Design of a Variable Mechanical Advantage mechanism for the Delft Cylinder Hand

Master of Science Thesis

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Design of a Variable Mechanical Advantage Mechanism for the Delft Cylinder Hand

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Abstract—The Delft Cylinder Hand and similar body powered hand prostheses require an input force that is too high for daily tasks. The force is perceived as uncomfortable and leads to a high rate of users abandoning their prosthesis. Reducing the input force by increasing the mechanical advantage of the system is not feasible, as this would unfavourably increase the required input displacement to close the prosthetic hand.

The goal of the research is to significantly reduce the input force, without exceeding the input displacement limit by designing a variable mechanical advantage (VMA). The VMA is specifically designed for the Delft Cylinder Hand. The input force, when applying a 30 N pinch force, should always be lower than 50±4 N, without compromising the 53 mm maximum input displacement. Two load cases are used to determine the VMA properties, the worst-geometry load case and the realistic-pinch load case.

Calculations show that a VMA design is feasible for the Delft Cylinder Hand. In the case of the worst-geometry load case, a design is only feasible when friction losses are excluded, while for the realistic-pinch load case the friction losses can be included. Simulations confirm that the designed VMA mechanism is able to pinch an object with 30 N, with an input force lower than 50±4 N for the feasible loading conditions. Practical testing was too inconclusive to validate the simulation.

I. INTRODUCTION

This thesis describes the design of a variable mechanical advantage (VMA) mechanism for the Delft Cylinder Hand [1], a body powered voluntary closing morphological hand prosthesis, shown in Figure I.1.

A. Body powered prostheses

In the field of upper limb prosthetic devices, there are two distinct methods of actuation, namely body powered and externally powered. Body powered prostheses are actuated and controlled by an uninjured part of the amputee’s body (most commonly by shoulder movement). The applied force from the shoulder muscle is transferred to the prosthetic hand to achieve a pinch force on a gripped object. Externally powered prostheses are controlled by the EMG signal that gets picked up through electronic sensors placed on the skin, after which the actuation is powered by an electric motor.

Externally powered prostheses weigh more than the typical body powered prostheses, but both are considered to be uncomfortable due to their large weight [2]. In addition, the body powered prostheses require a relatively high force to pinch an object, something that has hardly been improved over the last 25 years [3]. Externally powered prostheses do not have this drawback, but this type of device lacks proprioceptive feedback, an important sensory input the user needs to control the prosthesis [4]. The described problems lead users to abandon their prosthetic device [5].

The Delft Cylinder Hand has an acceptable weight and a lower required force compared to other body powered prostheses [6]. It has however been reported that the required input force is still too high. For that reason, the research focuses on improving the required input force of the Delft Cylinder Hand. Unfortunately it is not possible to reduce the input force by simply increasing the mechanical advantage (MA) of the device, as that would result in a too high shoulder displacement. An additional solution is required to reduce the input force to a sufficient level.

B. Basic Requirements

In order to find a solution to the described problem, one must fully understand the basic requirements of body powered prostheses in general.

Keller [7] shows the required pinch force for a collection of daily tasks. A minimum pinch force of 30 N is required to handle a wide range of different daily objects. The maximum input force is defined by Monod [8] as the 18% critical muscle force equal to 50±4 N. Taylor [9] focuses on body powered control with shoulder movement and mentioned a maximum displacement of 53±10 mm.

C. Variable Mechanical Advantage

A literature survey [10] showed that a VMA mechanism has the most potential in lowering the required input force for a body powered upper limb prosthesis. The idea of a VMA mechanism is to switch between two MA stages. Figure I.2 shows the ideal force displacement curve for pinching. In
theory it would require zero force to move the fingers of the prosthetic hand towards an object, while it would require no shoulder displacement to pinch an object. The dashed lines in Figure I.2 represent the maximum allowed input force and shoulder displacement.

![Ideal force displacement curve for pinching with: a) A curve showing an input force used for pinching exceeding the comfort limit, b) An increase of the mechanical advantage resulting in a shoulder displacement that exceeds the usage range, c) Implementing a VMA mechanism in order to achieve an acceptable input force as well as an acceptable shoulder displacement.](image1)

Figure I.2: Ideal force displacement curve for pinching with: a) A curve showing an input force used for pinching exceeding the comfort limit, b) An increase of the mechanical advantage resulting in a shoulder displacement that exceeds the usage range, c) Implementing a VMA mechanism in order to achieve an acceptable input force as well as an acceptable shoulder displacement.

Figure I.2 shows that without VMA mechanism, either the input force (a) or the shoulder displacement (b) exceeds the dashed line, but this will not be the case with the use of a VMA mechanism (c). A lever comparison for a VMA mechanism is shown by Figure I.3, where the first stage would result in a low MA and the second stage a large one. These two settings should be interchangeable, by switching to stage 2 whenever an object is pinched and switch back to stage 1 when it is released.

**D. Goal**

The goal of the research is to design a VMA mechanism for the Delft Cylinder Hand. The input force when applying a 30 N pinch force should always be lower than 50±4 N, without compromising the 53±10 mm maximum shoulder displacement requirement, for any pinch grip of the prosthetic hand.

**II. METHODS**

The literature study [10] indicates that only a few upper limb prostheses included a VMA mechanism. None of these were designed for a morphological prosthetic hand and neither are any of them currently available on the market. The attributes of the Delft Cylinder Hand and VMA mechanism are examined in order to reach the goal of the research.

![Mechanical advantage of a VMA mechanism indicated by a lever for a) Stage 1, b) Stage 2.](image2)

Figure II.1: Mechanical advantage of a VMA mechanism indicated by a lever for a) Stage 1, b) Stage 2.

**A. Delft Cylinder Hand attributes**

The Delft Cylinder Hand is a voluntary closing hydraulically underactuated morphologic body powered hand prosthesis. The prosthesis uses hydraulics as the energy transmission from shoulder movement to pinch motion instead of the traditional Bowden cable. LeBlanc [11] showed that using hydraulics results in less friction and energy losses compared to the use of a Bowden cable. The individual fingers of the prosthetic hand are able to move separately. The thumbs movement is passive and the four fingers are actuated by the same shoulder movement. The hand is underactuated as the prosthetic hand can use its multitude of fingers to generate more degrees of freedom than it has actuators. The prosthesis uses a hydraulic cylinder near the shoulder of the user that transfers the input force towards the hand with shoulder movement. Figure II-1 shows the prosthetic hand and input cylinder attached to a healthy subject.

![The Delft Cylinder Hand attached to a healthy subject. The hand can be closed by pulling the white shoulder strap, which is attached to the input cylinder.](image3)

Figure II.2: The Delft Cylinder Hand attached to a healthy subject. The hand can be closed by pulling the white shoulder strap, which is attached to the input cylinder.

Figure II.2 shows a schematic drawing of one of the fingers of the Delft Cylinder Hand as well as the currently used input cylinder. Shoulder movement from the user ensures piston movement of the input cylinder, which in turn would move the pistons of the proximal interphalangeal joint (PIP) and metacarpophalangeal joint (MCP) cylinders, exerting a pinch force on an object. The definition and value of all variables for Figure II.2 can be found in Appendix D.1.
C. **VMA mechanism attributes**

When a VMA mechanism is added to the current prosthesis, it should be placed somewhere in between the prosthetic hand and the input cylinder. The mass should be as low as possible and depending on the amputee there is limited space to place the VMA mechanism. This research however, only focuses on the proof of concept of the VMA mechanism and therefore omits the attributes of a certain mass, shape and dimension of the VMA mechanism.

One function of the VMA mechanism is to switch between two stages, each with a different MA. Stage 1 is used to move towards an object and stage 2 to pinch the object. Figure II.3 indicates the moment of switching, at 40 N. With the current input cylinder this corresponds to an input pressure of 0.56 MPa. The switching point, as seen in Figure II.3, is chosen at the moment just before the stiffness of the force displacement curve radically increases. More detail on the switching point is found in Appendix D.2.

The other function of the VMA mechanism is to provide an increased output force for the same input force after switching to stage 2. The estimation of the MA is done by the following equations.

\[
M_{\text{mcp}} = F_{\text{pinch}}(l_{\text{mcp}} + l_{\text{pip}}) \\
M_{\text{pip}} = F_{\text{pinch}} 
\]

\[
P_{\text{in}} = P_{\text{mcp}} = \frac{M_{\text{mcp}}}{N \cdot a_{\text{mcp}} \cdot 0.25 \pi \cdot d_{\text{mcp}}^2} \\
P_{\text{out}} = P_{\text{pip}} = \frac{M_{\text{pip}}}{N \cdot a_{\text{pip}} \cdot 0.25 \pi \cdot d_{\text{pip}}^2} \\
V_{\text{MA}} = \frac{P_{\text{out}}}{P_{\text{in}}} 
\]

When the fingers of the prosthetic hand are fully stretched \((\alpha=\beta=0)\) the MA of stage 2 is estimated to be 8.2 for a single finger pinch \((N=1)\) and 4.1 for a double finger pinch \((N=2)\). Note that the calculated MA is based on the currently used input cylinder and would change along any input cylinder adjustments. No friction or stiffness losses were taken in to account.

With the current input cylinder the prosthetic hand could perform any pinch grip with a maximum shoulder displacement of 37 mm (Figure II.3). When a VMA mechanism is included the required shoulder displacement for a pinch grip would increase, but as long as the shoulder displacement does not increase above the maximum requirement \((53\pm10 \text{ mm})\) this is acceptable. The required MA of stage 1 of the VMA is assumed to be equal to 1. A precise calculation of the MA is done in Chapter IV.

D. Requirements summary

- Minimum pinch force: 30 N
- Maximum input force: 50±4 N
- Maximum shoulder displacement: 53±10 mm
- Total volume for pinch grip: 2645 mm\(^3\)
- Switching point: 0.56 MPa
- Stage 1 MA: 1
- Stage 2 MA: Order of 4.1 for double finger pinch
  Order of 8.2 for single finger pinch
III. CONCEPTUAL DESIGN

Different design principles were made based on the requirements from Chapter II. Out of these principles multiple concepts were created.

A. Functions and design principles

Appendix B shows an in-depth consideration of different design principles, based on the requirements in the form of a morphologic chart. The design principles are compared to the different functions as defined by Appendix A. The functions and their chosen and rejected design principles are explained briefly.

- **Fitting:** Describes how the VMA mechanism should be connected to the input cylinder and prosthetic hand. The options are integration in the already present system as a whole or a plug and play connection. Integration is chosen because of the use of fewer parts. A plug and play system would only be useful when designing a VMA mechanism for multiple prosthetic devices.

- **Transfer Energy:** Describes the way how the energy flow from the input cylinder would be transferred to the prosthetic hand. The options are using a hydraulic, tendon or linkage energy transmission. There are two reasons to go with the hydraulic energy. First of all, both the input and the prosthetic hand already use a hydraulic transmission. If another medium than hydraulics were to be used, the mechanism would still need two hydraulic cylinders for the input and output, therefore increasing the number of different parts. Secondly, hydraulic components have more freedom in placement compared to the linkages and pulleys. In a limited space the hydraulic components can be positioned more efficiently.

- **Alter Mechanical Advantage:** Pistons, pulleys and pivoting bars are design principles that can be used to alter the mechanical advantage of a system. Each of these design principles only functions with their respective energy transmission method. In other words, pistons are the selected design choice.

- **Switch Mechanism:** For the same reason as for the Altering of the mechanical advantage, the chosen design choice is a piston acting as a switch. The morphological chart in Appendix B only depicts one switching method, despite more options are available. The different concepts describe the different switching method options.

- **Housing:** The research does not focus on the integration of the VMA mechanism inside the prosthetic device. It is suggested that for future work the VMA mechanism must have its own location inside the prosthetic device, as integration with a wrist prosthesis or integration with the prosthetic hand provide too little space.

B. Concepts

Six slightly different concepts have been worked out. The concepts are all hydraulic and differ only in the switch mechanism method. Out of the six concept one was picked as the optimal VMA design to be used for the Delft Cylinder Hand [Appendix C]. In addition, a second reference concept has been worked out in detail for comparison reasons. It is argued that the reference concept would not work for the current situations, but because it is very similar to existing hydraulic VMA mechanisms in other applications [12], the purpose is to compare it with the chosen concept.

1) Chosen concept:

Figure III.1 shows the schematic representation of the chosen concept. The small 3-way port drawing represents the cylinder responsible for the switching of the mechanism (switch cylinder) and the larger cylinder represents the cylinder creating the mechanical advantage (MA cylinder). The top drawing indicates the first stage of the VMA, where the light blue colour represents a low pressure and is equal throughout the entire system. The lower drawing shows the second stage of the VMA, with the blue colour indicating an increased pressure and the dark blue colour an even larger increase. The red lines represent the switch spring and the arrows show the direction of the hydraulic flow. Note that the input cylinder and prosthetic hand are not shown in the drawing.

Figure III.1: Chosen concept, with the MA cylinder depicted on the left and the switch cylinder on the right. Top picture shows stage 1 of the VMA mechanism while the bottom picture represents stage 2.

