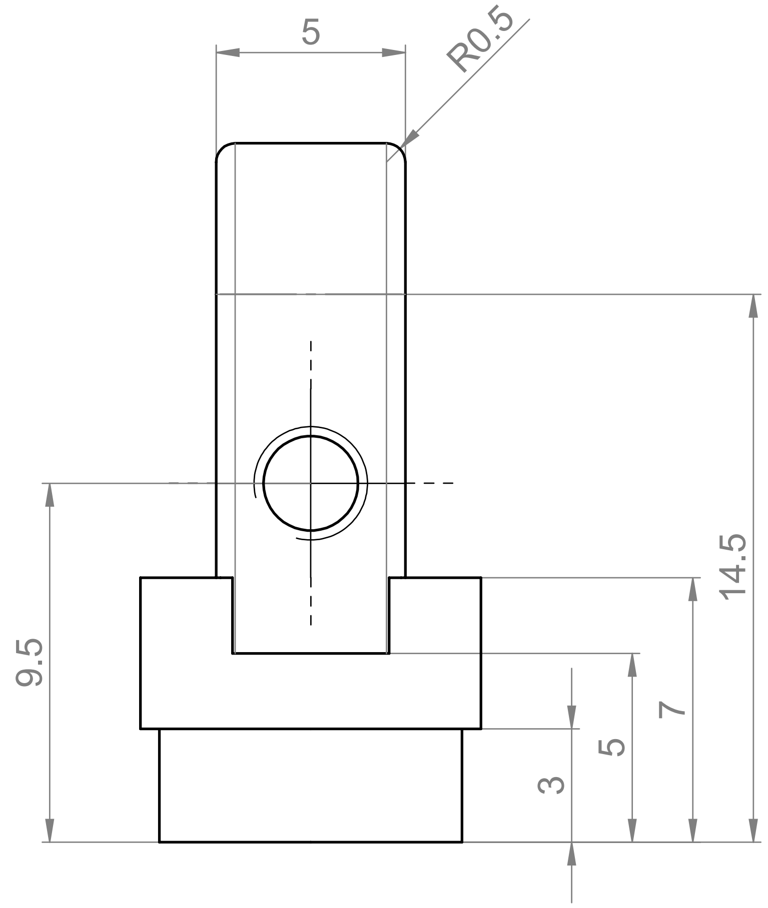
schaal 2:1		datum 23/07/2020	opmerkingen <<opmerkingen>>
maateenheid mm	gewicht 26 gram		
getekend <<(achter)namen & studienummers>>		groep <<dagdeel groep>>	

