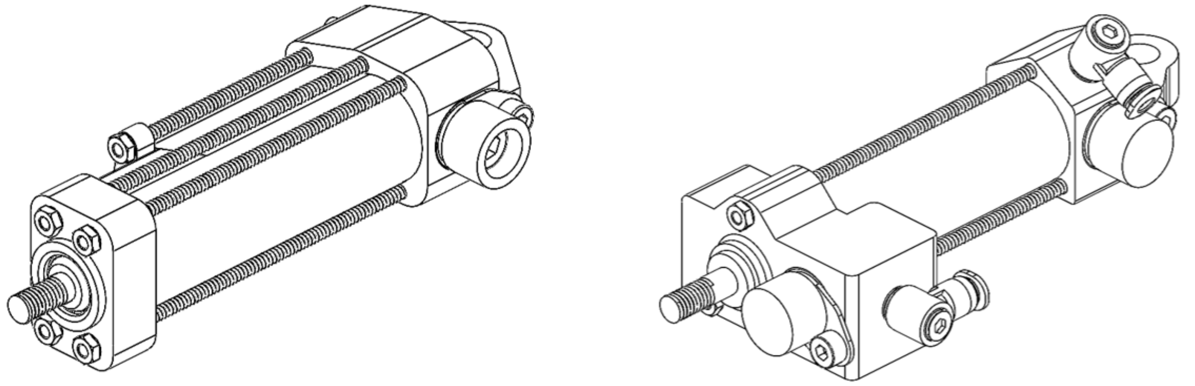
Design and evaluation of 3D-printed fluid-controlled actuators with integrated valves

by

B. van der Windt



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TU Delft

Preface

Before you lies the result of my master thesis, a project I worked on full-time for seven months. This research would not have been possible without the help of different people. First of all, I want to thank my great supervisors Heike Vallery, Sven Müller and Gerwin Smit. I want to thank you for your critical questions, good discussions and most of all your optimism always encouraging me to keep going. I also want to thank Jan van Frankenhuyzen for sharing his knowledge on designing fluid-controlled actuators and the fun hours we spent brainstorming about iterations and new ideas. I want to thank Damian de Nijs, Reinier van Antwerpen and Spiridon van Veldhoven for their help in manufacturing the 3D-printed fluid-controlled actuators. And I want to thank Jos van Driel and Jacques Brenkman for their help setting up the test rig and calibrating the sensors. Lastly, I would like to thank external committee member Dr. Jie Zhou for attending my presentation and reading my thesis.

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Bob van der Windt
Delft, October 2022

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Design and evaluation of 3D-printed fluid-controlled actuators with integrated valves

Bob van der Windt

***Abstract*—Fluid-controlled actuators are widely used in lower limb prostheses. Most fluid-controlled actuators have valves integrated into the cylinder systems and require complex manufacturing steps, making these systems expensive. A cost-effective production method for these complex actuator valve systems is 3D-printing. The goal of this research is to study the possibility of creating a pneumatic and hydraulic cylinder with integrated valves using 3D-printing and evaluate their performance.**

A 3D-printed pneumatic cylinder with integrated valves was designed, manufactured and tested on static and dynamic leakage for different pressure levels on a designed test rig. To evaluate the performance, the leakage data was compared with the performance of a commercial pneumatic cylinder. A 3D-printed hydraulic cylinder was designed and built according to the earlier design insights. The 3D-printed hydraulic cylinder was tested on hysteresis and internal and external leakage in open and closed valve mode.

Overall the commercial pneumatic cylinder performs better on static and dynamic leakage. In static leakage, a maximum pressure loss of 0.0095 MPa was measured at 0.6 MPa starting pressure after 20 minutes in the 3D-printed pneumatic cylinder. In dynamic leakage tests, a larger pressure difference of 0.035 MPa is measured at 0.5 MPa after 20 minutes in the 3D-printed cylinder. The higher leakage profiles of the 3D-printed cylinder are caused by a difference in roughness and clearance of the sealing seatings causing movement of the seals.

The 3D-printed hydraulic cylinder did not work as expected with 20 N force for moving the cylinder over its stroke, internal leakage of 0.007 MPa at a 0.01 MPa dynamic test and an average external leakage of 8.7 mL after 20 minutes. The tests gave important insights into sealing selection, which was not optimal for the hydraulic application.

All in all, this study shows that it is possible to create functional 3D-printed pneumatic cylinders for static applications. Thereby it gives important design insights into improving the performance of 3D-printed pneumatic cylinders for dynamic applications and 3D-printed hydraulic cylinders.

I. Introduction

A. Motivation - fluid controlled prostheses

Pneumatic and hydraulic actuators, or fluid controlled actuators, are used in a wide variety of lower limb prosthetic applications [1], [2]. Most fluid-controlled prostheses work by the principle of moving fluid or air by a piston which is coupled to the prosthetic limb. As the piston moves valves control a different degree of flow resistance controlling the speed of the piston and the limb [3], [4]. The use of fluid-controlled lower limb prostheses has a lot of advantages since the prosthetic limb can give progressive resistance along a movement, it can adjust to a wide range of motions and it can accurately mimic the function of a healthy joint e.g. knee or an ankle [4], [5]. However, fluid-controlled prostheses have also disadvantages. Most fluid-controlled prostheses are heavy, especially compared to mechanical friction knees, fluid-controlled prostheses are expensive making them only available for a small part of the world [3], [4], and fluid-controlled prostheses are complex systems that require a high level of expertise to manufacture and setting up the prosthesis [4], [6]. The level of expertise during manufacturing is needed due to the integration of valve system and cylinder requiring specialized skills to manufacture the internal ducts and passageways between the cylinder and a valve block especially when conventional manufacturing methods such as turning, milling, drilling and reaming are used. A possible solution for the manufacturing of integrated valve cylinder systems for use in prosthetics is 3D-printing. Since 3D-printing is based on building up parts by layer heights it is possible to build the same internal connections or even more complex internal cavities without the complex tooling steps and skilled craftsmen of the conventional manufacturing methods [7], [8]. With 3D-printing the costs of manufacturing integrated valve cylinder systems are also reduced and it will be easier to produce smaller volumes and personalize integrated valve cylinders for different users [7].

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B. State of the art - 3D-printed pneumatic and hydraulic cylinders with integrated valves

1) 3D-printing in fluid-controlled actuators, current patent literature: In a previous patent study by the authors, a comprehensive overview of different fluid-controlled valve cylinder systems in lower extremity prostheses is given [9]. No 3D-printed applications were found in the current patent literature. Most described fluid-controlled actuators are manufactured with conventional materials, mostly a combination of aluminium and steel. Most valves are directly integrated into the cylinder foot or the cylinder head of the described systems and require multiple manufacturing steps such as CNC milling, turning and reaming. The found patents that use other materials such as plastics or rubbers are soft actuators that are used for the cushioning of ankles and knees.

2) 3D-printing pneumatic actuators, literature: In literature, different attempts at creating 3D-printed pneumatic actuators are found. A part of the found papers focus on 3D-printing of soft actuators [10], [11]. Also, the manufacturing of linear pneumatic cylinders using 3D-printing is described in literature such as the design and manufacturing of a double-acting low-pressure pneumatic cylinder [12]. The cylinder is made using Fused Deposition Modelling (FDM) and the cylinder does not contain valves but a coupling for pneumatic hoses. Another found paper describes the design of a short-stroke high-force pneumatic actuator using

FDM. This cylinder does not contain valves integrated in the cylinder but connections for a pneumatic hose [13]. Also, Zillen et al. [14] investigated the functioning of a 3D-printed pneumatic piston-cylinder system and the effect of different piston sealings on static and dynamic leakage and on friction. The piston-cylinder systems were manufactured using Stereolithography (SLA) printing. Also, the possibilities of non-circular piston shapes and sealings are explored in this research.

3) 3D-printing hydraulic actuators, literature: Siegfahrt et al. describe the design and production of hydraulic cylinders using 3D-printing. In this research, FDM is used as a printing method for the piston, cylinder tube and seals using a multi-material printing set-up in which all hydraulic parts are printed at once. The system makes use of external valves which are connected by hoses [15]. Another interesting research is done by Martinez de Appelaniz Goenaga et al. [16] who researched the effect of different printing methods, FDM, SLA and Selective Laser Melting printing (SLM) on the static leakage and friction of piston-cylinder systems. In this research, SLA was selected as the most suitable 3D-printing method for hydraulic piston-cylinder systems.

4) Research gap: No papers and patents were found that describe the design and evaluation of pneumatic or hydraulic cylinders with integrated valves that are produced by 3D-printing.

C. Objective

This research aims to design a pneumatic and hydraulic cylinder with integrated valves using 3D-printing. Thereby the performance of the pneumatic cylinder is evaluated and compared with a commercial system. The performance of the pneumatic cylinders is measured by comparing the static leakage and dynamic leakage of both cylinders. This leads to the following two research questions:

1) Is it possible to design and build a pneumatic cylinder with integrated valves using 3D-printing and what design considerations influence the performance of such a system?
2) How much leakage occurs in a 3D-printed pneumatic cylinder with integrated valves and what is the comparison with a commercial pneumatic cylinder?

Lastly, a 3D-printed hydraulic cylinder with integrated valves using 3D-printing is designed and its performance is evaluated. Since less knowledge is available in the field of 3D-printing hydraulic cylinders, the design insights of the 3D-printed pneumatic cylinders are used for the design of the hydraulic cylinder and the performance of this hydraulic cylinder is checked according to the hysteresis in open valve mode and the internal and external leakage in open and closed valve mode. The research question is the following:

3) Is it possible to design and manufacture a hydraulic cylinder with integrated valves using 3D-printing according to the design insights of the 3D-printed pneumatic cylinder and what is the performance of such a cylinder?

II. Design and Manufacturing Method

A. Design requirements

1) Requirements for the 3D-printed pneumatic cylinder: Table I and II show the requirements for the design of the 3D-printed pneumatic cylinder. The dimensions in table I are based on the dimensions of a commercial pneumatic cylinder as described in subsubsection II-A2. The decisions as described in table II are explained below:

1) The cylinder must be a double-acting or differential cylinder.
2) The cylinder must have the possibility to close off the cylinder foot and cylinder head entrance independently.
3) The total system must be made with a standardized/ widely available 3D-printing method. Exceptions to this rule are valves, valve seatings and parts of the piston assembly.
4) The 3D-printed parts are only post-processed by hand-driven tools, e.g. a utility knife for removing supports, files for finishing support residues on parts, reamers for smoothening a printed hole and drilling for removing debris.
5) The total system is integrated and all functional systems e.g. valves, piston and cylinder are directly connected and no hoses and hose fittings are needed. Exception on this specification is the connection with sensors for measurement purposes e.g. a pressure sensor and the connection between a microcontroller and a powered valve, e.g. a solenoid actuated valve.
6) The total pneumatic integrated system makes use of available commercial seals and O-rings. A commercial valve system is also preferred.
7) The dimensions of the 3D-printed pneumatic cylinder will be based on an existing commercial pneumatic cylinder. The same commercial cylinder is used for the performance comparison.

Variable	Number	Unit
Piston diameter	20	mm
Stroke length	30	mm
Pressure range	0.1-1	MPa
Rod diameter	< 8	mm
Connection piston rod	$<$ M8	-
Weight (including valves)	< 210	gram

TABLE I: Dimensions of the 3D-printed pneumatic cylinder and the commercial pneumatic cylinder

2) Commercial pneumatic cylinder: The performance of the integrated pneumatic cylinder was compared with the performance of a commercial pneumatic cylinder. The Festo DSNU 20-30 [17] was selected for the comparison. This cylinder is widely available and can be connected to all Festo standardized hoses and hose connectors. For the set-up, the M5 knee screw couplings were connected to the cylinder and the Festo 4x0.75 pneumatic hose was selected. A simple Festo hand-driven valve was also selected. The dimensions as stated in table I are based on the dimensions of the Festo cylinder. Appendix subsubsection A-A2 shows the complete selection process of the commercial cylinder.

Specification	Description
Cylinder type	Double acting
Switching mode	Able to close off cylinder head and foot independenly
Manufacturing	3D-printing, except for piston rod and valves
Post-processing	Only hand driven, utility knive filing, reaming, drilling
Integrability	All parts and functions are integrated, no hose connections
O-rings and seals	Commercial, off the shelf
Valve type	Commercial valves, no self design
Comparison	Comparable with an off the shelf system

TABLE II: Specifications the 3D-printed pneumatic cylinder has to fulfil

3) Additional requirements for the 3D-printed hydraulic cylinder: In order to answer research question 3 most requirements of the 3D-printed pneumatic cylinder are the same for the 3D-printed hydraulic cylinder. The exceptions or additional requirements are given below:

- Switching mode, As stated in Landers et al. [18] the use of a hydraulic locking cylinder can be very useful in a pneumatic prosthetic system. Therefore it is chosen to design a hydraulic locking cylinder that has an open valve mode in which the cylinder can move over its full stroke without high forces and a holding mode or closed valve mode in which the cylinder has a closed valve and a movement in the retraction direction, or inward movements, is not possible. An extension movement is possible.
- Comparison, Since the designed cylinder, is a proof of concept no comparison with a commercial system is made.
- Accumulator, The 3D-printed hydraulic cylinder must contain an integrated accumulator in the system.
- Used fluid, the used fluid is water since the cylinder has to be filled multiple times and a lot of adjustments are needed. This is easier with water than with hydraulic oil.

B. 3D-printed pneumatic cylinder

This subsection describes the design details of the final design of the 3D-printed pneumatic cylinder. Appendices A and B describe the design and iteration process in detail.

1) Pneumatic circuit: The pneumatic circuit of the 3D-printed pneumatic cylinder consists of two two-position two-way valves. One valve connects the cylinder foot with the open air and the other connects the cylinder head with the open air. Figure 1 shows the pneumatic circuit of the 3D-printed pneumatic cylinder.

2) Main components: Figure 2 shows a CAD view of the 3D-printed pneumatic cylinder with annotation of the the six main components. A cylinder tube is connected by 3 M3 rod ends to a cylinder head and a cylinder foot. Both the cylinder head and cylinder foot have an integrated two-position two-way valve. The valves are connected to the cylinder via printed ducts in the cylinder head and foot. The cylinder tube is divided into two compartments by a piston rod assembly.

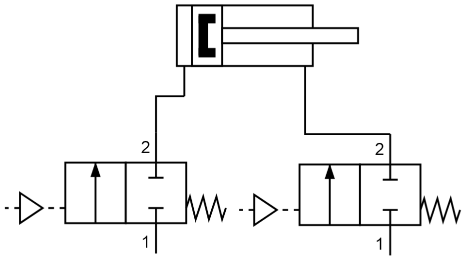


Fig. 1: Pneumatic circuit of the 3D-printed cylinder. To both cylinder ends a two way two-position valve is connected.

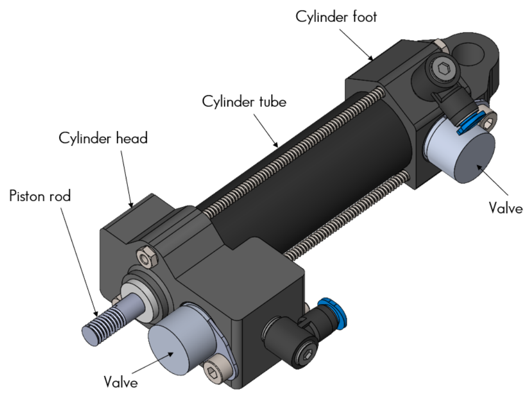


Fig. 2: CAD view of the designed 3D-printed pneumatic cylinder with annotation of the main components

3) Valve and valve seating design: The chosen valves are cartridge valves. A cartridge valve is a valve that is press fitted into a designed cavity. Such valve types are well suited for use in an integrated valve cylinder system since the valves can be integrated into a complex printed cavity. In the first instance, a commercial miniature two-way two-position valve was selected. The commercial valve is the Parker Hannifin (USA) C15 miniature pneumatic valve [19] which is well suited for the application. However, due to availability issues of this commercial valve it was decided to design a manual valve. The designed valve has the same dimensions as the C15 valve and consists of two parts. A top part with the dimensions of the C15 valve and a bottom part or valve seating. The top part has four small radial air ducts that are connected to a central air duct. The central air duct is connected to the valve seating which contains an M3 bolt that is sealed by an O-ring. When the bolt is tightened the valve is airtight and when the bolt is opened the valve is open and air can pass through. Figure 3(b) shows the designed valve and its seating. The valve and seating are pressed in the 3D-printed part. The top part is thereby sealed by an O-ring seated at the valve body and the seating is also sealed by an O-ring which is seated inside the 3D-printed part.

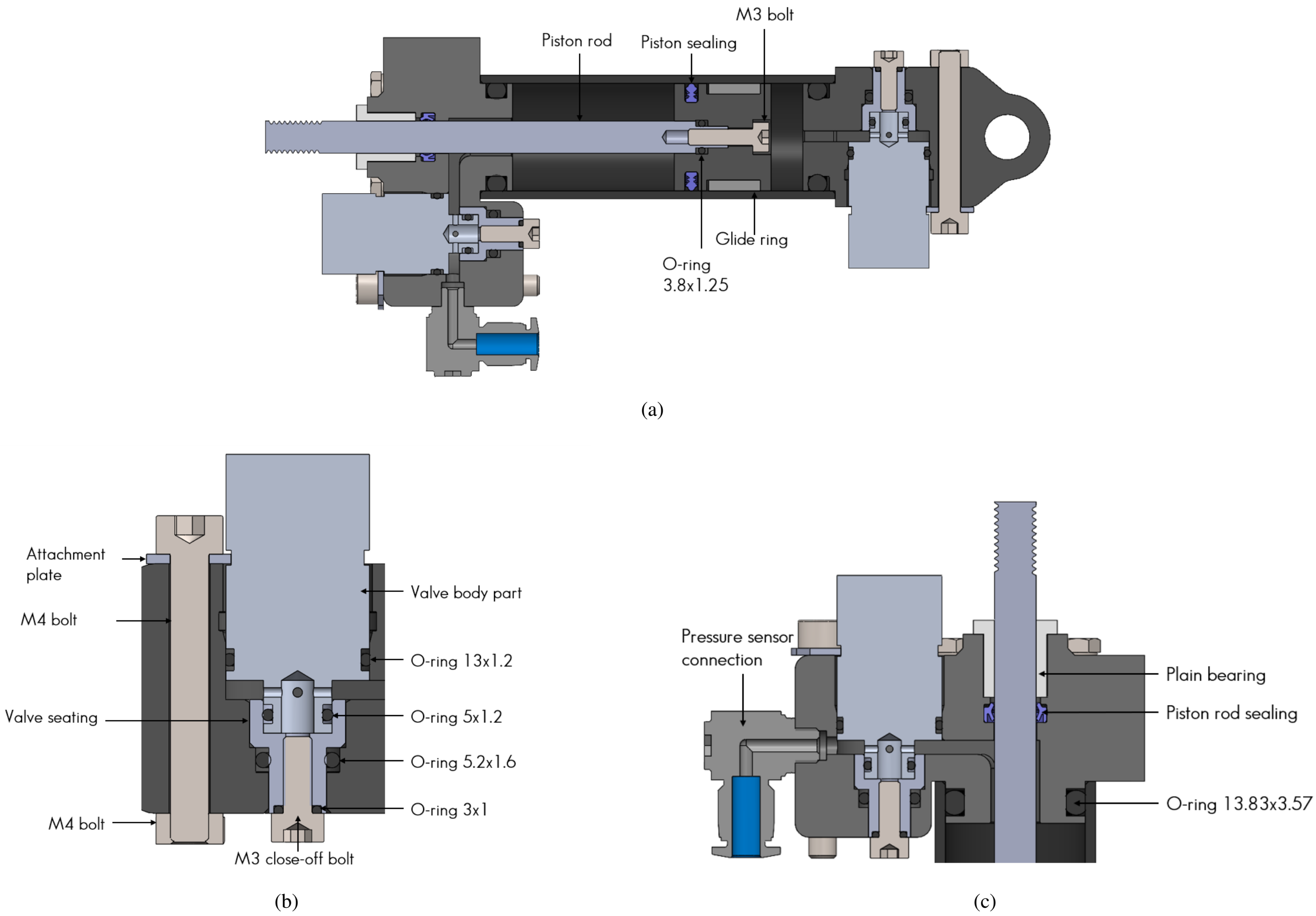


Fig. 3: (a) Section view of the 3D-printed pneumatic cylinder with annotations of the piston rod assembly. (b) Section view of the valve and valve seating assembly. (c) Section view of the cylinder head with annotation of functional parts

4) Cylinder foot: The cylinder foot forms the bottom part of the 3D-printed pneumatic cylinder. The cylinder foot functions as a connector between the lower-situated air chamber and the valve. The cylinder foot has seating for the valve and the valve connector which is sealed by two O-rings. The cylinder foot also has a seating for the O-ring that seals the connection between the cylinder and the cylinder foot. A connection point for an M8 bolt is made at the bottom of the cylinder foot. The cylinder foot also contains a connection point for a pressure sensor. Figure 3(a) shows a section view of the cylinder with the connected cylinder foot.

5) Cylinder head: The cylinder head forms the top of the 3D-printed pneumatic cylinder and functions as a connector between the upper cavity of the cylinder and the upper valve. The cylinder head contains seating for the cartridge valve and also has a specially designed seating for the piston rod sealing. The piston rod sealing is a Freudenberg (Germany) Nipsl 210 sealing [20]. Furthermore, the cylinder head contains a plain bearing for piston rod guiding. In the cylinder head, the valve seating, the seating for the plain bearing and the piston rod seal are parallel. This configuration is chosen so that all cavities are in the same direction and are printed with high quality and without supports. The cylinder head also contains a connection part for connecting a pressure sensor. Figure 3(c) shows a section view of the cylinder head.

6) Cylinder tube: The cylinder tube is the connecting part between the cylinder head and the cylinder foot. Furthermore, it functions as the housing of the piston rod assembly. The cylinder tube is a round tube with chamfers at the end to facilitate an easy fit of the O-ring connections.

7) Piston rod assembly: The piston rod assembly divides the cylinder into two non-communicating air chambers and consists of two parts. A piston rod and a piston are connected by an M3 bolt. The piston rod is made from stainless steel and the piston is 3D-printed. To ensure an air-tight connection the connection between the piston rod and the piston is sealed by an O-ring. The piston contains grooves for the piston seal which is a Freudenberg (Germany) KDN seal [21]. This seal was selected according to the results of Zillen et al. [14]. The piston also contains a groove for an Eriks (The Netherlands) piston glide ring which gives extra guidance to the piston. Figure 3(a) shows a section view of the piston rod assembly.

C. Manufacturing the 3D-printed pneumatic cylinder

1) Printing method: For the 3D-printed parts a Formlabs 3 printer was used. A formlabs printer is an SLA-printer that uses a resin to print solid parts. The resin used, is the Formlabs resin tough 1500 [22]. The layer height was set to 100 µm since a lower printing height leads to long printing times. All parts were orientated in such a way that there are no supports printed in sealing seatings.

2) Post-processing of the 3D-printed parts: All parts needed different steps to make them ready for assembly. Table III shows the different post-processing techniques which were needed.

Part	Removing supports	Filing	Reaming	Drilling
Cylinder foot	x	x	x	-
Cylinder head	x	x	x	-
Cylinder tube	x	-	-	-

TABLE III: Post-processing techniques for different 3D-printed pneumatic cylinder parts.

3) Production of valve, valve seating and piston rod: The valve top part, valve seating and piston rod were made on a lathe making use of the standard lathing and measurement tools available in a workshop. The valve top part is made out of aluminium and the valve seating and piston rod are made out of stainless steel.

4) Assembly procedure: The assembly process consisted of the following steps:

1) Post-processing of 3D-printed parts.
2) The seals and plain bearing are installed.
3) The valves are installed in their cavities by press fitting.
4) The piston rod is assembled, lubricated with Kilopoise and installed in the cylinder.
5) The cylinder foot and cylinder head are pressed on the cylinder tube and tightened by M3 rod ends.

Figure 4 shows the complete assembled pneumatic integrated cylinder.

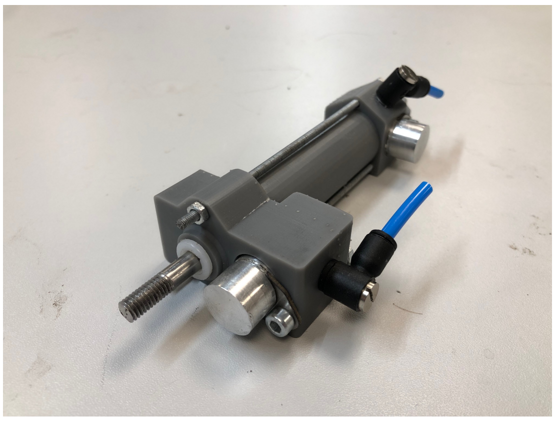


Fig. 4: Manufactured 3D-printed cylinder ready for testing.

D. Design of the 3D-printed hydraulic cylinder

A 3D-printed hydraulic cylinder with integrated valves was designed and built. This subsection describes the details of the final design. Appendices C and D describe the design and iteration process extensively.

1) Hydraulic circuit: Figure 5 shows the hydraulic scheme of the 3D-printed hydraulic cylinder. The hydraulic circuit consists of one two-position two-way valve which connects the cavity at the top of the piston and below the piston. In an open position, the cylinder can move freely and in a closed position the cylinder is in a blocking mode and will not move. The valve is connected to an accumulator which can compensate for the volumetric changes when the fluid flows from the below cylinder cavity to the top cylinder cavity, which has a smaller volume due to the piston rod.

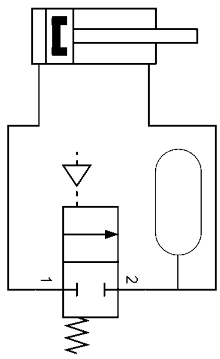


Fig. 5: Hydraulic circuit of the 3D-printed hydraulic cylinder. The two hydraulic chambers are connected by a 2/2 valve and accumulator

2) Main components: Figure 6 and 7 show a complete CAD-model of the 3D-printed hydraulic cylinder. The system consists of four components. The cylinder foot, the cylinder tube which houses the accumulator, the cylinder head and a two-position two-way valve. The cylinder foot, cylinder tube and cylinder head are connected by six M3 rod ends.

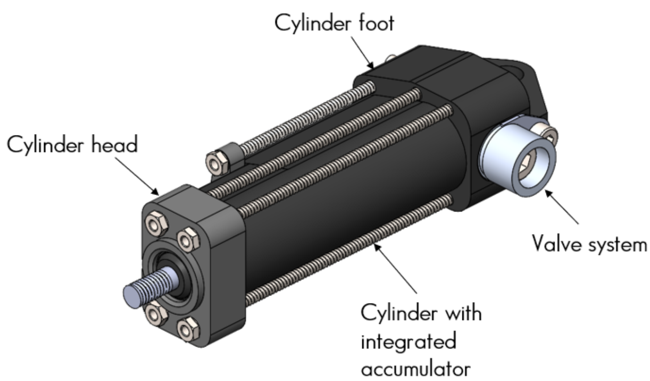


Fig. 6: CAD-model of the 3D-printed hydraulic cylinder with annotation of the main components.

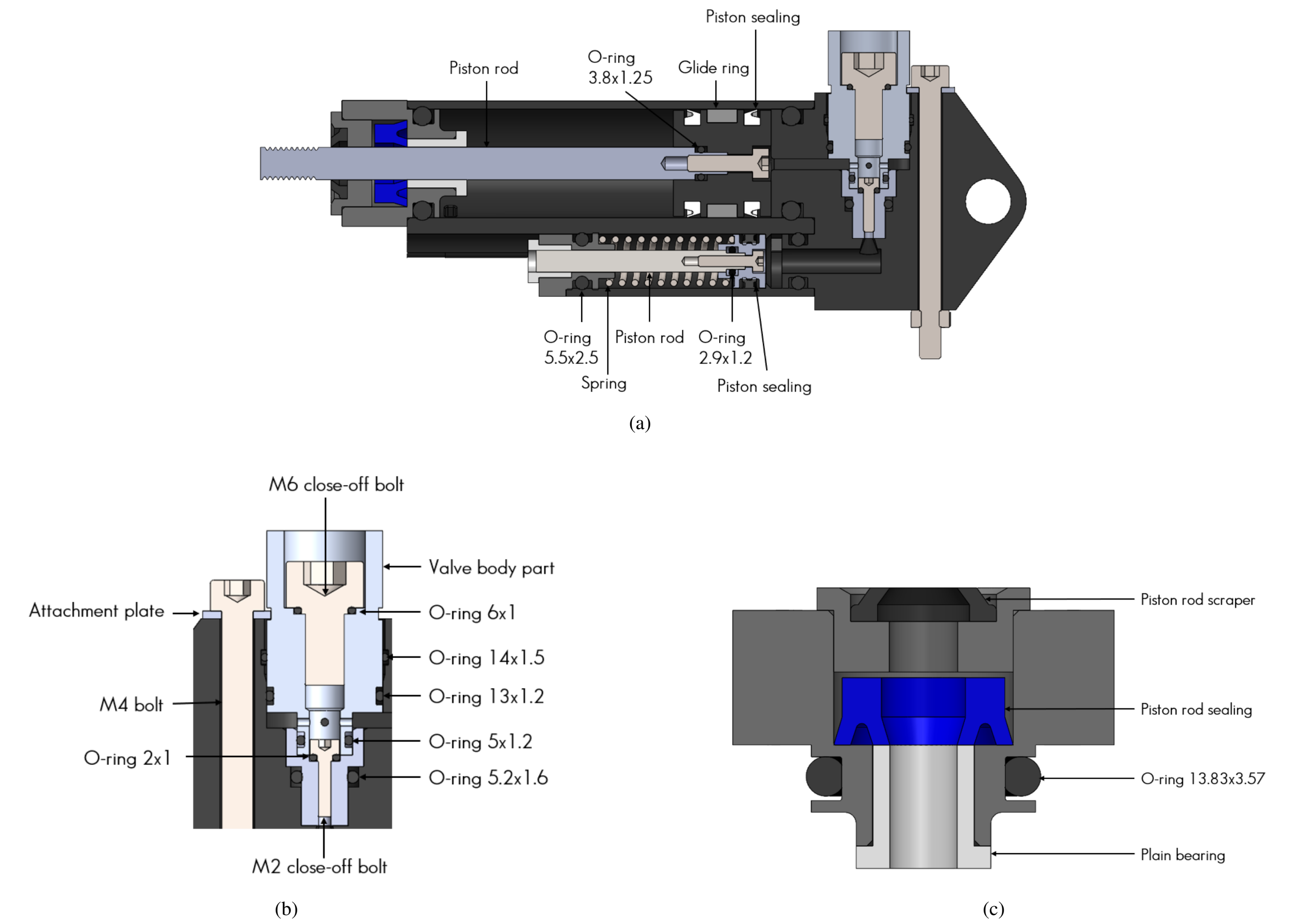


Fig. 7: (a) Section view of the 3D-printed hydraulic cylinder with annotations of the piston rod assembly and the accumulator assembly (b) Section view of the valve assembly with annotations of the different valve parts (c) Section view of the cylinder head assembly with annotations of the different seals and parts.