The input and output are bypassing the MA cylinder in stage 1 and are redirected through the MA cylinder in stage 2 of the VMA mechanism. The switch is depending on the output pressure and is controlled by the spring. Pinching of an object results in the pressure to increase and in return activates the switch. After switching to stage 2, the output pressure presses against the switch cylinder spring at an even greater force in comparison to stage 1, which means that the VMA mechanism would not switch back and forth when the pressure is slightly increased or decreased around the initial switch pressure. The MA cylinder does not have a spring, because its movement is retained by the fixed volume in stage 1. The advantage is that no additional work is lost, but the major drawback is a sudden increase in the output pressure after switching (Figure IV.6).
2) Reference concept

Figure III.2 shows that opposed to the chosen concept, the reference concept uses a 2-way switch. The movement of the MA cylinder is no longer retained by a fixed hydraulic volume and requires a spring. The spring must ensure the MA cylinder starts to move only after switching to stage 2. The minor difference in concept has huge impact in its behaviour. The spring of the MA cylinder stores energy from the input pressure. As a result the output pressure would not immediately increase after switching (Figure IV.8). On one hand this could be seen as an advantage, the major drawback on the other hand is that the concept has less contribution to the reduction of the input to output force ratio compared to the chosen concept. The mechanism would also immediately switch back to stage 1 when the pressure is slightly decreased.

![Reference concept diagram](image)

Figure III.2: Reference concept, with the MA cylinder depicted on the left and the switch cylinder on the right. Top picture shows stage 1 of the VMA mechanism while the bottom picture represents stage 2. The system includes an additional spring for the MA cylinder.

IV. IV DETAILED DESIGN

The concepts from Chapter III are elaborated in detail. The prosthetic hand remains the same, but the current input cylinder is adjusted. The dimensions of the VMA mechanism and input cylinder are determined based on different loading conditions.

A. Loading conditions

In order to design the components they must be put to the test by different loading conditions. A worst-geometry load case and a realistic-pin load case have been used. Each of these load cases could either be included or excluded by friction and stiffness losses taken from the measurements of the Delft Cylinder Hand with a prosthetic glove [1]. All load cases can be determined for a single finger pinch (N=1) or a double finger pinch (N=2). Table IV-1 shows the different loading conditions and the results of the VMA calculation. Each loading conditions takes in to account the minimum pressure to fully close the prosthetic hand equal to P = 0.56 MPa.

1) Worst-geometry load case

The worst-geometry load case uses the most unfavourable input force to pinch force ratio (fingers fully stretched) for pinching on an object. It also takes in to account the most unfavourable input displacement (fingers fully closed for a pinch grip) when moving towards an object. The ratio between the pinch force and output pressure can be determined from the calculations in section II.C, these are 5.2 and 10.5 N/MPa for a single and double finger pinch respectively. The maximum hydraulic volume displacement when moving towards an object is 2645 mm³. Note that the switch does not activate before all remaining fingers are at their end position, meaning forces will be exerted upon the object even before switching to stage 2.

2) Realistic-pin load case

The realistic-pin load case is based on pinching a small object used for the validation of the Delft Cylinder Hand in the research by Smit [1]. The PIP and MCP angles are unknown in this load case, thus the output to input force ratio is determined by Figure IV.1. It shows the relation between the input and output force when pinching an object. The graph shows that it takes up to 20 N before the object is starting to get pinched, which is caused by the stiffness losses from the prosthetic glove. The graph can be used to determine the ratio between the input force and pinch force after the remaining fingers of the prosthetic hand are fully closed. The ratio is 9.1 for a single finger pinch and 4.6 for a double finger pinch. The dimensions of the used input cylinder are known, therefore the ratio can be converted to the ratio between pinch force and output pressure, which are 7.9 and 15.7 N/MPa for a single and double finger pinch respectively.

![Graph of relation between input and output force](image)

Figure IV.1: Graph of the relation between the input and output force when pinching an object with the Delft Cylinder Hand. The graph indicates the ratio for a single and double finger pinch [1](modified)
friction losses on the other hand are assumed to be caused by O-rings throughout the entire system. For that reason the friction force is always equal in relation to the input force regardless of the stage of the VMA mechanism. Note that due to alternation of the dimensions of the input cylinder the 10 N friction losses are scaled accordingly. For an input cylinder with diameter of 11.4 mm, the friction is equal to 13 N [Appendix D.4].

**B. Components**

The different loading conditions are used to determine the required dimensions of the cylindrical components of the VMA mechanism as well as for the input cylinder.

1) **Input cylinder and MA cylinder**

The basis of the calculation for the required MA for the different stages is the same as done for the VMA mechanism attributes in Chapter II. The difference is an iteration process ensuring that the maximum input displacement does not exceed the requirement. Whenever a MA change is applied on a pinch motion, it will not only affect the pinch force for a certain input force but also affect the shoulder displacement.

![Figure IV.2: Sketch of the consequence of switching to a higher MA for a certain force displacement curve.](image)

It is not possible to design a VMA mechanism for every single loading condition. The strictest loading condition that does not compromise the requirements is the worst-geometry load case, for a double finger pinch, while excluding friction losses. The design of the of the MA and input cylinder is based on this loading condition. In that case the design of the VMA should also be sufficient for the less strict loading conditions as well.

<table>
<thead>
<tr>
<th>Load cases</th>
<th>MA_{stage 2}</th>
<th>(\theta_{\text{in}}) [mm]</th>
<th>(F_{\text{switch}}) [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>N=1</td>
<td>N=2</td>
<td>N=1</td>
<td>N=2</td>
</tr>
<tr>
<td>None</td>
<td>n/a</td>
<td>5.5</td>
<td>n/a</td>
</tr>
<tr>
<td>Stiffness</td>
<td>n/a</td>
<td>5.5</td>
<td>n/a</td>
</tr>
<tr>
<td>Friction</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Realistic</td>
<td>13.1</td>
<td>2.5</td>
<td>15.1</td>
</tr>
<tr>
<td>Stiffness</td>
<td>18.6</td>
<td>3.1</td>
<td>17.3</td>
</tr>
<tr>
<td>Friction</td>
<td>n/a</td>
<td>3.8</td>
<td>n/a</td>
</tr>
<tr>
<td>Friction&amp;</td>
<td>6.8</td>
<td>6.8</td>
<td>12.1</td>
</tr>
</tbody>
</table>

* Infringe the maximum input force requirement

**Table IV-1**: VMA settings for different load cases. The MA for stage 1 is always equal to 1, the MA for stage 2 has been calculated by iteration. Load cases that are not applicable have been indicated by ‘n/a’. The ‘none’ load case takes the stiffness and friction losses into account for the switching pressure but assumes no friction and stiffness losses for the pinch force.

The size of the MA cylinder should multiply the input by at least 5.5 (Table IV-1). The diameter of the MA cylinder is only dependent on the available O-rings. A O-ring with outer diameter of 12 mm is chosen for the input cylinder. The inner diameter has been increased from 3 to 5 mm to maintain the same piston area. The length of the input cylinder is given by the equation shown below, where \(V_{\text{hand}}\) is the total volume required to close the hand, \(V_{\text{MA-cyl}}\) is the total volume of the MA cylinder, \(V_{\text{out}}\) is hydraulic loss per 3 months per area of sliding O-rings and \(d\) is the diameter of the input cylinder. The result is a minimum required length of 73 mm.

\[
l_{\text{input-cyl}} = \frac{V_{\text{hand}} + V_{\text{MA-cyl}} + V_{\text{loss}} \cdot \sum_{i=1}^{N} \pi d_{\text{out},i}^2}{\frac{1}{4} \pi \left( d_{\text{out,input-cyl}}^2 - d_{\text{in,input-cyl}}^2 \right)}
\]

The size of the MA cylinder should multiply the input by at least 5.5 (Table IV-1). The diameter of the MA cylinder is only dependent on the available O-rings. A diameter of respectively 11 and 10 mm is a suitable choice, resulting in a MA of 5.7. The length of the MA cylinder should be at least 33 mm. This is determined by the required input displacement during pinching of an object multiplied by the MA. For the old input cylinder of the Delft Cylinder Hand the input displacement (X_{pinch}) is approximately 7.5 mm for a relatively...
stiff object [Appendix D.2]. Converting the input displacement from the old input cylinder to the newly designed input cylinder is done with the following equation.

\[
I_{MA_{cyl}} = \frac{X_{\text{pinch}} \cdot MA \cdot (d_{cm}^2 - d_{cm}^2)}{(d_{out,input_{cyl}}^2 - d_{in,input_{cyl}}^2)}
\]

2) Switch cylinder

As described by the chosen concept, the switch cylinder is designed such that it switches at a given switch pressure, but switches back at a lower pressure. It can also be easily modified such that the switch and return switch occurs at the same pressure, suitable for the reference concept. The switch cylinder is shown in Figure IV.3

![Figure IV.3: Schematic image of the switch cylinder. The piston, shown with the black outline is positioned inside the cylinder housing (grey outline). The piston is forced to the right until obstructed by the switch spring indicated by the red lines. The blue colouring shows the hydraulic fluid. The flow between port 2 and port 3 is normally closed and the flow between port 1 and port 3 is normally open.](image)

The smallest piston head has an O-ring of diameter 3 mm and a thickness of 1 mm, the remaining two piston head O-ring sizes will be 4x1 mm and 5x1 mm respectively. The inputs and output of the switch cylinder are spaced with a length of 5 mm of each other to prevent simultaneous opening of port 1 and 2.

The switch pressure is dependent on the switch cylinder piston areas and the pretension of the switch spring. The spring stiffness is chosen such that switching to stage 2 occurs after an object is being pinched and the remaining fingers are fully closed. The stiffness of the switch spring is determined such that the entire switch motion results in no more than 5% increase of the initial switch pressure [Appendix D.5].

3) Testing cylinders and springs

Two testing cylinders are used as a substitute to the Delft Cylinder Hand. One of the cylinders is used to imitate the pinching of an object, while the other is used to mimic the motion of the remaining fingers against the stiffness of the prosthetic glove. The total volume of the two testing cylinders is about equal to the total volume of the cylinders in the prosthetic hand. The diameter of the testing cylinders is 10 mm, requiring an O-ring size of 8x1 mm.

The piston of the testing cylinder is directly pushing against an object in contrast to the prosthetic hand, which has a lever between the output cylinder and the pinched object. A conversion factor of 0.133 is used to compare the output force of the testing cylinders to the worst-geometry load case and a factor of 0.2 for the realistic-pinch load case. The spring of the test cylinder that is used to imitate the stiffness of the prosthetic hand has a stiffness of 2.3 N/mm. The switch pressure displaces the piston of the testing cylinder to approximately 95% of its maximum stroke, which is comparable to the proposed switching point of the prosthetic hand in Figure II.3.

4) Valve cylinder

The valve cylinder is schematically shown in Figure IV. The function of the valve cylinder is to prevent hydraulic flow bypassing the MA cylinder during the pinching of an object, but allows back-flow when releasing an object. The function is a necessity for the VMA mechanism as the hydraulic volume in the MA cylinder can accumulate after pinching an object. A more detailed analysis of the use of the valve is described in Chapter V.

![Figure IV.4: Valve cylinder assembled in the configuration. Valve opens when input pressure is larger than pressure between the MA and switch cylinder.](image)

![Figure IV.5: depiction of the three configurations, a) configuration 1 based on chosen concept, b) configuration 2, based on chosen concept, c) and configuration R, based on reference concept. Cylinder on the left side represents the MA cylinder and the switch cylinder is shown on the right, the input cylinder and test cylinders are not shown.](image)
C. Configurations

Three different configurations are designed using the exact same cylindrical components and their relevant dimensions, but with slightly different connections of the hydraulic hoses. Configuration 1 and configuration 2 both match the chosen concept from Chapter III, but show a slightly different behaviour. Configuration R is an exception, it depicts a detailed representation of the reference concept and is analysed as a comparison to the other 2. Configuration R requires a weight to be placed on the MA cylinder and additional hose couplings to mimic a 2-way switch port. Figure IV.5 shows the schematic drawings of the different configurations of the VMA mechanism. The main cylinder and test cylinders (not shown) are connected to the input and output. The switch pressure is the same for each configuration, but the pretension of the switch spring is different.

1) Configuration 1

For configuration 1, the required pretension is 39 N and the maximum stiffness is 0.36 N/mm. The initial switch pressure is equal to 0.56 MPa and the return switching pressure is equal to 0.39 MPa. The switch behaviour is shown in Figure IV.6; the top drawing indicates the force acting upon the spring of the switch cylinder, for which the red dotted line indicates the pretension of the spring. The bottom drawing shows the output force in relation to the input force. Note that the output pressure is much higher for the same input pressure immediately after switching, causing a range of implausible output pressures where no stable input pressure could reliably hold the output pressure.

2) Configuration 2

The switch spring for configuration 2 must have a 12 N pretension and a maximum stiffness of 0.057 N/mm. The initial switch pressure is equal to 0.56 MPa and the return pressure is equal to 0.14 MPa shown in Figure IV.7. Both configurations have the same initial switch pressure, but configuration 2 has a much lower return pressure compared to configuration 1. There is a large range of input forces that have a different output force depending on the stage of the VMA mechanism. Therefore, configuration 2 has a smaller range of implausible forces compared to configuration 1.

3) Configuration R

As a reference to the other two configurations, configuration R is used to inspect the behavioural difference compared to currently known hydraulic VMA mechanisms. The required spring pretension is 16 N and the maximum stiffness is 0.051 N/mm. The MA cylinder uses a weight instead of a spring, to enforce zero stiffness for the piston movement. A weight is less practical if implemented in a prosthetic device, but due to the quite large MA piston movement and the great pretension a spring would not deliver the wanted result. The weight should be at least 44 N to retain any piston movement until switching to stage 2 has occurred. As a consequence the initial pressure of 0.56 MPa is identical to the return pressure, as shown in Figure IV.8. Note that the output pressure does not immediately increase after switching.
D. Results

The results show that it is possible to determine an appropriate VMA mechanism for both the worst-geometry and realistic-pin load cases. For the worst-geometry load case a VMA design is only feasible for a double finger pinch grip, while excluding the stiffness losses. For the realistic-pin load case it is feasible for a double finger pinch and including stiffness losses. The worst-geometry load case excluding stiffness and a double finger pinch has been chosen as the basis for the design of the VMA mechanism.