benaming **Hand cylinder assambly**

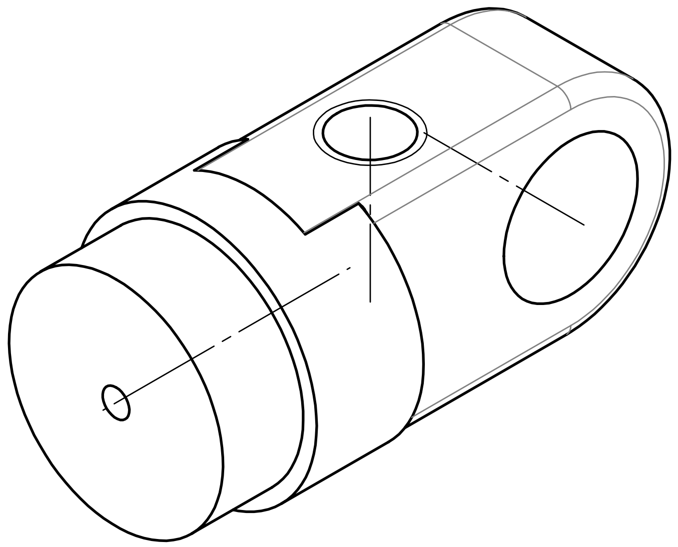
TU Delft
Industrial Design Engineering

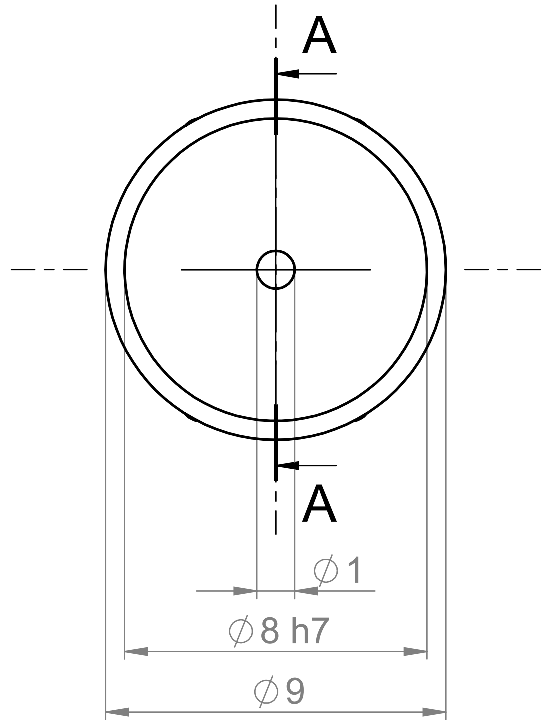
formaat A3

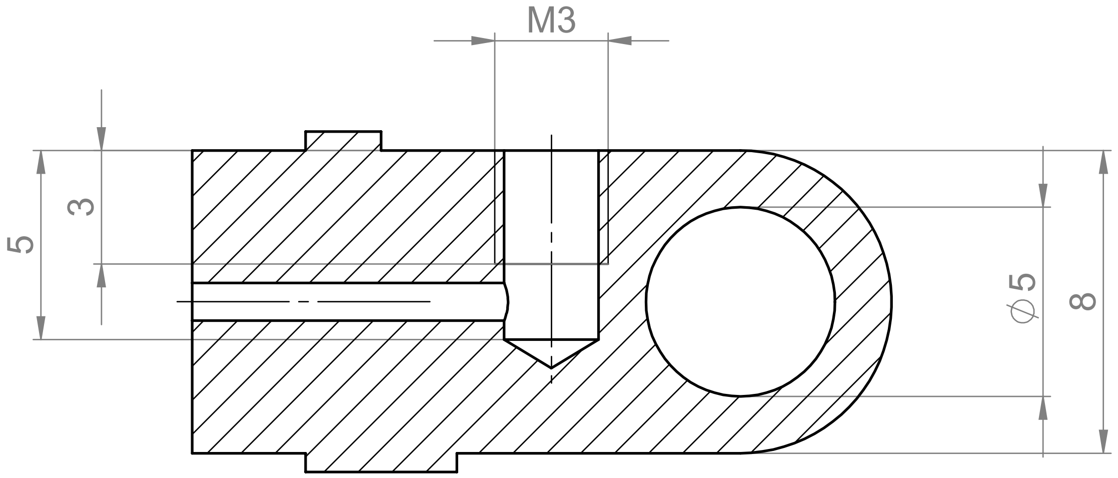
tekeningnummer <<tekeningnr>>



Mat.: RVS
Aantal: <<1 >>







A-A

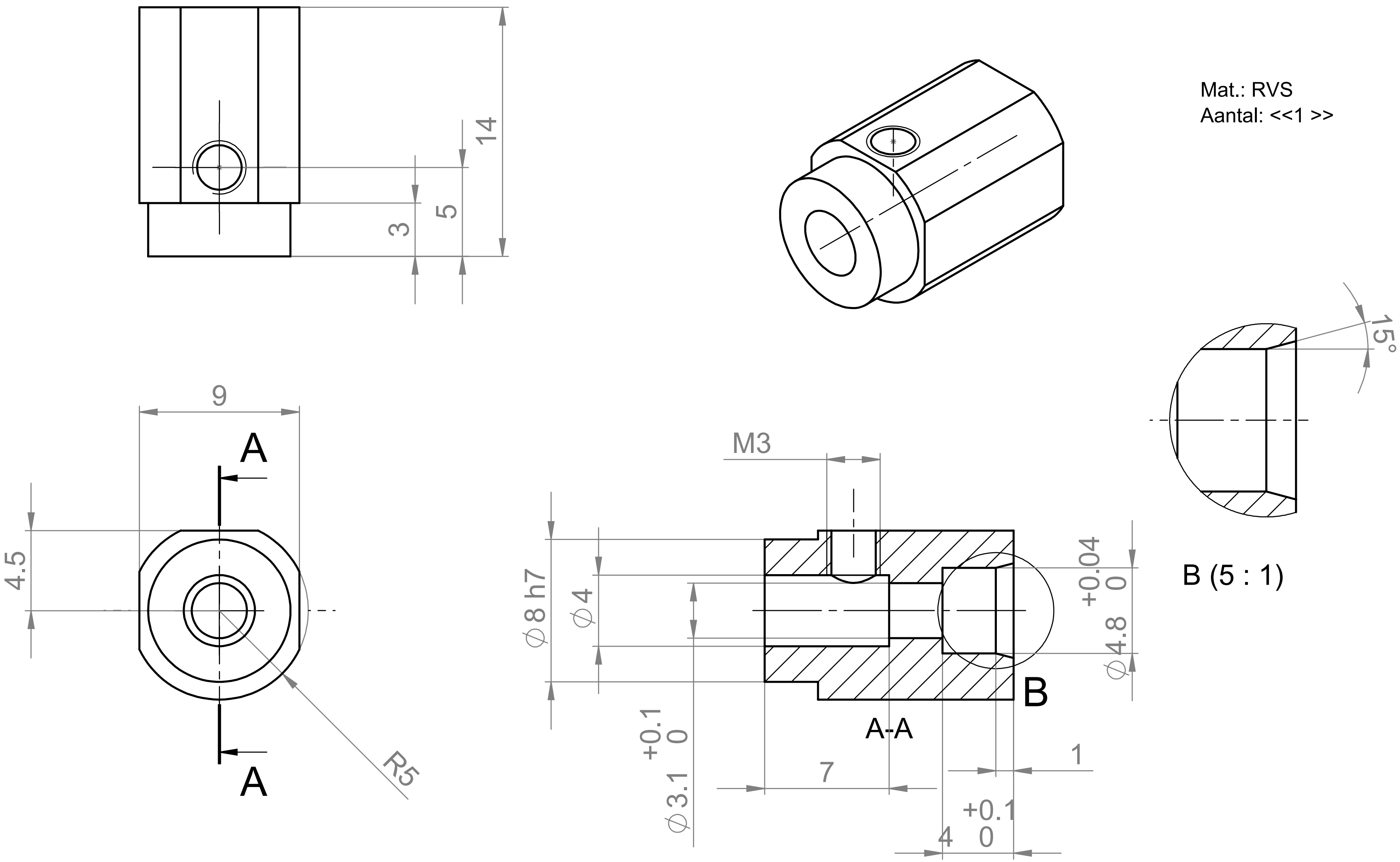
schaal 5:1		datum 23/07/2020	opmerkingen <<opmerkingen>>
maateenheid mm	gewicht 6 gram		
getekend <<(achter)namen & studienummers>>		groep <<dagdeel groep>>	

benaming **Hand cylinder end**

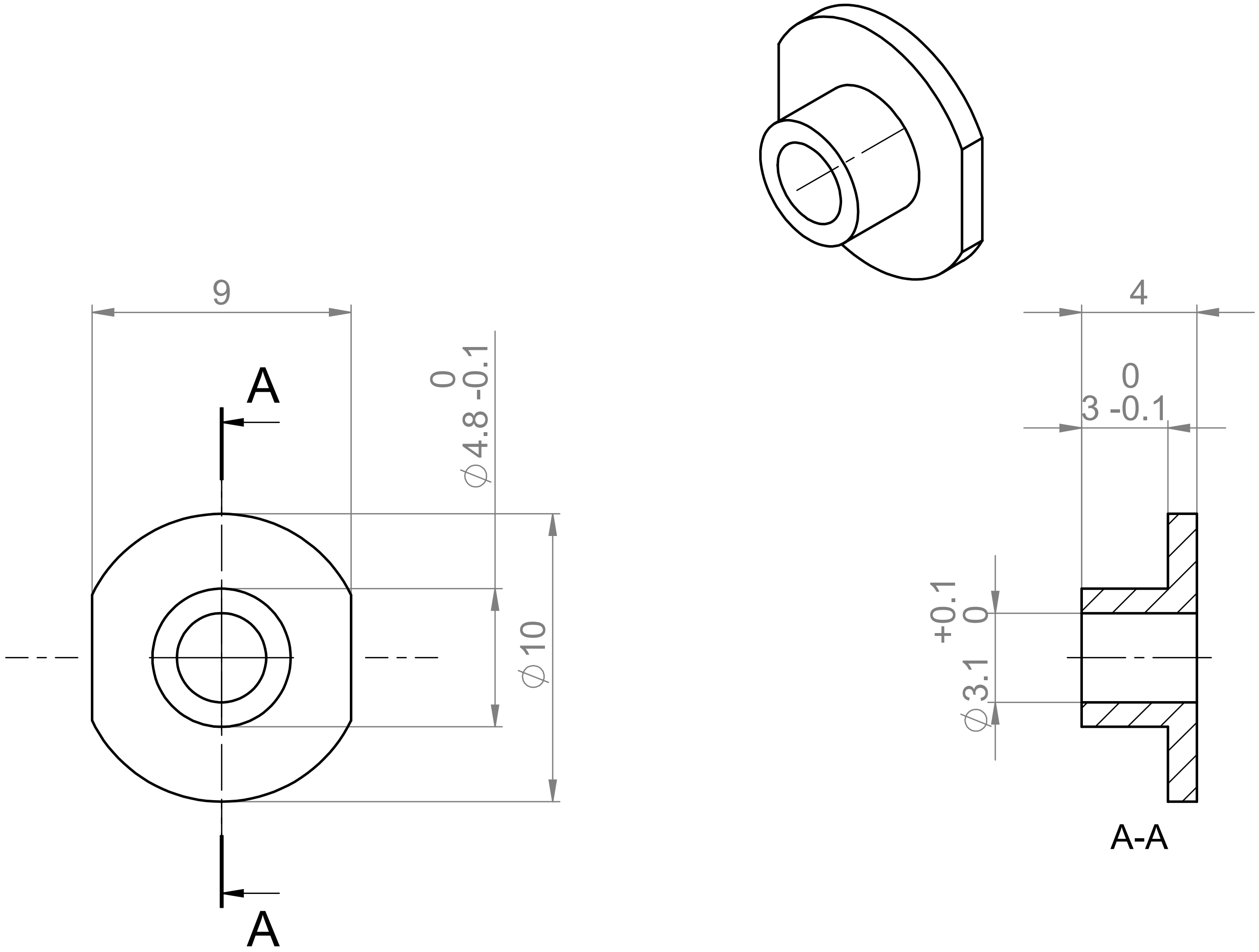
TU Delft
Industrial Design Engineering

formaat A3

tekeningnummer <<tekeningnr>>

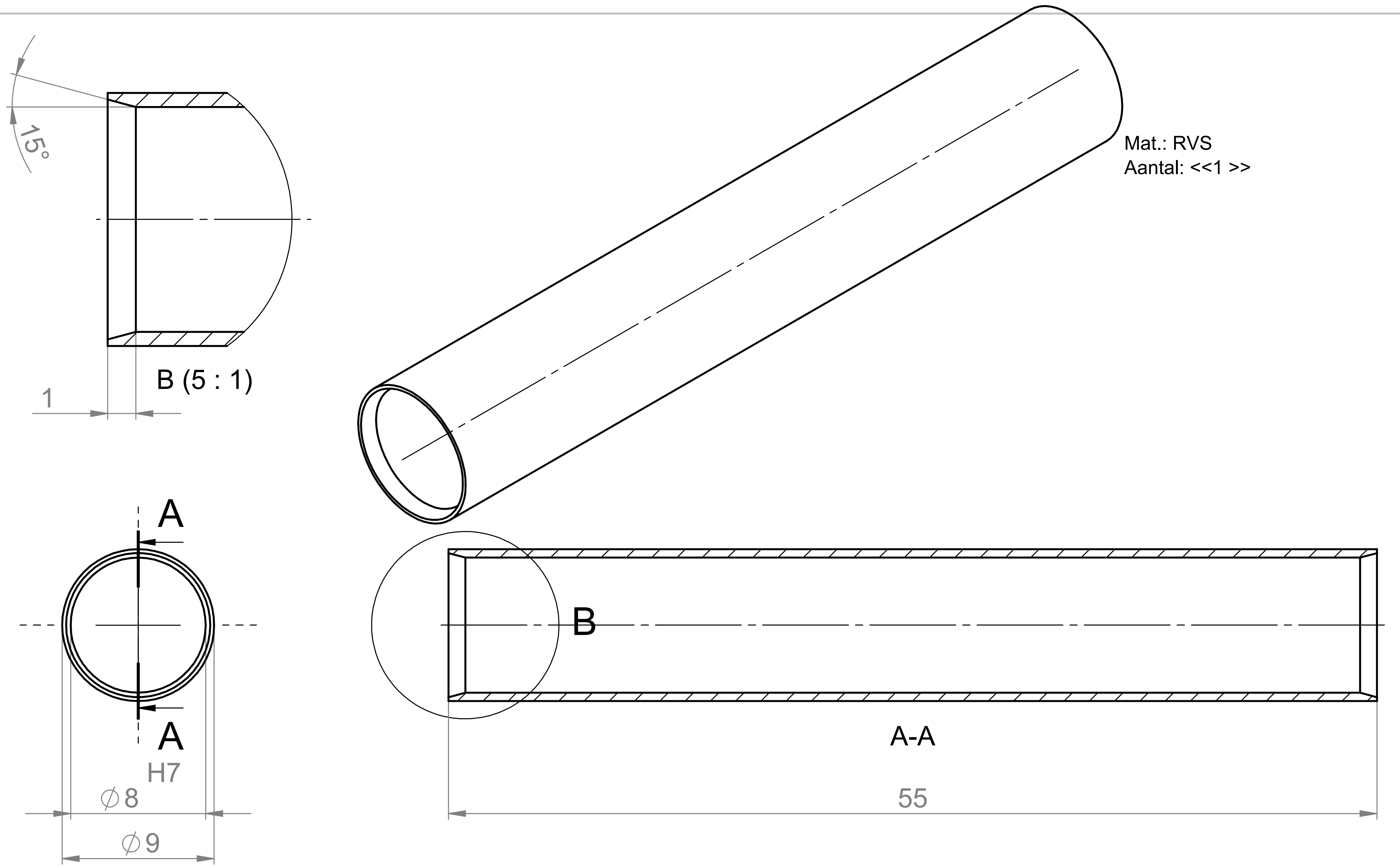


TU Delft Industrial Design Engineering	benaming Hand cylinder inner seal end	datum 23/07/2020		schaal 3:1	maateenheid mm
		getekend	groep <<dagdeel>>	formaat	gewicht 6 gram
		<<(achter)namen & studienummers>>		A4	tekening nr. / opmerkingen <<tekeningnummer>>