3) Valve and valve seating design: The valve used in the hydraulic integrated cylinder is a two-position two-way valve. The hydraulic version of the commercial valve as described in subsubsection II-B3 was selected. This commercial valve was also not available and therefore a hydraulic version of the manual valve as described in II-B3 was designed. The hydraulic manual valve has many similarities with the pneumatic manual valve. The main difference is that the hydraulic version has two close-off bolts. One is an M3 bolt which is used for closing off the connection between the top valve part and the bottom valve part. The second bolt is used for closing off the top of the valve part. Figure 7(b) shows a section view of the hydraulic valve in its seating.

4) Cylinder foot: The cylinder foot forms the connection between the lower cavity of the cylinder tube, the valve, the accumulator and the cavity that connects both cylinder cavities. The cylinder foot has two connection plugs. One is for the connection of the cylinder and the other is for the connection of the accumulator. Both connection plugs have a seating for an O-ring. The cylinder foot also has a cavity for the valve. In this cavity, two seatings for an O-ring are made. Furthermore, the cylinder foot contains a connection hole for connecting an M8 bolt. Figure 7(a) shows a section view of the cylinder with the connected hydraulic cylinder foot.

5) Cylinder head: The cylinder head forms the top of the hydraulic cylinder and closes off the cylinder and gives extra guidance to the piston rod. Two seatings for the piston rod seal and the rod scraper are situated in the cylinder head. The cylinder head also contains a plain bearing for extra guidance of the piston rod. Figure 7(c) shows a section view of the cylinder head.

6) Cylinder tube: The cylinder tube forms the connection between the cylinder head and cylinder foot and is the housing for the piston and piston rod assembly. The cylinder tube also houses the tube for the accumulator piston, piston rod and spring. The last function that is integrated into the cylinder tube is the connection between the upper and lower cavity of the cylinder. This connection is formed by two triangular-shaped cavities which lay in between the cylinder and accumulator tubes. Figure 8 shows a section view with the cylinder and accumulator tube and the two connecting cavities.

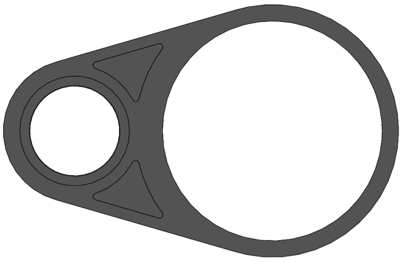


Fig. 8: Section view of hydraulic tube with accumulator tube and connecting triangular cavities

7) Piston rod assembly: The piston rod assembly divides the cylinder tube into two non-communicating chambers. The assembly consists of a stainless steel piston rod and a 3D-printed piston. The piston contains two single-acting hydraulic lip seals of the company Sealtech (Belgium) [23]. The piston also has a seating for a glide ring, which is the same glide ring used in the 3D-printed pneumatic cylinder. The piston rod and piston are connected via an M3 bolt. The connection is sealed by an O-ring which is seated in the piston. The piston rod has an M6 connection. Figure 7(a) shows a section view of the piston rod assembly.

8) Accumulator: The accumulator compensates for the change in volume when fluid flows from the below piston chamber to the upper piston chamber and vice versa. The designed accumulator is a spring-based accumulator and consists of the following parts:

- Single-acting piston with single-acting quad ring as a seal. The quad ring is used as a seal because it is hard to find a commercial piston seal for a piston diameter of 10 mm.
- Compression spring. In order to let the piston return to a low-volume state a compression spring is installed in the accumulator tube.
- Piston rod. For extra guidance, the piston is connected to a piston rod. The piston rod is guided at the top by a plain bearing.
- Accumulator head. The accumulator head houses the plain bearing for piston guidance and also has two holes for M3 rod ends that press the accumulator tube on the cylinder head.

Figure 7(a) shows the section view of the cylinder including the annotations for the accumulator assembly.

E. Manufacturing the 3D-printed hydraulic cylinder

1) Printing method: The 3D-printed parts were made with a Formlabs 3 resin printer. The used resin is the formlabs material Tough 1500 and the layer height is set to 100 µm to save printing time. Tough 1500 is a material that is stiff and has no reaction with fluids [22] therefore it is well suited for application in a hydraulic cylinder. All parts were printed in an orientation that the sealing seatings have no supports.

2) Post-processing of 3D-printed parts: Parts of the 3D-printed hydraulic cylinder needed different post-processing steps to make them ready for assembly. Table IV shows the different post-processing steps needed.

Part	Removing supports	Filing	Reaming	Drilling
Cylinder foot	x	x	x	-
Cylinder head	x	x	x	-
Cylinder tube	x	-	x	-
Cylinder Piston	x	x	-	-
Accumulator piston	x	x	x	-
Accumulator head	x	x	x	-

TABLE IV: Post-processing steps needed for the 3D-printed hydraulic cylinder

3) Production of valve, valve seating, piston rod and accumulator piston rod: The valve, valve seating, piston rod and accumulator piston rod were all produced on a lathe making use of standard lathe and measurement tools. The valve was made out of aluminium and the valve seating, piston rod and accumulator piston rod were made out of stainless steel. An instrument maker helped with the production of the accumulator piston rod..

4) Assembly procedure: The integrated hydraulic cylinder is assembled according to the following procedure:

1) Post-processing of 3D-printed parts as described in subsubsection II-E2.
2) Installation of seals and plain bearings.
3) The valve is installed in the cylinder foot. Using a press and a gummy hammer for fixation.
4) The piston rod is connected to the piston. The seals are installed in the piston and the glide ring is also installed in the piston. The piston is lubricated with Kilopoise.
5) The piston rod assembly, cylinder head and cylinder foot are assembled.
6) The accumulator is assembled with seals and spring and lubricated.
7) The accumulator is installed in the hydraulic cylinder.
8) The cylinder is tightened with 6 M3 rod ends, during tightening misallignment is taken into account.

Figure 9 shows a complete assembled integrated hydraulic cylinder.

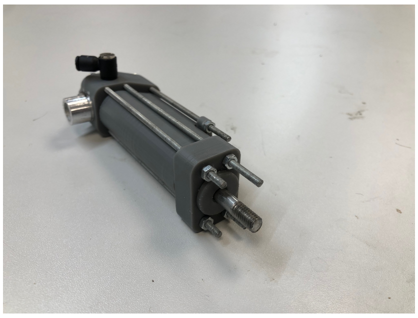


Fig. 9: The assembled 3D-printed hydraulic cylinder ready for testing

5) Filling the 3D-printed hydraulic cylinder: The 3D-printed hydraulic cylinder is filled with water. The filling procedure took the following steps:

1) A container (30 cmx30 cmx30 cm) is filled with water.
2) The cylinder is placed in the container and the piston rod is pushed in and out until there are no air bubbles escaping. This is repeated in other directions.
3) If the cylinder must be in blocking mode the M3 screw with the O-ring is tightened. Otherwise, this step is skipped. The M6 bolt is tightened with the O-ring and the system is ready for use.

III. Evaluation method

A. Test rig set up

Figure 10 shows the test rig. The test rig consists of the following components: A frame that consists of aluminium extrusion profiles, a stepper motor with a spindle drive, a laser distance sensor, a slider that connects the spindle drive to the force sensor, a rod end ball joint and a pressure sensor. In the next subsubsections, the different components and their specifications are described.

1) Aluminium frame: The frame is an assembly of aluminium 40x40 extrusion profiles. Figure 10(b) shows that there is a large horizontal extrusion beam in the middle of the test rig. With this horizontal beam, a horizontal distance can be created between the spindle drive and the tested cylinder. With this offset, a moment can be applied. The different extrusion profiles are connected by angle profiles and slotted nuts suitable for 40x40 extrusion profiles.

2) Stepper motor and spindle drive: The stepper motor is a NEMA23 stepper motor (123-3D, the Netherlands) that is coupled to a 2 mm pitch trapezium spindle via a flexible coupling. The stepper motor is connected to the frame by 3D-printed parts and slotted nuts. The stepper motor is controlled by an Arduino Uno (Italy) with a CNC stepper motor shield and programmed using a GRBL sender called ugsplatform. The stepper motor has an adjustable power supply which is set on 12 V.

3) Laser distance sensor: The laser distance sensor is a MicroEpsilon (Germany) optoNCDT sensor with a range of 50 mm [24]. The sensor is mounted on top of the stepper motor and the distance is sensed on a plastic plate that is mounted on top of the slider. Sensor values are measured in Labview.

4) Slider: The slider connects the spindle drive with the force sensor. The slider is a 3D-printed part that slides over the extrusion profile. To give the slider more guidance it has a taper that fits in the slot of the extrusion profile. A 2 mm spindle nut is connected to the slider and the slider has a cavity so that the spindle fits in the slider in small distance configurations. The slider has a slot for a plastic card for distance measurements and it has a connection point for the force sensor.

5) Force sensor: The force sensor is a Futek (USA) miniature S-beam jr. load cell 2.0 [25]. The force sensor can measure up to 444 N and has an amplifier. The force sensor has two M3 tapped holes for connection and is connected to the slider and rod end ball joint.

6) Rod end ball joint: Since there can be misalignment between the force sensor and the piston rod leading to misalignment forces and moments a rod end ball joint is placed between the force sensor and the piston rod. The rod end ball joint can compensate in 3 degrees of freedom for the misalignment.

7) Pressure sensor: The pressure sensor is a Sensor technics (Germany) CTU 8000 sensor. This sensor can measure the relative pressure (atmospheric pressure is seen as a baseline) from 0 to 1 MPa [26]. The pressure sensor is connected to the cylinder head or cylinder foot by a Festo (Germany) knee-screw coupling and a pneumatic hose to the cylinder. This coupling is made for the commercial pneumatic cylinder, the 3D-printed pneumatic cylinder and the 3D-printed hydraulic cylinder.

B. Experimental set up pneumatic testing

1) Preparing the cylinder for testing: Before a test was started the following procedure was followed:

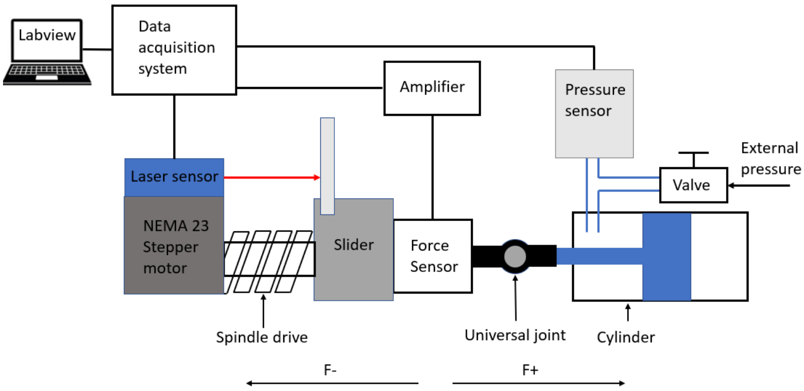
1) Depending on whether the cylinder foot or cylinder head is measured the test rig and the cylinder are brought in their minimal position or maximal position.
2) The valve in the foot is closed and the valve in the head remains open for cylinder foot measurement. For cylinder head measurement the valve in the cylinder head is closed and the valve of the cylinder foot remains open.
3) The cylinder is connected to the test rig frame and to the slider.
4) from a top view the connection between cylinder and slider is checked for misalignment.

After these steps the cylinder is ready for testing.

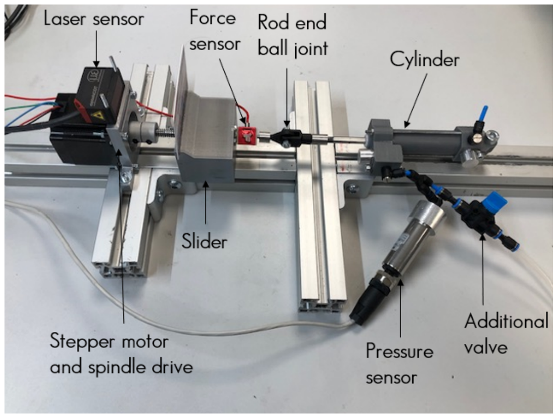
2) Static leakage testing, self induced pressure: In the static leakage tests the cylinder was held in a fixed position and the pressure was measured. The test procedure consists of the following steps:

1) When necessary an offset value is applied to the pressure sensor to ensure 0 MPa as a starting pressure.
2) The closed valve in the cylinder foot or cylinder head is checked.
3) The piston is moved to its maximum extension or retraction ensuring the same start position for all the cylinders. Or to the same stroke distance when an equal pressure test is done.
4) The pressure is measured for 20 minutes and recorded in labview.
5) The complete procedure is repeated three times.

The pressure drop during the test can be seen as static leakage.



(a)



(b)

Fig. 10: (a) Schematic overview of the designed test rig with annotations of all sensors and crucial components. The schematic drawing also shows the positive and negative direction of the force exerted by the spindle drive.(b) Photograph of the built test rig with annotation of all the crucial parts.

3) Static leakage testing, external pressure: In the static leakage test with external pressure, the cylinder was held in a fixed position and the pressure was measured. Before the test was started the cylinder was filled with compressed air. The test for static leakage consists of the following steps:

1) When necessary an offset value is applied to the pressure sensor to ensure 0 MPa as a starting pressure.
2) The closed valve in the cylinder foot or cylinder head is checked.
3) The pressure of the compressed air is set by opening the external pressure connection and additional valve.
4) The piston is moved to its maximum extension or retraction and the pressure is checked.
5) If the pressure is in the right range the test is started for 20 minutes, measuring the pressure drop. Otherwise, the above procedure is repeated.
6) The complete procedure is repeated three times

The pressure drop during the test was recognized as static leakage. The cylinder head and cylinder foot were tested on different pressure levels. The cylinder head was tested at a pressure of 0.6 MPa and 0.8 MPa in maximum extension and the cylinder foot was tested on 0.5 MPa and 0.7 MPa in maximum retraction.

4) Dynamic leakage with self-induced pressure: During the dynamic leakage tests, the pressure drop was measured while the piston moved in the cylinder.

1) If needed an offset value is applied to the pressure sensor and force sensor to ensure 0 MPa and 0 N as a starting pressure and starting force respectively.
2) The closure of the valve in the cylinder foot or cylinder head is checked.
3) The cylinder is moved back and forth over a stroke length of 30 mm for 20 minutes at a speed of 10 mm s^{-1}.
4) The cylinder ends in its starting position. During the test the pressure, force and distance are recorded in LabView.

With this method, the dynamic leakage was determined by analyzing the height of the pressure peaks for every cycle.

5) Dynamic leakage with external pressure: During the dynamic leakage tests the pressure drop was measured during piston movement. Before the test was started the cylinder was filled with compressed air.

1) If needed an offset value is applied to the pressure sensor and force sensor to ensure 0 MPa and 0 N as a starting value.
2) The closure of the valve in the cylinder foot or cylinder head is checked.
3) The pressure of the compressed air is set by opening the additional valve and external pressure connection.
4) The piston is moved to the maximum extension or retraction and the pressure is checked.
5) If the pressure is in the range, the test is started and the cylinder is moved over its full stroke at 10 mm s^{-1} speed for 20 minutes.
6) The cylinder ends in its starting position. During the test the pressure, force and distance are recorded in LabView.

With this method the dynamic leakage was determined by analysing the height of the pressure peaks. The dynamic leakage at the cylinder head and cylinder foot were measured at a pressure of 0.5 MPa.

C. Experimental set up hydraulic testing

1) Preparing the cylinder for testing: The preparation of the hydraulic cylinder was almost identical to the procedure described in E-A1. Apart from the opening or closing of the hydraulic valve. For a holding test, the valve must be in closed mode. For an open valve mode test the valve must be in an open position. After the valve adjustments were made the cylinder must be filled again according to the procedure described in II-E5.

2) Open valve mode testing: During the open valve mode test the piston rod was moved over its full stroke length and the pressure drop was measured. Also the stroke length itself was measured. The applied force was also measured for the hysteresis loop. The test follows the following procedure:

1) The filled cylinder is weighted.
2) If needed an offset is applied to the pressure sensor and force sensor to start the measurements with 0 MPa and 0 N respectively.
3) The cylinder is moved back and forth over the full stroke length for 20 minutes at $10\,\mathrm{mm\,s^{-1}}$.
4) The cylinder stops at its starting position. During the test pressure, force and distance are recorded in Labview.
5) After testing the cylinder is weighted again.

The pressure difference during the cycles was determined as internal leakage. The difference in weight was determined as external leakage. The distance and force data were used to plot a hysteresis curve.

3) Closed valve mode testing: The internal leakage, external leakage and applied force were measured as follows:

1) The filled hydraulic cylinder is weighed.
2) When necessary an offset value is applied to the pressure sensor and force sensor resulting in a 0 MPa and 0 N start value.
3) The piston rod with a closed valve is retracted by the spindle drive. At the locking point, the piston rod will stop moving.
4) During the test the pressure, force and distance are recorded in LabView.
5) After testing the cylinder is weighed again. The test is repeated three times.

A pressure drop, a drop in applied force and an increase in distance are analysed during the hold test. Also the weight difference is analysed for the external leakage.

D. Pneumatic testing data analysis

1) Static leakage: The pressure sensor data was sampled with a sliding average function in Matlab. After sampling the mean and standard error of the three data sets of the same test were calculated. Afterwards the normalized pressure drop was calculated by subtracting the first mean value from the other mean values in the array. This resulted in the normalized pressure drop. Also, the standard error was normalized.

2) Pressure drop calculation based on force sensor data: To measure the performance of the test rig, the measured static leakage and the calculated static leakage with the force sensor data were compared. The theoretical pressure is calculated by dividing the measured force sensor data over the known area of the piston for both cylinder head and cylinder foot measurements. After the calculation for all values was completed the results were filtered by a moving average filter in Matlab, movmean, and normalized by subtracting the first calculated value from all other calculated values.

3) Dynamic leakage: The absolute dynamic leakage profiles were plotted by plotting the time in seconds on the x-axis and the pressure in MPa at the y-axis. The normalized pressure was determined by finding the pressure peaks and the time stamp of the pressure peaks using the matlab function findpeaks. The vector with pressure peaks was normalized and the result was plotted.

E. Hydraulic testing data analysis

1) Internal leakage during open valve mode test: The pressure data collected during the open valve mode test was collected and plotted versus time. A pressure drop was recognized as a combination of internal leakage and external leakage.

2) Hysteresis during the free running mode: The collected force and distance data were plotted for the hysteresis plot.

3) Internal leakage during holding test: For the hold test the force sensor data, pressure sensor data and distance sensor data were collected. The force sensor data and the distance data were plotted. The data is shown until the point the motor stopped running and the hold point was reached. The travelled distance, pressure drop and drop in applied force were recognized as a combination of internal and external leakage.

4) External leakage in open and closed valve mode: The external leakage was calculated by comparing the starting weight of the filled cylinder and the weight after testing. With the weight difference and the known density of water the volume difference or external leakage was calculated.

IV. Results pneumatic cylinders

A. Static leakage with self-induced compressed air

1) Cylinder head, static leakage on maximum extension: Figure 11 shows the static leakage of the cylinder head for the 3D-printed pneumatic integrated cylinder and the commercial pneumatic cylinder. Both systems generate a different pressure in maximum extension, 0.32 MPa and 0.2 MPa for the 3D-printed and the commercial system respectively. The static leakage plot shows that the 3D-printed pneumatic cylinder leaks about 0.0016 MPa over a period of 20 minutes and the commercial pneumatic cylinders leaks around 0.0012 MPa over 20 minutes. Also, the error margin of the 3D-printed pneumatic cylinder is larger than the error margin of the commercial cylinder. Table VI shows that the calculated values for the pressure drop based on force sensor data, theoretical values, are lower than the measured pressure drops.

2) Cylinder head, static leakage at same pressure: Table V shows the results of the static leakage when both cylinders are set on a self-induced pressure of approximately 0.2 MPa. In this case, the two systems are not at the same stroke length, the 3D-printed pneumatic cylinder is set on a shorter stroke length to induce a pressure of 0.2 MPa. The table shows that the static leakage of the 3D-printed pneumatic cylinder is lower than the leakage of the commercial cylinder. However, the error margins of the 3D-printed parts remain higher than the error margin of the commercial pneumatic cylinder.

	Pressure drop (MPa)	Stroke length (mm)
Cylinder head 3D-printed	$0.001 \pm 4.6{\times}10^{-4}$	20
Cylinder head commercial	$0.0012 \pm 3.9{\times}10^{-4}$	30 Full stroke
Cylinder foot 3D-printed	$6.4{\times}10^{-4} \pm 2.5{\times}10^{-4}$	17
Cylinder foot commercial	$0.0013 \pm 3.2{\times}10^{-4}$	30 Full stroke

TABLE V: Pressure drop of the cylinder head and cylinder foot when both 3D-printed and commercial cylinder are set to the same pressure generating position, 0.2 MPa.

3) Cylinder foot, static leakage at maximum retraction: Figure 12 shows the static leakage at maximum retraction for the 3D-printed pneumatic cylinder and the commercial pneumatic cylinder in the cylinder foot. The 3D-printed cylinder and commercial cylinder generate a different pressure in maximal retraction. As can be seen, the commercial cylinder has a pressure drop of 0.0013 MPa over 20 minutes and the 3D-printed cylinder has a pressure drop of 0.0032 MPa. Table VI shows the difference between the measured static leakage and calculated leakage. The difference is 0.0087 and 0.011 MPa for the commercial and 3D-printed cylinder respectively in a 20 minute test.

4) Cylinder foot, static leakage at same pressure: Table V shows the static leakage when both cylinders generate the same pressure. The commercial system is in this case in maximum retraction and the 3D-printed cylinder is not in maximum retraction but in a position so that it generates 0.225 MPa. The plot shows that at the same pressures the 3D-printed pneumatic cylinder performs better with a pressure drop of 0.0006 MPa compared to the 0.0013 MPa pressure drop of the commercial system, both in a 20 minute test. The 3D-printed cylinder also has a lower standard error.

B. Static leakage with external compressed air

1) Cylinder head, static leakage at 0.6 MPa: Figure 11 shows the static leakage in the cylinder head of both systems at 0.6 MPa pressure. The figure shows that the 3D-printed pneumatic cylinder has a higher rate of static leakage than the commercial system. The pressure drop in the 3D-printed cylinder is around 0.01 MPa and in the commercial cylinder, the static leakage is around 0.005 MPa over 20 minutes. The error bars for the 3D-printed cylinder are larger compared to the error bars of the commercial system. Table VI also shows that the difference between measured leakage and theoretical leakage is approximately 0.0095 MPa for the commercial system and 0.01 MPa for the 3D-printed system in a 20 minute test.

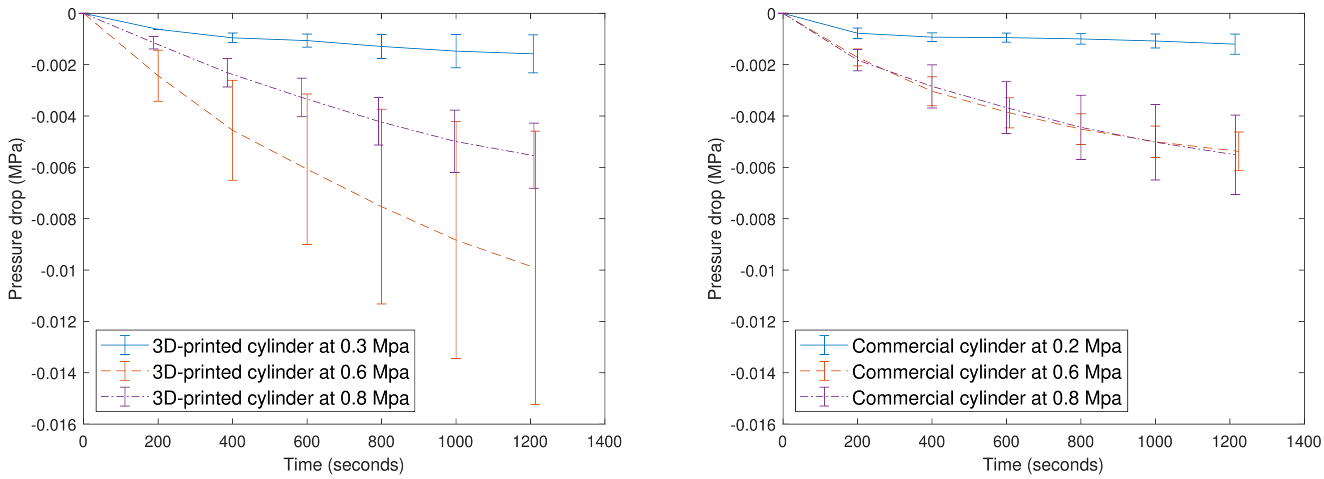
	Pressure drop measured (MPa)	Pressure drop calculated (MPa)
Cylinder head 3D-printed, 0.3 MPa	0.0016	0.0025
Cylinder head commercial, 0.3 MPa	0.0012	0.0025
Cylinder head 3D-printed, 0.6 MPa	0.01	0.02
Cylinder head commercial, 0.6 MPa	0.0054	0.012
Cylinder head 3D-printed, 0.8 MPa	0.0055	0.015
Cylinder head commercial, 0.8 MPa	0.0055	0.021
Cylinder foot 3D-printed, 0.2 MPa	0.0032	0.014
Cylinder foot commercial, 0.2 MPa	0.0013	0.01
Cylinder foot 3D-printed, 0.5 MPa	0.0052	0.014
Cylinder foot commercial, 0.5 MPa	0.0026	0.016
Cylinder foot 3D-printed, 0.7 MPa	0.0082	0.0058
Cylinder foot commercial, 0.7 MPa	0.0024	0.011

TABLE VI: The measured static leakage after 20 minutes compared to the calculated static leakage according to the force sensor data after 20 minutes

2) Cylinder head, static leakage at 0.8 MPa: Figure 11 shows the static leakage in the cylinder head for both systems at 0.8 MPa. The static leakage is lower for the 3D-printed system compared to the 0.6 MPa static leakage test of 20 minutes. Furthermore, the static leakage at 0.8 MPa seems to be almost the same for the 3D-printed pneumatic cylinder and the commercial system after 20 minutes. The error bars of the commercial system are higher than the error bars of the 3D-printed cylinder. The theoretical values of the static leakage are higher than the measured values. The difference is 0.01 MPa and 0.015 MPa for the 3D-printed pneumatic cylinder and the commercial pneumatic cylinder respectively, as can be seen in table VI.