The switch behaviour of configuration 1 and configuration 2 shows that the return switch pressure is lower than the initial switch pressure as intended. The behaviour of configuration R shows that the return switch pressure is equal to the initial switch pressure. Both configuration 1 and 2 show a range of implausible output pressures, with configuration 2 being less impactful. The effect of the implausible output pressures when operating a prosthesis is unknown.

V. SIMULATION

A simulation analysis has been performed to verify the calculated dimensions of the VMA mechanism. The simulation is done for each configuration and both load cases, using the VMA mechanism dimensions from Chapter IV.

A. Setup

The three different configurations have all been analysed by a mathematical simulation of the piston movement and the pressure in the system. It describes the pinching of an object to 1.5 times the initial switch pressure and then gradually releasing it by moving back to the starting position. In the simulation, the object is represented by a stiffness 50 times as strong as the stiffness used for the test cylinder spring. The simulation is static, meaning only looking over different equilibrium states of the system. The transition from one state to another will be elaborated where necessary. The simulation is done for both load cases, a double finger pinch, including prosthetic glove stiffness losses and excluding friction losses. The initial condition is a pressure of 0 MPa, with all pistons are on their minimum stroke, as shown by Figure V.1 for configuration 1.

B. Steps

Each step describes the movement of the cylinders to a certain position and the change of the input and output pressure. The calculation of each step and their visualization can be found in Appendix E.

1. Initial position
2. Hitting the object
3. Increasing pressure to switch pressure
4. Increasing pressure while switch port 1 is closing
5. Increasing pressure while both ports are closed
6. Increasing pressure while switch port 2 is opening
7. Increasing input pressure until to 1.5 of the switch pressure
8. Lower the input pressure, to 1.05 of the initial switch pressure
9. Lower the pressure, until return switch pressure
10. Decrease pressure, while switch port 2 is closing
11. Decrease pressure, both ports closed
12. Decrease pressure, while switch port 1 is opening
13. Decrease pressure, until object is dropped
14. Return to starting position

Figure IV.8: Behaviour of configuration R. Top) Indication of the switch pressure and return pressure; Bottom) Input to output pressure relation

Figure V.1: Analysis setup for configuration 1, included the main cylinder and test cylinders opposed to the Delft Cylinder Hand. One test cylinder is used to simulate the fingers moving and hitting an object, the other to simulate the remaining fingers.
C. Results

The results of the simulation are multiple graphs showing the motion of the individual cylinders and the pressure at the input and output of the system. Figure V.2 and V.3 show the graph for the worst-geometry load case for configuration 1. Figure V.2 shows the relation between the pinch force and input force and Figure V.3 shows the relation between the input force to input displacement. Appendix E includes the results for all loading conditions.

![Figure V.2: Configuration 1, worst-geometry load case, input force to pinch force relationship, per step of the analysis](image)

![Figure V.3: Configuration 1, worst-geometry load case, Input pressure to input cylinder piston movement, per step of the analysis](image)

Table V-1 indicates the requirement values from the simulation for each configuration and loading condition. An additional remark has been made if the requirement has been met for all users (coloured in green), a portion of the users (coloured in orange) or not been reached (coloured in red). For example, values below 46 N are coloured in green and values between 46 and 54 N are coloured in orange for the maximum input force requirement.

![Table V-1: Simulation results, showing if the different loading conditions meet the requirements. Green indicates a sufficient value, orange indicates that the requirements are met, but not for all users, red values are too large.](image)

The input force at switching is identical to all configurations. This is expected, as the switching point is defined for the dimensions of the input cylinder. The input force at switching is equal to the value calculated for the worst-geometry load case and a double finger pinch (Table IV.1).

Simulation shows that the requirements are met for both load cases, while using a double finger pinch grip and excluding friction losses. This only counts for configuration 1 and configuration 2 of the VMA mechanism. The results correspond to the expectations based on the calculations from Chapter IV.

D. Analysis

Next to the verification of the requirements, the results are used to analyse the behaviour of the different configurations.

1) Configuration 1 analysis

Figure V.4 shows similar behaviour of the configuration as previously determined by Figure IV.6. The transition from step 3 to step 6 (Switching from stage 1 to stage 2 of the VMA mechanism), results in a very large increase of the output pressure. Return switching occurs in step 9 and as a result there is a range of implausible pinch forces.

![Figure V.4: Configuration 1, worst-geometry load case, Input force to pinch force relationship plus remarks](image)

Another remark is the increment just after step 9. The sudden increase in pinch force is caused by the simultaneous closing of ports 1 and 2 of the switch cylinder (Figure IV.3), forcing the hydraulic volume towards the output cylinders when the switch cylinder piston is moving back.

After releasing an object and moving back to the starting position it can be noted in Figure V.3 that not all cylinders end up in their initial position. The MA cylinder and input cylinder still have a certain stroke and cannot move back any further. The problem is caused due to the switching at different input pressures. This can be resolved by using the valve cylinder (Figure IV). During the pinching of an object the pressure in the output is larger compared to the input and the valve should not allow any flow, but at under pressure, the output pressure will be smaller compared to the input pressure and the valve would allow flow.

2) Configuration 2 analysis

The results of the analysis of configuration 2 are shown by the graph in Figure V.5. The movement up until step 3 is identical to that of configuration 1. The initial switching behaviour and the return switching is a lot different from that of configuration 1. During switching, the MA cylinder is forced to move back which is impossible at zero displacement. This is further described in Chapter VI.
E. Configuration R analysis

Configuration R has none of the problems as described by the other two configurations. It has an identical behaviour up until switching as can be observed by Figure V.6. The return switch motion is equal to the initial switch motion. The MA cylinder returns to its initial position after the simulation, making the valve cylinder obsolete. The major difference is the delivered pinch force, which is in the current situation 2.2 times as less compared to configuration 1 and does not meet minimum the pinch force requirement.

Figure V.6: Configuration R input force to pinch force relationship, per step of the analysis

VI. QUANTIFY RISKS

This chapter covers the risks found by the analysis of the simulation as well other VMA mechanism related problems based on theory and experience.

A. Cylinder motion risks

Two major problems were identified during the simulation of configuration 2, making the prosthetic device unable to operate properly. The first problem, earlier mentioned, is the forced backwards motion of the MA cylinder during switching. Figure VI.1 schematically shows the phenomenon. The hydraulic volume between the MA cylinder and the left part of the switch cylinder is fixed. When the piston of the switch cylinder is moving towards the left, the volume inside the switch cylinder is increased. In order to compensate the MA cylinder must move backwards. Unwanted under pressure would occur if the MA cylinder is not able to move backwards possibly making switching more difficult. To avoid this risk the initial position of the piston of the MA cylinder must be placed forward. Calculations show that 1 mm displacement is sufficient [Appendix E].

Figure VI.1: Schematic drawing of the MA and switch cylinder for configuration 2, showing negative x-t motion for positive x-s motion.

The risk of getting stuck in a pinch grip when trying to switch back to stage 1 of the VMA mechanism is caused by the volume displacement of the switch cylinder when all ports are closed. The risk is related to the stiffness of the pinched object. By changing the objects stiffness from 50 times the prosthetic hand closing stiffness to only 5 times the stiffness, the result of the simulation is acceptable as shown by Figure IV.2.

Figure VI.2: Configuration 2, input force to pinch force relationship, 10 times lower stiffness compared to Figure V.5.

B. Leakage risks

Aside from the risk identified by the configuration simulation, there is one major risk to be treated carefully. The risk is the leakage of the hydraulic fluid from any one of the parts of the VMA mechanism and the consequence is the failure of the entire VMA mechanism. A single leakage would either immediately drop the output pressure, as the hydraulic fluid is incompressible or would gradually reduce the total hydraulic volume in the system until the user can no longer close the prosthetic hand. A tree diagram of the different hydraulic leakage risks mentioned in this section can be found in Appendix F.

The designed cylinders consist of many different parts, increasing the risk of leakage in between each part. A practical example is the glued cylindrical pipes inside the cylinder housings as shown in Figure VI.3. The adhesive is in contact with the hydraulics at one side and with the open world at the other end. Either glue shearing, cracks or incomplete padding would result in leakage, as shown by the red path.
A second practical example is shown in Figure VI.4, the MA cylinder is fabricated from three major parts; the cylindrical pipe, the input housing and the output housing. If, after assembly, the two entrances are not concentric, the piston would be burdened by asymmetric O-ring forces and forced to slope. This problem increases over distance when the gap between the two O-rings becomes smaller. If the slope of the piston becomes significant, an opening between the O-ring and the piston would occur, resulting in a hydraulic leak.

The design of the valve cylinder from Figure IV.4 is causing a lot of problems. Its function to block a high over pressure difference (50 bar) and to pass through low under pressure difference (between 0 and 1 bar) exceeded the design ability. It has been replaced by a manual switch, shown in Figure VI.5, which should be sufficient for testing the VMA mechanism as a proof of concept.

The last risk of leakage is based on the amount of hoses and couplings used (Figure VI.6). The hoses and couplings were prefabricated and are suited well for the design of the VMA mechanism. However, it only requires one of the many parts to break before the entire system fails. The hoses and couplings are connected by a plug and play mechanism with an O-ring. The risk of leakage by overpressure has been greatly reduced by stiffening each hose with a steel tube. The risk of leakage by a damaged O-ring in couplings can only be prevented by having enough spare parts. Damaging of the O-ring would only occur at assembly or de-assembly, thus shows no risk during the use of the prosthesis. The couplings are attached to the cylinders by means of an M3 connection and a sealing ring. The sealing rings are included with the couplings and are therefore limited. The sealing rings have a higher risk in damage over time compared to the O-rings from continued assembly and de-assembly. In order to compensate for the risk of damaged sealing rings alternative sealing rings are used as spare parts.

Figure VI.3: Leakage occurring in between the cylindrical housing (dark grey) and cylindrical tube (green) of the MA cylinder. The blue objects indicate the input and output couplings and the orange circles represent the O-rings.

Figure VI.4: Internal and external leakage caused due to a concentric mismatch between the major parts of the MA cylinder (exaggerated view)

Figure VI.5: The manual valve connected to the VMA mechanism with a hydraulic hose coupling and an adapter

Figure VI.6: Photo of the coupling including a metal tube reinforced hose, the original sealing ring on the left and the spare sealing ring on the right

VII. PRACTICAL TESTING

Practical testing of the configurations is done to verify the results found by the simulation. The chapter describes the equipment and procedure of the practical testing, as well as the results of each test.
Testing on low pressure is done in order to resolve a lot of the problematic risks as described by Chapter VI. The pressure is approximately 2.5 times lower than the pressure used for the calculation and simulation in Chapters IV and V.

1) Testing individual cylinders

The individual cylinders are being tested by using different weights on the input cylinder. Figure VII.3 shows an example of the setup for the test cylinders. The pinch force sensor measures the force of one of the testing cylinders and the hydraulic sensor measures the pressure in the system. The testing set up of all the individual cylinders are found in Appendix G.

2) Testing configurations

The simulations of the configurations from Chapter V are verified by testing the prototype on low pressure for each configuration. The testing setup of configuration 2 is shown by Figure VII.4. The pretension and stiffness of the springs are lowered to correspond for the low pressure setup. The testing procedure is done in the same manner as done for the simulation. The measured values are expected to be lower than the requirements and can only be compared with the low pressure simulations [Appendix E-2.2].
C. Results

Figure VII.5 shows the results of the individual testing of the test cylinders. Both the expected values from calculations and the measured values from are shown. The expected values do not take friction in to consideration, thus the measured values are slightly lower. The testing cylinder and sensors are working as intended.

The tests of the other individual cylinders have been successfully performed as well. Appendix H shows all results. The only remark that can be made is the relatively large friction in the MA cylinders. As a consequence a total of 0.3 MPa input pressure is lost when operating the VMA mechanism. This has a negative impact on the input force to pinch force relationship.

![Output pressure and output force for weight input](image)

**Figure VII.5: Expected and measured values of the output force and pressure for the individual testing of the input cylinder and testing cylinders.**

Due to an error in the prototype fabrication test results for the different configurations came back inconclusive. The VMA mechanism was able to switch to stage 2 at the correct switch pressure and also able to switch back to stage 1 at a lower than initial switch pressure, but was unable to build up any pressure after switching. The main source of leakage was identified at the switch cylinder.

VIII. DISCUSSION & RECOMMENDATION

The results of the research are split into three different sections; the results of the detailed design, the results of the simulation and the results of the practical testing.

A. Calculation of the VMA mechanism

Calculations showed that it is possible to design a VMA mechanism for the Delft Cylinder Hand, but it is highly dependent on the used loading conditions. In case of the worst-geometry load case, a VMA mechanism design is only feasible for a double pinch grip while friction losses are excluded. For the realistic-pinch load case a VMA mechanism design is feasible for a double pinch grip when either friction or stiffness losses are included, but not with both. A single pinch grip resulted in a too high input force before switching.

It is unknown how much each of the properties (Prosthetic glove, O-rings, hydraulic hoses from the Delft Cylinder Hand) contribute to the friction. However, it is certain that the prosthetic glove is responsible for most of the stiffness when closing the hand. The stiffness played a major role in the switching pressure, therefore even when stiffness and friction losses were not taken into account, the relatively high switch pressure could have caused the inability of calculating a feasible VMA setting for some loading conditions.