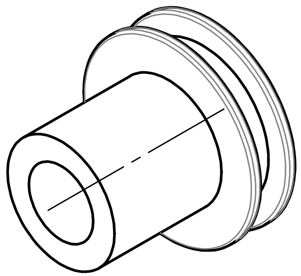


Mat.: RVS
Aantal: << 1>>

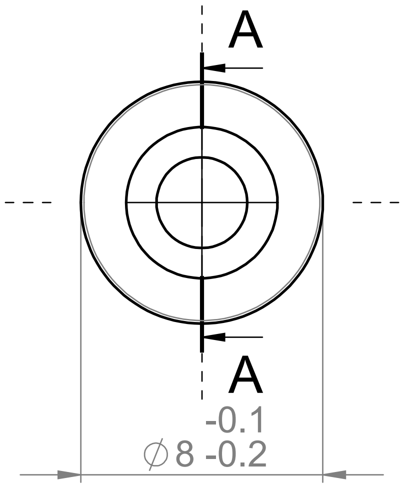
TU Delft Industrial Design Engineering	benaming Hand cylinder outer seal end	datum 23/07/2020		schaal 4:1	maateenheid mm
		getekend <<(achter)namen & studienummers>>	groep <<dagdeel>>	formaat A4	gewicht 1 gram
					tekening nr. / opmerkingen <<tekeningnummer>>

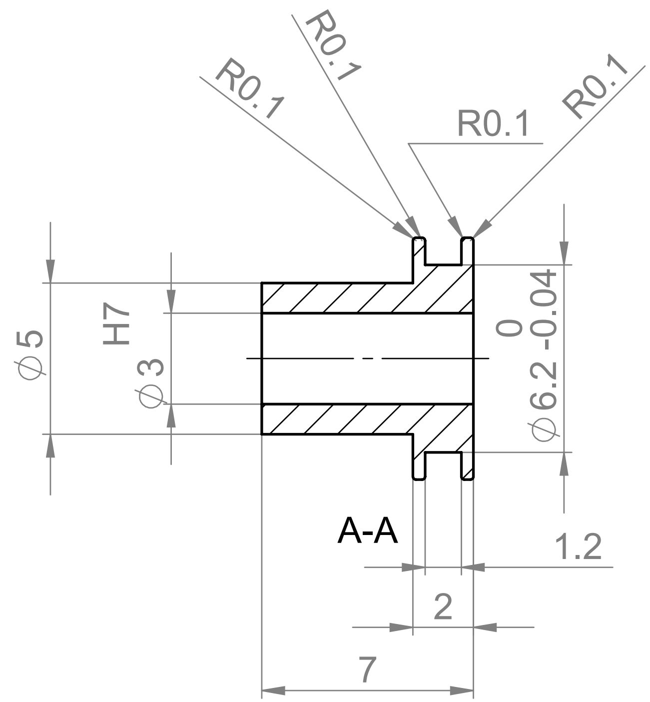


TU Delft Industrial Design Engineering	benaming Hand cylinder	datum 23/07/2020		schaal 3:1	maateenheid mm
		getekend	groep <<dagdeel>>	formaat A4	gewicht 6 gram
		<<(achter)namen & studienummers>>			tekening nr. / opmerkingen <<tekeningnummer>>

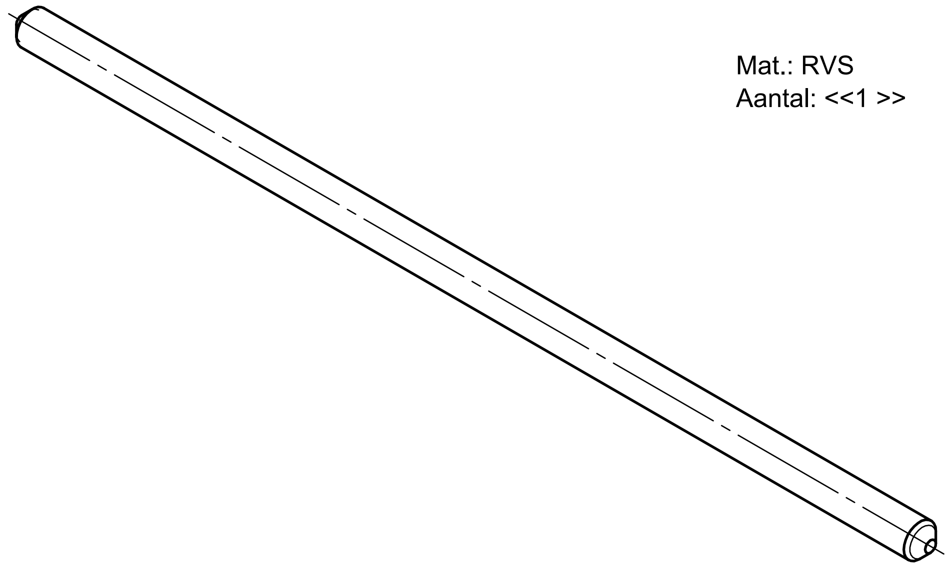


Mat.: RVS
Aantal: << 1>>

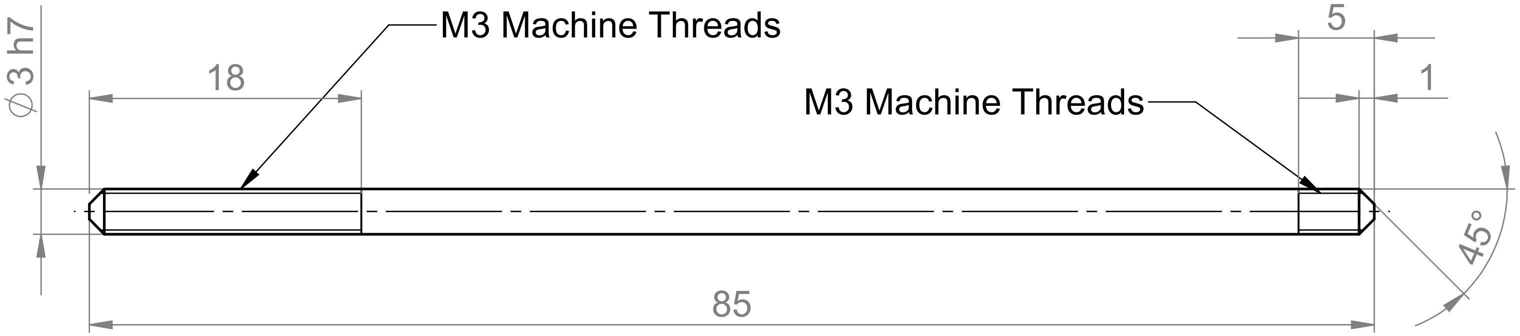




TU Delft Industrial Design Engineering	benaming: Hand plunger head	datum 23/07/2020		schaal 4:1	maateenheid mm
		getekend	groep <<dagdeel>>	formaat A4	gewicht 1 gram
		<<(achter)namen & studienummers>>			tekening nr. / opmerkingen <<tekeningnummer>>