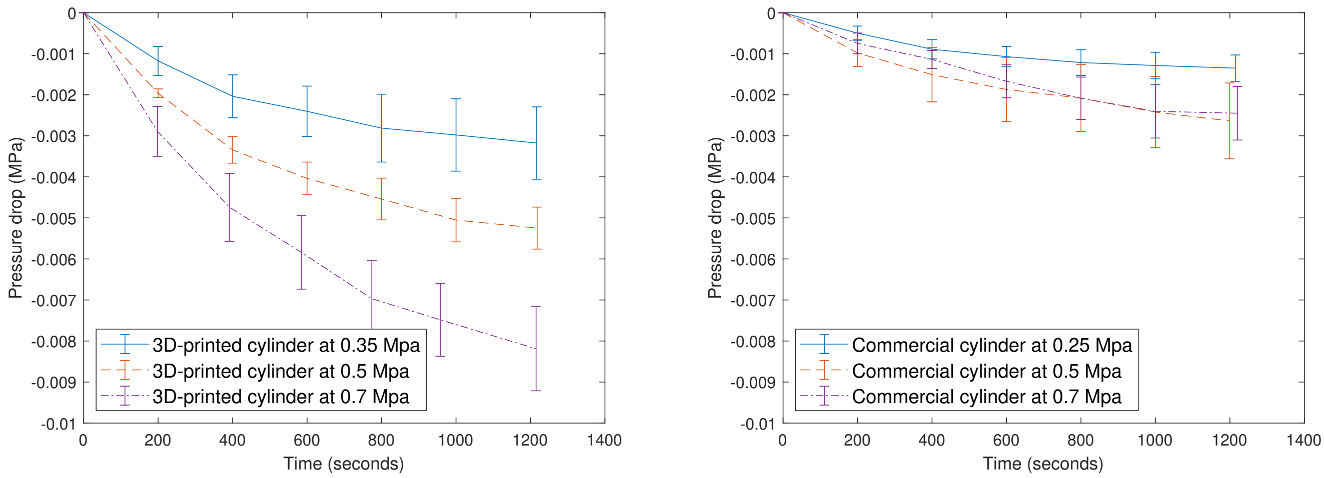
3) Cylinder foot, static leakage at 0.5 MPa: Figure 12 shows the static leakage in the cylinder foot for the 3D-printed pneumatic cylinder and the commercial cylinder at 0.5 MPa. The figure shows that the commercial cylinder has a leakage of 0.0026 MPa over a period of 20 minutes and the 3D-printed pneumatic cylinder has a leakage of 0.0052 MPa. The commercial cylinder has higher error bars. There is also a gap between the measured static leakage and calculated static leakage. Table VI shows that this gap is around 0.008 MPa for the 3D-printed pneumatic cylinder and around 0.013 MPa for the commercial pneumatic cylinder.

4) Cylinder foot, static leakage at 0.7 MPa: Figure 12 shows the static leakage in the cylinder foot of both systems at 0.7 MPa pressure. The figure shows that the commercial pneumatic cylinders performs better than the 3D-printed pneumatic cylinder. The static leakages are 0.0024 MPa and 0.0082 MPa for the commercial and 3D-printed cylinder respectively at the



(a) (b)

Fig. 11: (a) Pressure drop in the cylinder head of the 3D-printed pneumatic cylinder in a 20 minute static leakage test at different pressure levels. (b) Pressure drop in the cylinder head of the commercial pneumatic cylinder in a 20 minute static leakage test at different pressure levels



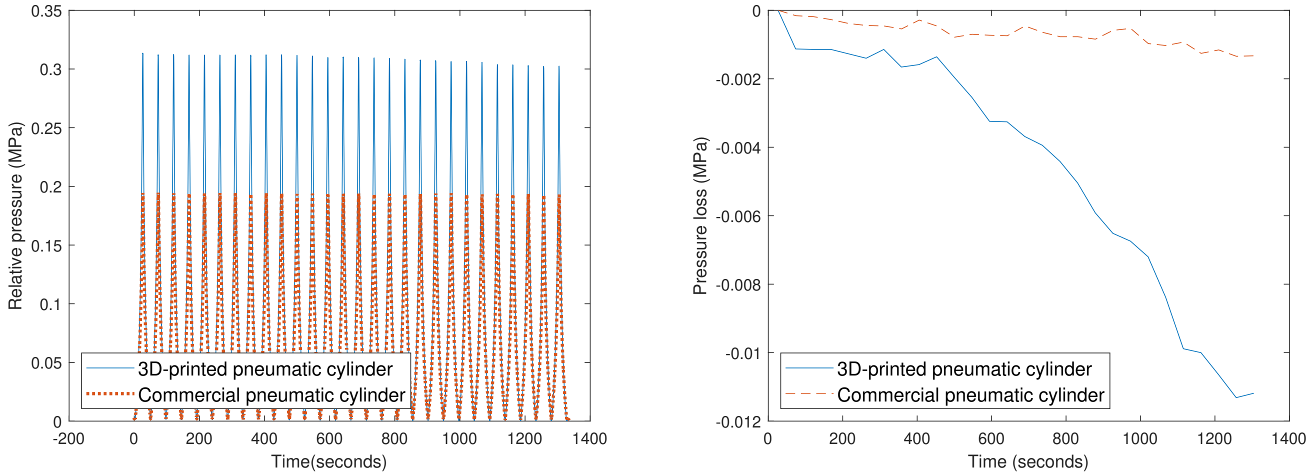
(a) (b)

Fig. 12: (a) Pressure drop in the cylinder foot of the 3D-printed pneumatic cylinder in a 20 minute static leakage test at different pressure levels. (b) Pressure drop in the cylinder foot of the commercial pneumatic cylinder in a 20 minute static leakage test at different pressure levels

end of a 20 minute test. Also, the error bars of the 3D-printed pneumatic cylinder are higher than standard error measured for the commercial pneumatic system. Table VI shows the calculated static leakage comparison for both systems. As can be seen the calculated static leakage of the 3D-printed pneumatic system is lower than the measured static leakage, around 0.0024 MPa after 20 minutes. The theoretical comparison of the commercial pneumatic system is almost 0.0086 MPa higher after 20 minutes.

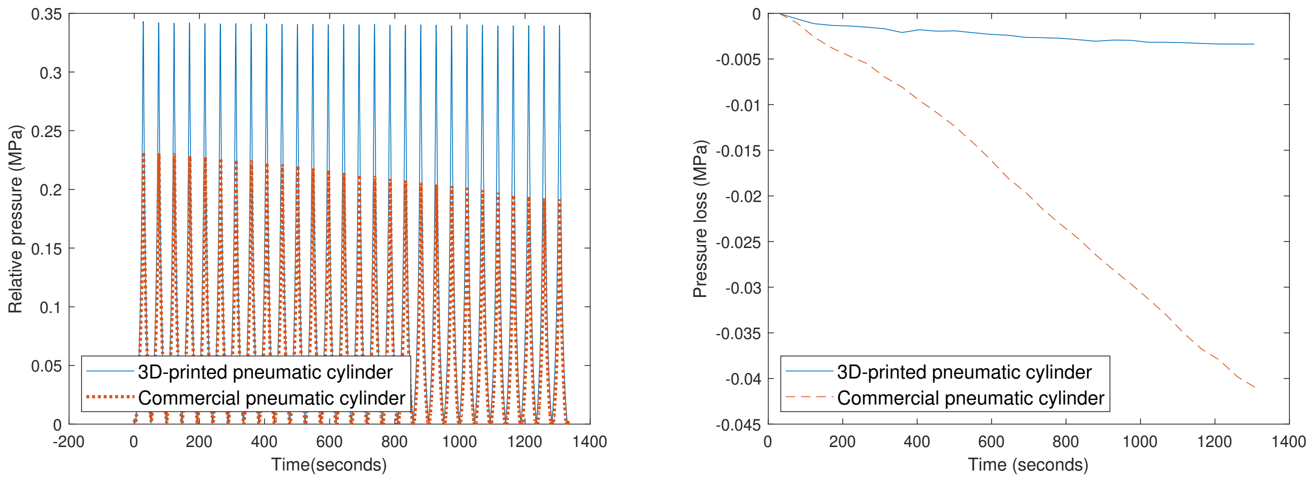
C. Dynamic leakage with self induced pressure

1) Cylinder head, dynamic leakage at maximum stroke: Figure 13(a) shows the dynamic leakage of the 3D-printed and commercial pneumatic cylinders. As can be seen, the 3D-printed cylinder generates a pressure of 0.32 MPa and has a gradual decline over 20 minutes to 0.3 MPa. The commercial cylinder starts at a lower pressure of approximately 0.195 MPa and also has less decent to 0.193 MPa after 20 minutes. In order to have a better view of the leakage of both systems, a normalized plot is made. Figure 13(b)shows the normalized dynamic leakage for both cylinders.



(a) (b)

Fig. 13: (a) Dynamic leakage in the cylinder head measured over 20 minutes for the 3D-printed and the commercial cylinder. (b) Normalized dynamic leakage in the cylinder head measured over 20 minutes for both cylinders.



(a) (b)

Fig. 14: (a) Dynamic leakage with self-generated pressure in the cylinder foot of both cylinders for 20 minutes. (b) Normalized dynamic leakage with self-generated pressure in the cylinder foot for 20 minutes.

2) Cylinder foot, dynamic leakage at maximum retraction: Figure 14(a) shows the dynamic leakage in the cylinder foot of both systems. The figure shows that the 3D-printed cylinder generates more pressure and also has less dynamic leakage over 20 minutes. The commercial cylinder generates less pressure and also has a larger leakage of approximately 0.04 MPa after 20 minutes. Figure 14(b) shows the normalized dynamic leakage on the pressure peaks.

D. Dynamic leakage with external pressure

1) Cylinder head, dynamic leakage at 0.5 MPa*:* Figure 15(a) shows the dynamic leakage of the cylinder head for both systems at maximum extension. The figure shows that both cylinders must be filled on another pressure level to reach 0.5 MPa pressure. Also, the 3D-printed pneumatic cylinder overshoots more than the commercial cylinder. The dynamic leakage of the 3D-printed pneumatic cylinder system is higher compared to the commercial cylinder, 0.035 MPa leakage and 0.0025 MPa, respectively after 20 minutes. Figure 15(b) shows the same dynamic leakage of both systems normalized on the pressure peaks.

2) Absence of cylinder foot data: Due to a dent in the cylinder wall of the commercial pneumatic cylinder near the cylinder foot, the dynamic leakage data with external pressures were not comparable. Therefore it was decided to exclude this data from the report. Subsubsection describes the dent in more detail VI-A5.

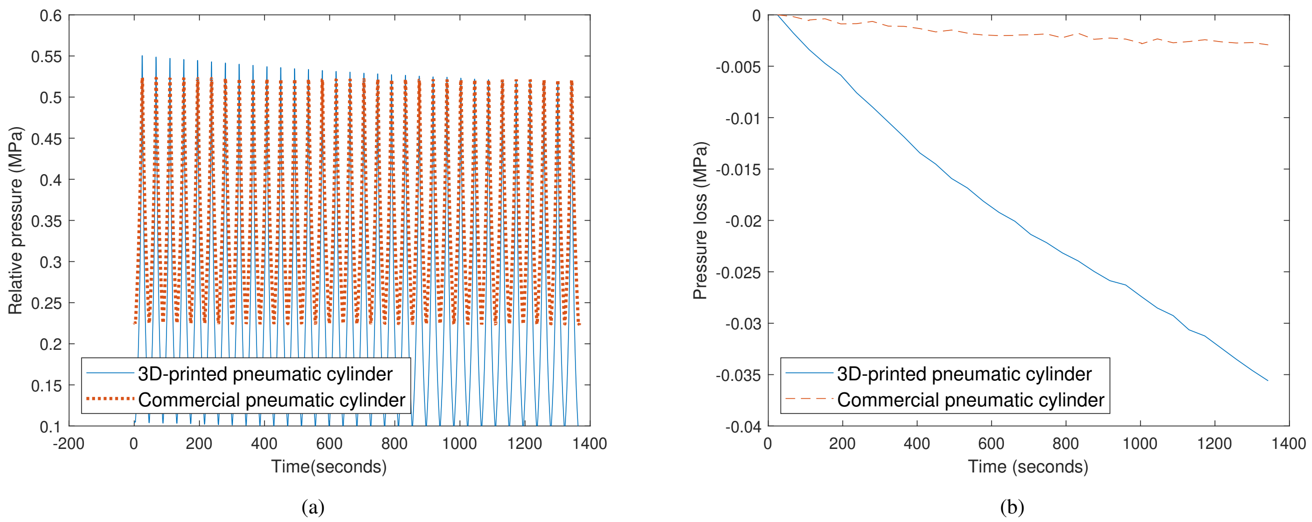


Fig. 15: (a) Dynamic leakage in the cylinder head at 0.5 MPa pressure for both cylinders for 20 minutes. (b) Normalized dynamic leakage in the cylinder head at 0.5 MPa pressure for both cylinders for 20 minutes.

V. Results hydraulic cylinder

A. Open valve mode

1) Hysteresis plot in open valve mode: Figure 16(a) shows the hysteresis plot of the 3D-printed hydraulic cylinder in an open valve mode over 20 minutes. The figure shows that 16 N is needed to move the piston inwards and approximately 20 N to move the cylinder outwards. Furthermore, the figure shows that there is a descending gradient in the retraction motion with small humps along the stroke and there is a coarse acceding gradient with the extension motion. There are two force peaks at the turning point. A high force peak at 0 mm distance of 28.08 N and a smaller force peak at 29 mm distance of −20.17 N.

2) Internal leakage: Figure 16(b) shows the dynamic leakage of the 3D-printed hydraulic cylinder during a 20 minute test run. The figure shows that there is a decline in the pressure over time of approximately 0.006 MPa with a maximum pressure drop of 0.007 MPa around 780 s. Furthermore, the figure shows that there is no constant descent in pressure. A last remark is on the low pressure plateaus at the end and beginning of each cycle. It seems there is a difference in the width of these low pressure plateaus, for example at 470 s and 1278 s.

3) External leakage: Table VII shows the external leakage as measured in 3 different test runs. The figure shows that the second test run had the lowest external leakage, 0.9 mL after 20 minutes. The first test run had the highest external leakage, 1.7 mL after 20 minutes.

Test run number	External leakage
Test run 1	1.7 mL
Test run 2	0.9 mL
Test run 3	1.1 mL
Average	1.2 mL

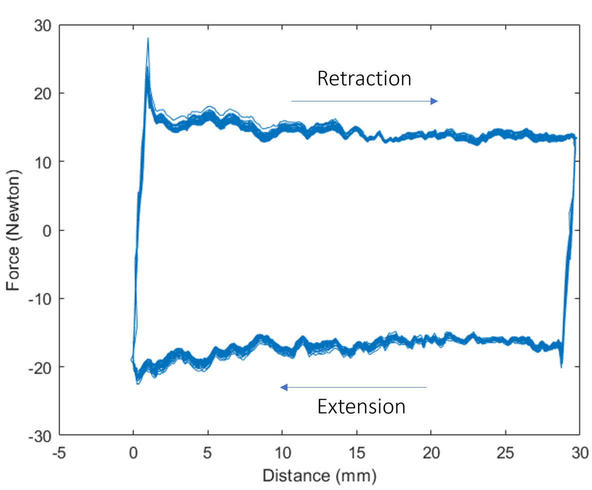
TABLE VII: External leakage after 20 minutes of the 3D-printed hydraulic cylinder in open valve mode.

B. Closed valve mode

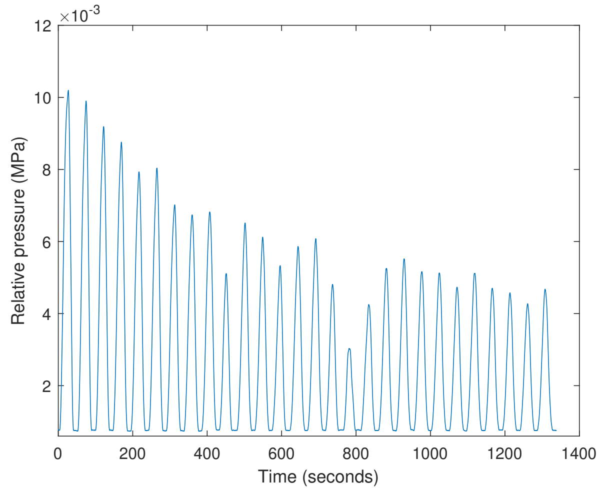
1) Force displacement in closed valve mode: Figure 17(a) shows the force versus distance plot until the holding point of the 3D-printed hydraulic cylinder for three closed valve tests. The figure shows that in the first test the cylinder is able to hold the increasing load. After a displacement of 10 mm and an increasing force of 120 N, the cylinder stopped moving and the holding point was reached. For the other two tests, the holding point was not reached and the spindle drive was able to push the hydraulic cylinder to the end of its stroke with a force of 20 N.

2) Pressure build-up in closed valve mode: Figure 17(b) shows the pressure over the distance when the 3D-printed hydraulic cylinder is pressed in holding mode. The figure shows that in the first holding test the system can build up a pressure of 0.32 MPa before the holding point is reached. In the other two tests, a pressure of 0.026 MPa and 0.033 MPa is measured respectively over the course of the hold test.

3) External leakage: During the three hold tests, the external leakage was measured. Table VIII shows the external leakages for the three hold tests and an average. The table shows that the highest external leakage is measured at the first hold test. The lowest external leakage is measured at the second hold test. It can also be seen that the results for the second and third hold test lay close.

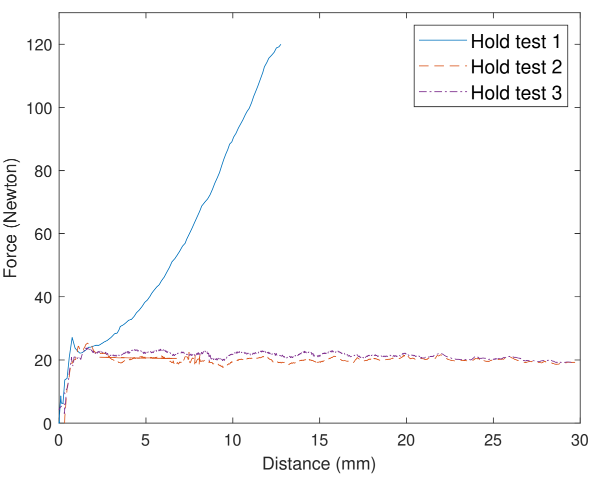


(a)

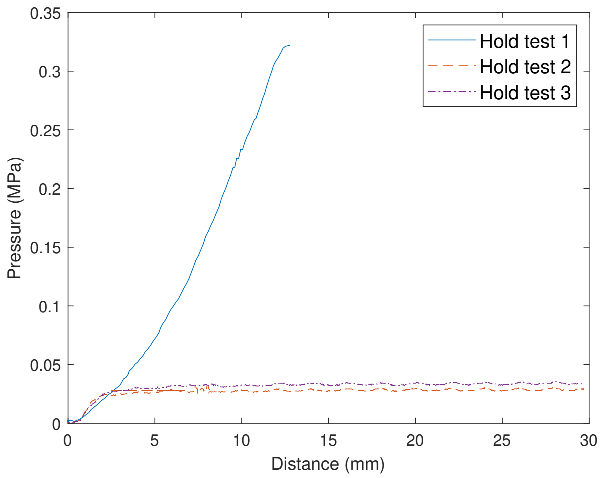


(b)

Fig. 16: (a) Hysteresis plot of the hydraulic cylinder in open valve mode, increasing distance corresponds with a retracting or inward movement. Decreasing distance corresponds with a extension or outward motion. (b) Internal leakage plot of the hydraulic cylinder measured for 20 minutes during a dynamic test.



(a)



(b)

Fig. 17: (a) Three hold tests with distance and force measured until the holding point. (b) Three hold tests with distance and internal pressure generation measured.

Hold test number	External leakage
Hold test 1	10.4 mL
Hold test 2	7.4 mL
Hold test 3	7.9 mL
Average	8.6 mL

TABLE VIII: External leakage measured over a run of the hold test for the 3D-printed hydraulic cylinder in closed valve mode.

VI. Discussion

A. Results pneumatic cylinders

1) Static leakage with self-induced pressure at maximum extension/retraction: Subsection IV-A shows the static leakage measured in the cylinder head and foot with self-induced pressure. The commercial system performs better than the 3D-printed pneumatic cylinder in the static leakage test at maximum extension and retraction. Also, the error bars of the 3D-printed pneumatic cylinder are higher than the error bars of the commercial system. The results also show that the cylinder foot leaks more than the cylinder head in the 3D-printed cylinder, 0.0015 MPa in the cylinder head and 0.003 MPa after 20 minutes in the cylinder foot, while the static leakage in the commercial system is almost the same after 20 minutes. A possible explanation for the higher leakage in the 3D-printed cylinder head and foot is the roughness and clearance of the sealing seatings. Since those seatings have a higher roughness, approximately 100 µm, and clearance in the 3D-printed system, the sealings can move at every test. Due to the roughness, the seal is not able to close off the entire seating but leaves small gaps causing leakage. Figure 18 explains the movement of the sealing due to clearance and roughness. The same explanation of clearance and roughness holds for the higher error bars in the 3D-printed cylinder. A wider range of static leakage is measured, due to the possibility of the sealing moving in the seating. A cause for the difference between static leakage in the 3D-printed cylinder head and cylinder foot is the difference in print quality of the sealing seatings. In the cylinder foot the two places of sealing seatings, the valve seating and the cylinder connection, are orientated at a 90° angle, causing a difference in print quality in the sealing seating that is not in the print direction. In the cylinder head, the sealing seatings are all in the same print direction and have the same print quality.

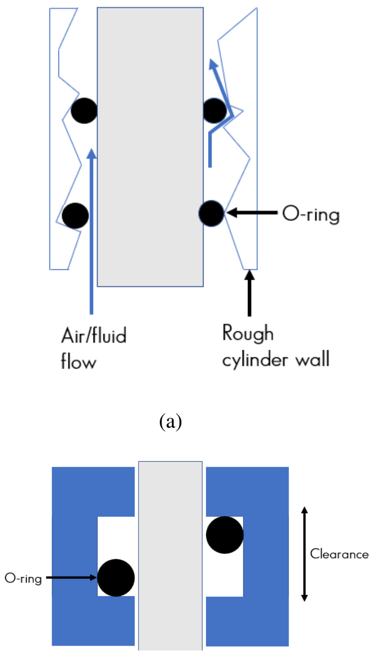


Fig. 18: (a) Explanation of the resettling of an O-ring encountering rough cylinder walls. As can be seen the O-ring settles differently at different rough point leaving passageways for the air. (b) Explanation of the resettling of an O-ring in a high clearance seating. The O-ring is able to move into a diagonal configuration leaving space between the part and the O-ring.

2) Static leakage with self-induced pressure at same pressure: Table V show that at the same self-generated pressure of 0.2 MPa and 0.225 MPa respectively the static leakage in the 3D-printed cylinder head and foot is lower than the leakage in the commercial pneumatic cylinder. However, the two cylinders are not on the same extension or retraction distance resulting in another pressure load on the seals [27]. The error bars of the 3D-printed cylinder head remain higher, at the 3D-printed cylinder foot the error bars are lower than the commercial cylinder. A possible explanation is the extra sealing, the piston rod sealing, that has a cup shape and can not close off the seating walls with high roughness, especially at low pressures [20].

3) Static leakage with external pressure: Figures 11 and 12 show the static leakage in cylinder head and cylinder foot at different external pressures. The commercial pneumatic cylinder performs better than the 3D-printed cylinder at all pressures in the cylinder head and foot. Figure 11(a) shows that a higher pressure of 0.8 MPa leads to less leakage in the 3D-printed cylinder head. An explanation is that at higher pressures the sealing is deformed more in its seating overcoming the roughness and movement due to clearance. The lower error bars confirm this theory for the 3D-printed cylinder head. Figure 11(a) shows a relative large pressure drop in the 3D-printed cylinder head and relative high error bars at 0.6 MPa. The explanation is a damaged valve seating sealing which was discovered after the first test. After the first test, the sealing was replaced and better results were collected. Figure 19 shows the results of the different tests at 0.6 MPa in the 3D-printed cylinder head. The damage is caused by installing the valve and valve seating in the 3D-printed part, this installation method can be improved as discussed in VI-D4. The static leakage in the cylinder foot shows expected behaviour.

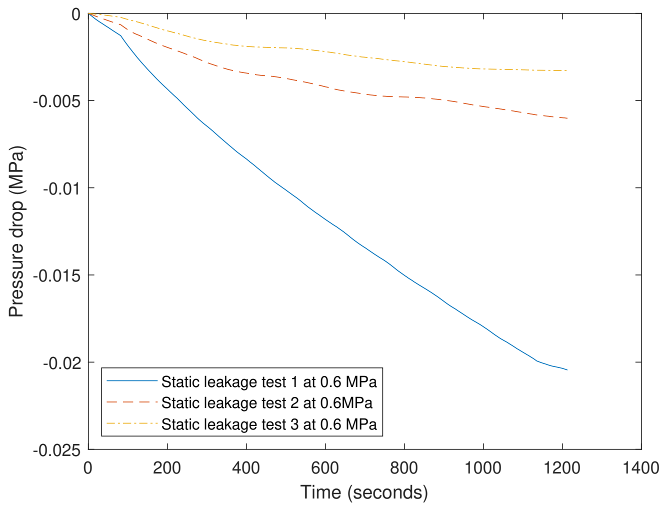


Fig. 19: Pressure drop diagram for three different static leakage tests in the cylinder head at 0.6 MPa.

4) Pressure calculations based on force sensor data versus measured results: Table VI shows a discrepancy between the measured values and the calculated values of static leakage according to force sensor data. The average discrepancy of the measured leakage and calculated leakage is 0.006 MPa after 20 minutes and this offset is caused by a misalignment force and the inclusion of a reaction moment. Figure 20 shows an exaggerated example of how the force sensor seating can exert a reaction moment. As stated in appendix E of Zillen et al. [14]

a small moment or misalignment force at the linear load cell can cause an error of 1.5% resulting in lower measured forces and a higher calculated static leakage. Although the test rig contains a universal rod end joint, a redesign is needed to avoid moment and misalignment forces in the force measurements. Subsubsection VI-D1 discusses a redesign of the coupling in the test rig and mentions other solutions as stated in literature.

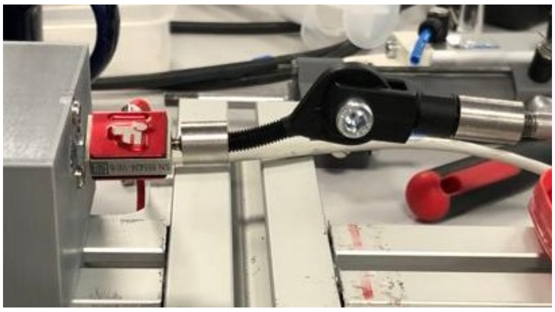


Fig. 20: An exaggerated view of the reaction moment that the force sensor coupling can exert on the force sensor

5) Dynamic leakage: Figure 13 and 14 show the dynamic leakage of the cylinder head and foot at maximum extension. As the figure shows both cylinders can not generate the same pressure due to a difference in dead space. The commercial system has a larger death space in the cylinder foot and cylinder head. The cylinder has also two hose connectors and a hose in between. Although the hose length is kept as small as possible there is still a larger dead space and lower pressures. The difference in generated pressure in the cylinder head and cylinder foot of both systems is due to a difference in area and volume due to the piston rod at the cylinder head. Moreover, figure 13(b) and 15(b) show that the leakage of the 3D-printed cylinder head is relative high compared to the dynamic leakage at the same pressure or higher pressure in the commercial cylinder. The reason for this higher leakage is again a higher roughness and clearance of the seal seatings. In a dynamic load, the sealings can settle differently during each pressurized load resulting in higher leakage profiles. Figure 14 shows the dynamic leakage in the cylinder foot. The figures show that the commercial pneumatic cylinder is the cylinder with the highest dynamic leakage. A closer look at the piston and cylinder wall of the commercial cylinder revealed a dent in the cylinder wall near the cylinder foot, approximately at 5/6 of the retraction length. This small dent will cause a higher leakage profile in the cylinder foot, in the cylinder head it has no influence when the stroke length is adjusted to 5/6 of the stroke length. Figure 21 shows the disturbance in the cylinder wall.

B. Results hydraulic cylinder

1) Hysteresis in open valve mode: Figure 16(a) shows the hysteresis of the 3D-printed hydraulic cylinder in open valve mode. The figure shows a high force in a range of 16 to 20 N for the movement of the cylinder over the full stroke. An explanation is that the piston seal used, Sealtech 20x14x3 [23], is a lip seal that has high friction forces when the seal is

Fig. 21: Dent in the cylinder wall near the cylinder foot of the commercial pneumatic cylinder, as indicated by the red rectangle.

pressurized since the total lip of the seal expands and presses against the cylinder wall. Since two lip seals are used the friction force is doubled. Another reason for the high forces during movement is the small ducts that are generating high fluid friction when the fluid flows through them. The last reason is the possibility of trapped air inside the cylinder. Resulting in higher forces. The figure also shows humps in both extension and retraction movement which are caused by the roughness of the cylinder wall resulting in stick-slip behaviour. The two peaks at the turning points from retraction to extension and vice versa are caused by an overshoot of the motor when the piston in the cylinder changes direction.

2) Internal leakage in open valve mode: Figure 16(b) shows the dynamic leakage of the 3D-printed hydraulic cylinder in open valve mode. The figure shows a relative large pressure drop at a relative low pressure build-up. One of the reasons for this pressure drop is the type of piston sealing. Since the sealing is a single-acting lip seal it is hard for the seal to follow the relatively rough cylinder wall leaving space for the fluid to flow along the sealing. Another reason for the high-pressure drop is the external leakage during the dynamic tests. An explanation for the pressure peaks at different heights is trapped air inside the cylinder.

3) External leakage in open valve mode: Table VII shows the external leakage of the 3D-printed hydraulic cylinder in open valve mode. In this mode, there was relatively small hydraulic leakage especially at the accumulator cylinder head. No movement of the accumulator piston was registered during the open valve tests or during the closed valve mode tests. A reason for the blocking of the accumulator piston is the high friction between the Eriks quad ring and the accumulator cylinder wall. Due to the blocking accumulator piston, there is volume build-up in the cylinder foot and the accumulator tube resulting in an outflow of fluid.