Another problem of making it difficult to find proper VMA settings is because of the relatively low stiffness during pinching of an object. Stage 2 of the VMA mechanism causes any input cylinder displacement to be multiplied by the mechanical advantage of the MA cylinder. Due to the relatively low stiffness the resulting input cylinder movement after switching to stage 2 would contribute to more than half of the maximum shoulder displacement requirement. This is the reason why switching to stage 2 should only occur when all prosthetic hand fingers have reached their end position even when an object is already pinched when the prosthetic hand is closed half way. The latter shows that a design of VMA mechanism is far more difficult for an underactuated hand prosthesis than for a conventional one.

B. Simulation of the VMA mechanism

Simulation shows that the requirements are met for both load cases, while using a double finger pinch grip and excluding friction losses. Friction losses were not taken in to account in the simulation, but it is possible to give an estimation of the results. When the friction of approximately 13 N (Chapter IV) is added to the input force when pinching an object (Table V-1), it can be said that the worst-geometry load case, with an input force of 60 N, would not meet the requirements and the realistic-pinches load case, with a pinch force of 50 N, could meet the requirements. In order to improve the estimation a detailed breakdown of the friction is required and needs to be added to the simulation.

The simulation showed a detailed behaviour during the switching stage. One conduct could be observed as an immediate increase in output pressure, resulting in implausible pinching forces. Figure V.4 showed a sudden increase in the output pressure for the same input pressure immediately after switching. The simulation only looked at the static behaviour of the VMA mechanism, thus the graph only shows equilibrium situations and assumes the input pressure does not increase. In reality, it is possible that the sudden switching would cause the user to decrease the input pressure. This is not an issue as long as the output pressure remains above the return switch pressure. If the output pressure would drop below the return switch pressure, the graph shows that the VMA mechanism switches to stage 1. This is an odd case, because in order to move the piston of the switch cylinder to its initial position, the input cylinder must move in reverse. Assuming the user wants to move further, it is questionable if the switch would actually immediately switch back to stage 1. Further studies on this subject could result in some real new insights.

Another behaviour found in the simulation, is the reverse output pressure alteration during switching (indicated by an increment on Figure V.4). The reverse pressure alteration is caused by the closing of both port 1 and port 2 of the switch cylinder during the switching stage (Figure IV.3). To prevent internal leakage, there is an allowance of 1 mm switch piston motion in which both ports are closed. During this motion the testing, cylinders are cut off from the input cylinder. Any motion of the switch piston would decrease (during initial switching) or increase (during return switching) the output pressure. The effect is largest for configuration 2, as the induced motion of the MA cylinder during switching must be
captured by the testing cylinders instead of the input cylinder. The results of the analysis show that the effect is only problematic during the return switching for configuration 2. In theory the prosthetic hand could get stuck in stage 2 if the pinched object is too stiff. A possible method to solve this problem is to switch at a lower input pressure, such that the remaining fingers are not on their end position when switching back. In this situation the remaining fingers could easily capture the hydraulic volume. The solution is undesirable as it would further increase the additional input cylinder motion in stage 2 and possibly infringe the maximum input displacement requirement. A different solution would be using an entire new switching technique for the switch cylinder. At first, the effect should be studied in detail, as the chosen stiffness for object pinching in the simulation might not be realistic.

C. Practical testing of the VMA mechanism

Practical testing showed that the behaviour of the VMA mechanism switch was working as intended, since the VMA mechanism did not immediately switch back to stage 1 when switching to stage 2. The function of the MA cylinder of the VMA mechanism could not be validated as no pressure build-up after switching was observed. It is assumed that the lack of pressure build-up was caused by a leakage found in the switch cylinder. In order to validate the entire working principle of the VMA mechanism, it is advised to improve the current prototype to prevent future leakage.

Raw results shown in Appendix H also indicated a very large increase of the input force during switching. It is reasoned that the sudden increase in pinch force is caused by the relatively high stiffness of the spring cylinder. Due to the previously described close-off of both ports of the switch cylinder during switching, an increase in the input pressure is required to fully move the switch piston. If the stiffness of the switch pressure is too high, it could lead to a very high undesired input force.

The results of the research show that slight changes in the VMA mechanism attributes already result in fairly big fluctuations on the output. This can be observed by the calculation, where different load cases suggest a big difference in the VMA mechanism dimensions. In the simulation it is shown that changing the stiffness of the pinched object has big consequences. Additionally, the tuning of the springs of the switch cylinder showed great influence on the test results. More accurate results can probably be achieved when future work is done with an improved version of the calculation and simulation algorithm.

IX. Conclusion

The goal of the research is to design a VMA mechanism for the Delft Cylinder Hand. The input force when applying a 30 N pinch force should always be lower than 50±4 N, without compromising the 53±10 mm maximum shoulder displacement requirement, for any pinch grip of the prosthetic hand.

Calculations show that a VMA design is feasible for both the worst-geometry and realistic-pinches load case when friction losses are excluded or for the realistic-pinches load case when friction losses are included. Simulation confirms that the designed VMA mechanism is able to pinch an object within the requirements for the feasible loading conditions. Practical testing was too inconclusive to validate the simulation.

REFERENCES

Appendix A: Functions and Requirements

Function and requirements are defined for the design of the VMA mechanism such that it fulfils the demands of the Delft prosthetic hand (Smit 2013). Chapter A-1 shows the different functions, thus the different systems and attributes the design should possess. Chapter A-2 shows the different requirements by making these functions S.M.A.R.T.

A-1: Functions

Table A.1 shows the functions defined for the design of the VMA mechanism. The functions are based on the goal of the design: creating a variable mechanical advantage (VMA) mechanism that would move towards an object and pinch it in its first phase and in the second phase after fully closing the hand would pinch the object with a larger mechanical advantage compared to the first phase. Additional functions include possible new problems that need to be overcome. The functions are meant as guidance for the conceptual design phase of the VMA mechanism.

<table>
<thead>
<tr>
<th>Functions:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>F1. The mechanism should transmit the energy from the input to the output</td>
<td></td>
</tr>
<tr>
<td>F2. The transmission should adapt to the optimal operating conditions to optimal grasping conditions.</td>
<td></td>
</tr>
<tr>
<td>F2.1. Alter the mechanical advantage to achieve optimal input/output force ratio</td>
<td></td>
</tr>
<tr>
<td>F2.2. Alter the mechanical advantage to achieve optimal displacement</td>
<td></td>
</tr>
<tr>
<td>F3. The mechanism should fit to the input and output of the Delft prosthetic hand</td>
<td></td>
</tr>
<tr>
<td>F3.1. Should fit on a hydraulic input cylinder</td>
<td></td>
</tr>
<tr>
<td>F3.2. Should fit on a hydraulic prosthetic hand</td>
<td></td>
</tr>
<tr>
<td>F4. The switching mechanism should switch the mechanical advantage when grasping an object</td>
<td></td>
</tr>
<tr>
<td>F4.1. Immediate switching</td>
<td></td>
</tr>
<tr>
<td>F4.2. Stable behaviour (no back and forth switching)</td>
<td></td>
</tr>
<tr>
<td>F5. Friction inside the mechanism should be reduces as much as possible</td>
<td></td>
</tr>
<tr>
<td>F5.1. Lubrication/Bearings reduces friction</td>
<td></td>
</tr>
<tr>
<td>F5.2. Least amount of parts reduce friction</td>
<td></td>
</tr>
<tr>
<td>F6. All parts of the transmission must be kept in place</td>
<td></td>
</tr>
<tr>
<td>F6.1. The housing must keep all parts in place</td>
<td></td>
</tr>
<tr>
<td>F6.2. Moving parts should be supported by bearings or something alike</td>
<td></td>
</tr>
<tr>
<td>F7. The transmission should be protected from the environment</td>
<td></td>
</tr>
<tr>
<td>F7.1. Shielding to protect moving parts from debris</td>
<td></td>
</tr>
<tr>
<td>F7.2. None oxidizing materials</td>
<td></td>
</tr>
<tr>
<td>F8. The environment should be protected from malfunctions</td>
<td></td>
</tr>
<tr>
<td>F8.1. Materials that could harm skin or clothes should be avoided</td>
<td></td>
</tr>
<tr>
<td>F8.2. Sharp parts should be shielded to protect the user</td>
<td></td>
</tr>
<tr>
<td>F9. The transmission should not fail during his pronounced lifetime</td>
<td></td>
</tr>
<tr>
<td>F9.1. The transmission should endure all forces acting on it</td>
<td></td>
</tr>
<tr>
<td>F9.1.1. Incoming operating forces should be transmitted to the housing</td>
<td></td>
</tr>
<tr>
<td>F9.1.2. Outgoing grasping forces should be transmitted to the housing</td>
<td></td>
</tr>
<tr>
<td>F9.1.3. The transmission should endure the reaction forces from the housing</td>
<td></td>
</tr>
</tbody>
</table>
### A-1: Requirements

Table A.2 shows the requirements based on the functions that need to be fulfilled. There is a difference between a demand and a wish. The demand is a hard requirement, usually based on literature or calculated from the prosthetic hand settings. A wish is sometimes written as a goal or an optimal setting in the literature, or it is just a common feature amongst other prosthetic devices. While a demand needs to be fulfilled a wish represents a requirement that is good to achieve, but not necessary. Each requirement will be explained briefly as not all of them are self-explanatory.

<table>
<thead>
<tr>
<th>D/W</th>
<th>Requirements:</th>
<th>Source:</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>R1. The maximum input displacement should be 53 ± 10 [mm] when pinching an object between the thumb</td>
<td>(Taylor 1954)</td>
</tr>
<tr>
<td>W</td>
<td>R2. The maximum input displacement is desired to be 39 ± 2 [mm] when pinching an object between the thumb</td>
<td>(Smit 2010)</td>
</tr>
<tr>
<td>D</td>
<td>R3. The minimum (output) pinch force should be 30 [N] for a maximum input force of 50 ± 4 [N]</td>
<td>(Keller 1947)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Monod 1985)</td>
</tr>
<tr>
<td>W</td>
<td>R4. The minimum (output) pinch force is desired to be 30 [N] for a maximum input force of 20-30 [N]</td>
<td>(Keller 1947)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Hichert 2010)</td>
</tr>
<tr>
<td>D</td>
<td>R5. The minimum MA for stage 1 should be of the order 4 and on the order of 8 for stage 2</td>
<td>-</td>
</tr>
<tr>
<td>W</td>
<td>R6. The output pressure in which the switch activates should be of larger value than the output pressure in which the switch deactivates</td>
<td>-</td>
</tr>
<tr>
<td>W</td>
<td>R7. The required energy of the operation of the VMA mechanism should be less than 230</td>
<td>(Smit 2013)</td>
</tr>
<tr>
<td>W</td>
<td>R8. The system should not weight more than 56[g]</td>
<td>(Smit 2013)</td>
</tr>
<tr>
<td>D</td>
<td>R9. There should be no leakage</td>
<td>-</td>
</tr>
<tr>
<td>D</td>
<td>R10. Non-oxidizing materials and non-hazardous materials should be used</td>
<td>-</td>
</tr>
</tbody>
</table>
R1-R2: Taylor focused on body-powered control with shoulder movement. The maximum excursion by shoulder control is 53± 10 mm. It must be taken in to account that Taylor mentioned one certain type of should movement, as it would be possible to increase the excursion with a different type of movement. For the reason described above, it is demanded to stay within the limits for a pinch grip only, ignoring the displacement required to fully close the prosthetic hand. Doubler (1984) mentioned that improved control can be achieved by smaller motions instead of using the full range of the shoulder. No optimal excursion was mentioned, but it is still desired to achieve a lower excursion than Taylor, which would be ± 39 mm based on similar prostheses (Smit 2010)

R3-R4: Keller (1947) defined the required grasp or pinch forces for several daily tasks when operating a prosthesis. The forces were based on conventional hooks or hands that were used for that research. It is required that the daily task that needs the highest pinch force should be within the maximum input force. The maximum input force is defined by Monod as the 18% critical muscle force before fatigue would occur or as the optimal muscle force described by Hichert (2010). With the dimensions of the Delft Prosthetic hand (Smit 2013) and the input cylinder it is possible to calculate the required transmission ratio of the VMA mechanism. On a side note, it is plausible that the Delft Prosthetic Hand could perform the daily tasks as described by Keller with lower pinch forces, but this study or other recent studies have not been found.

R6: Figure D.1 shows a schematic drawing of one of the articulating fingers of the prosthetic hand including attachment of the hydraulic cylinder. The required force of 30 N is located on the tip of the distal finger. If the angles α and β are known it is possible to calculate the joint torques $M_{\text{pip}}$ and $M_{\text{mcp}}$ which in turn can be used to calculate the required pressure in the system. The calculations are shown in Appendix D.2.
Appendix B: Morphologic Chart

By using the functions from Appendix A, a morphologic chart could be created. The morphologic chart includes design principles that fulfill one or more functions as described by Table A.1.

**B-1: Design principles**

Table B.1 shows the morphologic chart ordered by function. Each function shows one or more design principles. Each design principle will be explained briefly. Unless otherwise mentioned, tubes are schematically drawn by blue lines, cylinders by grey lines, where the piston is shaded. Orange lines represent tendon based design principles. In this case the tendon itself is drawn in black while the pulleys are indicated in orange. Green lines are used to represent linkages. The angulated red lines represent springs.