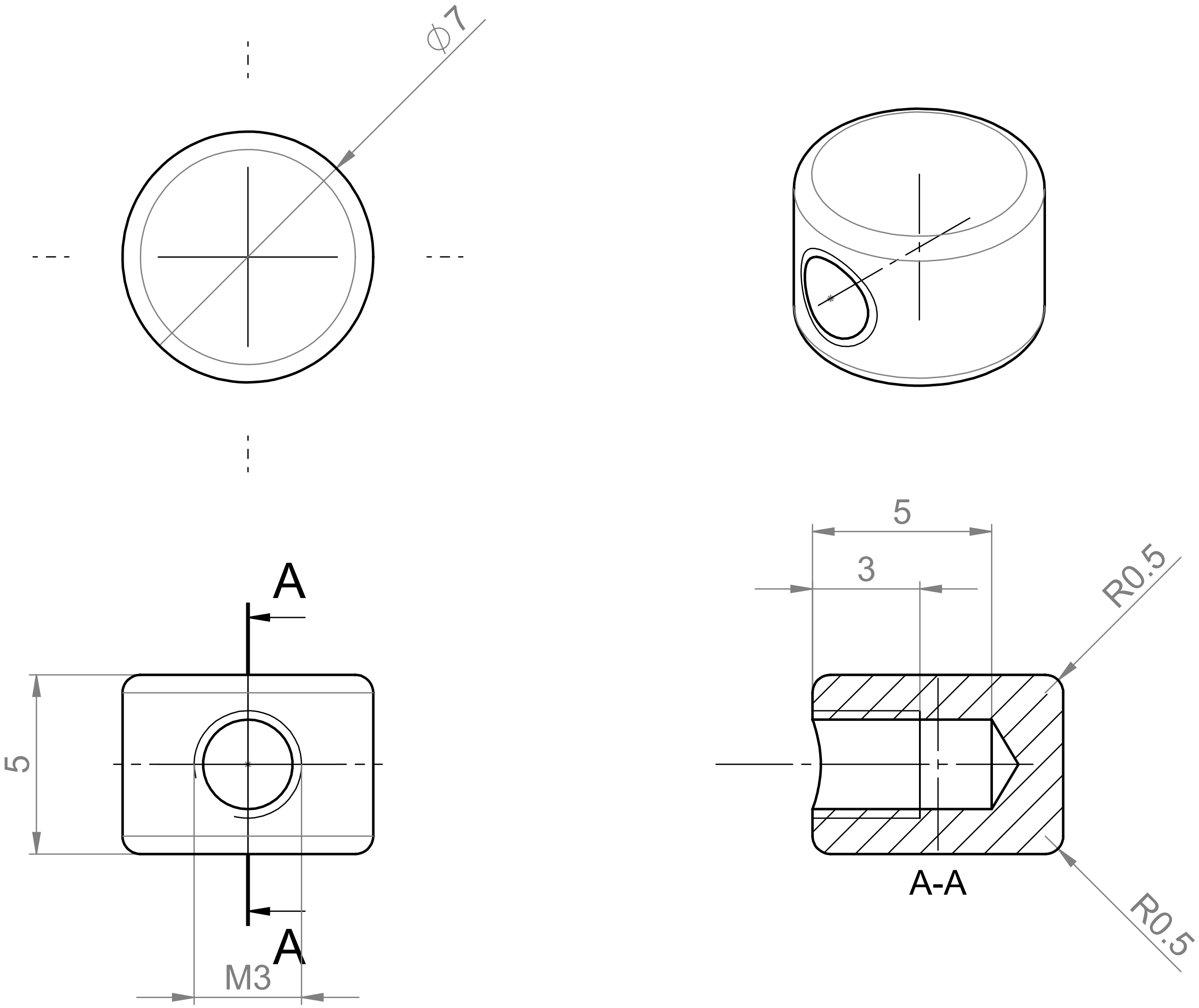


Mat.: RVS
Aantal: <<1 >>



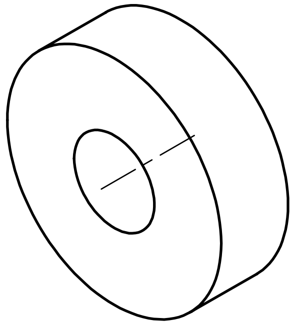
TU Delft Industrial Design Engineering	benaming # Hand plunger rod	datum 23/07/2020		schaal 2:1	maateenheid mm
		getekend <<(achter)namen & studienummers>>	groep <<dagdeel>>	formaat A4	gewicht 5 gram
					tekening nr. / opmerkingen <<tekeningnummer>>

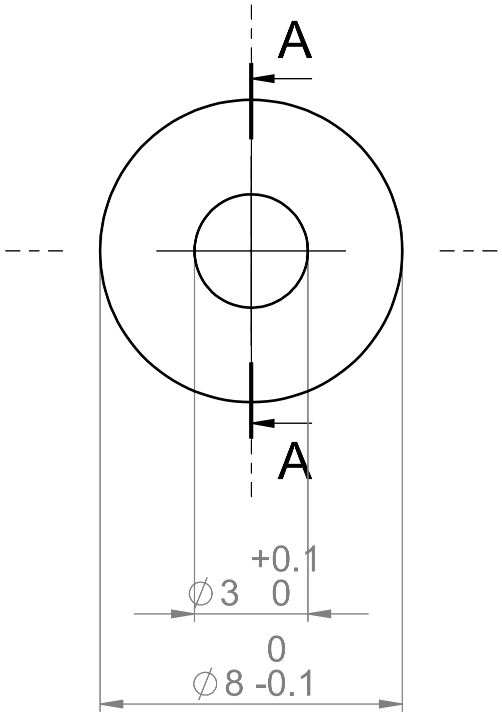
Mat.: RVS
Aantal: <<1 >>

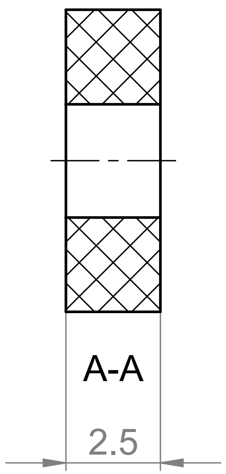


TU Delft Industrial Design Engineering	benaming Hand prosthesis end attachment	datum 23/07/2020		schaal 5:1	maateenheid mm
		getekend	groep <<dagdeel>>	formaat A4	gewicht 1 gram
		<<(achter)namen & studienummers>>			tekening nr. / opmerkingen <<tekeningnummer>>