4) Testing in closed valve mode: Figure 17 shows the force and pressure build-up respectively of three independent tests in closed valve mode. The figures show that the first hold test was successful with a displacement of 10 mm before a total holding scenario was reached. This displacement is caused by a mix of external leakage and trapped air, since the pressure build-up does not show a decline in pressure a marginal internal leakage is assumed. Table VIII shows the external leakage during the closed valve mode tests. The second and third hold tests show a full stroke displacement of the cylinder with a minimal force and pressure build-up of 20 N and 0.02 MPa respectively. A reason for this low holding force and pressure is the designed hydraulic valve. Since the valve is integrated into the cylinder foot and the close-off mechanism was designed in the valve seating, no visual check was possible if the valve and the close-off sealing were closed correctly. It was also hard to tighten the close-off screw due to a too high clearance between the valve seating and the valve seating cavity resulting in a rotating valve when the screw was tightened. An improvement is to design a new hydraulic valve that is easier to open and close and is also not based on a press fit as a connection but on for example a tapped hole connection. Subsubsection VI-D4 describes a redesign of the valve seating.

C. Comparing the state of the art

1) 3D-printed pneumatic cylinder data: To the best of the authors' knowledge no literature was found, that evaluates a 3D-printed pneumatic cylinder with integrated valves on static and dynamic leakage and makes a comparison with a commercial system. The closest research is the work of Zillen et al. [14] that tests the leakage of different piston sealings in a single-acting piston-cylinder system with coupled pressure sensor and an external Festo manual valve for opening and closing the cylinder. A comparison is made between the static leakage test data of Zillen et al. for a KDN sealing at 0.5 MPa and the 3D-printed pneumatic cylinder foot at a 0.5 MPa static leakage test in the cylinder foot. The comparison shows that the 3D-printed cylinder as designed in this study has a leakage of 0.005 MPa over 20 minutes while the leakage in Zillen et al. at the same pressure is around 0.0042 MPa. Although the 3D-printed integrated pneumatic cylinder leaks more for the same conditions, the result is positive since the increased complexity of an integrated valve only leads to an increase in leakage of 0.0008 MPa over 20 minutes.

2) Commercial pneumatic cylinder data: To the best of the authors' knowledge no literature or checked data, e.g. in a catalogue or datasheet, was found that describes the static leakage and dynamic leakage of the used commercial cylinder. Due to the lack of leakage data no comparison for the cylinder foot on high-pressure dynamic leakage is made since the commercial cylinder used in this research has a dent in the cylinder tube that leads to a false non-comparable leakage profile for dynamic leakage tests. Another option is to compare the 3D-printed cylinder with the bubble tight statement, which means that the cylinder can not leak more than 10 mL per minute. However, this benchmark is applicable for pneumatic cylinders connected to a constant feed of pressurized air and with switching valves [28]. Therefore the bubble tight statement is not applicable to the tests done in this research.

3) Commercial gas spring data: The use and type of application of the designed 3D-printed pneumatic cylinder is more in line with gas springs since both systems make use of a closed volume without a constant feed of external pressure. Also both systems are designed for a minimum static and dynamic leakage during usage. According to information provided by the company Meusburger(Germany) a short stroke gas spring can function without a measurable force difference for 1000000 dynamic cycles [29]. The designed system can not be compared with a commercial gas spring since for example at 0.5 MPa the force difference after 32 cycles is 10 N. Although, gas springs do not have integrated valves, the performance of the 3D-printed pneumatic cylinder can not be compared to such a system.

4) 3D-printed and commercial hydraulic cylinder data: To the best of the authors' knowledge, no literature was found on the evaluation of 3D-printed valve-integrated hydraulic cylinders. Martinez de Apellaniz Goenaga [16] describes the static and dynamic leakage behaviour of single-acting piston-cylinder systems sealed by an O-ring for different printing methods. The tested cylinders are filled with water. On the SLA printing method, both results can be compared. Martinez de Apellaniz Goenaga's system can hold loads of 0.4 MPa, while the cylinder in this research only holds 0.325 MPa before going into holding mode. It was also hard to find commercial standards for comparison. One of the comparisons found was the allowed displacement in lock mode, which is a HAWE Hydraulik standard. This displacement in hold mode is set to 1 $\mathrm{mm\,s^{-1}}$. As the results in V-B1 show, there is a larger displacement in the hydraulic cylinder of approximately 3 $\mathrm{mm\,s^{-1}}$. Another HAWE standard for hydraulic cylinders is the maximum force at maximum speed. This force is set to 20 N for both retraction and extension movements. Since the tested system does not reach its maximum speed during testing, 10 $\mathrm{mm\,s^{-1}}$ with a maximum force of 20 N, this standard is also not met.

D. Limitations

1) Force sensor limitations: As stated in Appendix E of Zillen et al. [14] a small misalignment error in the force sensor can lead to a force offset of 1.5 %. Although the designed test rig contains a universal rod end joint, the force sensor attachment is still able to exert a reaction moment that is not measured by the sensor. Figure 20 shows an exaggerated position of the test rig which shows that with the universal joint it is still possible to exert a reaction moment. Figure 22 shows the free-body diagram of the current coupling between the force sensor and the universal joint in the test rig. The figure shows that the force sensor has to withstand moments and radial forces. To avoid moment shielding and cross-talk in the test rig a new coupling design is needed with two universal joints that are coupled to a two-force member. The two force member is guided by a rail so that the system can only exert linear forces without misalignment. Another option is to connect the force sensor to the piston rod so that no moment shielding takes place. Another option is to design a coupling as used in Belforte et al. [30].

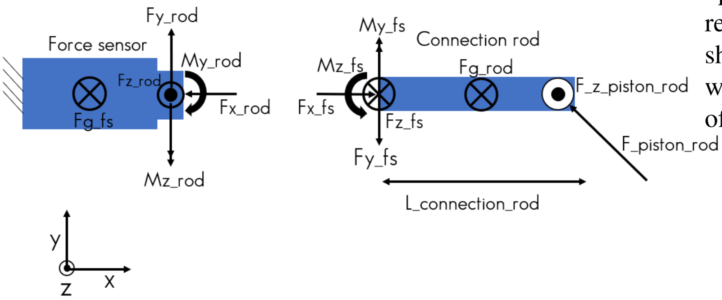


Fig. 22: Free body diagram of the coupling between force sensor and connection rod of the universal joint when there is misalignment. The end of the connection rod is coupled to a universal joint which is coupled to the piston rod. The FBD seen from a top view.

2) Force and speed of spindle drive: The stepper motor used, the NEMA 23, was not able to exert forces higher than 250 N which was a problem in for example dynamic leakage tests at pressures higher than 0.5 MPa. To avoid these problems a more powerful motor with more amperage can be selected resulting in higher torque. Another option is to select a stronger stepper driver since the current driver, a standard Arduino CNC shield, can not deliver the maximum amperage. A suitable driver is the SL2690A stepper driver. However, it is hard to connect such a driver to a universal G-code sender program and Arduino. Also, another driver will solve the force-exerting problem but will not solve the speed problem since spindle drives are relatively slow actuation mechanisms [31]. A good option to solve both problems is by using a hydraulic or pneumatic cylinder as a driving unit. In Belforte et al. [30] a hydraulic unit is used as an actuator. A downside of using a hydraulic or pneumatic cylinder is that it is hard to program force-dependent actuation. Also position-based control is hard with a pneumatic or hydraulic drive unit.

3) Stiffness and alignment of the test rig frame: Initially, moment testing was part of the measurement plan. In a moment test a horizontal offset between the spindle drive and the piston rod is created so that a moment can be applied to the piston rod. However, due to the force-dependent actuation of the stepper motor, it was decided to exclude these tests. To conduct moment tests a horizontal frame part was connected between the frame part with the spindle drive mounted on and the frame part with the cylinder mounted on. This extra connection results in less stiffness and an extra chance for misalignment. Therefore it is advised to mount the drive unit and cylinder all on one stiff aluminium frame part when no moment tests are planned.

4) Damage of valve sealing and 3D-printed part due to press fit: A lot of damage to the seals was caused due to the press-fit installation of the valves. A small misalignment of the metal valve seating during the press-fit could already lead to a damaged O-ring or a damaged valve cavity. A press-fitted valve seating makes it also hard to tighten and loosen the opening and closing bolt since a loose fit in a 3D-printed part results in a rotating valve seating during tightening. Figure 23 shows a possible solution. A tapped hole in the 3D-printed part will house a valve seating. This solution guarantees fixation of the valve seating and avoids damaging press fit handlings.

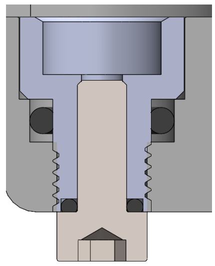


Fig. 23: Section view of the new design for the valve seating with outer thread connected in a tapped hole in the cylinder head or foot.

5) Availability of hydraulic sealings: It was hard to find available hydraulic sealings in the dimensions as stated in subsection II-D. This resulted in using a lip sealing and x-ring sealing for the cylinder and accumulator piston respectively, although earlier research stated that these sealing are not optimal regarding friction and dynamic leakage [14]. Hydraulic seals for small dimensions do exist [32] however they are not available for small orders. A possible solution for this limitation is to 3D-print seals as is recommended and described in subsubsection VI-E3.

E. Future recommendations

1) Improving sealing seating roughness and clearance using multiple tolerance prints: All sealings will function optimal on a surface roughness of 4 µm [27]. However, to save time the prints in this research are set to a layer height of 100 µm resulting in static and dynamic leakage as shown in the results. The minimal layer height that a Formlabs printer can reach is 25 µm, a way to improve the roughness of the valve seating without a high increase in printing time will be to make multiple tolerance prints with a low roughness in the valve seatings and higher allowed roughness in structural parts. As showed by Beer et al. it is possible to make different levels of details within one print [33]. Research can focus on how to make such multiple tolerance prints and on the performance evaluation of different multiple tolerance prints.

2) Evaluation of the current design process using SLM printing: In the current research the 3D-printed pneumatic and hydraulic cylinder are produced using SLA-printing, a method that can print a wide range of plastics with different properties. However, in high force applications the material properties of the resins provided by formlabs [34] are not sufficient enough and a transition to steel printing or SLM printing has to be made. Martinez de Apellaniz Goenaga already showed the possibilities of printing a simple cylinder piston system with SLM [16]. Further research can focus on the question if the current design steps and choices will also work for metal printing and which changes are needed to come to the same or an even better performance.

3) Printing sealings and multimaterial printing: As stated in VI-D5 a bottleneck for microfluidic hydraulic and pneumatic cylinder design is the availability of sealings for small dimensions. Research can focus on manufacturing sealings using SLA-printing and evaluate their performance according to static leakage, dynamic leakage and friction. Research can focus on the design and performance evaluation of piston and piston rod sealings, since those sealings are hard to find for small dimensions. Another option is to combine the printing of structural pneumatic and hydraulic parts and their sealings in a multi-material printing set-up as was also done in a study by Siegfarht et al. [15]. Also Roach et al. showed a method to combine SLA-printing and FDM-printing in one print [35].

4) Life cycle test and full scale cylinder: The maximum test duration in this study is 20 minutes. To get a better insight into the use and feasibility of 3D-printed pneumatic and hydraulic cylinders in a prosthetic application, a life cycle test must be performed with both cylinders and compared to the commercial standard. Also, the designed cylinders are relative small, especially the stroke length. To get a better view of the performance in a prosthetic application a cylinders can be designed and manufactured according to the design principles of this thesis and with the dimensions of the cylinder as calculated and designed by Landers et al [18] for an assistive biarticular knee-ankle joint.

5) Performance of hydraulic seals on internal leakage, external leakage and friction: In this research, the insights of performance tests on pneumatic piston seals were extrapolated to hydraulic seals to see if it is possible to design a hydraulic cylinder with the same design principles as a 3D-printed pneumatic cylinder. The hydraulic cylinder was not working as expected, as was stated in the discussion. The non-sufficient performance was partly a problem of the wrong sealing choice, according to research done on pneumatic sealings, but it also raised the question to find out the performance of different hydraulic sealings in a 3D-printed cylinder. Future research can focus on evaluating the performance of hydraulic seals regarding friction, internal and external leakage in a 3D-printed piston-cylinder system. The focus can be on piston and piston rod sealings.

6) Topology optimized design, combined with non-circular cylinder shapes: 3D-printing creates a large design freedom [8], therefore a good option for further research is the use of topology optimization in the design of different cylinder parts. Xie et al. already proved the use of topology optimization in the design of a hydraulic valve block which was manufactured by 3D-printing [36]. The use of topology optimization can be combined with the design methods for non-circular cylinder shapes and seals as stated by Zillen et al. [14].

VII. Conclusion

This study presents a design for a 3D-printed pneumatic and hydraulic cylinder with valves integrated in the cylinder. To answer **research questions 1 and 2** the 3D-printed pneumatic design was tested on static and dynamic leakage and compared with a commercial pneumatic cylinder. The pneumatic commercial cylinder performs better on both static and dynamic leakage. In static leakage, the differences between both pneumatic cylinders are small with a maximum pressure difference of 0.0095 MPa in the cylinder head at 0.6 MPa after 20 minutes. Therefore it is stated that for static leakage the 3D-printed pneumatic cylinder has the same performance range as the commercial cylinder. In dynamic leakage, the results of both systems are further apart with a maximum leakage in the 3D-printed cylinder head of 0.035 MPa compared with 0.0025 MPa leakage of the commercial system after 20 minutes. Therefore the current 3D-printed pneumatic cylinder has not the same performance range as the commercial cylinder for dynamic leakage. The main reason for the difference in static and dynamic pressure drop between both cylinders is the roughness and clearance in the sealing seatings. The print quality and thereby the print direction are the most important design factors and all high precision design details e.g. sealing and valve seatings must be designed in the same direction so that they can be printed with high precision and without supports.
To answer **research question 3** the 3D-printed hydraulic cylinder with integrated valves was tested on hysteresis, internal leakage and external leakage. Tests were done with open valve mode and closed valve mode. Although the 3D-printed cylinder does not work properly with a too high force to move the cylinder in open valve mode of 20 N, internal leakage of 0.007 MPa after 20 minutes testing and external leakage of 8.6 mL in closed valve mode it gave important design insights in sealing selection and valve design. The tests show that the insights for designing a 3D-printed pneumatic cylinder can not be used in the design of a 3D-printed hydraulic cylinder and more research is needed in selecting the right sealings for 3D-printed hydraulic applications.

VIII. Data availability

The test data and the data analysis scripts used in this research are available at: https://github.com/BvanderWindt/3D-printed-fluid-controlled-actuators. The patent review, as mentioned in subsection I-B is also available in this data base.

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APPENDIX A
DESIGN PROCESS, 3D-PRINTED PNEUMATIC CYLINDER

In this appendix the design process of the 3D-printed pneumatic cylinder is described. Subsection II-B shows and explains all facets of the final design.

A. Design requirements

The pneumatic integrated cylinder and all its subsystems must fulfil a set of requirements. The main requirements and specifications of the commercial system are mentioned in subsection II-A. This subsection gives a total overview of the design requirements and the assumptions made to come to this set.

1) Preliminary specifications: Before the requirements was made a list of specifications was set up. The following specifications were set up:

- The cylinder must be a double acting or differential cylinder.
- The system must be able to control the inlet at the cylinder foot and head independently.
- The total system must be manufactured with a standardized/ widely available 3D-printing method. Exception on this rule are valve and valve seatings and parts of the piston assembly.
- The 3D-printed parts are only post-processed by hand driven tools, e.g. a utility knife for removing supports, files for finishing supported parts, reamers for smoothening a printed hole and drilling for removing debris.
- The total system is integrated, this means that all needed systems e.g. valves, piston, cylinder are directly connected and no hose and hose fittings are needed. Exception on this specification is the connection with sensors for measurement purposes e.g. a pressure sensor and the connection between a microcontroller and a powered valve, e.g. a solenoid actuated valve.
- The total pneumatic integrated system makes use of available commercial seals and O-rings. A commercial valve system is also preferred.
- The dimensions of the 3D-printed pneumatic cylinder are based on the dimensions of a commercial pneumatic cylinder. The same commercial cylinder is used for performance comparison.

2) Commercial pneumatic cylinder selection: As described above in A-A1 the designed system is compared with a commercial off the shelf pneumatic cylinder. The selection of a commercial pneumatic system sets a bench mark and also gives guiding in the design process of the 3D-printed pneumatic cylinder. The commercial system was selected on the following criteria: Piston diameter, stroke length, availability, compatibility. Table IX shows the desired values for the criteria set. The criteria are listed as follows:

- The piston diameter is chosen to be in a range between 20 and 30 mm. This value is desired because it is in line with the diameter that is already available in many pneumatic and hydraulic cylinders in prosthetic applications. Also, the cylinder as designed in Landers et al. [18] has a diameter in this range.
- A stroke length of 30 mm is chosen because such a cylinder can be printed on multiple 3D-printers. It also needs a smaller test rig and smaller test actuator range to gather data over the full stroke length of the 3D-printed cylinder.
- Pressure range, the pressure range is chosen because this is a very standard pressure range for cylinders in this dimension range. Furthermore a lot of prosthetic applications are in this low pressure range.
- Availability, since a standardized cylinder is wished the cylinder must be in stock. It is not wished to compare with a specialized and rarely available cylinder.
- The cylinder must be compatible with standardized pneumatic hoses and hose connectors.

Criteria	Requirement description	Value	Scale
Piston diameter	Diameter of the piston and inner cylinder wall	20	mm
Stroke length	The total movement space of the piston rod	30	mm
Pressure range	Range in which the cylinder functions properly	1-10	Bar
Availability	Is the product in stock?	Off the shelf	-
Compatibility	Can the cylinder be combined with different hoses and hose connectors	Combined with stand. Components	-

TABLE IX: Criteria for the selection of a commercial pneumatic cylinder

According to the criteria, the Festo DSNU 20-30 standard cylinder was selected. This widely available cylinder suits our set specifications and is also available in the Robotics lab of the 3mE faculty of Delft University of Technology. The cylinder is compatible with all festo standardized hoses and hose connectors. For the set up the Festo M5 knee screw couplings were connected to the cylinder and the 4x0.75 Festo pneumatic hose was selected. For the valves, a simple Festo hand driven valve was selected.

3) Design requirements : With the preliminary specifications and specifications of the commercial pneumatic cylinder as described in A-A1 and A-A2 a list with all requirements and wishes was set. Table X shows all number related requirements and table XI shows the extra specifications.

Variable	Number	Unit
Piston diameter	20	mm
Stroke length	30	mm
Pressure range	1-10	Bar
Rod diameter	< 8	mm
Connection piston rod	$<$ M8	-
Weight (including valves)	< 210	gram

TABLE X: Requirements the integrated pneumatic cylinder has to fulfil

Specification	Description
Cylinder type	Double acting
Switching mode	Able to close off cylinder head and foot independenly
Manufacturing	3D-printing, except for piston rod and valves
Post-processing	Only hand driven, stanley knive filing, reaming, drilling
Integratability	All parts and functions are integrated, no hose connections
O-rings and seals	Commercial, off the shelf
Valve type	Commercial valves, no self design
Comparison	Comparable with an off the shelf system

TABLE XI: Specifications the integratd pneumatic cylinder has to fulfil

B. Pneumatic schematic design process

1) Concept generation/ ideation: With the known specifications and requirements the first ideation can start. In this ideation round different pneumatic lay-outs are designed and evaluated. The pneumatic schemes were designed with the SMC pneudraw software. In total 3 feasible concepts were designed and evaluated below.

2) Concept 1: Pneumatic cylinder with two 2/2 valve systems: Figure 24 shows the pneumatic lay-out of this cylinder valve system. The Cylinder head and foot are both coupled to a two-position two-way valve which can be actuated mechanically or electrically. The two valves can be controlled independently so that both the extension and retraction movement can be controlled, the same holds for the closing position of the valves. Both valves are connected with the outside air.

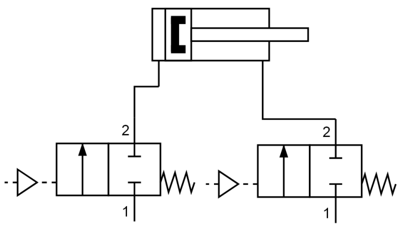


Fig. 24: Pneumatic circuit of the first concept, two 2/2 valves connected to the cylinder head and foot

3) Concept 2: Pneumatic cylinder with 3/2 valve: Figure 25 shows the schematic overview of the second concept. In this concept the cylinder foot and cylinder head entrance are connected to the ports of a two-position three-way valve. The 3/2 valve can be switched in two positions. In the first position, as shown in the figure, the cylinder foot is closed off and the cylinder head entrance is opened and connected to the outside air. When the valve is switched the cylinder head is closed and the cylinder head is opened Resulting in an energy storing extension movement.

4) Concept 3: Pneumatic cylinder with 3/3 valve: Figure 26 shows the third concept. The pneumatic lay-out consists of a pneumatic cylinder and and a three-position three-way

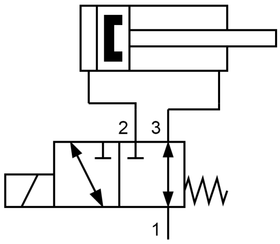


Fig. 25: Pneumatic circuit of the second concept, a 3/2 valve connected to the cylinder head and foot

valve. The valve can switch into three modes. A first mode is a complete locking mode in which both the cylinder foot and cylinder head are locked. A second position is a position in which the cylinder head is opened and and the cylinder foot is locked. A third position is when the cylinder foot is opened and the cylinder head is closed.

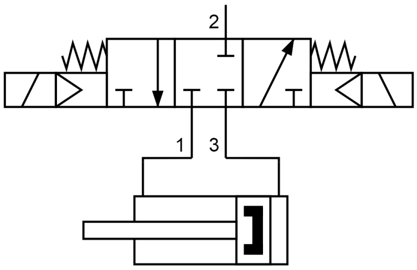


Fig. 26: Pneumatic circuit of the third concept, 3/3 valve connected to the cylinder head and foot.

5) Evaluation and concept selection: After a first ideation three concepts were selected for an evaluation and selection. Before a selection was made the possible movements or modes of the different pneumatic systems were analysed. Table XII shows the different modes that every concept can make.

Concept	Cylinder foot lock	Cylinder head lock	Total locking	Free running
Concept 1: 2/2 valves	x	x	x	x
Concept 2: 3/2 valve	x	x	-	-
Concept 3: 3/3/ valve	x	x	x	-

TABLE XII: Overview of possible modes for each concept

According to the results of table XII the first concept with two two-position two-way valves was selected as the most feasible pneumatic lay-out since enables a lot of movements and is capable of controlling the valves independently.

C. Valve selection

1) Valve connection types: With a pneumatic lay-out and a chosen valve type, the valve connection can be selected. According to the specifications as stated in subsubsection A-A1 no hose connections are allowed in the 3D-printed cylinder design. In this subsubsection different possible connections/ valve types are described:

- Plug/ connection valve, the plug or connection valve is a valve type that only needs a connection with the cylinder. All connections to the different ports and the actuation of the valve are accommodated in the valve housing outside the cylinder. This valve type can be connected to the cylinder in different manners for example via a screw connection, press connection or bolt connection.
- Cartridge/ manifold valve, a cartridge or manifold valve is a valve that is integrated into the cylinder. The cartridge valve only facilitates the actuation of the valve, all connections to ports, the housing and the seating of the cartridge valve must be facilitated in the cylinder or in a manifold. Most cartridge valves make use of a press fit or a cartridge plug for their connections.

Table XIII shows the pros and cons of both valve types.

Connection type	Pro	Con
Plug valve	- Easy to change valve - Simple and leakage free connection between cylinder and valve possible - Actuator and valve connections are a commercial product, plug and play without leakage	- Hard to integrate in cylinder. - Large system
Cartridge valve	- Easy to integrate in cylinder - Compact system - Design freedom in designing pneumatic lines	- Leakage can occur easily due to press fit and 3D-printing - Hard to change valve

TABLE XIII: The pros and cons of the two valve types.

2) Valve selection: With the pros and cons as described in table XIII a decision can be made on the valve connection type. Since the specification of integration is one of the requirements of the 3D-printed pneumatic cylinder, the cartridge valve type is chosen. Although the plug valve has better specifications on leakage and a simple connection it can not be integrated in the 3D-printed cylinder which will result in a sub-optimal design and research. Therefore the cartridge valve is chosen.

3) Description of the chosen commercial valve: With the known 2-position 2-way valve configuration and the known cartridge connection type the catalogues of different commercial producers of such valves were consulted. The catalogues of Parker Hannifin (USA), Buerkert (Germany), Festo (Germany), Gemue (Germany) and SMC (Japan). In this search one valve type/product seems to fit our demand in all facets. The Parker-Hannifin C15 miniature pneumatic valve is a very compact two-position tw- way valve with an integrated solenoid in the valve for actuation.

D. Valve connection design

With a chosen commercial valve with known cavity specifications a pneumatic connection was designed. It is important to choose one type of connection that can be used in the different pneumatic parts. This subsection will describe the requirements of the valve connection, different concepts and a concept selection.

1) Requirements and specifications: According to the requirements and specifications as described in A-A1 a more specified list with requirements is made for the valve connection design:

- Printability, the designed connection must be printable in different angles without using hard removable supports.
- Space saving, the designed connection must be fitted in different parts and cavities without making the part too big.
- Flexible, when in the design process the dimensions or lay-out of the designed part change, it must be no issue to change the pneumatic connection.
- Design freedom, the designed connection must fit in different parts.

According to the set specifications three concepts were made:

2) Concept 1, Bezier curve connections: According to Xie et al. [36] a feasible method to design hydraulic connections in 3D-printed manifolds is using a Bezier curve. A Bezier curve is a curve type that can connect a sequence of set points, The set points are in a pneumatic application a cylinder entrance, a dictated point along a cylinder wall and the entrance of the valve. Due to the dictation of the Bezier curve by points this type of connection is very flexible. For the cross section of the pneumatic lines different shapes can be chosen that will not generate supports inside the connection during printing. Xie et al. [36] researched pressure loss of different connections and found out that a 45 degree window/diamond shape will work out the best. Figure 27 shows an example of the Bezier curve valve connection type.

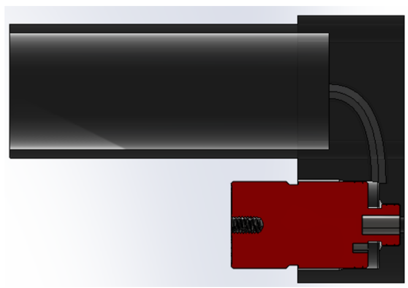
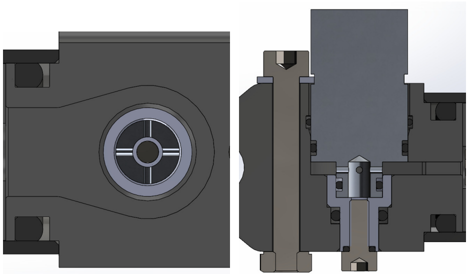


Fig. 27: Section view of a Bezier curve as a pneumatic connection line

3) Concept 2, Droplet connections: The second concept is a droplet connection concept. In this concept the entrance of the valve is placed in a cavity that encircles the valve. The cavity forms a droplet shape and culminates in the cylinder. The shape of the droplet can be changed according to the designed part and connection. Furthermore it already fits in the desired cavity for the valve fitting. At last, it can be printed in different directions since it has a smooth profile and no hard cutting transitions. Figure 28 shows a section view of a droplet shape in the cylinder foot.

4) Concept 3, direct connection/ flipped connection: The third concept is the direct connection or flipped connection



(a) (b)

Fig. 28: (a) Top view of the droplet connection concept. (b) Side view of the droplet connection concept.

interface. In this concept the valve is directly connected to the cylinder. The designed cylinder foot and head are designed around the valve so that a minimal connection is formed. In this connection the entrances of the valve are flipped. The valve entrance is used as an exit and vice versa. Figure 29 shows the direct connection concept.

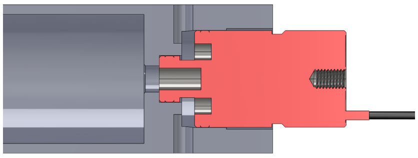


Fig. 29: Section view of the direct connection concept

5) Selection of the pneumatic connection type: The three concepts are analysed on the different specifications as set in subsubsection A-D1. The specifications were weighted and with the weighted specifications a score was given to the different concepts, ranging from -2 to 2. Table XIV shows the Harris Profile.