<table>
<thead>
<tr>
<th>Function</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmit Energy</td>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
<td><img src="image3" alt="Diagram" /></td>
</tr>
<tr>
<td>Alter MA</td>
<td><img src="image4" alt="Diagram" /></td>
<td><img src="image5" alt="Diagram" /></td>
<td><img src="image6" alt="Diagram" /></td>
</tr>
<tr>
<td>Switch</td>
<td><img src="image7" alt="Diagram" /></td>
<td><img src="image8" alt="Diagram" /></td>
<td><img src="image9" alt="Diagram" /></td>
</tr>
<tr>
<td>Housing</td>
<td><img src="image10" alt="Diagram" /></td>
<td><img src="image11" alt="Diagram" /></td>
<td><img src="image12" alt="Diagram" /></td>
</tr>
</tbody>
</table>

Table B.1: Morphological Chart with different design principles
Fitting:
1) Integration of the VMA inside the system (which includes the input cylinder and the prosthetic hand) or something that could easily attached to the rest of the system. In the figure, the blue rectangle represents the hose filled with water, which is currently the connection between the input cylinder and the prosthetic hand. The box with the X on it represents the design of the VMA.
2) This option shows a separation of the design which then could be connected to the hose filled with water. In addition to the first option, the figure shows 2 hydraulic cylinders (in grey) which are used to attach the design to the rest of the system. The hydraulic cylinders are required to connect the design to the rest of the system, as the design has its own energy transfer system independent of that of the rest of the system.

Transmit energy:
1) In the figure the box represents the inside of the design and focusses on the energy transfer from input and output. The blue rectangle represents energy transfer by means of hydraulic pressure. Note that this is the only option when choosing for an integrated design.
2) The orange drawing represents a pulley and the energy transfer method is using a tendon.
3) The green rectangles represent stiff structures connected to pivots, thus the energy is transferred as stress through the construction.

Alter Mechanical advantage:
1) a) When using a hydraulics as energy transfer one of the options for altering the mechanical advantage would be by using pistons with different area with hydraulics in between
   b) Another possibility is having a single piston with different area inside a tube. Pressurizing one side of the piston will result in a change in the mechanical advantage
2) a) When using a tendon as energy transmission it would be possible to alter the mechanical advantage by changing the point of attachment on the pulley.
   b) it is also possible to use two pulleys of different diameter.
3) When using a mechanical structure the mechanical advantage can be altered by using pivoting bars of different length.

Switch Mechanism:
The Morphological chart only shows one option per different energy transmission principle. Appendix C, conceptual design, will further deduce the possible solutions.
1) The figure shows a combined hydraulic cylinder controlling the switch mechanism as well as the mechanical advantage of the system. The cylinder has 2 inputs and 1 output, the pressure inside the cylinder and the return spring determine which input is opened. The input that is initially opened results in a lower mechanical advantage on the output compared to the 2nd input.
2) By switching the cable between two different pulleys the output can be altered. In the figure the output is initially controlled by the first pulley. When the force on the output increases it activates the derailleur therefore changing the cable towards the second pulley. The second pulley could have a different diameter compared to the first one, thus therefore changing the mechanical advantage of the system.
3) In this figure there is a bar connected to the input and output, which initially rotates around pivot 1. When the resistance on the movement of the output is increased (the pressure of the
hydraulics in the prosthetic hand increases), further rotation of the bar at the input will force the fulcrum attached to the return spring to move upwards. Due to this motion the linkage is actually rotating around pivot 2, therefore the mechanical advantage has been changed.

**Housing:**
1) The first figure shows a photo from an actual wrist prosthesis. The wrist prosthesis could be attached to the hand prosthesis for another degree of freedom of the hand (although passively). This option suggests the VMA design to be a part of the wrist prosthesis.
2) This options shows the VMA design to have a separate housing behind the hand prosthesis and, if present, the wrist prosthesis. It requires the design to be connected to the prosthetic arm.
3) The prosthetic hand on the figure is the hydraulic hand used. It might be possible to include the VMA device as a part of the prosthetic hand.

**B-2: Chosen design principles**

Based on the requirements from Table A.2 one can determine probable combinations of the design principles to come up with different concepts. Table B.2 shows the chosen design principles in green. The decision will be elaborated briefly.

<table>
<thead>
<tr>
<th>Function</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fitting</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>Transmit Energy</td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>Alter MA</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
</tr>
<tr>
<td>Switch</td>
<td><img src="image10.png" alt="Image" /></td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
</tr>
<tr>
<td>Housing</td>
<td><img src="image13.png" alt="Image" /></td>
<td><img src="image14.png" alt="Image" /></td>
<td><img src="image15.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Table B.2: Morphological Chart with optimal solutions based on requirements.
Fitting:
Integration of the VMA mechanism has the advantage of requiring fewer parts, therefore decreasing the total mass and risk of failure. A separate system that can easily be attached to a prosthetic hand and body powered device would be more useful when designing the mechanism for multiple prosthetic devices. This is, however, at the moment not the case, thus the first solution should fulfill the fitting function perfectly.

Transmit energy:
Even though the prosthetic hand and the body powered device are operated by hydraulics it is not necessary to design the VMA mechanism with a hydraulic medium. There are 2 reasons to choose for hydraulics as energy transmission.
- For the same reason as with the fitting choice, using the same medium as the prosthetic hand requires less parts which would results in a lower risk of failure.
- It is required to have a transmission ratio around 1:4-1:8. This would result in quite large part for the mechanical advantage. (e.g. if the a linkage around a pivot needs to have a minimum length of 20 mm, the resulting mechanical advantage linkage would need to be 100 mm). In hydraulics the relative large transmission could be handled more easily as a piston with a diameter of 20 mm would require a second piston with a diameter of only 45 mm.

Alter Mechanical Advantage:
Since the decision is made to go with a hydraulic energy transmitting system, only 2 possible solutions for altering the mechanical advantage remain. Both solutions are very similar and even usable together in the same system. The focus lies on using solution 1b. The reasoning is the amount of space required for the conceptual design. In Appendix A it can be seen that a minimum displacement of 40 mm is required. This would result more or less in the same displacement for the pistons used in the VMA mechanism. By using one piston that could a far distance inside a tube, it would safe on the amount of materials used compared to two large cylinders moving in one end and the other.

Switch mechanism:
Table B.2 shows one example of a switching mechanism for each energy transmission method. In reality there are far more examples to achieve a switching mechanism per energy transmission method but are not shown in the morphological chart. The decision is made to use a hydraulic energy transmitting system, therefore a hydraulic switching mechanism will be used. To be clear, this is not necessary the mechanism as shown in Table B.2. Appendix C goes deeper in to the selection of the switch mechanism for different concepts.

Housing:
By taken the MA requirements in to consideration, it would turn out that the VMA mechanism could result to be quite large. The space inside a prosthetic wrist (solution 1) or the space left over in the prosthetic hand (solution 3) is too small to be considered for the VMA mechanism. For that reason solution 2, having a separate housing behind the hand prosthesis is the optimal choice. It must be noted that the housing is not worked out in this research, as the prototype serves as a proof of concept, but for future designs it is recommended to use this solution.
Appendix C: Conceptual Design

In appendix B the optimal solutions of the morphological chart were decided to be an integrated design of the VMA mechanism based on hydraulic energy transmission, to be fitted behind the hand prosthesis. The altering of the mechanical advantage and the switching mechanism are both based on a system using hydraulic energy transmission. There are still numerous possibilities to design concepts based on these conceptual solutions.

C-1: Concepts

The design of the concepts described in this section all fulfill the conceptual solutions chosen in Appendix B. Each concept uses hydraulics as energy transmission, has the same input from the ‘input cylinder from actuation method’ and has the same output to the hydraulic prosthetic hand. The combination between switch mechanism and altering of the mechanical advantage is different for each concept. The concepts are shown in Figure Table C.1. The working principle of the different concepts will be explained briefly. From top left to bottom right the concepts will be named (1,1) to (3,2).
<table>
<thead>
<tr>
<th>External switch</th>
<th>Switch based on input pressure</th>
<th>Switch based on output pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-way port on switch</td>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
</tr>
<tr>
<td>Stage 1</td>
<td><img src="image3" alt="Diagram" /></td>
<td><img src="image4" alt="Diagram" /></td>
</tr>
<tr>
<td>Stage 2</td>
<td><img src="image5" alt="Diagram" /></td>
<td><img src="image6" alt="Diagram" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Internal switch</th>
<th>Switch based on input pressure</th>
<th>Switch based on output pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-way port on switch + spring on MA cylinder</td>
<td><img src="image7" alt="Diagram" /></td>
<td><img src="image8" alt="Diagram" /></td>
</tr>
<tr>
<td>Stage 1</td>
<td><img src="image9" alt="Diagram" /></td>
<td><img src="image10" alt="Diagram" /></td>
</tr>
<tr>
<td>Stage 2</td>
<td><img src="image11" alt="Diagram" /></td>
<td><img src="image12" alt="Diagram" /></td>
</tr>
</tbody>
</table>

| 3-way port on switch + spring on MA cylinder | ![Diagram](image13) | ![Diagram](image14) |
| Stage 1 | ![Diagram](image15) | ![Diagram](image16) |
| Stage 2 | ![Diagram](image17) | ![Diagram](image18) |

Table C.1: Different concepts based on chosen conceptual solution, from top left to bottom right the concepts are named (1,1) to (3,2)
**Concept 1,1:**
This concept has a separated switch from the rest of the system. This means that the output is either connected directly to the input through the switch or through the MA cylinder and the switch. The switch has 1 input and 2 outputs. As long as the input pressure is low, the piston within the switch will not move, thus input I1 will be connected to output O1. When the pressure increases to medium, output O1 will be cut off and output O2 will open. As a result, the output pressure $P_{out}$ will be high. The switch is based on the input pressure $P_{in}$, therefore the system will switch back from stage 2 to stage 1 if the input pressure drops below medium (which is the initial pressure to switch from stage 1 to stage 2).

**Concept 1,2:**
The same components are used for concept 1,2 as for concept 1,1. The configuration of the components is different, such that the switch is now based on the output pressure. The input I1 is initially connected to output O1. When the pressure increases to medium, output O1 will be cut off and output O2 will open. The system will switch back from stage 2 to stage 1 on a lower pressure than the pressure required to switch the system from stage 1 to stage 2. This pressure difference is dependent on the geometry of the switch and the transmission ratio of the MA cylinder.

**Concept 2,1:**
This concept is familiar to concept 1,1 with two changes. Instead of a 3-way port, the switch has only 1 input and 1 output and is there either open or closed. The input pressure is directly coupled to the MA cylinder. For that reason the MA cylinder has a return spring to prevent the piston from moving while the switch is open. The pretension of the spring in the MA cylinder must result in the same pressure on the system as the spring in the switch does. At medium pressure the switch closes and the MA cylinder starts moving resulting in a high pressure on the output. Same as for concept 1,1; the system will switch back from stage 2 to stage 1 if the input pressure drops below medium.

**Concept 2,2:**
The same components are used for concept 1,2 as for concept 1,1. The configuration of the components is different, such that the switch is now based on the output pressure. The switching from stage 1 to stage 2 will be equal of that of concept 1,2 as the piston of the MA cylinder will only move until the pretension of the spring has been overcome. In contrary to concept 1,2, there will be no pressure build up in the MA cylinder due to the spring’s force counter reaction. This means that even though the switching is based on the output pressure, the system will switch back from stage 2 to stage 1 at the same pressure as it initially switched from stage 1 to stage 2. It can be said that even though the configuration of concept 2,1 and 2,2 are different, the end result is the same.

**Concept 3,1:**
This concept has the switch integrated in to the MA cylinder. The cylinder performs both the mechanical advantage alteration as well as the switching mechanism. It is very similar to the two-phase hydraulic brake system[x]. At first the pressure is low and the input is directly connected to the output. The piston starts moving as soon as the pretension of the spring has been overcome, which will be at medium input pressure. Initially the output pressure will be at medium level as well, since the return spring applies a counter force to the piston. As the pressure increases the output pressure will be higher as the input...
pressure. Returning from stage 2 to stage 1 will be at the same pressure (just below medium) as the pressure it took to initially switch from stage 1 to stage 2. Notice that the end result of the system is identical to that of concept 2,1 and 2,2.

**Concept 3,2:**
This is a hypothetical concept that has an integrated makes use of an integrated switch, while still being dependent on the output pressure. The system should switch at medium pressure, resulting the piston to move. The output pressure has 2 chambers, $P_{ma}$, controlling the output pressure of the system and $P_{ma}$ controlling the switch of the system. The problem is that the volume of the hydraulic representing $P_{ma}$ must stay the same while the piston is moving. However, this is only possible when the areas of the moving piston heads are the same. If those areas are the same, then the pressure $P_{ma}$ result in equilibrium between moving the piston to the right or to the left. Therefore, the drawing of the concept is invalid. There has not been found an alternative solution that complies with the stated concept attributes.

**C-2: Tradeoff:**

Table C.2 shows a tradeoff between the different concepts that led to the final concept. All of the concepts already met the defined functions of Appendix A and could all theoretically meet the requirements. The trade-off criteria are based on the potential to meet all requirements, complexity of the design for fabrication and the risk of failure of the design. Each concept is judged by the criteria with a color mark. The green tile indicates a satisfactory result of the concept towards the criteria, while the red tile indicates unwanted effects. The criteria are valued by an importance factor showing which criteria considered to be more valuable. In the end the table can be used to decide which concept has most potential in succeeding the goal of the research.