Mat.: PTFE (general)
Aantal: <<1>>



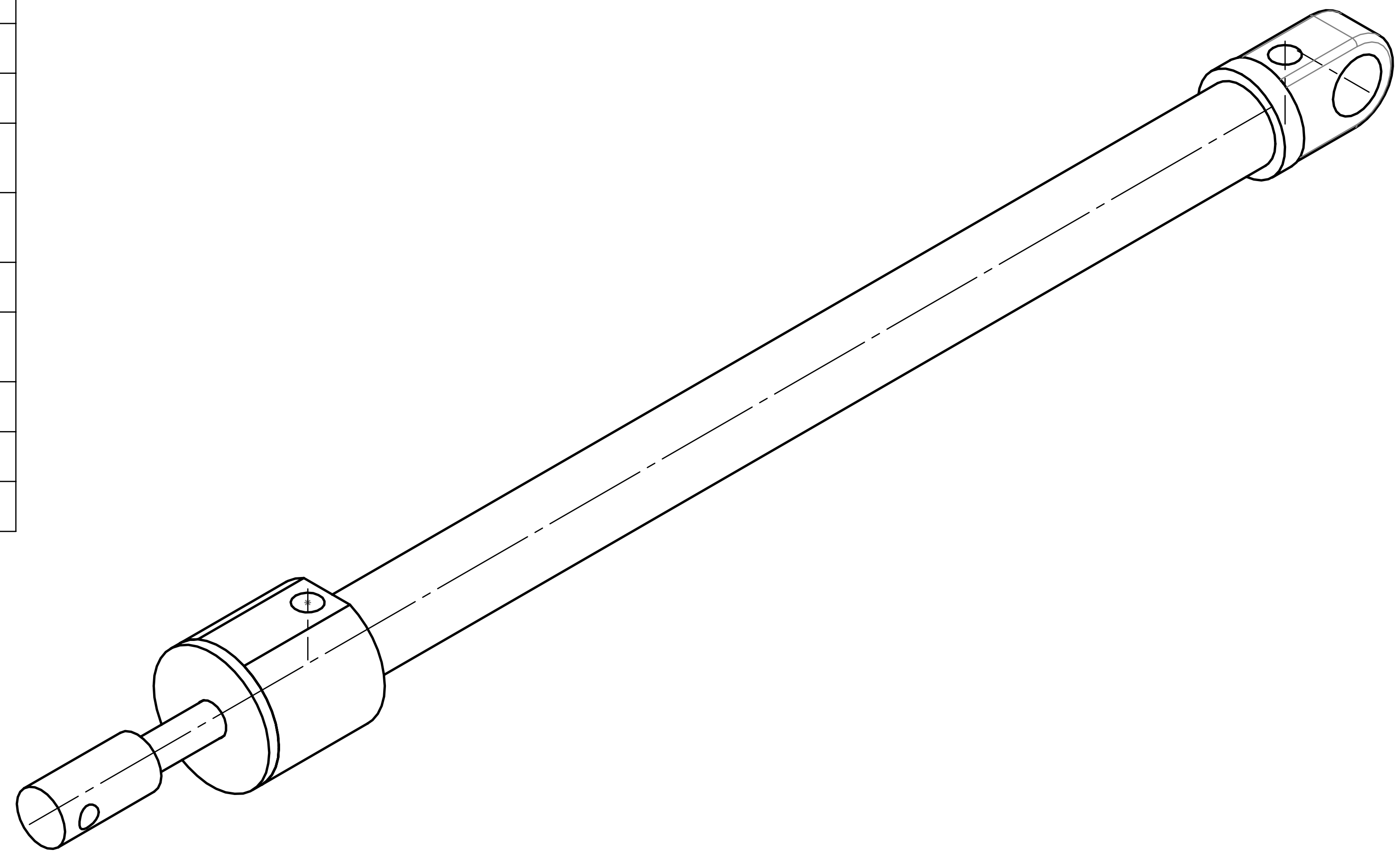


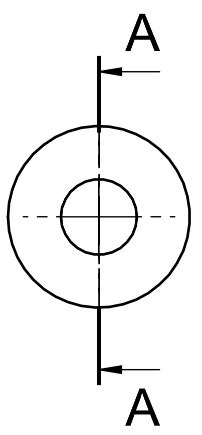


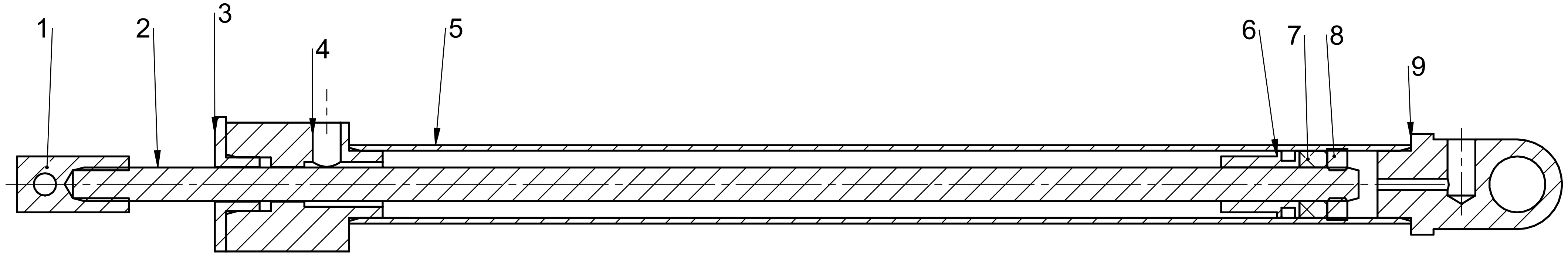
TU Delft Industrial Design Engineering	benaming **Hand teflon ring**	datum 23/07/2020		schaal 5:1	maateenheid mm
		getekend <<(achter)namen & studienummers>>	groep <<dagdeel>>	formaat A4	gewicht 0 gram
					tekening nr. / opmerkingen <<tekeningnummer>>

Shoulder cylinder drawings

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Cable attachment		1
2	Shoulder plunger rod		1
3	Shoulder cylinder outer seal end		1
4	Shoulder cylinder inner seal end		1
5	Shoulder cylinder		1
6	Shoulder plunger head		1
7	Shoulder teflon ring		1
8	ISO - 4036 - M3 - N		1
9	Shoulder cylinder end		1