Weight	Design criteria	Concept 1 Bezier	Concept 2 Droplet	Concept 3 Direct connection
3	Printability	+2	+1	-1
3	Design Freedom	+1	+2	-2
2	Space Saving	-1	+1	+2
1	Flexible	+1	+1	-2
9		8	12	-7

TABLE XIV: Harris profile for the choice of a pneumatic connection

The following considerations were made according to the requirements and the three concepts:

- Printability, this requirement was given a weight factor 3 since it is important that the connections are printable without supports. As discussed in the different concepts the Bezier profile has a cross section that is optimized for support less printing with minimal pressure loss. Therefore this concept receives 2 points. The droplet concept receives 1 point because this connection with its smooth curves can be printed in wide range of angles however in a top down setting supports are needed. The direct connection configuration is hard to print in different angles and supports are needed therefore it receives -1.
- Design freedom, Design freedom also has a weight factor of 3 since it is important that the connection type can be combined with different designs. The Bezier curve concept receives 1 point since there is a lot of design freedom, however there must be room for the smoothening curve that is not space saving. The droplet concept receives 2 points since the connection can be fitted in different design concepts of the cylinder head and foot. The direct connection concept receives -2 since apart from the configuration as shown in 29 no other configurations are possible.
- the space saving requirement receives weight factor 2 since it is less important than printability and design freedom but still more important than flexibility. The first concept scores -1 since the smooth Bezier curves requires a lot of space. The droplet concept receives +1 since it saves a lot of space. However, the conncept needs distance to form the droplet. The direct connection receives 2 points since it is most space saving and the system is built around the valve.
- Flexible, the flexibility requirement receives 1 point as weight factor since it is not common to change a design lay-out that critical after the first iteration so that the connection will not fit anymore. However, it is more or less a wish to have flexible connections. The Bezier curve concept and the droplet concept are both flexible and receive one point. Since there is only one configuration in which the direct connection concept works, it receives -2 points.

E. Configuration design and selection

Different orientations of the valve with connection were considered in a concept cylinder foot and cylinder head. The different orientations are discussed below.

1) Orientation concepts cylinder foot: For the cylinder foot four different orientation concepts were made. The different concepts are discussed below. All figures as showed in the below subsubsections are sketched in a top view.

2) Concept 1, vertical orientation in the cylinder foot: In this concept the valve is integrated in the cylinder foot vertically. The droplet shape lays in the horizontal plane and connects the valve and cylinder with an opening that is also orientated in the horizontal plane. Figure 37 shows the vertical orientation in the cylinder foot.

3) Concept 2, horizontal orientation in the cylinder foot: The second concept shows the orientation of the valve integrated in the cylinder foot in a horizontal way. The droplet shape is orientated in the vertical plane and the valve and cylinder are connected with a rectangular opening that is also in the vertical plane. Figure 31 shows the orientation in the vertical position.

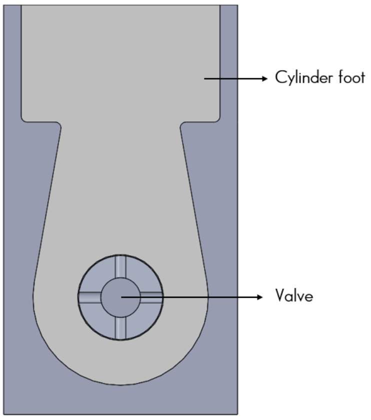


Fig. 30: Section view of the vertical orientation concept in the cylinder foot

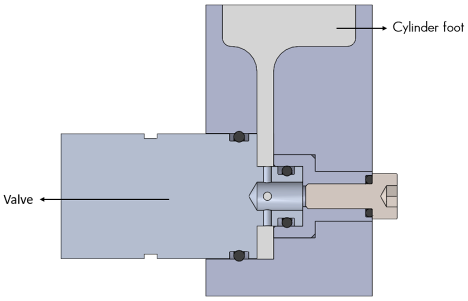


Fig. 31: Section view of the horizontal orientation concept in the cylinder foot

4) Concept 3, vertical orientation parallel to the cylinder foot: In this orientation the valve is positioned next to the cylinder foot and a droplet like shape connects the cylinder and valve in the horizontal plane. Due to the position of the valve the connection becomes longer and also the dead space increases with this longer connection droplet. The cylinder foot itself will become shorter. Figure 32 shows a sketch of the cylinder foot orientation.

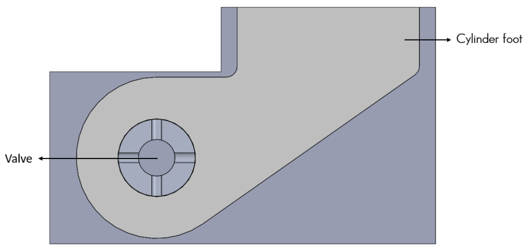


Fig. 32: Section view of the parallel vertical orientation concept in the cylinder foot

5) Concept 4, horizontal orientation parallel to the cylinder foot: The last concepts orientates the valve horizontal next to the cylinder foot. A droplet shape in the vertical plane connects the cylinder and valve resulting in a connection between the two components. In this orientation the dead space remains small but the global dimensions of the cylinder foot increase, especially the width. Figure 33 shows the orientation of the horizontal parallel concepts.

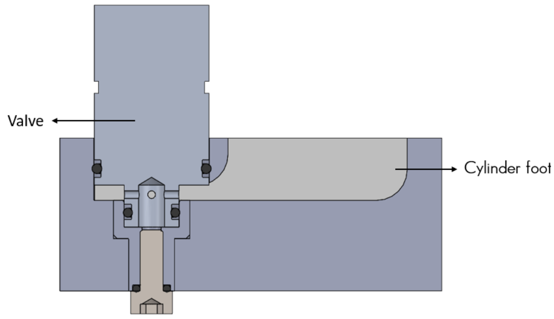


Fig. 33: Section view of the parallel horizontal orientation concept in the cylinder foot

6) Orientation concepts cylinder head: In the following subsubsections different concepts for the orientation of valve and connections in the cylinder head are given. A total of 3 concepts will be presented. All the sketches and figures are given in a top view orientation.

7) Concept 1, vertical parallel to cylinder head: The orientation of this concept is a vertical positioned valve that is connected with the cylinder head via a droplet shape in the horizontal plane. The valve positioned next to the cylinder head, results in a wider cylinder head. Figure 34 shows the configuration.

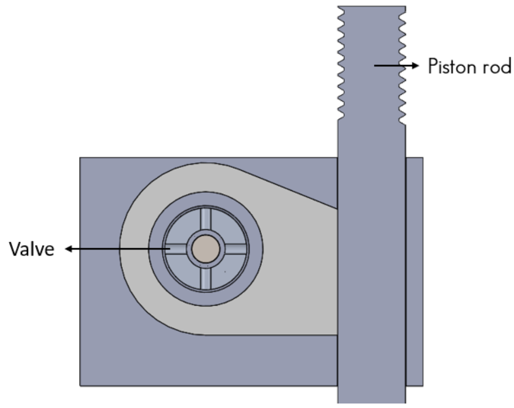


Fig. 34: Section view of the parallel vertical orientation concept in the cylinder head

8) Concept 2, horizontal parallel to cylinder head: In this configuration the valve is orientated in the horizontal plane and lays parallel to the cylinder head. The valve and cylinder are connected via a vertical orientated droplet shape. Due to the parallel configuration the cylinder head is wider. Figure 35 shows the second concept.

9) Concept 3, horizontal top side orientation: In the last concept configuration the valve lays on top of the cylinder head and is connected by a vertical droplet shape into the cylinder. In this orientation no extra or wider body is needed

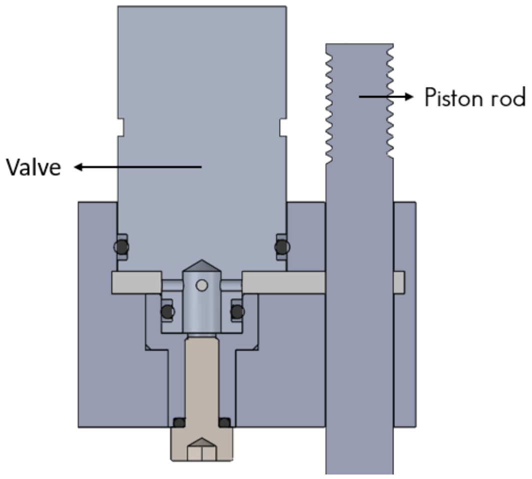


Fig. 35: Section view of the parallel horizontal orientation concept in the cylinder head

but the cylinder becomes higher. The concept is the same as shown in figure 35 but not in the same plane, but in a vertical orientation.

10) Concept evaluation: In order to select the configurations for cylinder foot and cylinder head a list of requirements was set up, in line with the requirements as stated in A-A1. The following requirements were set up:

- Printability, the orientation must be printable and the supports or support removal residues must not obstruct the working of the valve.
- Dead space, the dead space, the space between valve and cylinder opening, must be minimized.
- Dimensions, the height and width of the cylinder foot and cylinder head must be minimized for the orientation.
- Accessibility, the valve must be accessible for replacement or adjustments when the cylinder is in use.
- Integrability, the orientation has a high level of integrability.

With the known requirements a Harris Profile was set up for the cylinder foot and cylinder head. Table XV shows the Harris profile of the cylinder foot and table XVI shows the Harris profile of the cylinder head.

Weight	Design Criteria	Concept 1 Vert. Int.	Concept 2 Hor. Int.	Concept 3 Parrallel vert.	Concept 4 Parallel hor.
3	Printability	1	1	1	2
3	Integrability	2	2	1	1
2	Accesability	2	2	2	1
2	Dead space	2	2	1	1
1	Dimensions	1	2	-1	-2
11		18	19	11	11

TABLE XV: Harris profile of Cylinder foot valve orientation

11) Concept selection cylinder foot: Table XV shows the results of the Harris evaluation. Thereby it can be seen that the scores of the different orientations come really close. An explanation of the scores are given below:

Weight	Design Criteria	Concept 1 Vertical parallel	Concept 2 Horizontal parallel	Concept 3 Horizontal Top side
3	Printability	1	2	2
3	Integrability	2	1	2
2	Accesability	2	1	1
2	Dead space	1	1	1
1	Dimensions	2	1	-1
11		17	14	12

TABLE XVI: Harris profle of the cylinder head valve orientation

- Printability, Concept 4 receives a higher score since both the cavity for the valve and the cylinder foot are in the same orientation. This has advantages according to print orientation and less supports that are generated.
- Integrability, the integrated vertical and horizontal orientations receive the highest scores since the valve is integrated in the cylinder foot, resulting in less space and material.
- Accessibility, in the fourth concept the accessibility of the valve is lower since it is close to the cylinder wall and piston rod.
- Dead space, In the concepts 3 and 4 the dead space is increased compared with concepts 1 and 2, therefore this concepts are rated lower.
- Dimensions, the parallel concepts need a larger cylinder foot therefore these concepts are rated with a negative score. The horizontal integrated concept is rated higher than the vertical concept since it better to build a wider cylinder foot with valve than a higher cylinder foot with valve.

The integrated cylinder foot with horizontal orientation is chosen as the orientation of preference for the design of the integrated pneumatic cylinder.

12) Concept selection cylinder head: Table XVI shows the Harris scores for the concept selection of the cylinder foot. The motivation for the scores of the concepts is given below:

- Printability, The horizontal parallel and horizontal top side systems are both scored with the maximum score since all detailed holes are printed in the same direction.
- Integratability, both the vertical parallel and horizontal top side receive the highest score since these concepts are better integrated/ need less space than the horizontal parallel orientation.
- Dead space, since all concepts are based on a parallel structure not directly integrated in the cylinder head, the dead space is the same in the conceptual orientations.
- Dimensions, the vertical parallel concept is the last demanding concept regarding global dimensions, it is very compact. The horizontal parallel concept is less compact than the vertical parallel but better than the topside horizontal model that is relative high and therefore less in favourite in this requirement.

The Harris profile shows that the cylinder head with vertical parallel orientation is the most favourable concept.

F. Detailed design

In this subsection the detailed CAD design of the first design is discussed. Appendix B describes the iterations and the final design. The final design is also discussed in subsection II-B.

1) Design choice summary: The following design choices were made in the previous subsections: The system consists of a double acting cylinder with two two-way two-position valves that can be controlled independently. The valves are so called cartridge valves and a commercial valve, the Parker Hannifin C15 pneumatic cartridge valve, is selected. The valves are connected to the cylinder by droplet cavities and the valve is integrated in the cylinder foot in a horizontal orientation. The valve is orientated in the cylinder head parallel to the cylinder head in a vertical orientation.

2) Main components: A first detailed design is made in the CAD-program Solidworks. Figure 37 shows the total assembly of the first design. The design consists of the following main components: A combined cylinder foot with cylinder tube, a cylinder head, two valves with valve seating and a piston assembly. The cylinder head and cylinder foot are connected by M3 extended hex bolts.

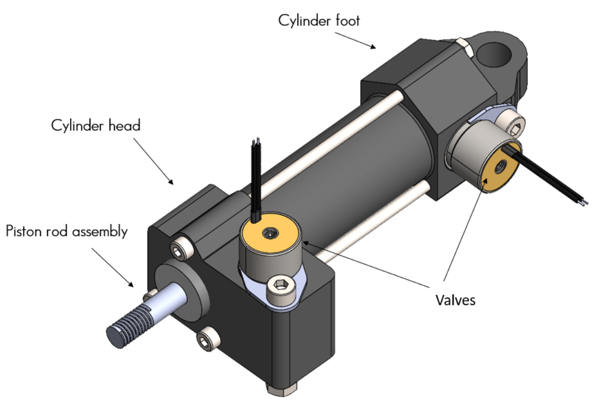


Fig. 36: Isometric view of the total assembly with annotation of the main components

3) Valve seating: The valves are integrated in the cylinder head and foot with a so called valve seating. Since it is hard to make a proper press fit in a 3D-printed part a so called valve seating is designed. This valve seating consists of a stainless steel press bus and an O-ring. An extra cavity is created in the 3D-printed part where the O-ring and the press bus can be pressed in. Due to the shape specifications of the 0-ring this fit can be loose. The valve is than pressed in the fit bus with a high tolerance. Figure 37 shows a section view of the valve seating.

4) Cylinder foot: The cylinder foot forms the bottom of the cylinder and forms the connection between the cylinder and the outside world. The cylinder foot has an integrated valve seating and connects the cylinder to the valve by a vertical orientated droplet connection as discussed in subsection A-D.

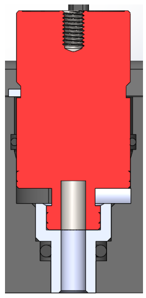


Fig. 37: Section view of the valve seating with commercial valve

The cylinder foot and the cylinder tube are integrated in one part so that no seal is needed between the cylinder tube and the cylinder foot.

5) Cylinder head: The cylinder head forms the top of the cylinder, houses the valve for controlling the top part of the cylinder and guides the piston rod. The valve is centred in a vertical parallel configuration as discussed in A-E. The cylinder head connects the valve and cylinder via a horizontal droplet connection. The cylinder head houses a Freudenberg NIPLS 210 piston rod sealing which is held in place by a custom designed plain bearing. The cylinder head and cylinder tube are connected by three M3 rods and the connection is sealed by an Eriks O-ring 13.8x3.57.

6) Piston rod assembly: The piston rod assembly consists of a 3D-printed piston and a stainless steel piston rod. The piston houses a Freudenberg KDN piston seal and an Eriks glide ring for guiding the piston through the cylinder. The piston and piston rod are connected via a M3 bolt which is also sealed. The piston rod has a M6 outer thread to connect the cylinder with the test rig.

APPENDIX B
ITERATIONS OF INTEGRATED PNEUMATIC CYLINDERS

A. Valve iteration

Before the iterations of the complete system are discussed the iteration of the valves is described.

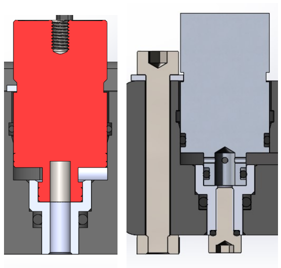
1) Availability of the Parker Hannifin C15 cartridge valve: Unfortunately after the design was set and all commercial parts were ordered the Parker Hannifin C15 cartridge valves were no longer available in small quantities. A redesign is discussed in the following subsubsections.

2) Requirements of the valve redesign: For the valve redesign the following requirements were set:

- Cartridge valve type, the design must be a cartridge valve and easily be plugged in a cavity.
- Dimensions, the valve must have the same dimensions as the C15 cartridge valve so that we can prove that a certain cartridge connection will work in a 3D-printed part.

- Manual control, to save time and test issues it was chosen to build a manual valve that can be opened and closed by a screw.

3) Design of the manual valve: Figure 38 shows the section view of the designed manual valve next to the Parker Hannifin valve. As can be seen in the new design in the valve seating a screw with an o-ring is attached at the bottom of the valve seating. When the screw is tightened a leakage free connection is made. When the screw is opened the air can just pass through. The designed valve uses the same seating as the Parker Hannifin valve and also the outer dimensions are the same. The O-rings used in the valves are the Eriks 13.1x1.2 O-ring and the 5.1x1.2 O-ring.



(a) (b)

Fig. 38: (a) section view of the Parker-Hannifin valve (b) section view of the designed manual valve assembly

4) Building the valves: The valves are build in the employee workshop of Delft University of Technology using a standard lathe and standard production tools. The top part is made out of aluminium and the bottom part is made from stainless steel. After production both valve parts are pressed together and the valve is ready for installation. Figure 39 shows the valves after production.

Fig. 39: Valve parts after manufacturing

B. Producing the separated parts of the first design

1) Printed parts: Figure 40 shows the cylinder foot just after the supports were removed. As can be seen there is a lot of damages/ scratches inside the valve cavities which will cause leakage when a sealing is placed. The main reason for the many supports in the valve cavity of the cylinder foot is the trade-off between putting supports in the valve cavity or in the cylinder tube. In both places no supports are wished since there will always be small residues. In the cylinder head the trade-off must be made between the piston rod guiding hole and the valve cavity. Here it is easier to make this trade-off since the piston rod guiding hole needs less precision than the valve cavity.

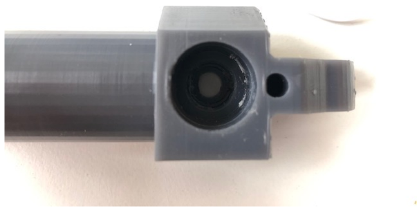


Fig. 40: Picture of one of the first printed parts with a lot of damages after support removal in the cavity

2) Producing the customized plain bearing: A professional instrument maker produced the customized plain bearing out of teflon. However, it was hard to produce the thin walled bearing with the right dimensions and tolerances and the instrument makers needed four trials before it was produced within the tolerances.

3) Producing the piston rod and valve elements: With the production of the piston rod and the valve parts no major issues were recorded.

C. Assembling the first prototype and iteration steps

1) Assembly process: During the assembly process the following points of improvement were recognized.

- Fitting of sealings, due to the residues of supports in the valve cavity the seatings are not well fitted and cause leakage by the first tests.
- Fitting of valves in cylinder foot, due to the print direction and support residues it is hard to fit the valves inside the cavities. Especially with only hand reaming.
- The designed plain bearing was not only hard to produce but also hard to fit in the cylinder head and to make the piston rod fit well and run smoothly.

2) Improvements in first iteration: According to the previous subsubsection the following iteration steps were made in the first design:

- Decoupling of cylinder foot and cylinder tube, to avoid the problem of support residues in sealing seatings, the cylinder tube and cylinder foot are decoupled so that the critical cavities can both be printed in a support less direction.
- Higher tolerance on valve seating, after measurements on the seating it was seen that the dimensions in solidworks and the real dimensions differ 0.1. Resulting in a too tight fitting. Therefore the tolerances of the valve seating are higher to make fitting easier.

- Commercial plain bearing, the customized plain bearing is replaced by a commercial plain bearing which is designed and fabricated with the right dimensions. The cylinder head is redesigned to fit this plain bearing.
- Change of the lubrication, The lubrication of the cylinder is changed from Molykote to Kilopoise.

Figure 41 shows the section view of the first iteration.

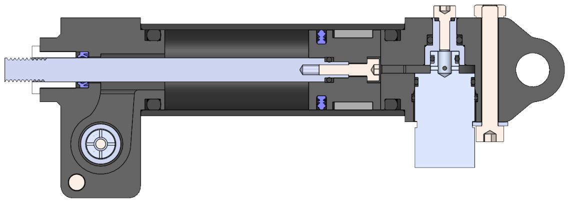


Fig. 41: Section view of the first iteration.

D. *Second iteration of the pneumatic system*

1) Assembling the first iteration: Figure 42 shows the first iteration assembled. The system was assembled and some preliminary tests were done on the system.

Fig. 42: Picture of the manufactured first iteration of the 3D-printed pneumatic cylinder

2) Preliminary test: Bubble testing: In the bubble testing phase two tests were conducted. A first test is a test in which both valves are closed and the piston rod is pushed by hand. On all the sealed connections is soapy water. When there is leakage bubbles appear on the connections. Figure 43 shows a picture of the first bubble test.

The second bubble test consists of closing off both valves and move the piston rod in a tub with water for approximately one minute. During the movement it is checked if bubbles will escape from the sealings and in what pace. Both tests were succesfull and a quantative test on static leakage was conducted.

3) Prelimanry test: Weight testing: Figure 44 shows the test set up of the weight test. Different weights were attached to the cylinder representing a different pressure. During 20 minutes it was measured how fast the piston rod dropped by

Fig. 43: Pictured of the first bubble test

measuring every five minutes the height of a fixed point on the piston rod. The tests were done for the cylinder head and foot for four different weights: 5, 10, 15 and 20 kg, representing 0.15, 0.3, 0.45 and 0.6 MPa respectively. Figure 45 and 44 show the results of the tests.

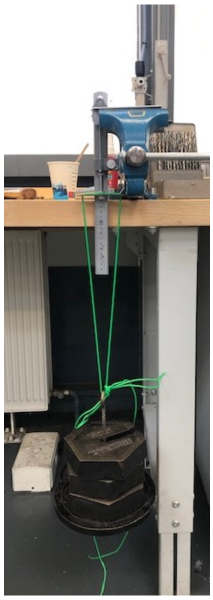


Fig. 44: Test set up for weight testing for the cylinder head

Figures 45 and 46 show that for all weights the cylinder is leakage free. The only outlying result is the cylinder head with a weight of 20 kg. In this case there is no settling distance and it seems like the piston rod is not moving at all. A reason for this is result is that the system uses its dead space for compensation and the piston rests on its end stop.

4) Iteration points for the second iteration step: The iteration worked out very well and the first preliminary results look promising. However, in the current design there is no place for a pressure sensor connection. A design was for this pressure bus connection. Figure 47 shows the section view of the updated design with connection.

E. *Second iteration and first results*

1) Pressure sensor fit: The fit busses for the pressure sensor are made and pressed into the 3D-printed parts. The pressure

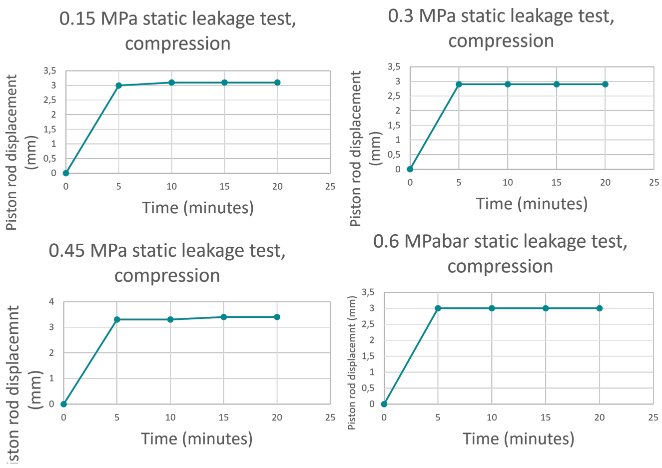


Fig. 45: Results of the weight test for compression at different weights

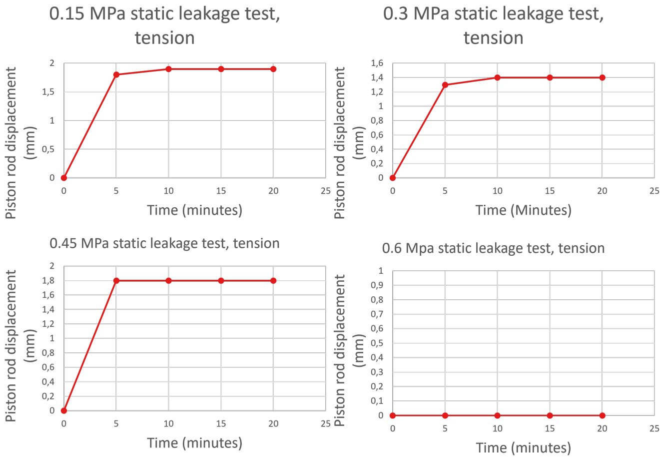


Fig. 46: Results of the weight test for tension at different weights

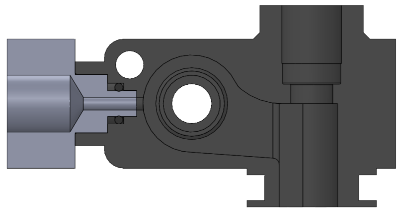


Fig. 47: Section view of the designed pressure sensor fit

Fig. 48: The manufactured and assembled pressure sensor connection

sensor fits well in the 3D-printed part, however when attached to the test rig it has play in its 3D-printed seating and can create leakage or pop out of its seating at high pressure. Figure 48 shows the pressure sensor fitting.

2) First results on dynamic leakage: Figure 49 shows the dynamic leakage of the 3D-printed cylinder head. As can be seen in the plot the 3D-printed cylinder has different pressure heights and also has a long period of low pressure instead of a continuous profile as can be seen in the commercial cylinder. Also the pressure of the 3D-printed cylinder drops very fast especially for a low pressure.

3) Analysis of the first results and possible explanations, hook test: The results as shown in figure 49 show that the dynamic leakage of the 3D-printed cylinder head is too high and an explanation must be found of the leakage. To find out where the leakage could take place the test set up was altered by changing the unidirectional joint with a hook as can be seen in figure 50. With the hook only a pulling force can be exerted on the cylinder and when there is no leakage the cylinder will return partly after pulling. However when leakage occurs no returning stroke or a small returning stroke can be observed. In the pulling test only a small returning stroke (about 5 mm) was observed so that it was concluded that there is leakage in the cylinder head.

4) Analysis of the first results and possible explanations, additional bubble test: A bubble test after the pull test showed that leakage is caused by a leaking piston rod seal. Replacement of the piston rod seal did not work out and the same leakage was noticed in the static and dynamic tests. A closer look at the cylinder head revealed the cause of the leakage. Due to other print setting the roughness, clearance and especially the roundness of the piston rod sealing seating are changed. Due to less roundness the piston rod sealing is pushed to a closed position resulting in no pressurization of the lips and a leakage. Figure 51 shows the cylinder head with a lower roundness and lower print quality.

5) Improvements of the second iteration: According to the assembly process and first tests a couple of iteration points are considered:

- Changing the direction of the valve seating, as described in the previous subsubsection the leakage in the cylinder head occurred due to a lower print quality and other print settings. Although the easiest solution would be to change the settings and print the cylinder head again, the direction of the valve seating will be changed by 90 degrees so that the valve seating and the piston rod sealing seating lay in the same direction and can be printed supportless with high quality.
- Change pressure sensor connection to a standardized

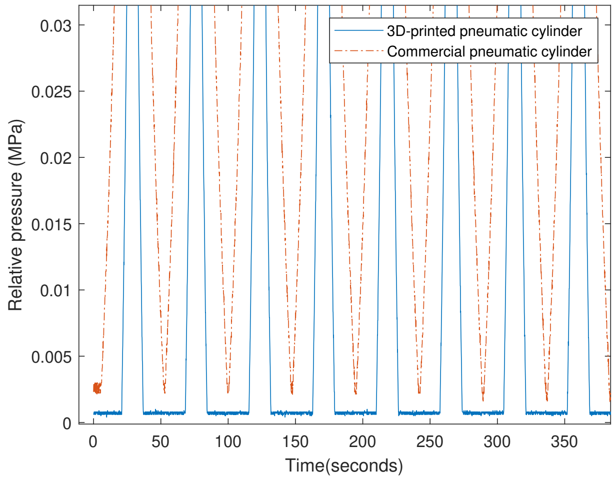


Fig. 49: Plot of the preliminary dynamic leakage test of the cylinder head with self generated pressure

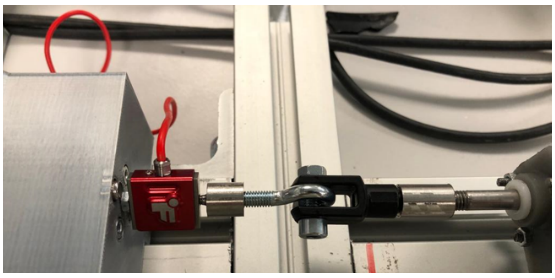


Fig. 50: Test rig set-up for the pulling test with a hook that can only pull and not push the cylinder

hose connection, although the pressure sensor connection seems not to leak at low pressures the connection feels unstable and can cause a leakage by a small disturbance. Therefore the current pressure sensor connection is replaced by a standardized hose connector on which a standardized pneumatic hose can be connected. The pressure sensor also receives a hose connection.

6) *Final design:* Figure 52 shows a section view of the final design as also showed in II-B. The design has a cylinder head with valve seating and piston rod sealing seating in the same direction. Also the piston rod sealing seating and plain bearing seating are decoupled and two apart seatings are created leading to a better fitting of both parts. Furthermore the pneumatic hose couplings are added, the Festo QDMLV-M5 is added in the cylinder head and cylinder foot.

Appendix C
Design of integrated hydraulic cylinder

In this appendix the design process of the 3D-printed hydraulic cylinder is described. The final design with all its details and facets is described in II-B.