<table>
<thead>
<tr>
<th>Trade-off Criteria</th>
<th>Requirements</th>
<th>Failure</th>
<th>Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Switching back range</td>
<td>Output/ Input Force</td>
<td>Input Displacement</td>
</tr>
<tr>
<td>Importance</td>
<td>2x</td>
<td>3x</td>
<td>3x</td>
</tr>
<tr>
<td>Concepts</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3.2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Green          | Good          |
| Yellow         | Fair          |
| Red           | Poor          |
Switching back range:
The switching back range is the difference between the pressure it takes for the VMA to switch from one phase to another and the pressure at which they are switched back again. A larger switching back range is favorable as described in the requirements section of Appendix A. Only concepts 1.2 and 3.2 are designed such that the switching back pressure is lower than the initial switch pressure. The other concepts switch back at the same initial pressure as they are either based on the input pressure or, with concept 2.2, have a reaction spring in the MA cylinder enforcing equal switching back pressure. The switching back range is not an essential trade-off criteria, but still important for the research.

Output/Input Force:
The concepts are criticized on the ratio between the in- and output force of the system. This is a major criterion and has therefore the highest importance factor. Table C.2 shows that the concepts using the 3-way port without additional spring score the best on this criteria, followed by the internal switch concepts. Figure D.10 shows graphs of a simulated in and output force done with MATLAB. After switching from phase 1 to phase 2, the output force of concepts 1.1 and 1.2 is much lower compared to the others. The reason concepts 2.1 and 2.2 score lower than 3.1 and 3.2 even though the graphs look similar is because of the many more O-rings required in the design of the concept. As mentioned earlier, friction was omitted in the simulation, but will be present in the actual situation. More O-rings results in more friction and a lower output/input force ratio, hence the lower score.

Input Displacement:
Equally important is the input displacement. Switching from a high to a low transmission ratio, results in a larger input displacement for the same output displacement. All concepts switch at the same moment (namely, the pressure required to fully close the hand). When using a VMA mechanism, the input displacement will always increase, but by choosing a lower mechanical advantage for the input cylinder compared to the original hand the input displacement could still be rated fair for all concepts. The trade-off is having a lower Output/Input force ratio as a result.

Size/Mass:
Ultimately the VMA mechanism must be fit between the body and the prosthetic hand as being a part of the prosthesis. The concepts are rated on their estimated size and mass. From Table C.1 it is easy to observe that the concepts with integrated designs have an advantageous over the ones that have an external switch. The criterion has a low importance, as it is less relevant to the current research.
Ultimately the VMA mechanism should be fit in the prosthesis and it is therefore important to design a light and small mechanism, but at this stage it is more important to achieve more important criteria such as the force ratio.

Unwanted movements:
Concepts that are less likely to fail are more desirable. With good safety cautions it is possible to design a VMA mechanism based on any of the concepts. Yet, there is always a risk a system can fail, thus the criteria receives an importance factor of 2. Unwanted movements is the summarization of all (piston) movements that occur that should not have moved, moved too little or too much, or got stuck when they should have moved. Concepts 3.1 and 3.2 have a low risk in unwanted movements, mainly because
the switch and mechanical advantage are controlled by the same cylinder. The only thing that could go wrong is when the piston gets stuck. Concepts 2.1 and 2.2 have are similar to concept 3.1 and 3.2 in Output / Input force behavior, but have 2 separated cylinders for the switching and mechanical advantage. In theory the 2 springs are designed such that the MA Cylinder starts moving as soon as the switched closed off the input for phase 1. A spring stiffness mismatch however could cause unwanted movement of the MA cylinder piston. Concept 1.1 cannot move until a switch occurs and has therefore not the same problem as concept 2.1 and 2.2. However, since the MA Cylinder is not constraint, undesired movements could occur (due to leakage for example). Concept 1.2 has the same problem as concept 1.1 and on top of that faces a geometrical mismatch due to its switching back range. This can be visualized as the piston of the MA cylinder to be not in the same position when the piston of the input cylinder moved back to a certain position after moving forward. The geometrical mismatch is caused by unwanted displacement of the different hydraulic volumes in the system. Additional measurements need to be taken in to account to prevent this problem.

**Detailed design:**
The criteria for complexity of the detailed design marks the difficulty of designing a working prototype starting from the prototype. It is an indication on how precise the detailed design must be carried out. A higher detailed design complexity is less desirable as it might be difficult to change or add certain features of the design in the future. The importance is not great and is therefore chosen to have a factor of 1. Concepts 2.1 and 2.2 have the most flexibility in their design because of the separate cylinders and a dependency of the MA cylinder due to the spring constraint. Concept 3.2 is very complex, to the point that thus far no viable detailed design has been thought of.

**Fabrication/Assembly:**
Same as for the detailed design criteria the fabrication and assembly complexity should be considered. A high complexity could possibly lead to a higher risk of failure of the system if the fabrication and/or assembly are not performed thoroughly. It has an importance factor of 1. Each concept have their own disadvantage which are likely to be of equal complexity with the exception of concept 3.2, which is more complex to fabricate. The complexity for the other concepts are; precise input/output port locations for the switch cylinder for concepts 1.1 and 1.2, the additional spring assembly for concepts 2.1 and 2.2 and lastly the fabrication of a combined cylinder for concept 3.1.

**C-3: Decision:**

Table C.3 shows the trade-off score for each concept. The score is determined by assigning a value of 0, 1 and 2 for the red, yellow and green tiles respectively and then multiplying by the importance factor. Concept 1.2 has the highest trade-off score and is a really good candidate for the detailed design. It is important to be careful of unwanted movements, but this could be resolved with an additional switch. Concept 3.1 has the second highest trade-off score. It is essentially the same system as used for the hydraulic brake found in the literature [citation needed]. One important problem in the detailed design phase might be the much larger movement in the second phase of the VMA mechanism as compared to the hydraulic brake. In contrary to the hydraulic brake, the objects as well as the prosthetic hand have much lower stiffness resulting in a larger movement. This might cause a lot of difficulty in placing such
spring inside the mechanism. Another good score is giving to concept 1.1. This concept shows a lot of similarities to concept 1.2, but due to its switching back range concept 1.2 is the winner between these 2. The other concepts have significant lower scores and concept 3.2 is even unviable at this stage because of the complexity.

<table>
<thead>
<tr>
<th>Concepts</th>
<th>Trade-off score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>13</td>
</tr>
<tr>
<td>1.2</td>
<td>15</td>
</tr>
<tr>
<td>2.1</td>
<td>8</td>
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<tr>
<td>2.2</td>
<td>8</td>
</tr>
<tr>
<td>3.1</td>
<td>14</td>
</tr>
<tr>
<td>3.2</td>
<td>11</td>
</tr>
</tbody>
</table>

Table C.3: Trade-off score.

Literature has found no other device that uses concept 1.2 for their application. The effect of the immediate increase in output force on controlling a prosthetic device is unknown. Concept 2.2 on the other hand is comparable to other devices that use a hydraulic VMA mechanism. It would be interesting to make a detailed design for both concept 1.2 and concept 2.2 in order to test the possible effect of the immediate increase in output force. Thus, concept 1.2 is chosen to be the most promising design and the design of concept 2.2 is used as reference.
Appendix D: Detailed Design Calculations

A detailed design is given for each part of the VMA mechanism and the input cylinder of the system. Appropriate dimensions for the piston area, cylinder lengths and return spring stiffness’s are calculated for each part based on MATLAB calculations and simulations. The foundation of the MATLAB calculations are the defined requirements from Appendix A and the measured prosthetic hand output forces from the Delft Cylinder Hand (Smit 2013). The values and calculations are used to define the required dimension of the each part of the VMA mechanism including the input cylinder. Elaborations of the obtained values and calculations are made where necessary.

D-1: List of obtained variables and constants

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount of fingers used for pinching</td>
<td>$N$</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Pinch force</td>
<td>$F_{\text{pinch}}$</td>
<td>30</td>
<td>N</td>
</tr>
<tr>
<td>Input force</td>
<td>$F_{\text{input}}$</td>
<td>25</td>
<td>N</td>
</tr>
<tr>
<td>Input displacement when pinching</td>
<td>$x_{\text{input}}$</td>
<td>39</td>
<td>mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount of fingers used for pinching</td>
<td>$N$</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Pinch force</td>
<td>$F_{\text{pinch}}$</td>
<td>30</td>
<td>N</td>
</tr>
<tr>
<td>Input force</td>
<td>$F_{\text{input}}$</td>
<td>50</td>
<td>N</td>
</tr>
<tr>
<td>Input displacement when pinching</td>
<td>$x_{\text{input}}$</td>
<td>53</td>
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</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fully closed PIP joint angle</td>
<td>$\alpha_f$</td>
<td>0.5π</td>
<td>rad</td>
</tr>
<tr>
<td>Fully closed MCP joint angle</td>
<td>$\beta_f$</td>
<td>0.5π</td>
<td>rad</td>
</tr>
<tr>
<td>Ratio between Grasp and Pinch displacement</td>
<td>$\text{Grasp}$</td>
<td>1.38</td>
<td>-</td>
</tr>
<tr>
<td>Input displacement when grasping</td>
<td>$x_{\text{input,B}}$</td>
<td>$\text{Grasp} \cdot x_{\text{input}}$</td>
<td>mm</td>
</tr>
<tr>
<td>Lower phalanx length</td>
<td>$l_{\text{mcp}}$</td>
<td>30</td>
<td>mm</td>
</tr>
<tr>
<td>Upper phalanx length</td>
<td>$l_{\text{pip}}$</td>
<td>37</td>
<td>mm</td>
</tr>
<tr>
<td>Diameter lower phalanx cylinder</td>
<td>$e_{\text{comp,d}}$</td>
<td>8</td>
<td>mm</td>
</tr>
<tr>
<td>Diameter upper phalanx cylinder</td>
<td>$c_{pip,d}$</td>
<td>7</td>
<td>mm</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>-------------</td>
<td>---</td>
<td>----</td>
</tr>
<tr>
<td>Initial arm of the lower phalanx cylinder</td>
<td>$a_{cmp,i}$</td>
<td>7</td>
<td>mm</td>
</tr>
<tr>
<td>Initial arm of the upper phalanx cylinder</td>
<td>$a_{pip,i}$</td>
<td>5</td>
<td>mm</td>
</tr>
</tbody>
</table>

**Table D.4: Initial input cylinder geometry**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial outer diameter</td>
<td>$c_{m,d}$</td>
<td>10</td>
<td>mm</td>
</tr>
<tr>
<td>Initial inner diameter</td>
<td>$c_{mi,d}$</td>
<td>3</td>
<td>mm</td>
</tr>
</tbody>
</table>

**Table D.5: Geometry worst case load case used for determining VMA properties**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>PIP joint angle when pinching object</td>
<td>$\alpha$</td>
<td>0</td>
<td>rad</td>
</tr>
<tr>
<td>MCP joint angle when pinching object</td>
<td>$\beta$</td>
<td>0</td>
<td>rad</td>
</tr>
</tbody>
</table>

**Table D.6: Measurements from prosthetic hand actuation (see section D-2)**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured input force* for VMA switching</td>
<td>$F_m$</td>
<td>40</td>
<td>N</td>
</tr>
<tr>
<td>Minimum force for displacement (static friction)</td>
<td>$F_{m,x}$</td>
<td>10</td>
<td>N</td>
</tr>
<tr>
<td>Input displacement for moving to 0 mm object*</td>
<td>$x_m$</td>
<td>37</td>
<td>mm</td>
</tr>
<tr>
<td>Input displacement for pinching stiff object*</td>
<td>$x_{m2}$</td>
<td>7.5</td>
<td>mm</td>
</tr>
<tr>
<td>Pinch force stiffness reduction (Geometry worst case)</td>
<td>$c_{glove}$</td>
<td>0</td>
<td>%</td>
</tr>
<tr>
<td>Pinch force stiffness reduction (Realistic pinch case)</td>
<td>$c_{glove}$</td>
<td>50</td>
<td>%</td>
</tr>
</tbody>
</table>

*This counts only for the currently used input cylinder
**D-2: Delft Cylinder Hand attributes**

The section includes the theoretical calculation of the prosthetic hand, which served as a basis for determining the VMA requirements. It also includes measurements and the interpretation of these measurements. The load cases described in section 4.3 are based on the theoretical and measured attributes.