A-A

schaal 2:1

datum 23/07/2020

opmerkingen
<<opmerkingen>>

maateenheid mm

gewicht 30 gram

getekend
<<(achter)namen & studienummers>>

groep
<<dagdeel groep>>

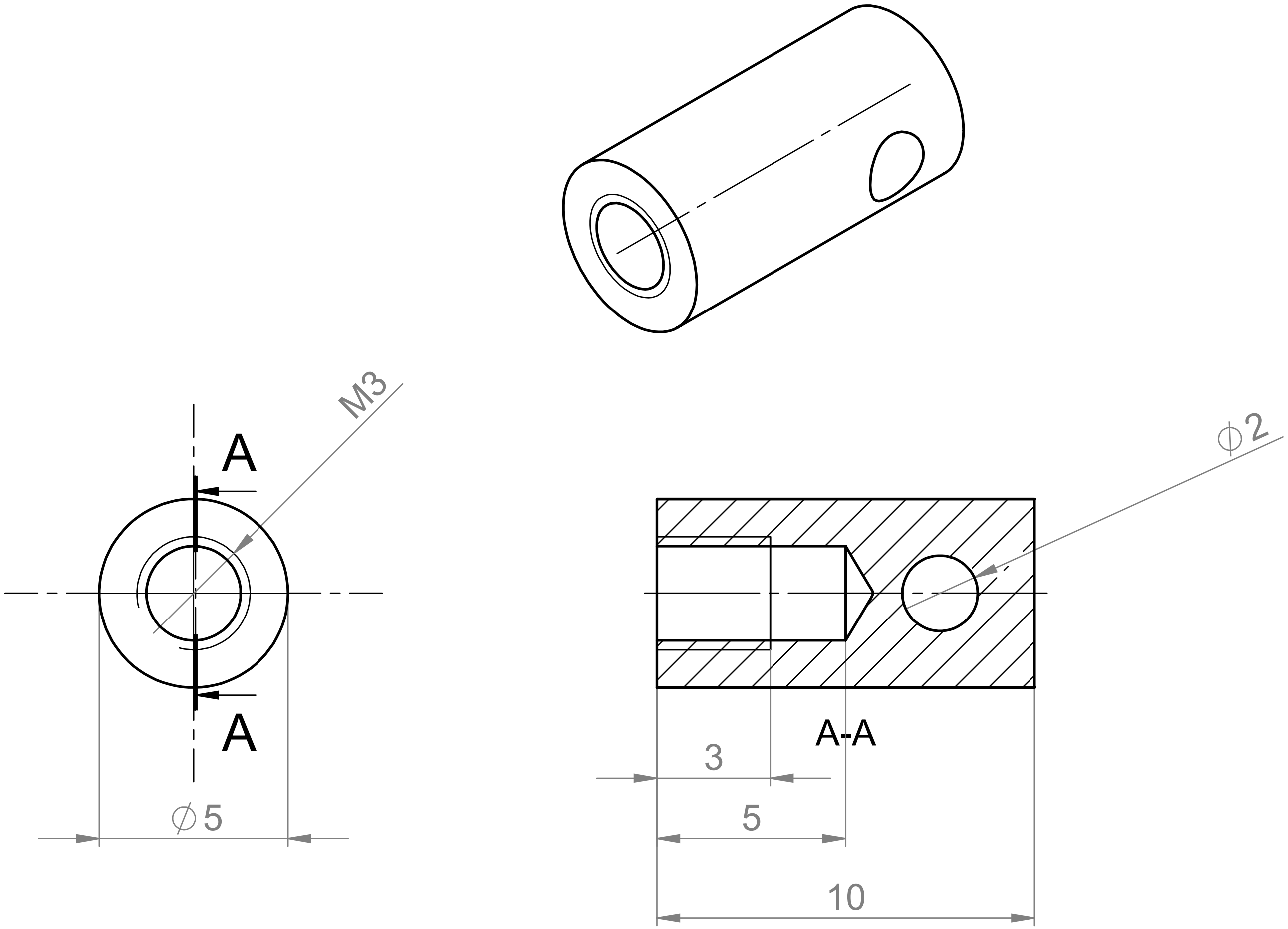
benaming
Shoulder cylinder assambly

TU Delft
Industrial Design Engineering

formaat A3

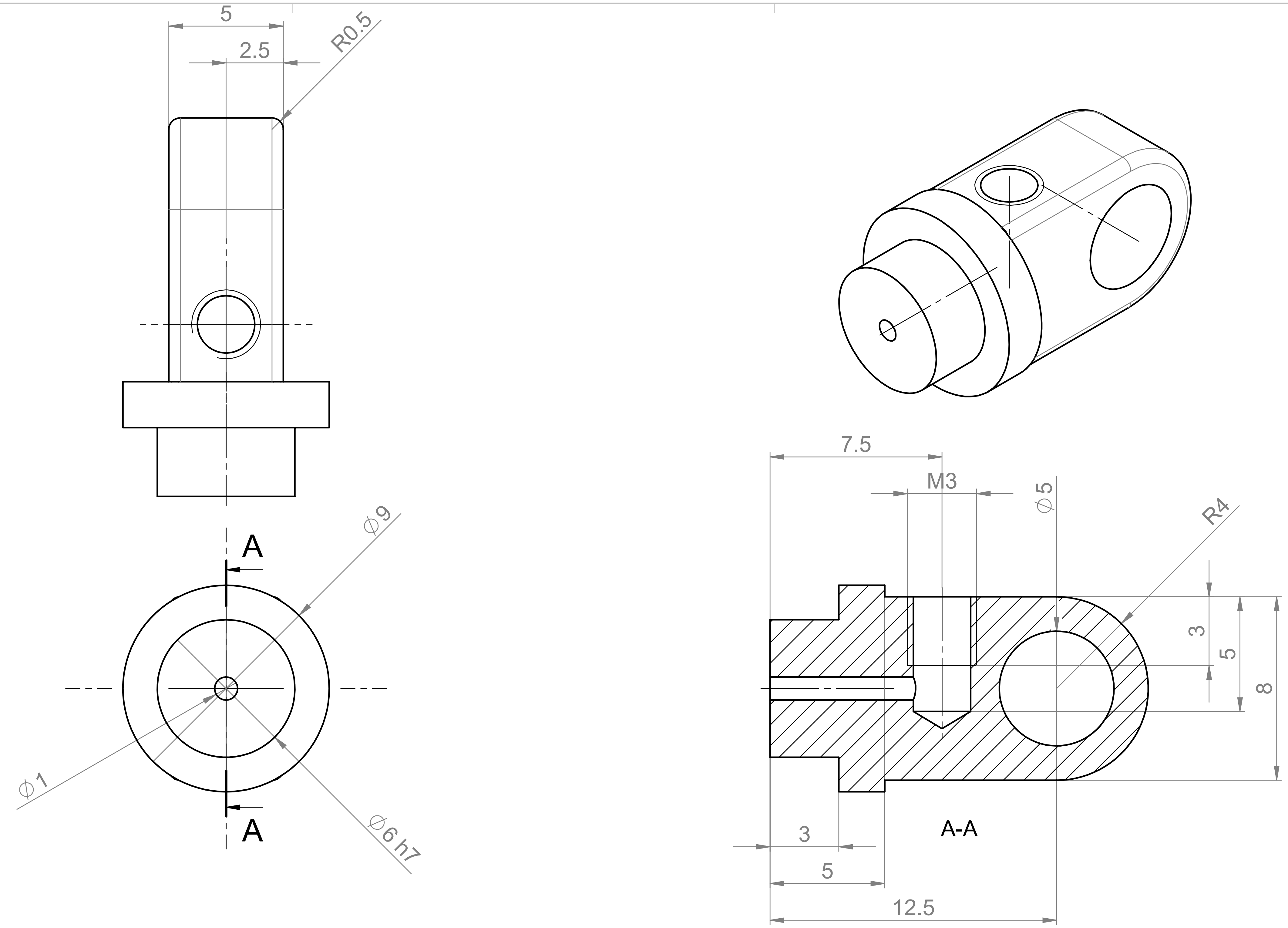
tekeningnummer
<<tekeningnr>>

Mat.: RVS
Aantal: <<1 >>



TU Delft Industrial Design Engineering	benaming Cable attachment	datum 23/07/2020		schaal 5:1	maateenheid mm
		getekend <<(achter)namen & studienummers>>	groep <<dagdeel>>	formaat A4	gewicht 1 gram
					tekening nr. / opmerkingen <<tekeningnummer>>

Mat.: RVS
Aantal: <<1 >>



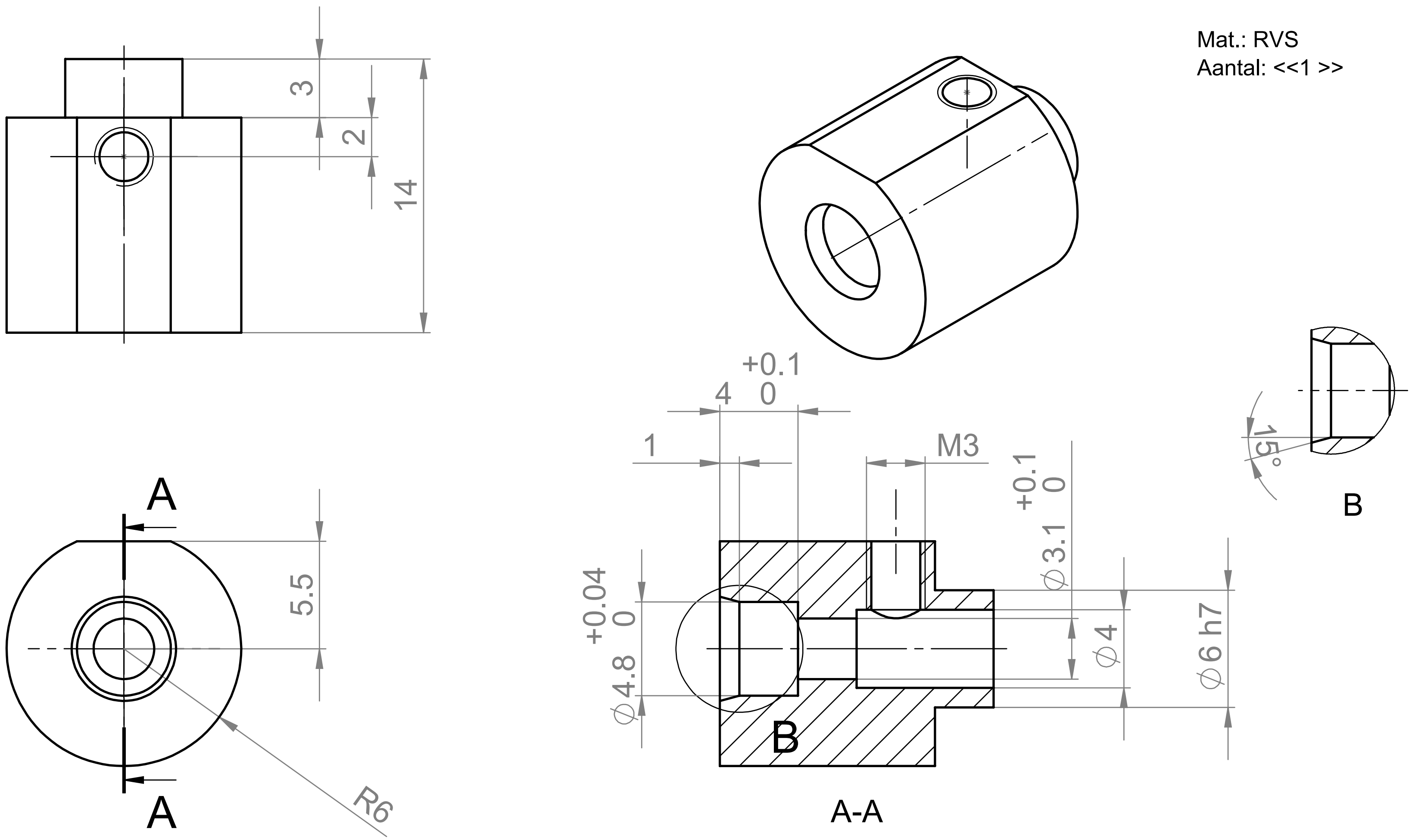
schaal 5:1		datum 23/07/2020	opmerkingen <<opmerkingen>>
maateenheid mm	gewicht 4 gram		
getekend <<(achter)namen & studienummers>>		groep <<dagdeel groep>>	