A. Design requirements

1) *Comparable requirements with the 3D-printed pneumatic cylinder:* In order to answer the third research

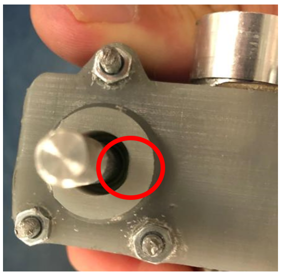


Fig. 51: Close up of the cylinder head, the red circle indicates the unroundness of the plain bearing seating and piston rod seal seating

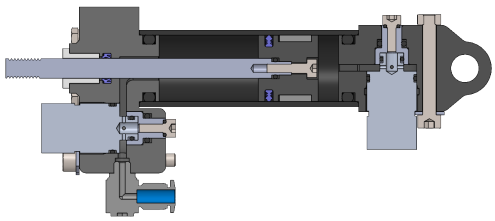


Fig. 52: Section view of the final design of the integrated pneumatic cylinder

question as stated in subsection I-C a lot of the requirements as stated in subsection A-A are kept the same. The exceptions or additional requirements are given in the subsubsection below.

2) *Additional requirements for the 3D-printed hydraulic cylinder:* The following additional requirements are stated for the hydraulic cylinder:

- Switching mode, As stated in Landers et al. [18] the use of a hydraulic locking cylinder is very useful in a pneumatic prosthetic system. Therefore it is chosen to design a hydraulic locking cylinder that has a so called open valve mode in which the cylinder can move over it's full stroke without high forces and a closed valve mode in which the cylinder has a closed valve and a movement in the retraction direction is possible. Extension can still be possible.
- Comparison, Since the designed cylinder is more a proof of concept no comparison with a commercial system will be made.
- Accumulator, The 3D-printed hydraulic cylinder must contain an integrated accumulator in the system.
- Used fluid, Water is chosen since the cylinder has to be filled multiple times. This is easier with water than with hydraulic oil.

B. Hydraulic circuit design

1) *Concept 1: Hydraulic scheme with two 2/2 valves:* Figure 53 shows a concept hydraulic lay-out in which both

cylinder entrances are coupled to a two-way two-position valve. In this way both movements of extension and retraction can be controlled. In between the two valves an accumulator is situated that can compensate for the difference in volume between both cylinder sides.

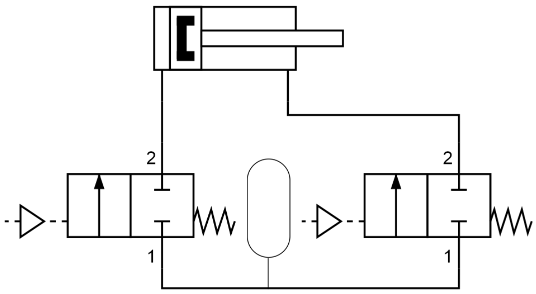


Fig. 53: Hydraulic circuit of the first concept with two 2/2 valves connected to the cylinder head and cylinder foot.

2) Concept 2: Hydraulic scheme with one 2/2 valve: Figure 54 shows the hydraulic schematic of the second concept. This concept has only one two-position two-way valve which can control both movements of extension and retraction. Due to the position of the valve directly after the cylinder foot and the accumulator between the cylinder head entrance and the valve the system can hold a retraction movement with allowing an extension movement by the accumulator.

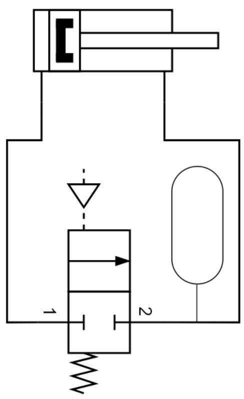


Fig. 54: Hydraulic circuit of the second concept with one 2/2 valve coupled to the cylinder head and the cylinder foot.

3) Concept selection: The two different concepts are compared on movement possibilities. An overview of the movements of both concepts is given in table XVII. As can be seen in the table both concepts can make the desired movements as stated in C-A2. The first concept is able to make two more movements namely a cylinder head block and a total block. Since both movements are not in the requirements and an extra valve only adds complexity concept 2 is chosen as the most feasible concept.

C. Accumulator design

1) Accumulator types: The accumulator forms an important part of the 3D-printed hydraulic cylinder. As stated in the subsubsection C-A2 the accumulator must be integrated in the cylinder. Roughly three types of accumulators can be distinguished for integration in a hydraulic cylinder:

Concepts	Free running mode	Cylinder foot lock	Cylinder head lock	Total lock
Concept 1 2 2/2 valves	x	x	x	x
Concept 2 1 2/2 valve	x	x	-	-

TABLE XVII: Overview of possible modes for each hydraulic circuit concept

- Piston accumulator with mechanical spring: This accumulator is a single acting piston with or without a piston rod. On one side of the piston the fluid has access and can push the piston up and down. On the other side of the piston a mechanical spring is situated which counteracts the movement of the piston and can return the piston to its begin position when no pressure is applied. The counteracting of the piston is coupled to the spring constant of the mechanical spring.
- Piston accumulator with pressurized gas: This accumulator works almost the same as the mechanical spring accumulator. The only difference is that instead of a mechanical spring the top side of the piston is a closed chamber filled with a pressurized gas. The piston has a double acting seal and by moving the piston in an upward position the gas is compressed and counteracts the movement of the piston. When no pressure is applied the gas spring returns the piston to the begin position. The gas can be pressurized or at atmospheric pressure.
- Membrane accumulator with pressurized gas: The last described accumulator consists of a flexible membrane, mostly made of a flexible material e.g. rubber or a thin metal sheet, that divides two chambers. In one chamber the fluid of the hydraulic cylinder is situated and in the other a gas is situated. As more fluid enters the hydraulic chamber the membrane will deform in the direction of the gas chamber and the gas is compressed. The bending is counteracted by the pressurized gas and this pressurized gas can also return the membrane in its neutral position. The gas chamber can be filled with pressurized or atmospheric gas.

Table XVIII shows the pro's and cons of the three different hydraulic accumulators.

2) Accumulator selection: According to table XVIII the piston accumulator with mechanical spring was chosen. This decision was made based on the simplicity of the accumulator lay-out and the simplicity of integration such a system in a 3D-printed hydraulic cylinder. The high friction and chance of jamming can be fixed by choosing the right piston sealing and design a accumulator piston rod in the system. Since the accumulator only needs to compensate a volume and not has to store energy there is no direct issue with no chance of altering the spring constant.

Accumulator type	Pro	Con
Piston mechanical spring	- Simple design - Easy to integrate	- High friction - Chance of jamming - Fixed spring constant
Piston gas spring	- Variable spring constant - Easy to integrate	- High friction - Chance of jamming - Complex design - Chance of leakage
Membrane gas spring	- No friction or sliding parts - Not fixed to a linear movement - Variable spring constant	- Complex system - Hard to integrate - Chance of leakage

TABLE XVIII: Pro's and cons of the different integrated accumulator types.

D. Design choices based on the design process of the 3D-printed pneumatic cylinder

The following design choices were based on earlier design choices as made in subsections A-C, A-D, A-E.

1) Valve selection: The hydraulic version of the Parker-Hannifin C15 cartridge valve was selected for the integrated hydraulic design.

2) Valve connection design: The same valve connection design is used in the hydraulic design, based on a droplet.

3) Configuration design: For the configuration of the hydraulic design the same configuration as the pneumatic cylinder foot is chosen. Since there is only one valve in the hydraulic design this is the only configuration in the system.

E. Detailed design

Only one iteration was performed between the original and final design regarding dimensions, as described in appendix D. Therefore the final design and all it's details can be read in subsection II-D.

APPENDIX D
ITERATIONS OF THE INTEGRATED HYDRAULIC CYLINDER

A. Hydraulic valve iteration

1) Hydraulic valve design: As already described in subsection B-A the Parker Hannifin C15 valves were not available and the alternative was to design a manual valve. The hydraulic counterpart of this manual valve follows the same design requirements as the pneumatic valve. Figure 55 shows a section view of the designed hydraulic valve. As can be seen in the figure the valve is a cartridge valve that contains two close-off screws. The lowest bolt is an M3 bolt that can close off the connection between both chambers of the hydraulic cylinder. The larger bolt is an M6 bolt which closes off the the top part of the hydraulic valve so that after filling the hydraulic cylinder the cylinder and valve form a closed system.

2) Producing the valves: The valve parts were made in the workshop of Delft University of Technology using a lathe and the standard tools of a lathe. Advice and help from a professional instrumentmaker were used during the production.

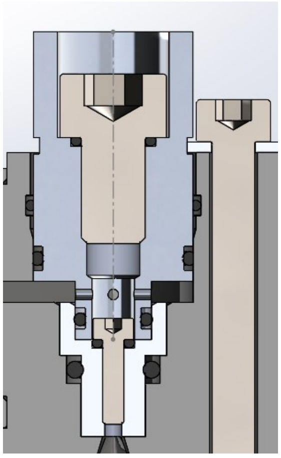


Fig. 55: Section view of the hydraulic valve

B. Producing the separated parts

1) 3D-printed parts: All 3D-printed parts were printed with high quality and with the insights of the 3D-printed pneumatic cylinder parts in the right direction so that supports were only attached at non-precise regions of the parts.

2) Piston rod and accumulator piston rod: The piston rod and accumulator piston rod were produced using a lathe and with help of a professional instrumentmaker. Due to small crosssection of the accumulator piston rod this part started to bend in the lathe during production. Due to the bending the part had to be made again with another connection in the lathe.

C. Assembly process and iterations

1) Assembly and points of improvement: Almost all parts could be assembles very well as figure 56 shows. The following points of improvement were recognized:

- The quad ring for the accumulator piston sealing had a too tight fit in the accumulator cylinder tube causing friction and jamming.
- The two O-rings for the static sealing of the accumulator do not fit in the accumulator cylinder tube, causing extra length of the cylinder.
- The cylinder foot attachment point at the end of the cylinder is in the middle of the accumulator tube and the cylinder tube. This will cause a moment when the cylinder is attached to the test rig since the piston rod is not in the middle of both cylinders.

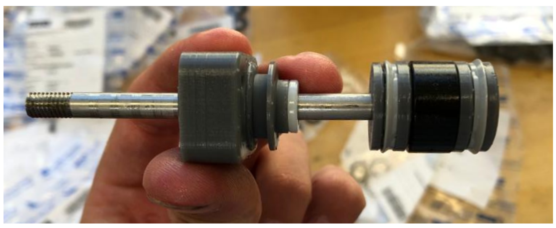


Fig. 56: Picture of the cylinder head and with piston rod assembly

2) Iteration points: The following iteration points are used in the next design:

- A larger diameter of the accumulator cylinder tube, so that the piston sealings and O-rings will have a better fit and there is less friction between the sealing and the piston.
- The attachment point is designed in line with the cylinder tube so that no moment can be transferred.

With this iterations a new design was made which has two dimensions changed and has the same working principle as the design as presented in subsection II-D.

APPENDIX E
EXTENSIVE EXPERIMENT DESCRIPTIONS

A. Experimental set up pneumatic testing

In this appendix the extensive versions of the experiments as described in subsections III-B and III-C are given:

1) preparing the cylinder for testing: Before a test was started the following procedure was followed:

1) Depending on whether the cylinder foot or cylinder head is measured the test rig is brought in its minimal position or maximal position.
2) Both valves are opened and the piston rod is set in its maximal retraction of maximal extension, this depends on the measurement of the cylinder head or cylinder foot respectively.
3) The valve in the foot is closed and the valve in the head remains open for cylinder foot measurement. For cylinder head measurement the valve in the cylinder head is closed and the valve of the cylinder foot remains open.
4) An M8 bolt is put in the eye connection at the cylinder foot. The bolt is locked with an M8 nut. A second nut is put on the bolt and a slotted nut is also put on the bolt.
5) The slotted nut is slid in the extrusion profile and the rod end ball joint is connected with the cylinder with an M5 bolt and nut.
6) The M8 bolt is tightened or unscrewed until the connection between the slider and cylinder looks straight. Afterward the second M8 nut is tightened on the extrusion profile so that a rigid connection is created.
7) from a top view the cylinder is checked for misalignment.

2) Static leakage testing, self induced pressure: In the static leakage test the cylinder is held in a fixed position and the pressure is measured. The test for static leakage consists of the following steps:

1) When necessary an offset value is applied to the pressure sensor to ensure 0 MPa as a starting pressure.
2) The valve in the cylinder foot or cylinder head is checked if it is closed.
3) The piston is moved to the maximum extension or retraction ensuring the same start position for all the cylinders. Or to the same stroke distance when an equal pressure test is done.
4) The pressure is measured for 20 minutes and recorded in labview.
5) The complete procedure is repeated three times.

3) Static leakage testing, external pressure: In the static leakage test with external pressure the cylinder is held in a fixed position and the pressure is measured. Before the test is started the cylinder is filled with compressed air. The test for static leakage consists of the following steps:

1) The T-connection piece with the additional valve (see figure 10) and compressed air connection are attached to the cylinder.
2) When necessary an offset value is applied to the pressure sensor to ensure 0 MPa as a starting pressure.
3) The valve in the cylinder foot or cylinder head is checked if it is closed.
4) The additional valve is opened and the compressed air connection is also opened.
5) The pressure of the compressed air is set.
6) The piston is moved to the maximum extension or retraction ensuring the same start position for all the cylinders. And the pressure of the cylinder in maximum extension or retraction is checked.
7) The cylinder is brought back to it's initial starting position.
8) If the pressure in maximum extension or retraction was too high or too low the pressure of the compressed air is changed and the same procedure is repeated.
9) If the pressure was good the cylinder is filled with the same starting pressure and the cylinder is brought to its maximum extension or retraction.
10) The pressure, distance and force are measured for 20 minutes and recorded in labview.
11) the complete procedure is repeated three times

4) Dynamic leakage with self induced pressure: During the dynamic leakage tests the pressure drop is measured while the piston moves in the cylinder.

1) If needed an offset value is applied to the pressure sensor and force sensor to ensure 0 MPa and 0 N as a starting pressure and starting force respectively.
2) The closure of the valve in the cylinder foot or cylinder head is checked.
3) The cylinder is moved back and forth over a stroke length of 30 mm for 20 minutes at a speed of 10 mm s^{-1}.
4) The cylinder ends in its starting position. During the test the pressure, force and distance are recorded in LabView.

5) Dynamic leakage with external pressure: During the dynamic leakage tests the pressure drop is measured while the piston moves in the cylinder. Before the test was started the cylinder was filled with compressed air.

1) The T-connection piece with the additional valve (see figure 10) and compressed air connection are attached to the cylinder.
2) If needed an offset value is applied to the pressure sensor and force sensor to ensure 0 MPa and 0 N as a starting pressure and starting force respectively.
3) The fixed starting position for cylinder foot or cylinder head measurements is checked.

4) The closure of the valve in the cylinder foot or cylinder head is checked.
5) The additional valve is opened and the compressed air connection is also opened.
6) The pressure of the compressed air is set.
7) The piston is moved to the maximum extension or retraction ensuring the same start position for all the cylinders. And the pressure of the cylinder in maximum extension or retraction is checked.
8) The cylinder is brought back to it's initial starting position.
9) If the pressure in maximum extension or retraction was too high or too low the pressure of the compressed air is changed and the same procedure is repeated.
10) If the pressure was good the cylinder is filled with the same starting pressure and the cylinder is moved over a stroke of 30 mm for 20 minutes at a speed of $50\,\mathrm{mm\,s^{-1}}$.
11) The cylinder ends in its starting position. During the test the pressure, force and distance are recorded in LabView.

B. Experimental set up hydraulic testing

1) Free running mode: During the free running mode test the piston rod is moved over it's full stroke length and the pressure drop is measured. Also the stroke length itself is measured. The applied force is also measured for the hysteresis loop. The dynamic leakage test is done according to the following procedure:

1) The filled cylinder is weighted.
2) If needed an offset is applied to the pressure sensor and force sensor so that the measurements can start with 0 MPa and 0 N respectively.
3) It is checked that the valve is opened.
4) the starting position of the piston rod is checked.
5) The cylinder is moved back and forth over a stroke of approximately 30 mm for 20 minutes at a a speed of $10\,\mathrm{mm\,s^{-1}}$
6) The cylinder stops at it's starting position. During the test pressure, force and distance are recorded in Labview.
7) After testing the cylinder is weighted again.

2) Holding test: The internal leakage, external leakage and applied force are measured as follows:

1) The filled hydraulic cylinder is weighted.
2) When necessary an offset value is applied to the pressure sensor and force sensor resulting in a 0 MPa and 0 N start value.
3) The valve is checked if it is closed.
4) The piston rod is retracted by the spindle drive. At the locking point the piston rod will stop moving, the motor tries to move it further inward increasing the force when there is no movement the motor will stop automatically.
5) During the test the pressure, force and distance are recorded in LabView.
6) After testing the cylinder is weighted again.
7) This test is repeated three times

Appendix F
Bill of materials integrated pneumatic cylinder

BOM level	Part name	Quantity	Manufacturing	Supplier
1	Cylinder head part	1	SLA-printing	TU Delft, printing lab
2	O-ring 13.87x3.53	2	Order part	Eriks
3	Piston rod seal, combi seal NIPSL210 FKM 6x9	1	Order part	Eriks
4	O -ring 5.6x1.6	2	Order part	Eriks
5	Plain bearing 6x9	1	Order part	TU Delft, workshop
6	Knee-screw coupling QSMLV	2	Order part	Festo
7	Cylinder tube	1	SLA-printing	TU Delft, printing lab
8	Cylinder foot part	1	SLA-printing	TU Delft, printing lab
9	Valve body part	2	Turning	TU Delft, workshop
10	Valve seating	2	Turning	TU Delft, workshop
11	O-ring 5x1.2	2	Order part	Eriks
12	O-ring 13x1.2	2	Order part	Eriks
13	O-ring 3x1	2	Order part	Eriks
14	Piston	1	SLA-printing	TU Delft, printing lab
15	Piston rod	1	Turning	TU Delft, workshop
16	KDN-piston sealing 20x12.9	1	Order part	Eriks
17	O-ring 3.8x1.25	1	Order part	Eriks
18	M3 bolt	3	Standard part	TU Delft, workshop
19	Glide ring, 16x20	1	Order part	Eriks
20	M4 bolt	2	Standard part	TU Delft, workshop
21	M4 nut	2	Standard part	TU Delft, workshop
22	Structural plate	2	Laser cutting	TU Delft, workshop
23	M3 rod end	3	Standard part	TU Delft, workshop
24	M3 Nut	6	Standard part	TU Delft, workshop

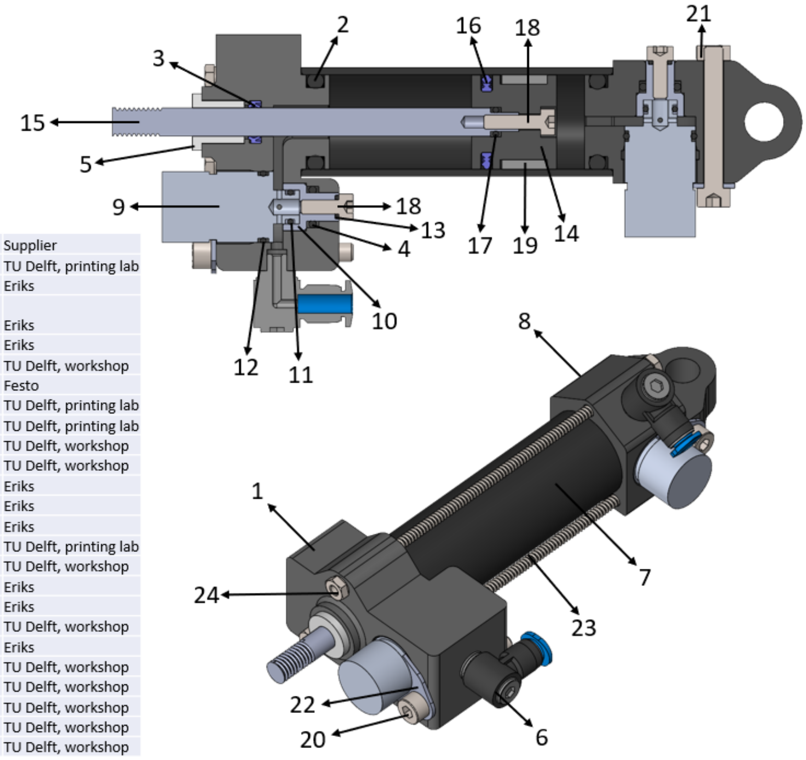
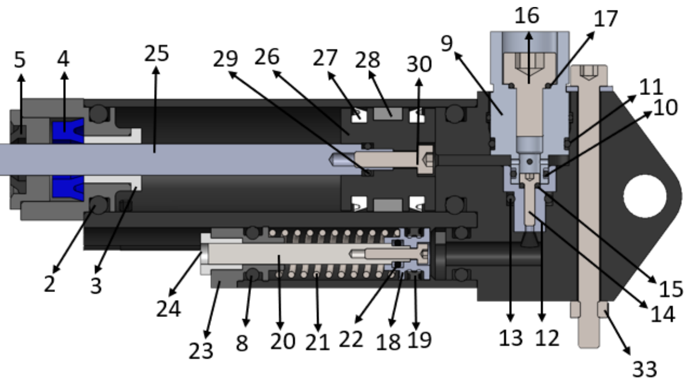


Fig. 57: Bill of materials with annotations of the parts in the section view and the isometric view.

Appendix G
Bill of materials integrated hydraulic cylinder

BOM number	Part name	quantity	Manufacturing	Supplier
1	Cylinder head	1	SLA-printing	TU Delft, printing lab
2	O-ring 13.57x3.83	2	Order part	Eriks
3	Plain bearing 6x9	1	Standard part	TU Delft, workshop
4	Piston rod sealing, Kramp 6x16x6	1	Order part	Indi
5	Scrape ring, afstrijker 6x10x4	1	Order part	Eriks
6	Cylinder tube	1	SLA-printing	TU Delft, printing lab
7	Cylinder foot	1	SLA-printing	TU Delft, printing lab
8	O-ring 5.5x2.5	2	Order part	Eriks
9	Valve body	1	Turning	TU Delft, workshop
10	O-ring 5x1.2	1	Order part	Eriks
11	O-ring 13x1.2	1	Order part	Eriks
12	Valve seating	1	Turning	TU Delft, workshop
13	O-ring 5.6x1.6	1	Order part	Eriks
14	M2 bolt	2	Standard part	TU Delft, workshop
15	O-ring 2x1	1	Order part	TU Delft, workshop
16	M6 bolt	1	Standard part	TU Delft, workshop
17	O-ring 6x1	1	Standard part	TU Delft, workshop
18	Accumulator piston	1	SLA-printing	TU Delft, printing lab
19	X-ring 5.23x2.62	1	Order part	Eriks
20	Accumulator piston rod	1	Turning	TU Delft, workshop
21	Compression spring, Tevema D22165	1	Order part	Tevema
22	O-ring 2.9x1.2	1	Order part	Eriks
23	Accumulator cylinder head	1	SLA-printing	TU Delft, printing lab
24	Plain bearing 4x7	1	Standard part	TU Delft, workshop
25	Piston rod	1	Turning	TU Delft, workshop
26	Piston	1	SLA-printing	TU Delft, printing lab
27	Piston seal, lip seal 20x14	2	Order part	Indi
28	Glide ring, 16x20	1	Order part	Eriks
29	O-ring 3.8x1.25	1	Order part	Eriks
30	M3 bolt	1	Standard part	TU Delft, workshop
31	Structural plate	1	Laser cutting	TU Delft, workshop
32	M4 bolt	1	Standard part	TU Delft, workshop
33	M4 nut	1	Standard part	TU Delft, workshop
34	M3 rod end	6	Standard part	TU Delft, workshop
35	M3 nut	12	Standard part	TU Delft, workshop



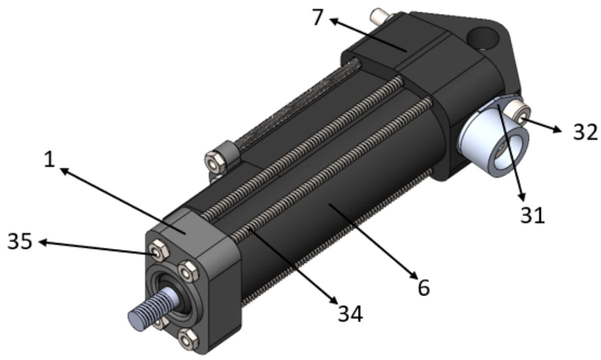
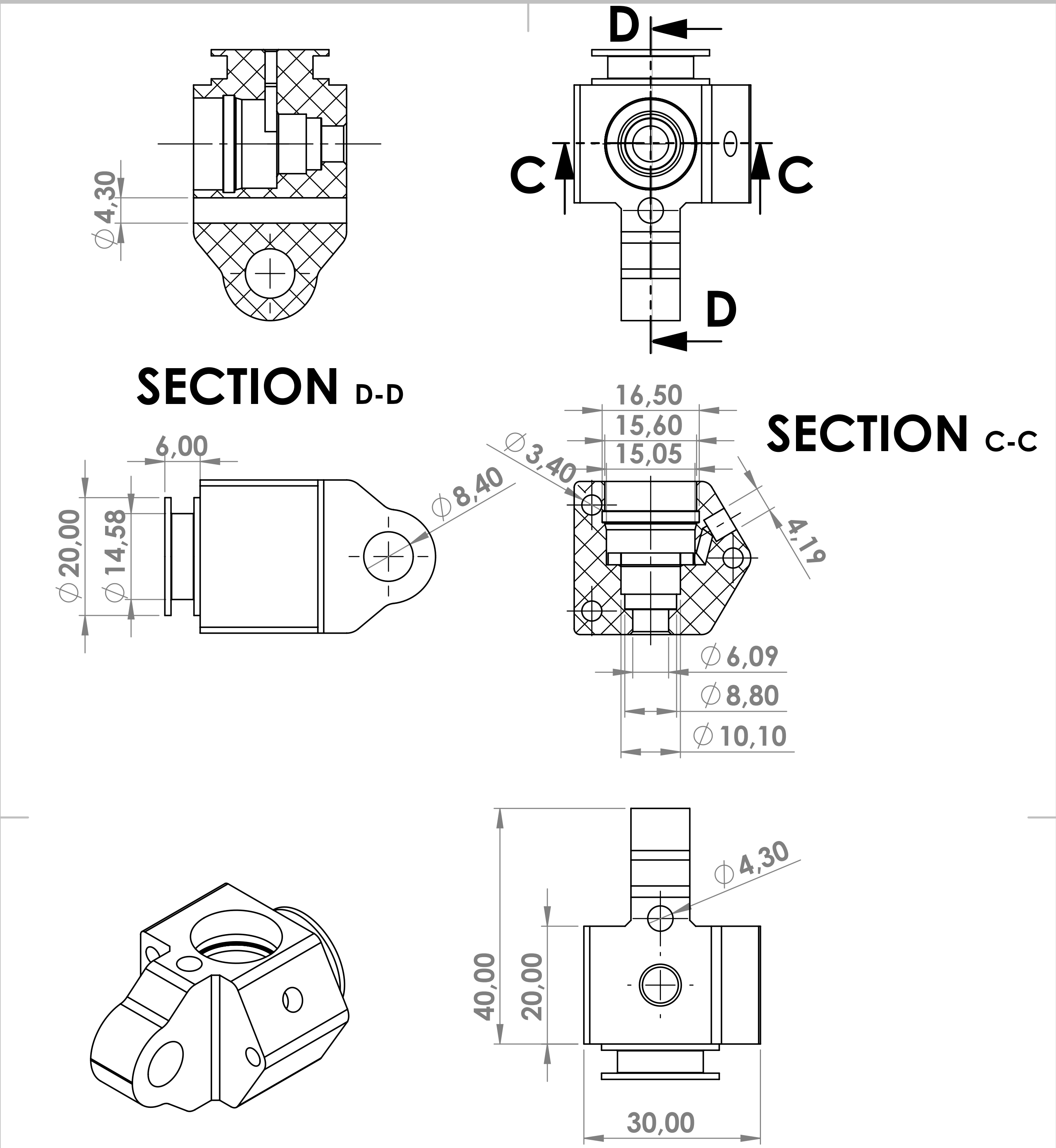


Fig. 58: Bill of materials with annotations of the parts in the section view and the isometric view.

Appendix H
Technical drawings

The last pages of this report show the technical drawings of the parts of the 3D-printed pneumatic cylinder and 3D-printed hydraulic cylinder.