**D-2.1: Prosthetic hand geometry**

Figure A.1 shows a schematic drawing of a single finger of the Delft Cylinder Hand on the left and the currently used input cylinder on the right. The ratio between the pinch force $F_{\text{pinch}}$ and the system pressure $P$ is shown by the formulas below. Using the maximum input force requirement the minimum mechanical advantage for stage 2 of the VMA mechanism is calculated. Table D.7 shows the values for a fully stretched finger (largest momentum). Additional required forces, due to return springs, friction and elasticity are omitted in this calculation.

$$a_{\text{mcp}} = a_{\text{mcp},j} (\sin(\alpha) + \cos(\alpha)) \quad , \quad a_{\text{pip}} = a_{\text{pip},j} (\sin(\beta) + \cos(\beta))$$

$$M_{\text{mcp}} = F_{\text{pinch}} (l_{\text{mcp}} + l_{\text{pip}}) \quad , \quad M_{\text{pip}} = F_{\text{pinch}} \cdot l_{\text{pip}}$$

$$P_\text{out} = P_{\text{mcp}} = \frac{M_{\text{mcp}}}{N \cdot a_{\text{mcp}} \cdot 0.25 \pi \cdot c_{\text{mcp},d}^2} = P_{\text{pip}} = \frac{M_{\text{pip}}}{N \cdot a_{\text{pip}} \cdot 0.25 \pi \cdot c_{\text{pip},d}^2}$$
With, Table D.7: Delft Prosthetic hand dimensions and required pressure

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount of fingers used for pinching</td>
<td>(N)</td>
<td>1,2</td>
<td>-</td>
</tr>
<tr>
<td>Pinch force</td>
<td>(F_{\text{pinch}})</td>
<td>30</td>
<td>N</td>
</tr>
<tr>
<td>Input force</td>
<td>(F_{\text{input}})</td>
<td>50</td>
<td>N</td>
</tr>
<tr>
<td>Initial arm of the upper phalanx cylinder</td>
<td>(a_{\text{pip,i}})</td>
<td>5</td>
<td>mm</td>
</tr>
<tr>
<td>Upper phalanx length</td>
<td>(l_{\text{pip}})</td>
<td>37</td>
<td>mm</td>
</tr>
<tr>
<td>Diameter lower phalanx cylinder</td>
<td>(c_{\text{comp,d}})</td>
<td>8</td>
<td>mm</td>
</tr>
<tr>
<td>Diameter upper phalanx cylinder</td>
<td>(c_{\text{pip,d}})</td>
<td>7</td>
<td>mm</td>
</tr>
<tr>
<td>Initial outer diameter</td>
<td>(c_{\text{m,d}})</td>
<td>10</td>
<td>mm</td>
</tr>
<tr>
<td>Initial inner diameter</td>
<td>(c_{\text{mi,d}})</td>
<td>3</td>
<td>mm</td>
</tr>
<tr>
<td>Output pressure for given pinch force*</td>
<td>(P_{\text{out}} (N = 1)(\alpha = 0))</td>
<td>5.74</td>
<td>MPa</td>
</tr>
<tr>
<td>Output pressure for given pinch force*</td>
<td>(P_{\text{out}} (N = 2)(\alpha = 0))</td>
<td>2.87</td>
<td>MPa</td>
</tr>
<tr>
<td>Ratio between pressure and pinch force*</td>
<td>(\varphi(N = 1)(\alpha = 0))</td>
<td>5.23</td>
<td>N/MPa</td>
</tr>
<tr>
<td>Ratio between pressure and pinch force*</td>
<td>(\varphi(N = 2)(\alpha = 0))</td>
<td>10.45</td>
<td>N/MPa</td>
</tr>
</tbody>
</table>

*only valid if \(\alpha=0\), excluding external forces induced by springs

Rough calculation of the required transmission ratio of the VMA mechanism (no stiffness and friction)

\[
P_{\text{in}} = \frac{F_{\text{input}}}{0.25\pi \cdot (c_{\text{m,d}}^2 - c_{\text{mi,d}}^2)^{**}}
\]

\[
VMA_{\text{min}} = \frac{P_{\text{out}}}{P_{\text{in}}}
\]

Table D.8: Values of the transmission ratio for pinching with 1 or 2 fingers

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input pressure for given input force</td>
<td>(P_{\text{in}})</td>
<td>0.70</td>
<td>MPa</td>
</tr>
<tr>
<td>Minimum required transmission for phase 2**</td>
<td>(VMA_{\text{min}} (N = 1))</td>
<td>8.2</td>
<td>MPa</td>
</tr>
<tr>
<td>Minimum required transmission for phase 2**</td>
<td>(VMA_{\text{min}} (N = 2))</td>
<td>4.1</td>
<td>MPa</td>
</tr>
</tbody>
</table>

**This counts only for the currently used input cylinder

**D-2.2: Prosthetic hand measurements**

Table D.6 contains the values of attributes of the Delft Cylinder Hand. The values are based on measurements shown by Figure D.2 to D.5. The measurements were done including a prosthetic glove. As a result the required input force drastically increases as can be observed by Figure D.2. [zondag] update figuur maybe
Figure D.2 shows that the maximum input displacement for pinching is 37 mm for the currently used input cylinder. The maximum input displacement when grasping is 51 mm when using the same cylinder. This value is based on the calculation of the fully closed PIP and MCP joints of all the hand cylinders, as shown by the following equation.

Calculation of the required volume to fully close the hand:

\[
c_{\text{mcp,s}} = a_{\text{mcp,s}} \left(1 - (\cos(\alpha) - \sin(\alpha))\right)
\]

\[
c_{\text{pip,s}} = a_{\text{pip,s}} \left(1 - (\cos(\beta) - \sin(\beta))\right)
\]

\[
V_B = 3(c_{\text{mcp,s}} \cdot 0.25\pi \cdot c_{\text{mcp,d}}^2) + 4(c_{\text{pip,s}} \cdot 0.25\pi \cdot c_{\text{pip,d}}^2)
\]

\[
V_A = \frac{V_B}{\text{Grasp}}
\]

\[
x_{\text{input,B}} = \frac{V_B}{0.25\pi \cdot (c_{m,d}^2 - c_{m_i,d}^2)}
\]
Table D.9: Total volume for pinching and grasping

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stroke lower phalanx cylinder</td>
<td>$c_{mcp,t}$</td>
<td>14</td>
<td>mm</td>
</tr>
<tr>
<td>Stroke upper phalanx cylinder</td>
<td>$c_{pip,t}$</td>
<td>10</td>
<td>mm</td>
</tr>
<tr>
<td>Total volume displacement when grasping</td>
<td>$V_b$</td>
<td>3651</td>
<td>mm$^3$</td>
</tr>
<tr>
<td>Total volume displacement when pinching</td>
<td>$V_a$</td>
<td>2645</td>
<td>mm$^3$</td>
</tr>
<tr>
<td>Amount of upper and lower phalanx cylinders</td>
<td>-</td>
<td>3, 4</td>
<td>-</td>
</tr>
</tbody>
</table>

The calculation can be verified by comparing Figures D.2 to D.5. Figure D.3 shows a schematic drawing of the 4 actuated fingers of the prosthetic hand as a link pivot combination. The stationary stops O,A,B and C indicate the positions one or more of the fingers could be in. O is the starting position, A is pinching an object of +/- 10 mm, B is pinching an object of 0 mm and C is fully closing the hand in a grasp motion.

![Figure D.3: Schematic drawing of a link and pivot combination representing the fingers of the Delft prosthetic hand.](image)

The 4 following statements can be made:

1) All fingers closed to B requires 37 mm input displacement (Figure D.2)
2) Finger 1 closed to A and others closed to C required 38-42 mm input displacement (Figure D.4)
3) Finger 1,2 closed to A and the others closed to C required 30-32 mm input displacement (Figure D.5)
4) All fingers closed to C requires 51 mm input displacement (theory to be verified)

If statement 4 is true then it takes 14 mm to move all fingers from B to C and approximately 10 mm to move 1 finger from A to C. One finger holds 30% of the total volume (the pinky is smaller), thus it takes 33.3 mm to move all fingers from A to C. Consequently, it would take 18mm to move all fingers from O to A. So if statement 4 is true, then statement 2 must be 18mm + 0.4 * 33 = 41.3 and statement 3 must be 18mm + 0.4*33.3 = 31.3. Both are correct, thus statement 4 is true.
Figure D.4: Different stages of a single finger pinch with the Delft prosthetic hand.
It is important to switch to stage 2 of the VMA mechanism after all the remaining finger of the hand are fully closed. The measured input actuation force to move all fingers from O to B is 48 N (Figure D.2). This force is lower than the required force of approximately 70 Newton for a single pinch and ... Newton for a double pinch to move all fingers to point C as indicated by the letter F in Figure D.4 and D.5. Yet, the VMA switching force used in Table D.6 is lower than both of the measured values. The reason a lower switch force is because of a tipping point in stiffness around 40 N shown in Figure D.2. The graph before this point shows a stiffness of 1.3 N/mm and after this point the stiffness is 4.6 N/mm. This means that for each millimeter the switching from phase 1 to phase 2 would be postponed, that the input actuation force would increase with 4.6 Newton, while the input force decrease with 40/35 N due to the necessity of a lower mechanical advantage difference. Therefore it would be efficient to choose the switching point at 40 N for the current input cylinder (which corresponds to 0.56 MPa input pressure for any input cylinder).

![Graphs]  
*Figure D.5: Different stages of a double finger pinch with the Delft prosthetic hand*
The reasoning of choosing this switching point is also explained by Figure D.5. It shows a steep incline and a gradual incline. The steep incline benefits from early switching, while the gradual incline does not. The behavior can be explained by the limited input displacement, meaning that the initial MA must be increased if the maximum input displacement is reached.

Figure D.6: Illustration of the dependency of the switch point between phase 1 and 2 for a VMA mechanism (mechanical advantage difference of 2). Early switching is better for a steep inclination, while it is better to wait before switching for a gradual inclination.

Figure D.7 shown below shows the relation between the input and the output force when pinching an object. The ratios are the different in stiffness of the graphs D.4 and D.6 in between point ‘D’ and ‘E’ when closing the hand, and point ‘F’ and ‘G’ when pinching an object. With the currently known dimensions of the input cylinder, the ratios be converted to pressure to pinch force ratios as shown in Table D.10. The ratios represent a good comparison between the ratios determined from geometry calculations in Table D.7. The ratios are lower than the calculated ones because the PIP and MCP joint angles are not equal to zero. The result forms the basis of the realistic pinch load case as described by section D.3.
\[
\phi_{\text{measure}} = \frac{0.25 \pi \left( c_{m,d}^2 - c_{m_i,d}^2 \right)}{n} \\
P_{\text{out \ (measure)}} = \frac{F_{\text{pinch}}}{\phi_{\text{measure}}}
\]

Table D.10: Ratio and required output pressure from Delft Cylinder Hand measurements (Figure D.7)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount of fingers used for pinching</td>
<td>(N)</td>
<td>1,2</td>
<td>-</td>
</tr>
<tr>
<td>Input force to pinch force ratio while pinching*</td>
<td>(n(N=1))</td>
<td>9.1</td>
<td>N/N</td>
</tr>
<tr>
<td>Input force to pinch force ratio while pinching*</td>
<td>(n(N=2))</td>
<td>4.6</td>
<td>N/N</td>
</tr>
<tr>
<td>Ratio between pressure and pinch force</td>
<td>(\phi(N=1))</td>
<td>7.9</td>
<td>N/MPa</td>
</tr>
<tr>
<td>Ratio between pressure and pinch force</td>
<td>(\phi(N=2))</td>
<td>15.7</td>
<td>N/MPa</td>
</tr>
<tr>
<td>Output pressure for required pinch force</td>
<td>(P_{\text{out}}(N=1))</td>
<td>3.8</td>
<td>MPa</td>
</tr>
<tr>
<td>Output pressure for required pinch force</td>
<td>(P_{\text{out}}(N=2))</td>
<td>1.9</td>
<td>MPa</td>
</tr>
</tbody>
</table>

*) only valid for the initial input cylinder

Figure D.7: Graph of the relation between the input and output force when pinching an object. The graph indicates the ratio for a single and double finger pinch.
**D-3: Load cases**

The prosthetic hand behaves different based on the loading conditions. For example, pinching a small object could require a different input force compared to pinching a large object with the same output force. This has to do with the way morphological hand works. Figure D.7 shows that the arm of the prosthetic hand changes as the fingers are closing. For different sized objects a different transmission between input and output is encountered. In addition, the reaction force due to stiffness of the prosthetic glove plays a role. It requires force to fully close the hand as indicated in the previous section. Therefore smaller objects require more input force to be pinched with equal force compared to larger objects. The load cases that are considered are the geometry worst case scenario and the realistic pinch scenario. Each load case can either be included or excluded from stiffness and friction losses load cases.

![Diagram](image)

*Figure D.8: Example of a morphological hand in which the arm becomes smaller as the fingers close*

**D-3.1: Geometry worst case scenario**

The worst case geometry scenario would be pinching a very large object such that all fingers are fully stretched (α=β=0). Table D.7 showed the calculation of the input and output force ratio for the Delft Cylinder Hand and the currently used input cylinder. It also showed the minimum MA for stage 2 of the VMA mechanism. The calculation is too simplified as the input displacement has not been accounted for. Figure D.6 shows that the MA of stage 1 would increase if when a VMA mechanism is included. In the specific case of pinching a very large object, the input displacement would be small, but the Prosthetic hand must be able to pinch both a very large and very small object with the same VMA settings. Therefore in the calculation of the VMA mechanism for the geometry worst case scenario, both the stretched fingers and fully closed fingers should be reckoned with. On a side note, the maximum input displacement requirement applies to a pinch motion and not a grasp motion (Pinch finger to point B in Figure D.3), which has a volume difference of 1.39 times as shown by Table D.9.
D-3.2: Realistic pinch scenario

The realistic pinch load case is based on measured of the Delft Cylinder Hand as described in the previous section. The measurements were done for pinching an object of a size of 10 mm. The PIP and MCP angles are unknown in the situation, thus the required transmission ratio cannot be calculated as in done for Table D.7. Instead the relationship between the input and output force has been measured in Figure D.7 and the results can be found in Table D.10. The load case also takes in to account the need to fully close the hand before pinching, the same for the worst scenario load case. The geometry of the prosthetic hand results in a more profitable calculation for the VMA mechanism. The disadvantage is the need to stretch the prosthetic glove before pinching occurs, as the fingers must first move towards a smaller object. Based on the stiffness of the prosthetic glove this has a negative influence on the required MA of the VMA mechanism.

D-3.3: Stiffness and friction:

As can be seen by Figure D.2, the further the hand closes, the larger the combined force of stiffness and friction becomes. The forces caused by the stiffness are hard to simulate for different objects. For example, if the PIP joints α and β are set on 0, the force caused by stiffness would not be 0, because the remaining fingers still need to be closed. Another reason why stiffness is difficult to simulate is because the effects of the prosthetic glove could change over time, while the geometry would not change. It is however assumed that the force required to fully close the hand is independent of the size of the object and the fingers used for pinching. The friction losses are assumed to be equal as well, which could also be checked by comparing Figures D.2, D.4 and D.5.