benaming **Shoulder cylinder end**

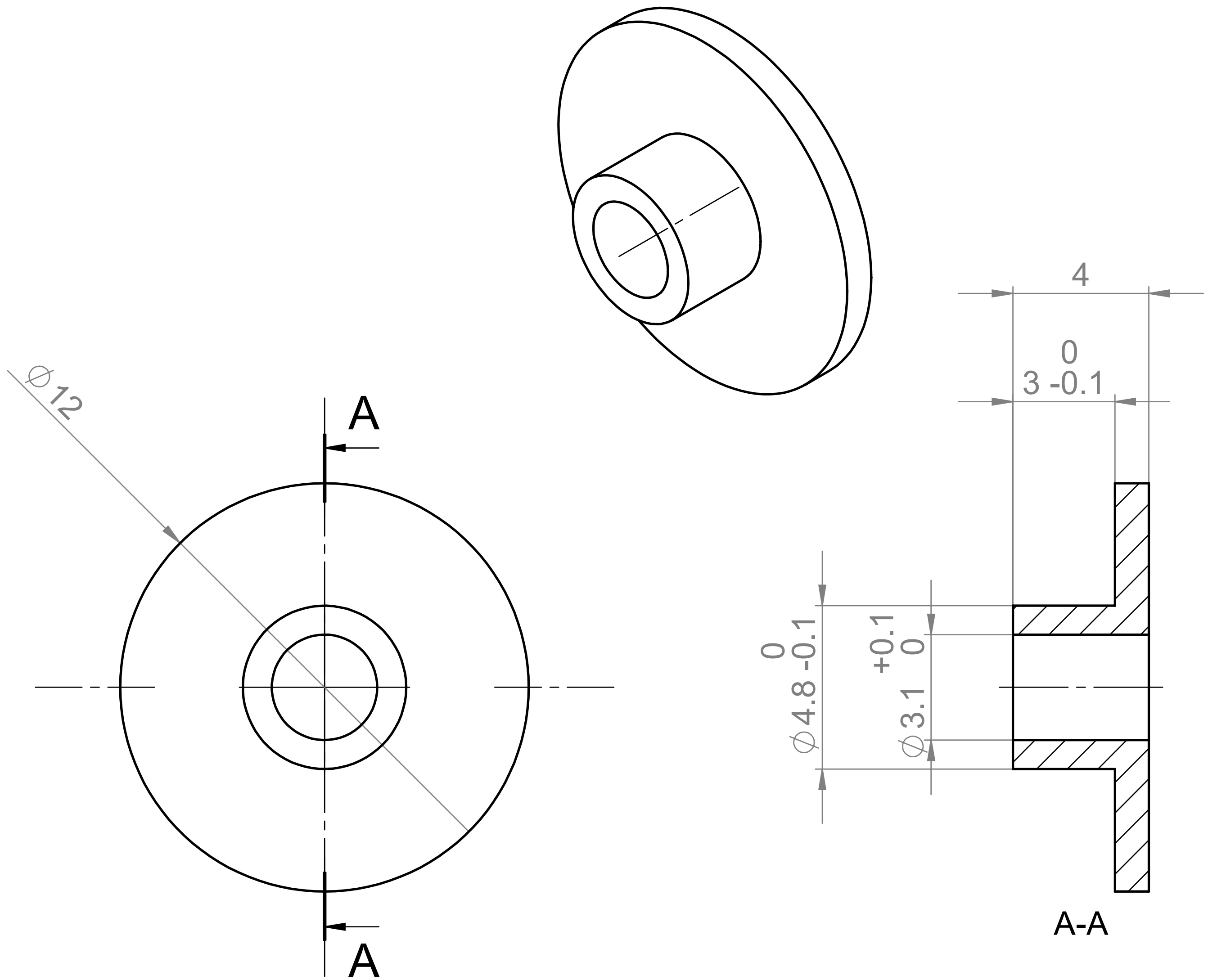
TU Delft
Industrial Design Engineering

formaat	tekeningnummer
A3	<<tekeningnr>>

Mat.: RVS
Aantal: <<1 >>

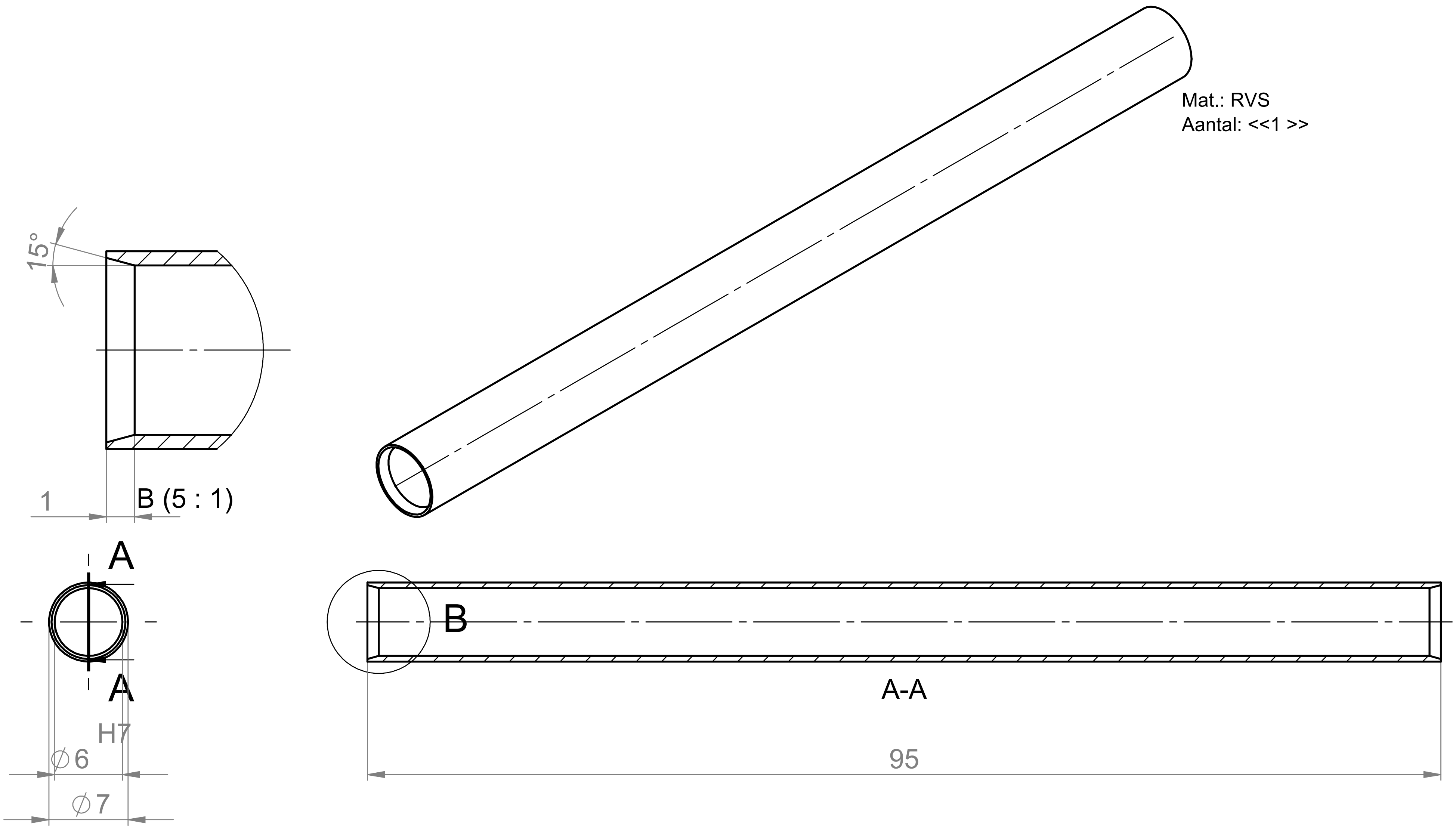


TU Delft Industrial Design Engineering	benaming Shoulder cylinder inner seal end	datum 23/07/2020		schaal 3:1	maateenheid mm
		getekend	groep <<dagdeel>>	formaat A4	gewicht 9 gram
		<<(achter)namen & studienummers>>			tekening nr. / opmerkingen <<tekeningnummer>>



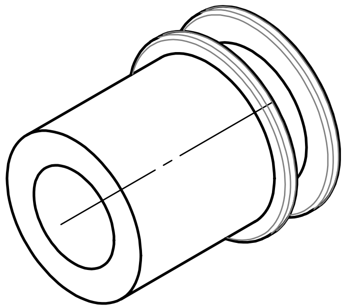
Mat.: RVS
Aantal: <<1 >>

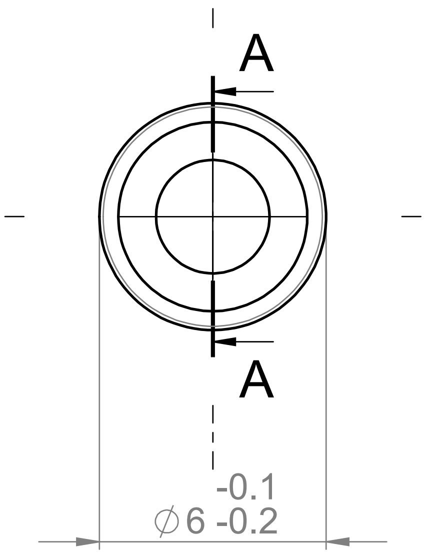
TU Delft Industrial Design Engineering	benaming: Shoulder cylinder outer seal end	datum: 23/07/2020		schaal: 5:1	maateenheid: mm
		getekend	groep: <<dagdeel>>	formaat: A4	gewicht: 1 gram
		<<(achter)namen & studienummers>>			tekening nr. / opmerkingen: <<tekeningnummer>>

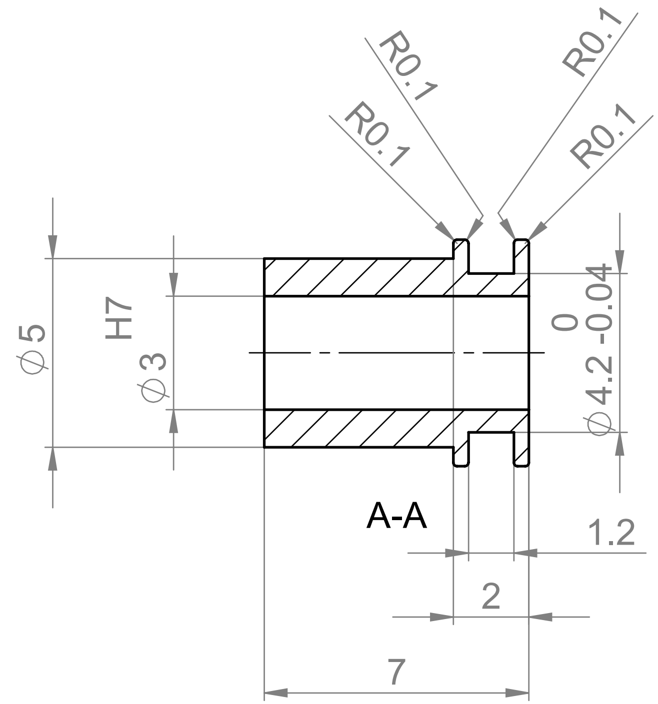


TU Delft Industrial Design Engineering	benaming: Shoulder cylinder	datum: 23/07/2020		schaal: 2:1	maateenheid: mm
		getekend: <<(achter)namen & studienummers>>	groep: <<dagdeel>>	formaat: A4	gewicht: 8 gram
					tekening nr. / opmerkingen: <<tekeningnummer>>