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DEBURR AND BREAK SHARP EDGES

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REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL: Though 1500 (formlabs)

DWG NO. **Cylinder foot**

A4

WEIGHT:

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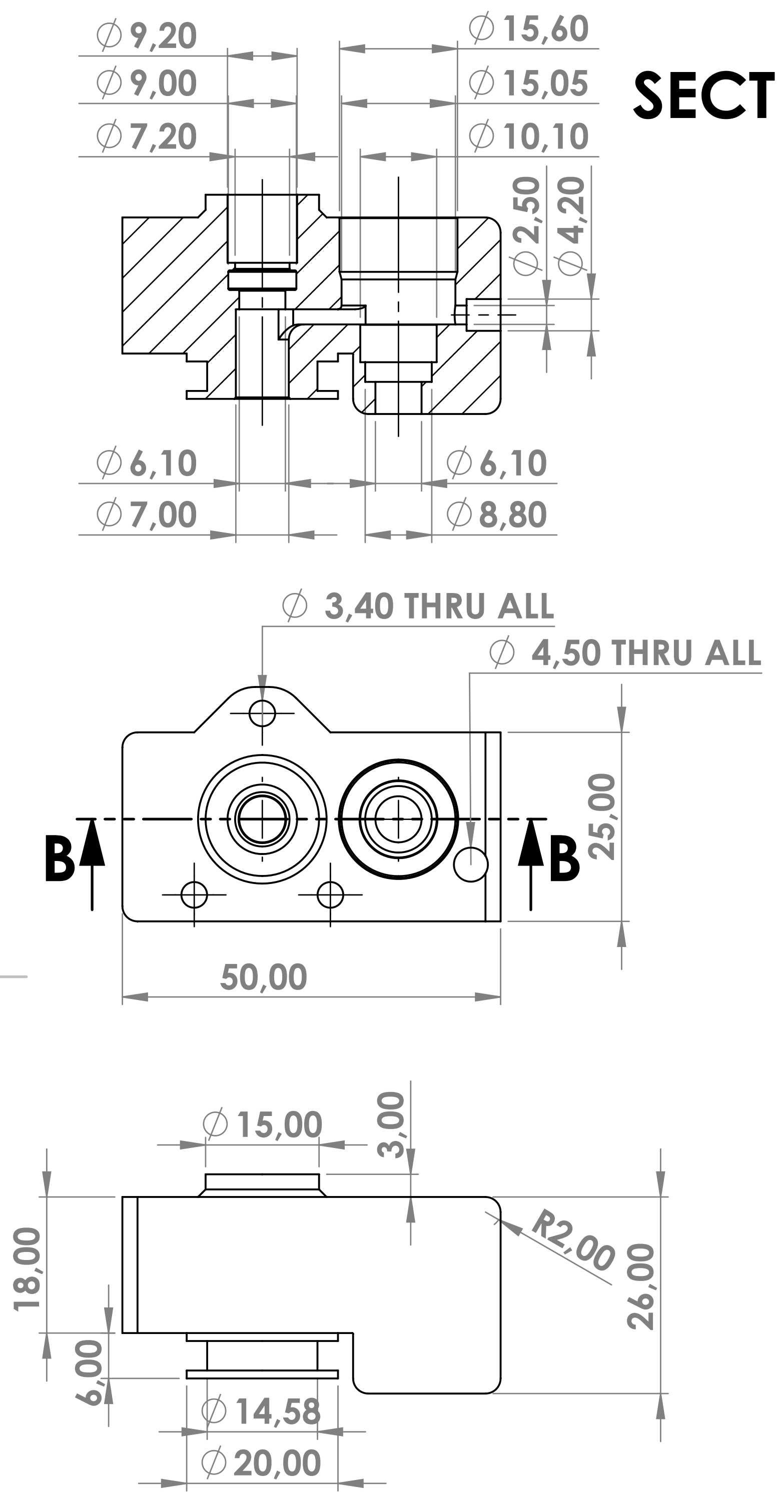

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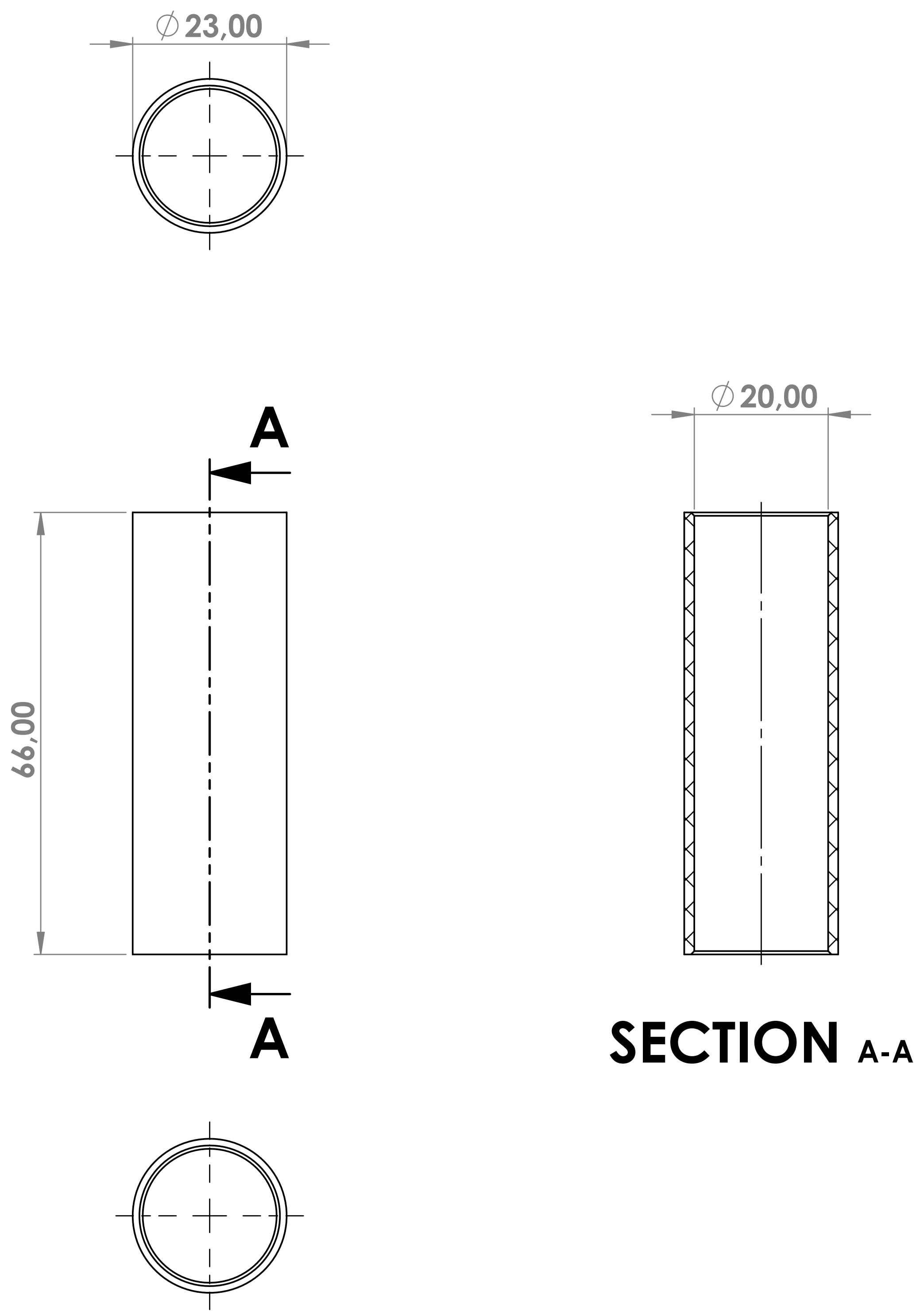

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TITLE:

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DWG NO.
Cylinder tube

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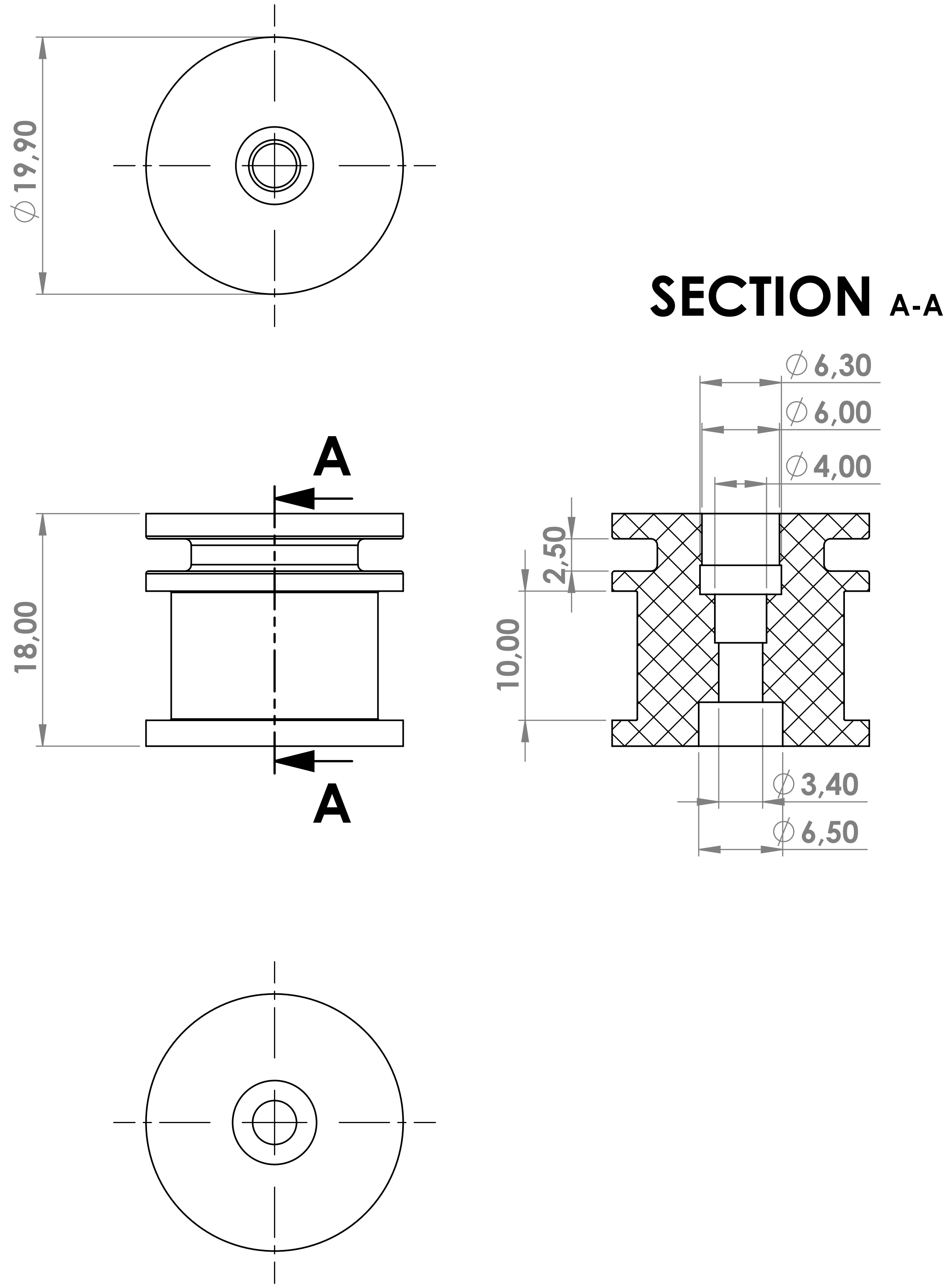

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TITLE: **Piston pneumatic**

MATERIAL: Though 1500 (Formlabs)

DWG NO.

A4

WEIGHT:

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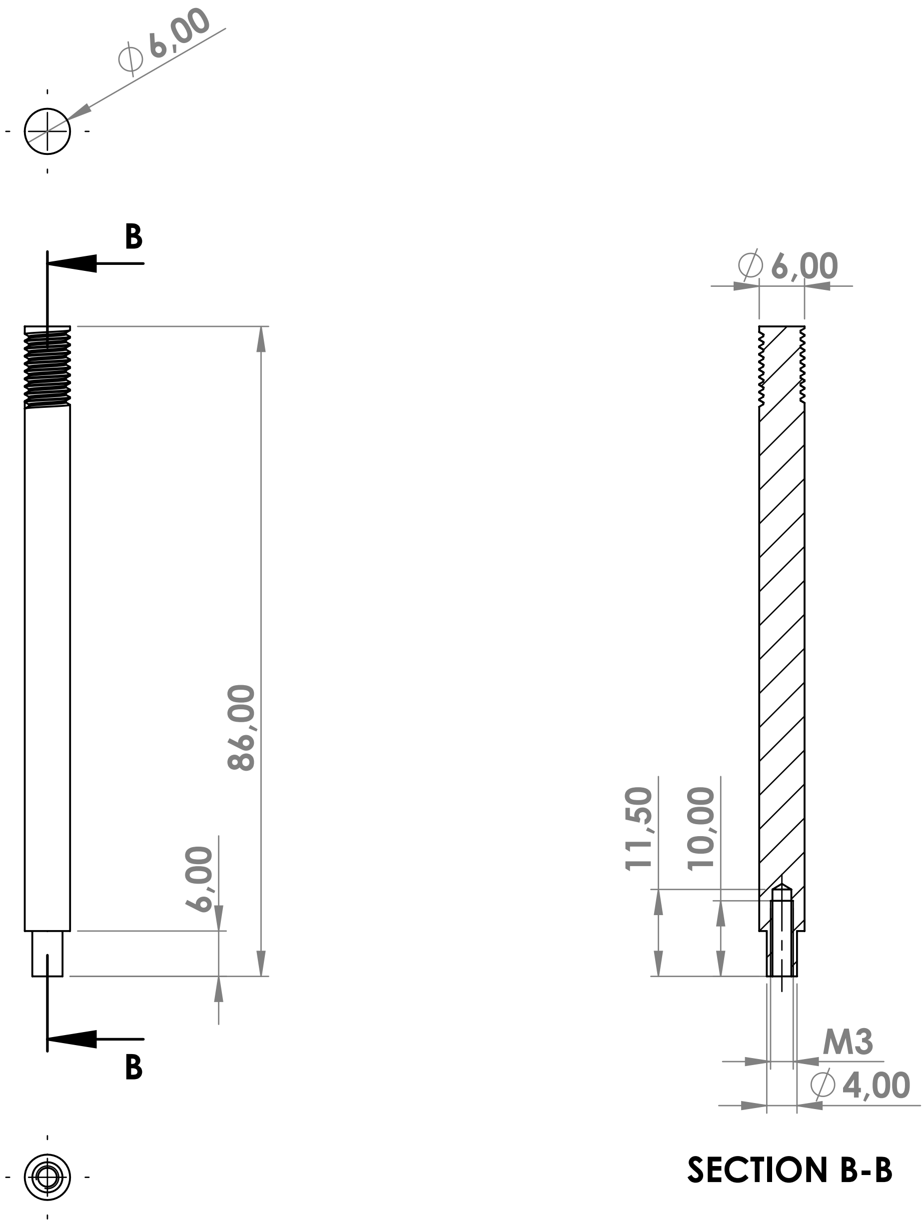

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Q.A			

TITLE:

Piston rod pneumatic

MATERIAL:
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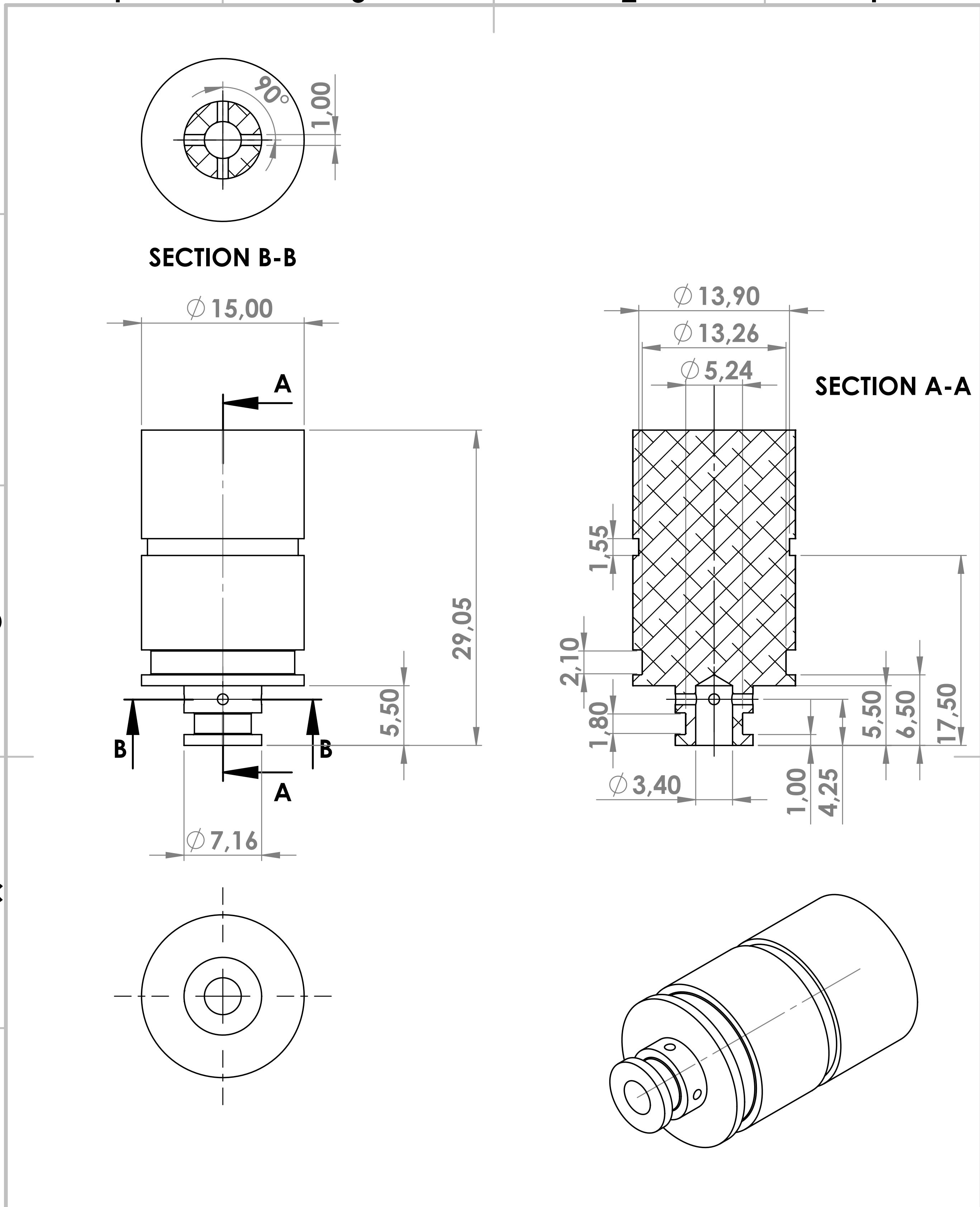
DWG NO.

A4

WEIGHT:

SCALE:1:1

SHEET 1 OF 1



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REVISION

	NAME	SIGNATURE	DATE
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CHK'D			
APPV'D			
MFG			
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TITLE:

Alternative valve

MATERIAL:
Tough 1500 (formlabs)

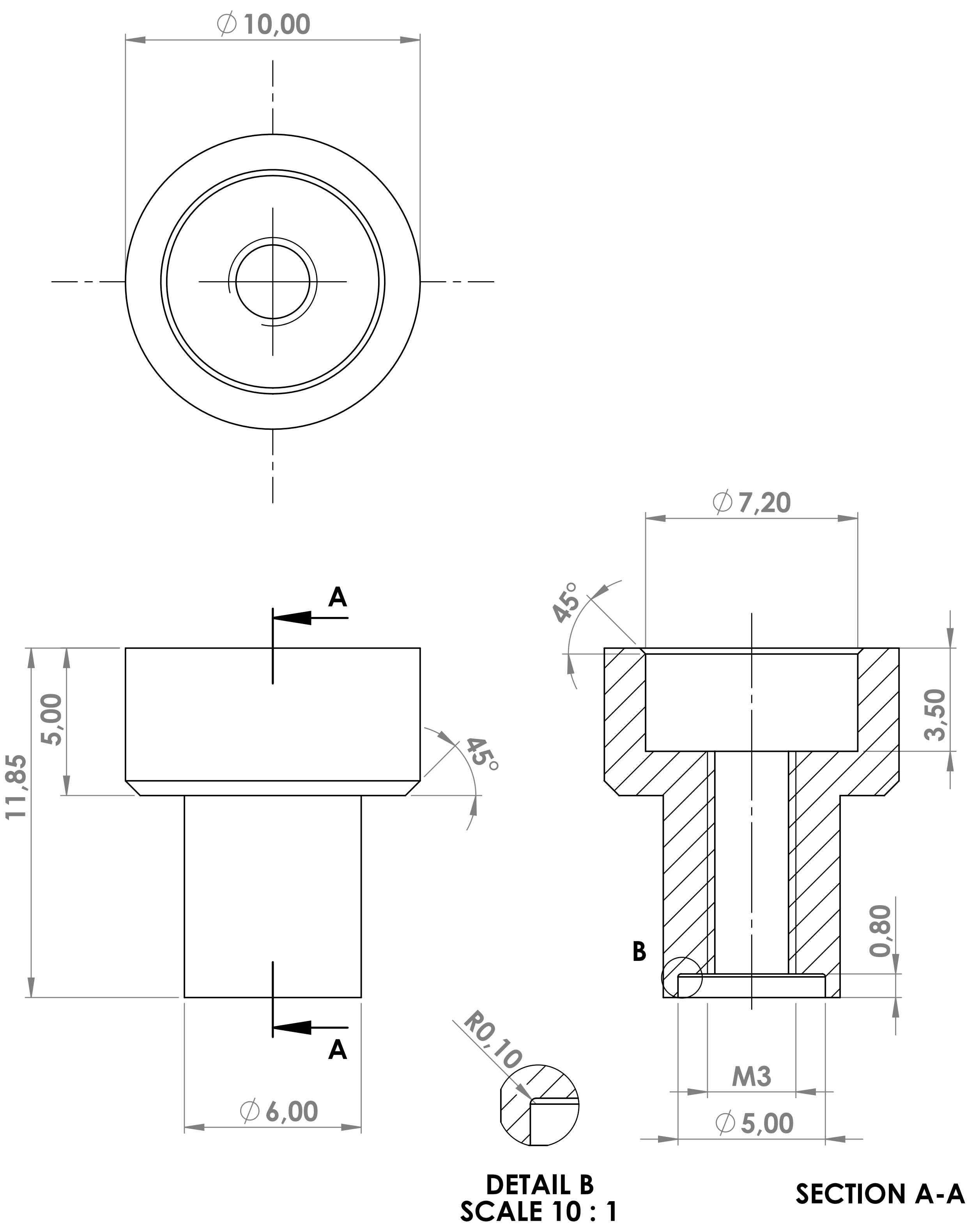
DWG NO.

A4

WEIGHT:

SCALE:2:1

SHEET 1 OF 1



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DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

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	NAME	SIGNATURE	DATE
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CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: **Valve seating pneumatic**

MATERIAL: Tough 1500 (formlabs)

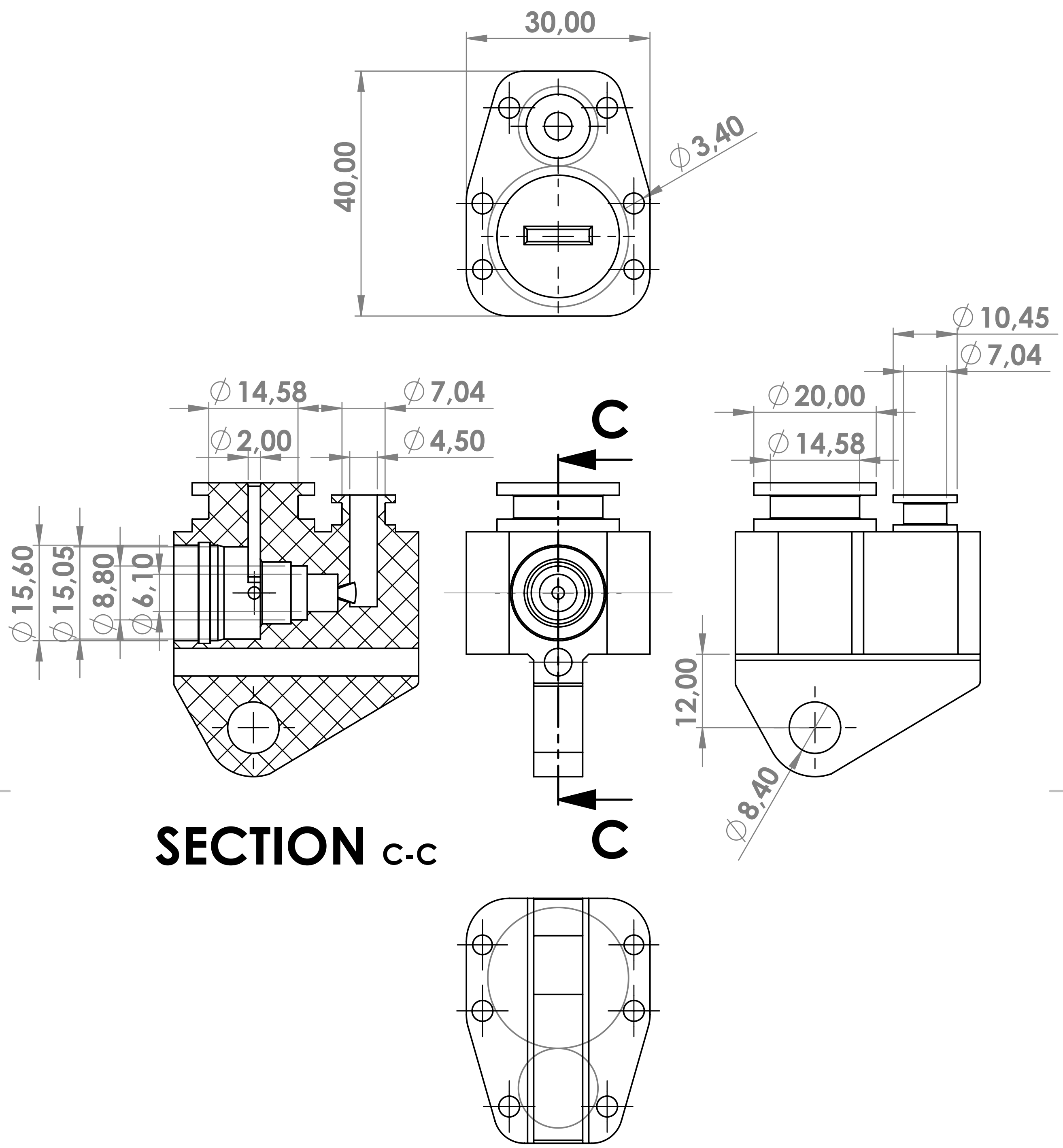
DWG NO.