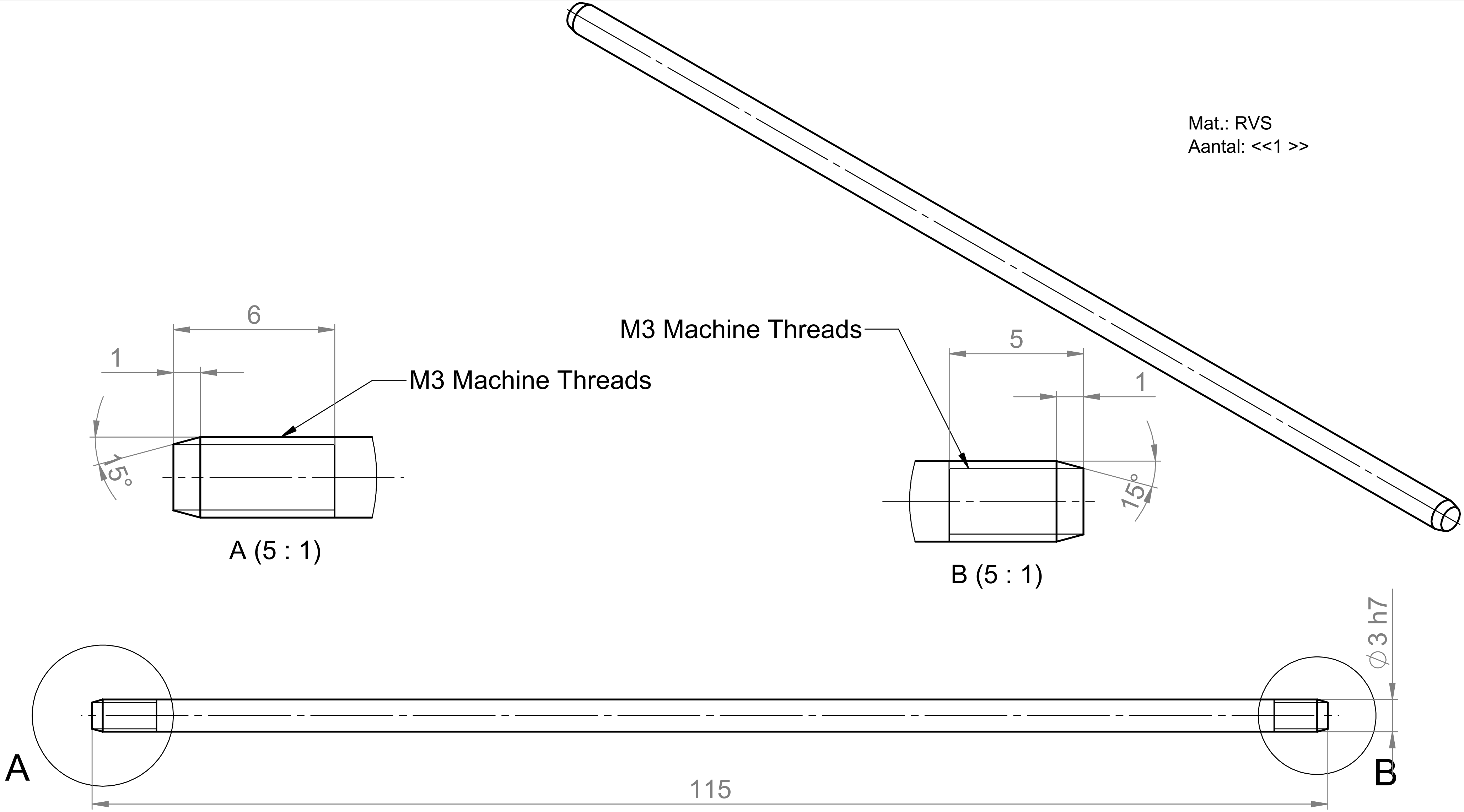
Mat.: RVS
Aantal: <<1 >>





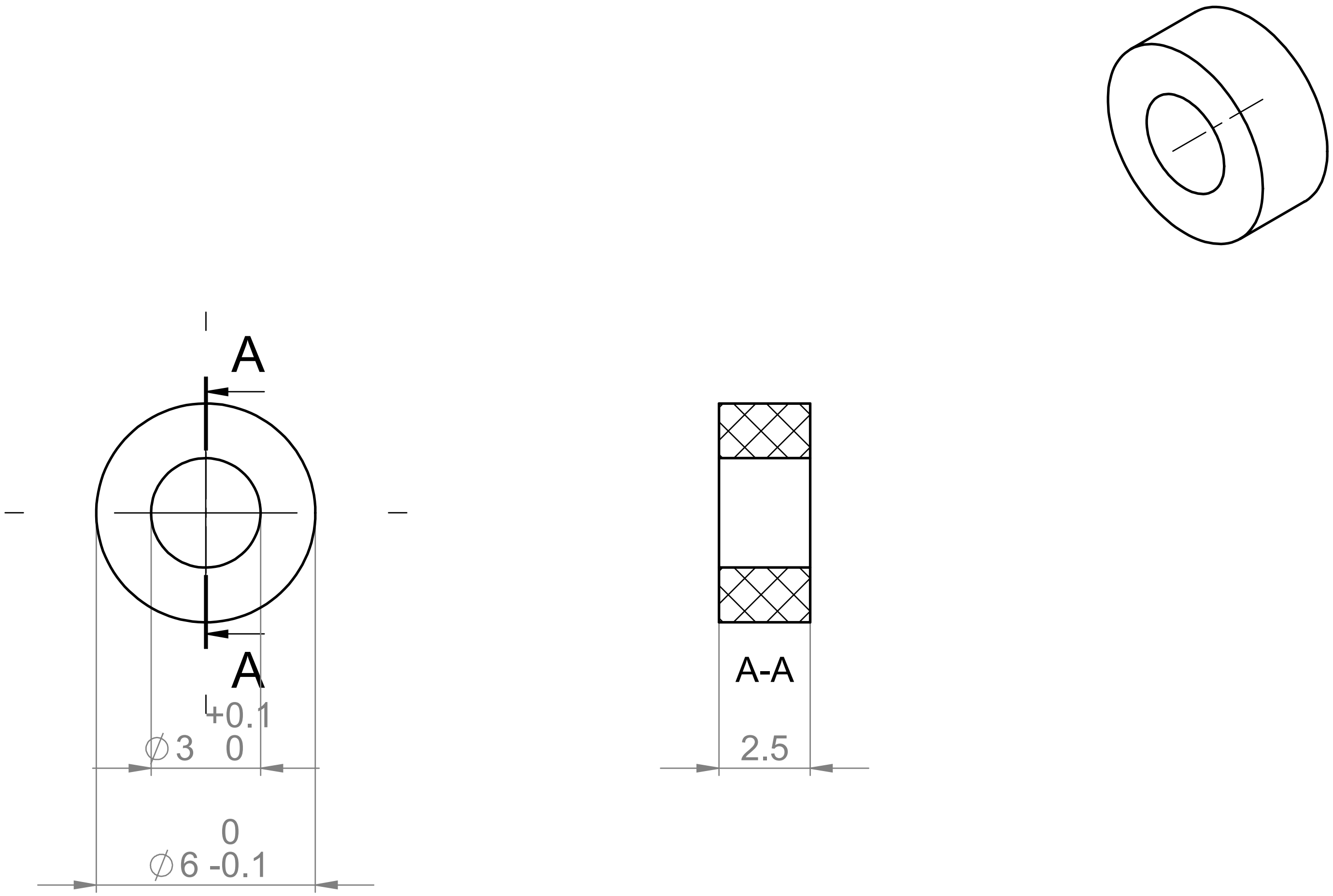


TU Delft Industrial Design Engineering	benaming Shoulder plunger head	datum 23/07/2020 getekend <<(achter)namen & studienummers>>	groep <<dagdeel>>	schaal 5:1 formaat A4
				maateenheid mm gewicht 1 gram tekening nr. / opmerkingen <<tekeningnummer>>



TU Delft Industrial Design Engineering	benaming Shoulder plunger rod	datum 23/07/2020		schaal 2:1	maateenheid mm
		getekend	groep <<dagdeel>>	formaat A4	gewicht 7 gram
		<<(achter)namen & studienummers>>			tekening nr. / opmerkingen <<tekeningnummer>>

Mat.: PTFE (general)
Aantal: <<1 >>



TU Delft Industrial Design Engineering	benaming: Shoulder teflon ring	datum: 23/07/2020		schaal: 5:1	maateenheid: mm
		getekend	groep: <<dagdeel>>	formaat: A4	gewicht: 0 gram
		<<(achter)namen & studienummers>>			tekening nr. / opmerkingen: <<tekeningnummer>>