A4

WEIGHT:

SCALE:5:1

SHEET 1 OF 1



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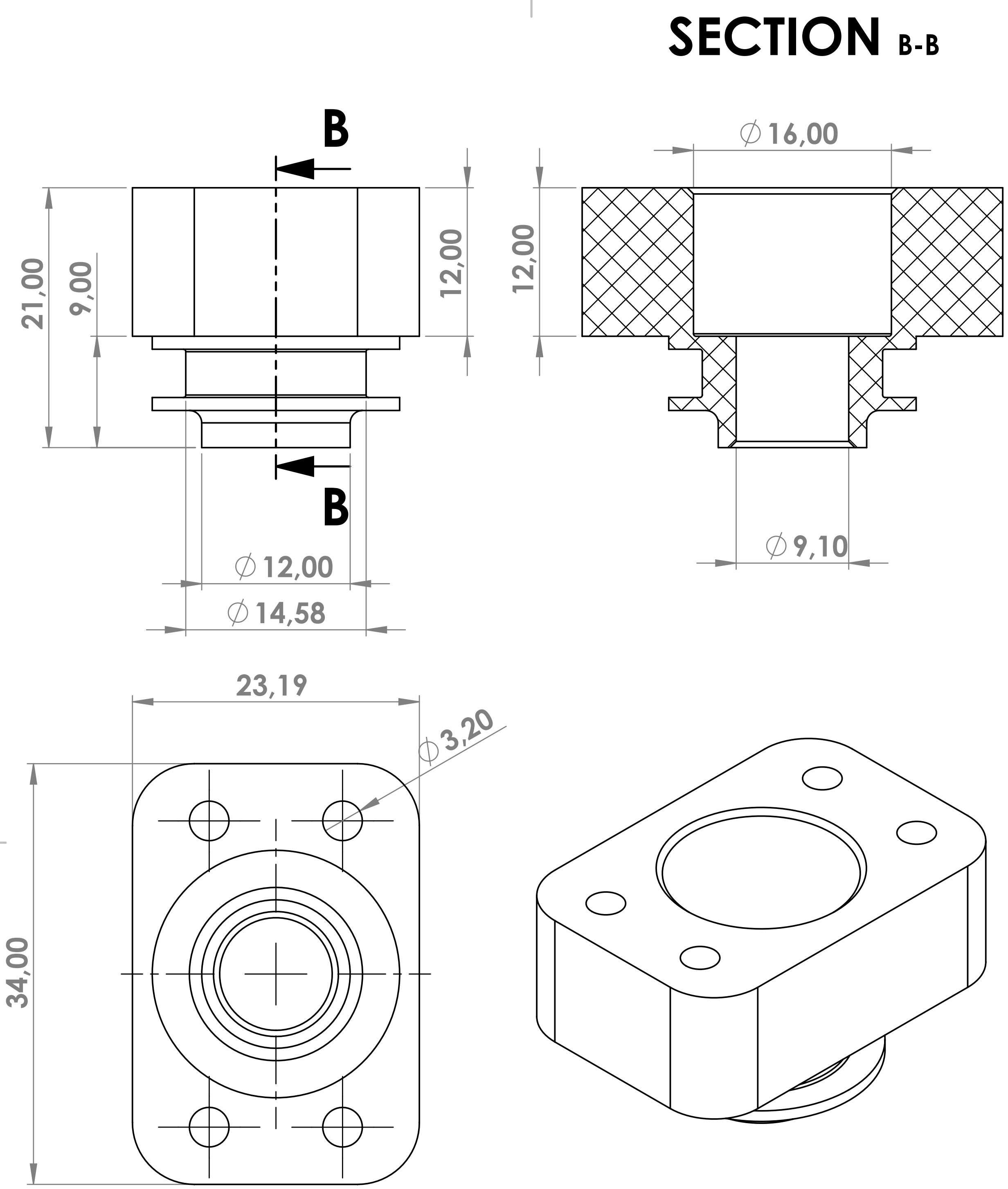
CHK'D							
APPV'D							
MFG							
Q.A				MATERIAL: Tough 1500	DWG NO.		A4
				WEIGHT:	SCALE:1:1	SHEET 1 OF 1	



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING / REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: **Cylinder head hydraulic**

MATERIAL: Tough 1500 (formlabs)

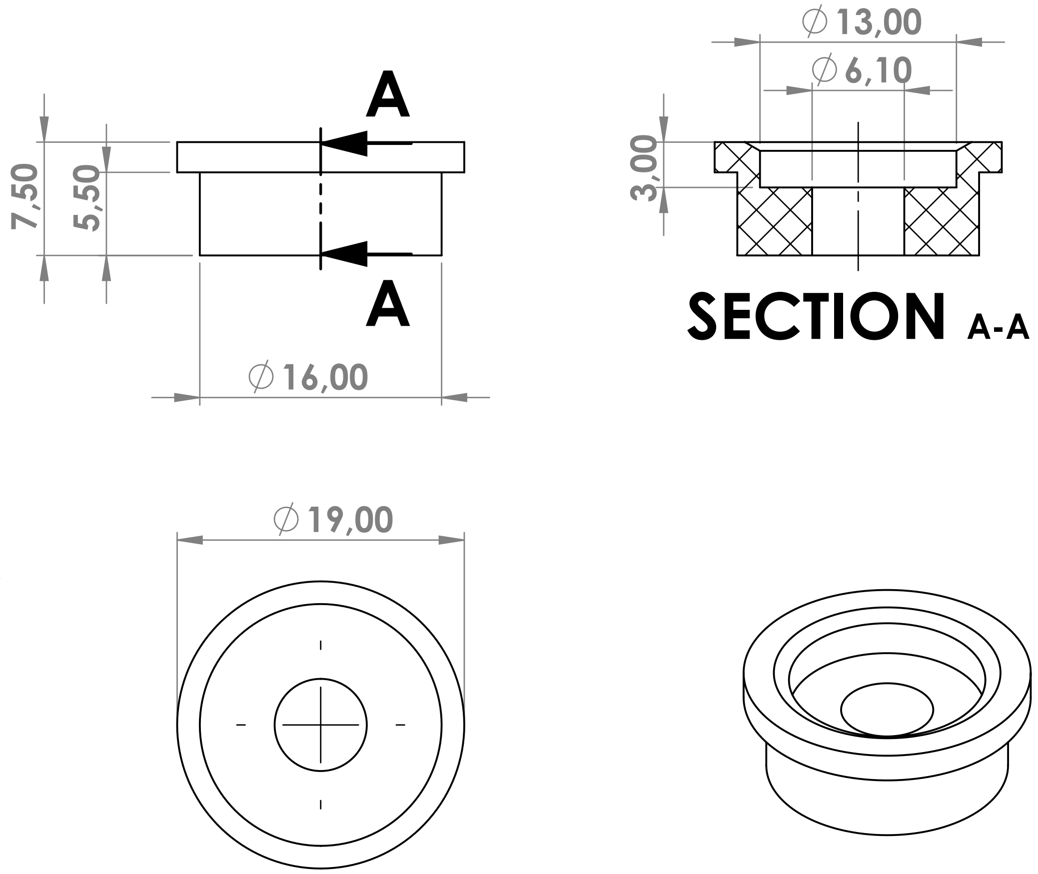
DWG NO.

A4

WEIGHT:

SCALE:2:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Push in part

MATERIAL:

Tough 1500 (formabs)

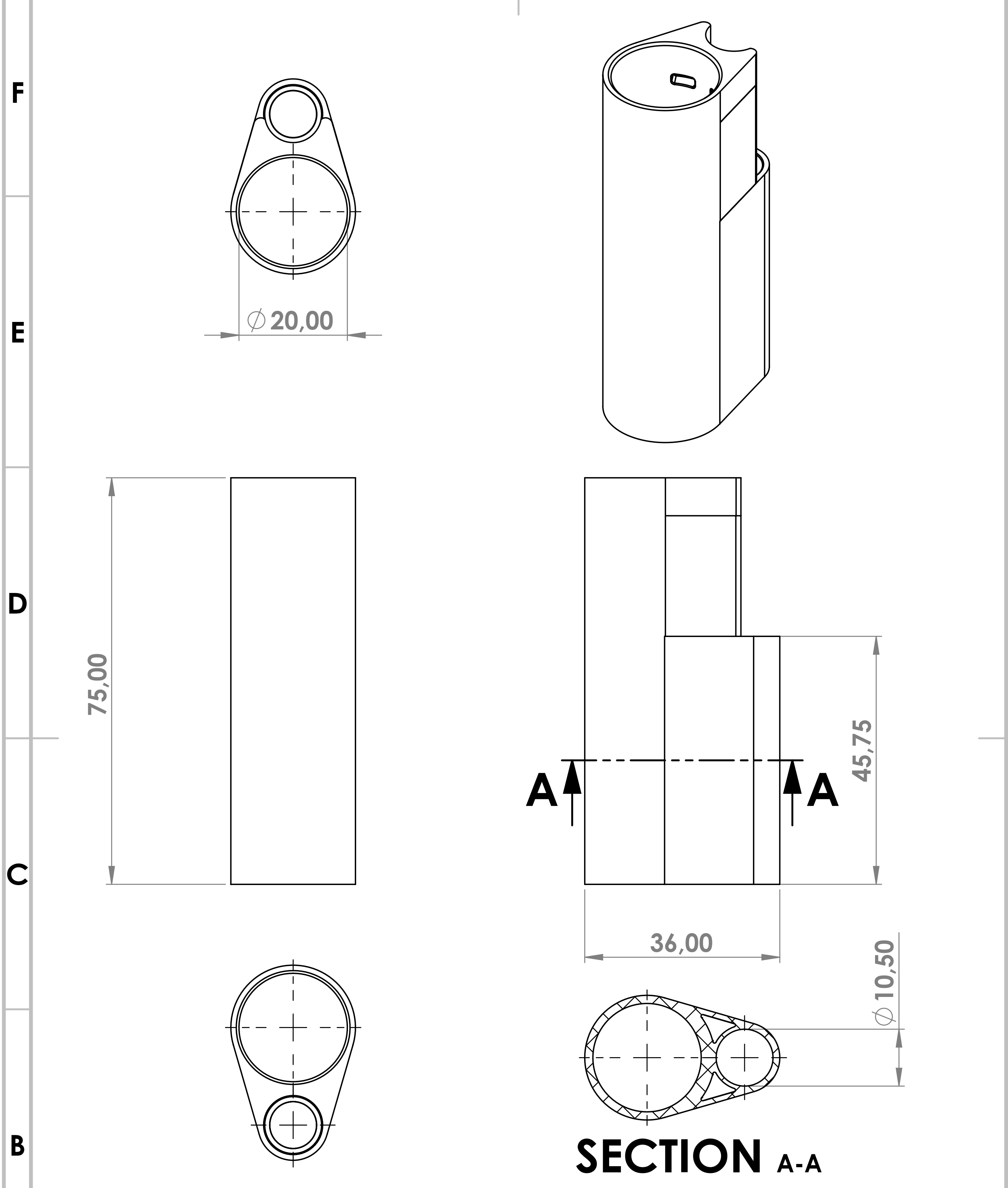
DWG NO.

A4

WEIGHT:

SCALE:2:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION

	NAME	SIGNATURE	DATE		
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A					

TITLE: **Cylinder tube hydraulic**

MATERIAL: Tough 1500 (formlabs)

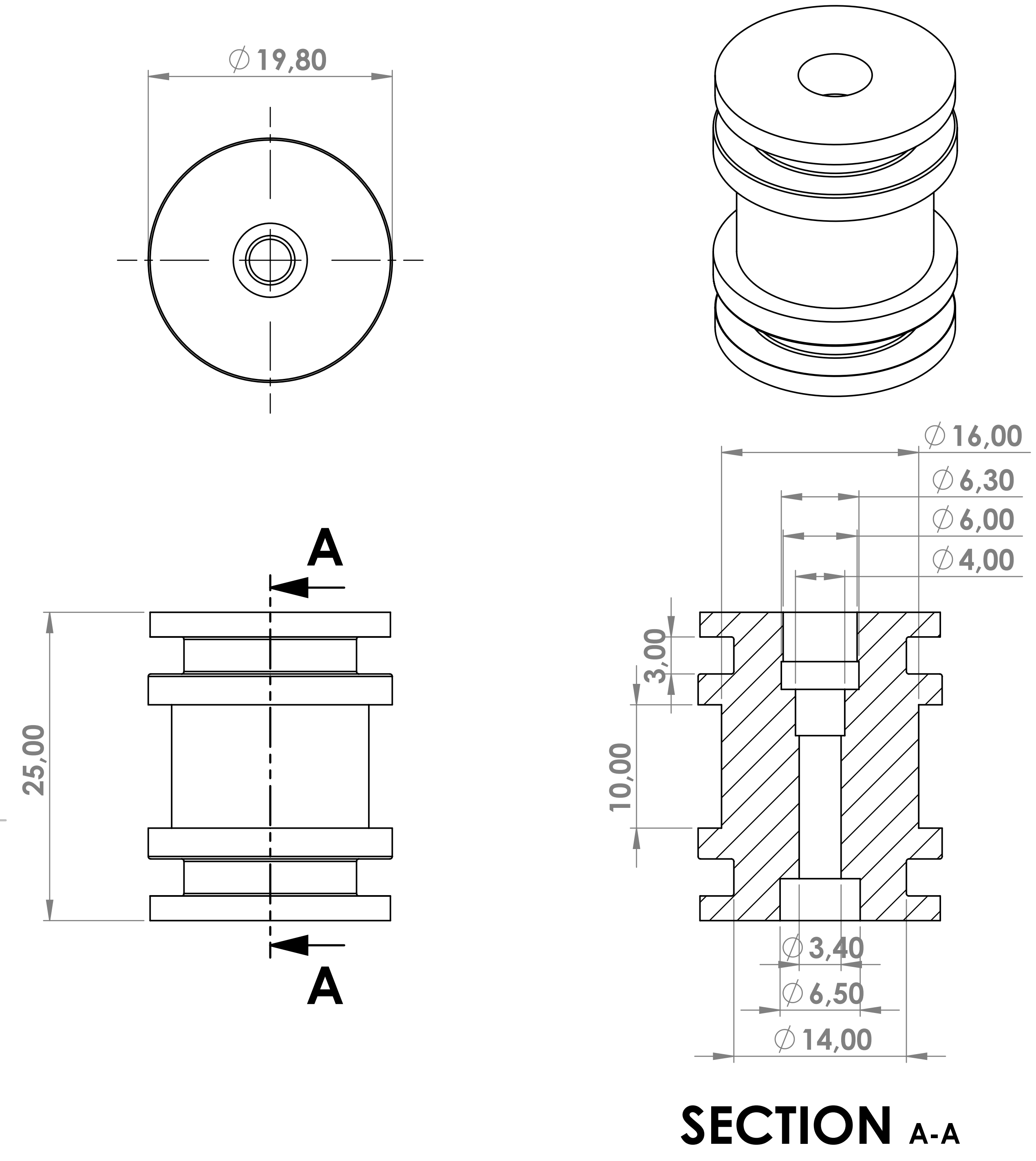
DWG NO.

A4

WEIGHT:

SCALE:1:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Piston hydraulic

MATERIAL:
Tough 1500 (formlabs)

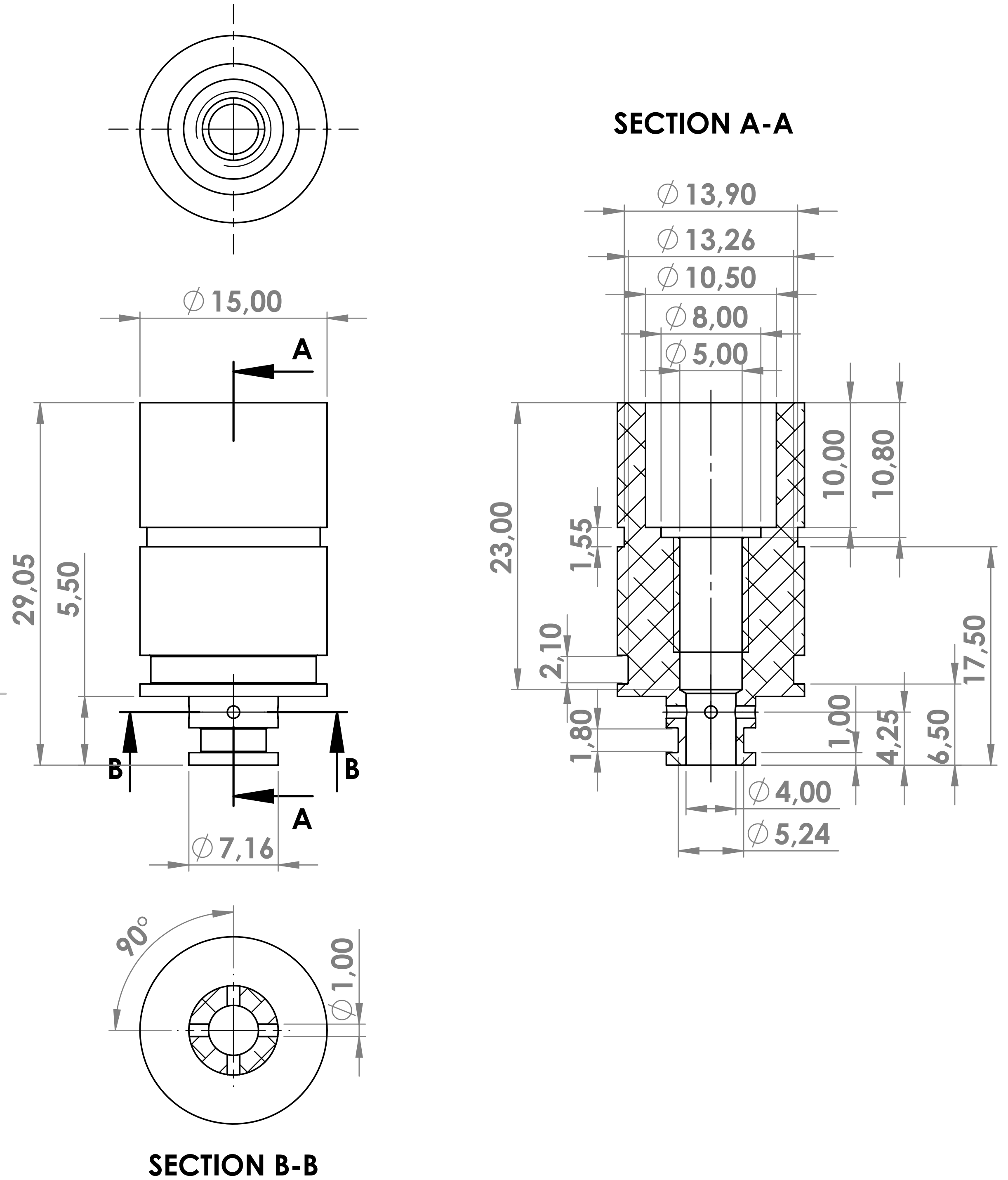
DWG NO.

A4

WEIGHT:

SCALE:2:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Valve hydraulic

MATERIAL:

Tough 1500 (formlabs)

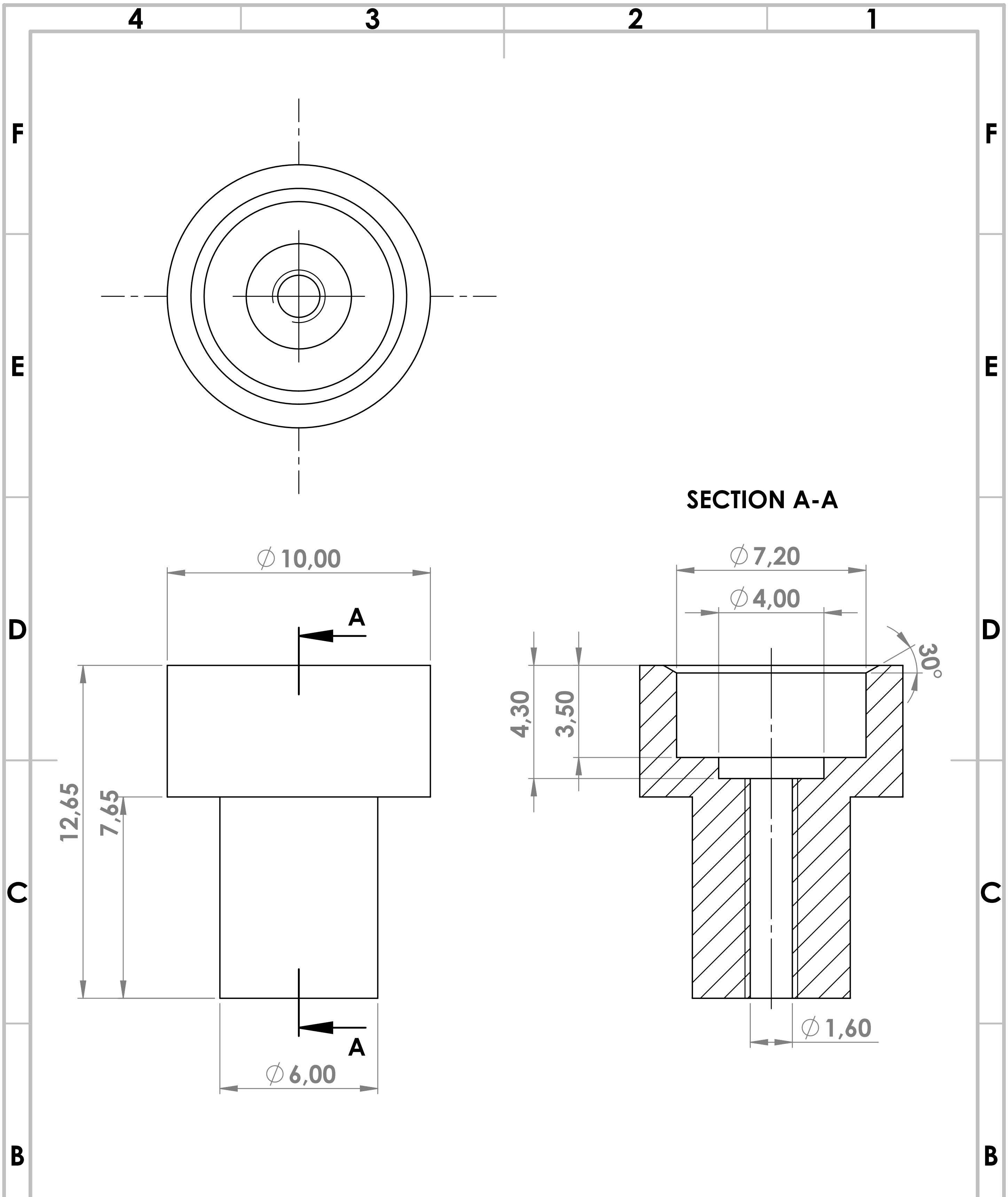
DWG NO.

A4

WEIGHT:

SCALE:2:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: **Valve seating hydraulic**

MATERIAL: Tough 1500 (Formlabs)

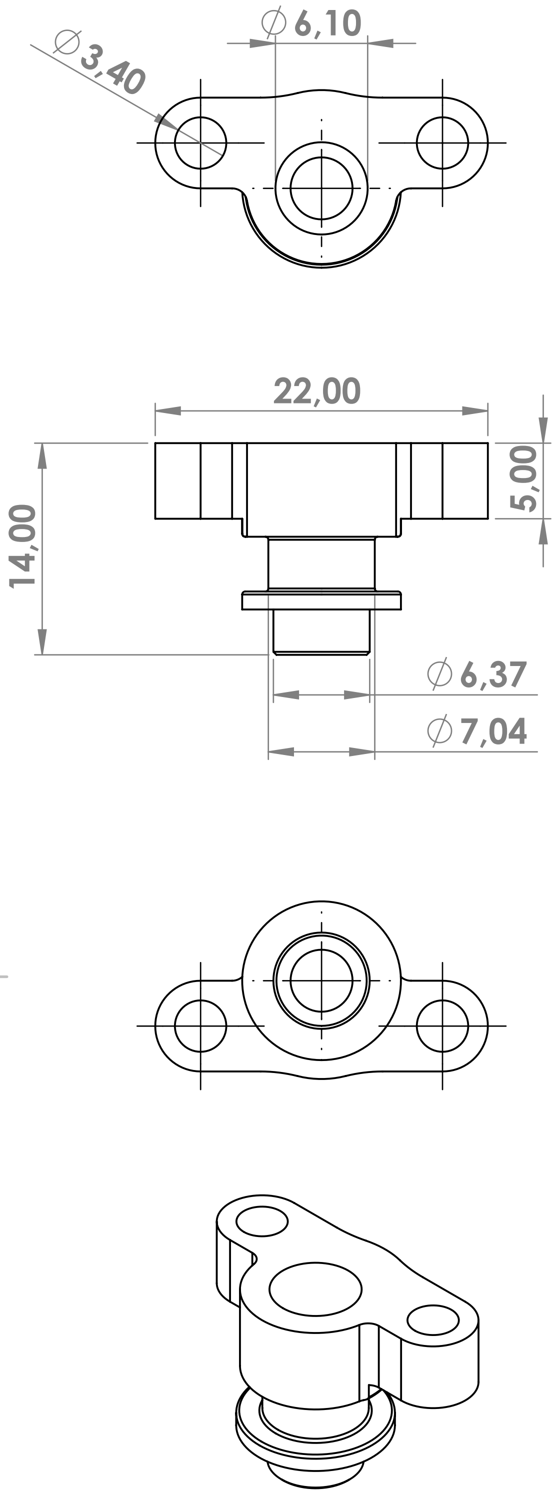
DWG NO.

A4

WEIGHT:

SCALE:5:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING	REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Accumulator cylinderhead

MATERIAL:

Tough 1500 (formlabs)

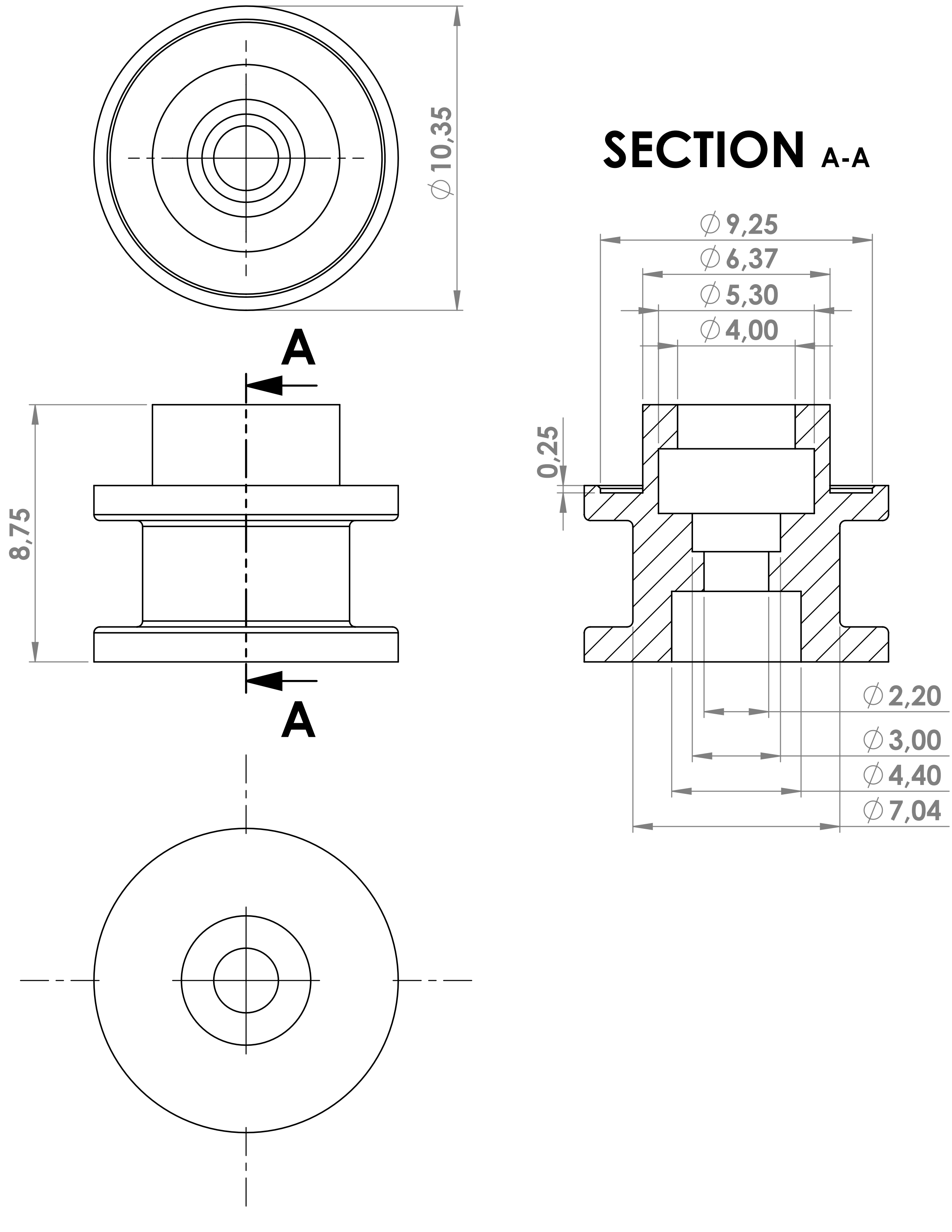
DWG NO.

A4

WEIGHT:

SCALE:2:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Piston Accumulator

MATERIAL:
Tough 1500(Formlabs)

DWG NO.

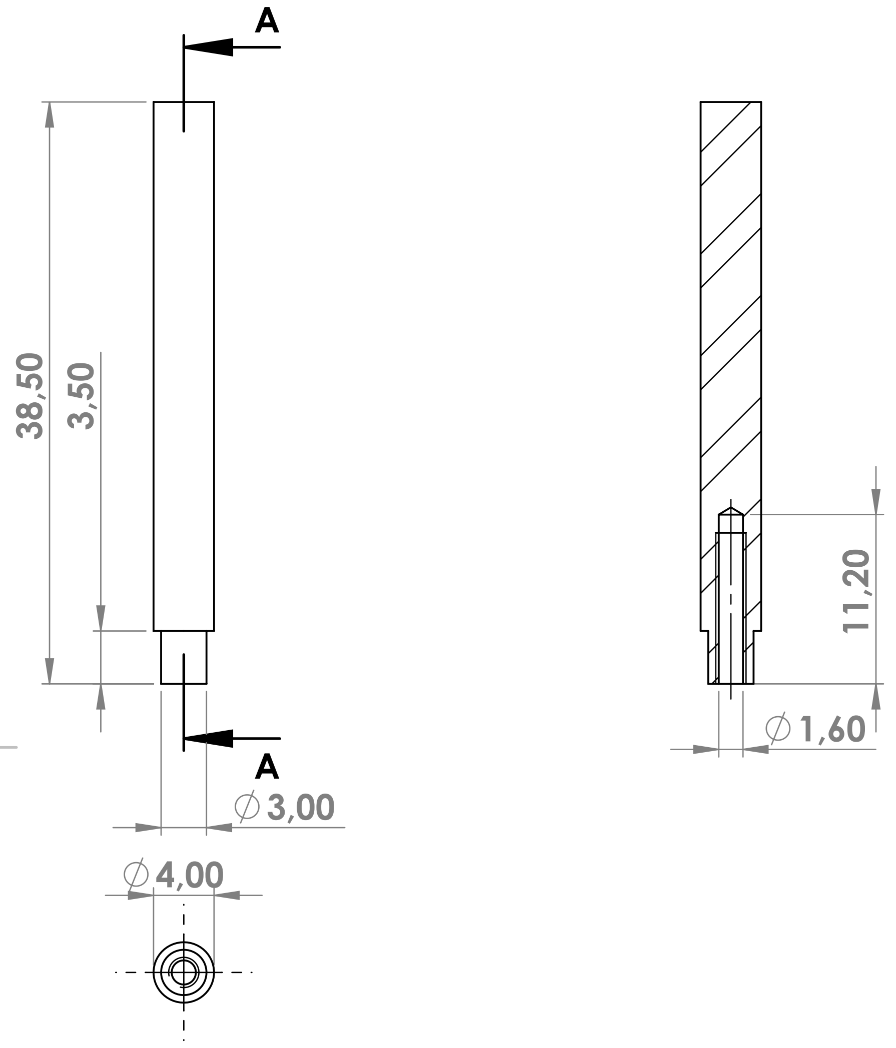
A4

WEIGHT:

SCALE:5:1

SHEET 1 OF 1

SECTION A-A



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Piston rod accumulator

MATERIAL: Tough 1500 (formlabs)

DWG NO.

A4

WEIGHT:

SCALE:2:1

SHEET 1 OF 1