The different load cases mentioned can either be included or excluded from stiffness and frictional force losses. Keep in mind that excluding the stiffness losses from the calculation is not the same as removing the prosthetic glove. In all situations switching would occur on the switch pressure, based on the closing the prosthetic hand including the prosthetic glove, which is always the same. Adding stiffness losses to the calculation means that the required force to deform the prosthetic glove is not used for the pinching part. For the geometry worst case scenario this has no effect, as the closing of the remaining fingers goes simultaneous with the pinching of the very large object, but for the realistic pinch this means that approximately 50% of the force required to close the hand is unused for pinching. This value is based on Figures D.4 and D.5 where the first pinch is registered half way the input displacement.

The static friction can also be included to the calculation. It is depended on the size of the input cylinder. The size of the input cylinder in return is depended on the required increase in MA, which on top is depended on the additional motion after switching to stage 2. The properties can be found in D.6 and the calculations are done in section D-4.
**D-4: Calculation of the VMA dimensions**

Section D-4 makes use of user defined MATLAB equations to calculate the required dimensions of the detailed designed VMA mechanism. The calculation of the new input cylinder and the MA cylinder are dependent of the used load case. The final design has been done such that both load cases would fulfill the requirements. Note that for the worst geometry load case, the friction losses were excluded for the final design as the calculations for a VMA mechanism including friction were not sufficient.

**D-4.1: Optimization of the Input and MA cylinder**

The combination of the input and MA cylinder determine both stage 1 and stage 2 of the VMA mechanism. The calculations of the dimensions are optimized by means of an iteration process, such that pinching of an object within the maximum force requirements could be done while staying within the maximum displacement requirement. The assumptions, equations, results and verification of the calculations and the realization to a detailed design are shown below.

**Assumptions:**
- Maximum displacement, pinch force and input force as by requirements (Table A.2)
- Static friction and input displacement for pinching stiff object as by Table D.6
- Initial displacement equal to \( x_m \) as by Table D.6
- Initial input cylinder diameter equal to \( c_{m,d} \)
- Phalanx angles for geometry worst case load case as by Table D.5 (\( \alpha = \beta = 0 \))
- Required pressure for geometry worst case load case as by Table D.7
- Required pressure for realistic pinch load case as by Table D.10
- Total volume displacement when pinching (Table D.9)

**Equations:**

\[
V = V_A
\]

\[
i = 1
\]

\[
x_{(i)} = x_m
\]

\[
c_{m,d-new(i)} = c_{m,d}
\]

\[
P_{out} = P_{out} \cdot \frac{c_{glove} \cdot F_m}{0.25\pi(c_{m,d}^2 - c_{m,d}^2)}
\]

\[
\text{while} \quad \frac{x_0(i)}{x_{(\infty)}} \geq 10^{-4}
\]
\[ c_{m,d,\text{req1}} = \sqrt{\frac{V}{0.25\pi x_{(i)}}} + c_{mi,d}^2 \]
\[ c_{m,d,\text{req2}} = \sqrt{\frac{F_{\text{input}} - F_{m,s}}{0.25\pi P}} + c_{mi,d}^2 \]
\[ c_{m,s,\text{req1}} = \frac{V}{0.25\pi (c_{m,d,\text{req1}}^2 - c_{mi,d}^2)} \]
\[ c_{m,s,\text{req2}} = \frac{V}{0.25\pi (c_{m,d,\text{req2}}^2 - c_{mi,d}^2)} \]
\[ c_{m,s,\text{new}} = \frac{V}{0.25\pi (c_{m,d,\text{new(i)}}^2 - c_{mi,d}^2)} \]

\[ MA_{VMA,1} = \frac{c_{m,s,\text{req1}}}{c_{m,s,\text{new(i)}}} \] (In this design always equal to 1)

\[ MA_{VMA,2} = \frac{c_{m,s,\text{req2}}}{c_{m,s,\text{new(i)}}} \]

\[ VMA_{\text{diff}(i)} = \frac{MA_{VMA,2}}{MA_{VMA,1}} \]

\[ x_{(i-1)} = x_{\text{input}} - x_{m2} \left( VMA_{\text{diff}(i)} - 1 \right) \]
\[ x_{m2} = x_{m2} \frac{x_{(i+1)}}{x_{(i)}} \]

\[ c_{m,d,\text{new(i)}} = \sqrt{\left( c_{m,d,\text{new(i)}}^2 - c_{mi,d}^2 \right) \frac{x_{(i)}}{x_{(i-1)}} + c_{mi,d}^2} \]
\[ F_{m,s} = F_{m,s} \frac{x_{(i)}}{x_{(i+1)}} \]

\[ i = i + 1 \]

End while
Results:

The results of the optimization for the different load cases as described by section D-3 are shown in Table D.11 for a double finger pinch and in Table D.12 for a single finger pinch. The load cases are either included or excluded from stiffness and friction losses. Note that the outcome of the geometry worst case load case without stiffness losses is identical when stiffness losses are included. This has to do due by the immediate pinching of a very large object. Not all load cases resulted in a solution, those which have not are indicated by not applicable (n/a) in the table. The double pinch geometry worst case loading condition excluding friction losses shows the minimum required VMA dimensions still viable for the Delft Cylinder Hand. The results of the load case will be worked out in to the detailed design of the input and MA cylinder after verification.

Table D.11: Variables used the optimization of the input and MA cylinders, for a double finger pinch, for the different load cases (LCG = geometry worst case load case, G+S = geometry included stiffness losses, G+F = geometry included friction losses, LCR = realistic pinch load case, R+S = realistic pinch + stiffness losses, R+F = realistic pinch + friction losses)

<table>
<thead>
<tr>
<th>Variables used for double finger pinch</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>LCG</td>
</tr>
<tr>
<td>Amount of steps</td>
<td>$i$</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Glove stiffness for pinch force reduction</td>
<td>$C_{glove}$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>New input cylinder diameter</td>
<td>$C_{m,d-new}$</td>
<td>11.4</td>
<td>11.4</td>
</tr>
<tr>
<td>New input cylinder stroke</td>
<td>$C_{m,s-new}$</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>Input cylinder diameter requirement for stage 1</td>
<td>$C_{m,d-req1}$</td>
<td>11.4</td>
<td>11.4</td>
</tr>
<tr>
<td>Input cylinder diameter requirement for stage 2</td>
<td>$C_{m,d-req2}$</td>
<td>5.6</td>
<td>5.6</td>
</tr>
<tr>
<td>Input cylinder stroke requirement for stage 1</td>
<td>$C_{m,s-req1}$</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>Input cylinder stroke requirement for stage 2</td>
<td>$C_{m,s-req2}$</td>
<td>152</td>
<td>152</td>
</tr>
<tr>
<td>VMA mechanical advantage stage 1 (based on req)</td>
<td>$MA_{VMA,1}$</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>VMA mechanical advantage stage 2 (based on req)</td>
<td>$MA_{VMA,2}$</td>
<td>5.5</td>
<td>5.5</td>
</tr>
<tr>
<td>Ratio between VMA stage 2 and stage 1</td>
<td>$VMA_{ratio}$</td>
<td>5.5</td>
<td>5.5</td>
</tr>
<tr>
<td>Input displacement before switching to stage 2</td>
<td>$x$</td>
<td>27.9</td>
<td>27.9</td>
</tr>
<tr>
<td>Input displacement pinching stiff object (Updated)</td>
<td>$x_{m_{2}}$</td>
<td>5.6</td>
<td>5.6</td>
</tr>
<tr>
<td>Friction force for new input cylinder (Updated)</td>
<td>$F_{m,s}$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total input displacement</td>
<td>$x_{input}$</td>
<td>53</td>
<td>53</td>
</tr>
<tr>
<td>Input force before switching to stage 2</td>
<td>$F_{in,stage1}$</td>
<td>53.1</td>
<td>53.1</td>
</tr>
<tr>
<td>Input force at pinch force requirement</td>
<td>$F_{in,stage2}$</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>

*) including stiffness losses for the geometry worst case loading condition has no additional effect on the outcome, due immediate pinching.
Table D.12: Variables used the optimization of the input and MA cylinders, for a single finger pinch, for the different load cases (LCG = geometry worst case load case, G+S = geometry included stiffness losses, G+F = geometry included friction losses, LCR = realistic pinch load case, R+S = realistic pinch + stiffness losses, R+F = realistic pinch + friction losses)

<table>
<thead>
<tr>
<th>Variables used for single finger pinch</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount of steps</td>
<td>$i$</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Glove stiffness for pinch force reduction</td>
<td>$C_{\text{glove}}$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>New input cylinder diameter</td>
<td>$C_{n,d-new}$</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>New input cylinder stroke</td>
<td>$C_{n,s-new}$</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Input cylinder diameter requirement for stage 1</td>
<td>$C_{n,d-req1}$</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Input cylinder diameter requirement for stage 2</td>
<td>$C_{n,d-req2}$</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Input cylinder stroke requirement for stage 1</td>
<td>$C_{n,s-req1}$</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Input cylinder stroke requirement for stage 2</td>
<td>$C_{n,s-req2}$</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>VMA mechanical advantage stage 1 (based on req)</td>
<td>$MA_{VMA,1}$</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>VMA mechanical advantage stage 2 (based on req)</td>
<td>$MA_{VMA,2}$</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Ratio between VMA stage 2 and stage 1</td>
<td>$VMA_{\text{diff}}$</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Input displacement before switching to stage 2</td>
<td>$x$</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Input displacement for pinching stiff object (Updated)</td>
<td>$x_{m2}$</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Friction force for new input cylinder (Updated)</td>
<td>$F'_{m,i}$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total input displacement</td>
<td>$x_{\text{input}}$</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Input force before switching to stage 2</td>
<td>$F'_{in,stage1}$</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Input force at pinch force requirement</td>
<td>$F'_{in,stage2}$</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

*) including stiffness losses for the geometry worst case loading condition has no additional effect on the outcome, due immediate pinching

Verification:
The results can be checked with different formulas to see if the iteration process has been done correctly and to verify if the results are within all requirements. The optimization was made based on the maximum input requirement in stage 2 of the VMA mechanism and the total maximum displacement when pinching an object at maximum range. The following two formulas show the calculation for the resulting input force and input displacement. Table D.11 and D.12 show this is equal to the requirements for all loading conditions.

$$F_{\text{in,stage2}} = \frac{0.25 \pi P_{\text{out}}}{VMA_{\text{diff}}} \left( c_{n,d-new(i)}^2 - c_{m,d}^2 \right) + F_s$$

$$x_{\text{input}} = x_{(i)} + x_{m2} \left( VMA_{\text{diff}} - 1 \right)$$

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The required input cylinder displacement to fully close the prosthetic hand before switching to stage 2 is different for each loading condition. It is calculated by the updated initial input force for the current input cylinder as shown in the formula below.

\[ F_{in-stage1} = F_m \cdot \frac{X_m}{X} \]

In table D.11 and D.12 the outcome of the required input force to switch to stage 2 is colored in green, orange or red. Green indicates that the results are within the requirements for all range of users (below 46 N), orange indicates the results to be within the requirements, but not for all users (50 ± N) and red indicates that the results are not within the requirements (54 N).

**Choice and recalculation**

The choice of the loading condition to be used to finalize the dimensions of the input and MA cylinder is the worst case geometry loading condition without friction losses and double pinching. It is clear that the geometry load has a worse performance than the realistic pinch load case. If a VMA mechanism is designed such that it could live up to the worst loading condition, then it would also work for less severe loading conditions. It could be argued that the realistic pinch load case with double pinch + stiffness + friction losses included, single pinch + stiffness losses included or single pinch + friction losses included, all performed worse. This is true, but for each loading condition, the input force to switch to stage 2 was not acceptable. Table D.13 shows the results of all loading conditions with the chosen VMA mechanism dimensions. The coloured values show if the results are within the requirements. Note that due to the fixed input cylinder dimensions, that the total input displacement and input force for switching to stage 2 is the same for each loading condition (equal to the requirement set).

**Table D.13: Requirements calculation for the VMA mechanism dimensions for the different loading conditions** (LCG = geometry worst case load case, G+S = geometry included stiffness losses, G+F = geometry included friction losses, LCR = realistic pinch load case, R+S = realistic pinch + stiffness losses, R+F = realistic pinch + friction losses)

<table>
<thead>
<tr>
<th>Variables used for single finger pinch</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>New input cylinder diameter</td>
<td>( c_{m,d,new} )</td>
<td>11.4</td>
<td>mm</td>
</tr>
<tr>
<td>Ratio between VMA stage 2 and stage 1</td>
<td>( VMA_{diff} )</td>
<td>5.5</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Double finger pinch</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Required system pressure for pinch force</td>
<td>( P_{out} )</td>
<td>2.9</td>
<td>MPa</td>
</tr>
<tr>
<td>Total input displacement</td>
<td>( X_{input} )</td>
<td>53</td>
<td>mm</td>
</tr>
<tr>
<td>Input force before switching to stage 2</td>
<td>( F_{in-stage1} )</td>
<td>53.1</td>
<td>N</td>
</tr>
<tr>
<td>Input force at pinch force requirement</td>
<td>( F_{in-stage2} )</td>
<td>50.0</td>
<td>N</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Single finger pinch</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Required system pressure for pinch force</td>
<td>( P_{out} )</td>
<td>5.7</td>
<td>MPa</td>
</tr>
<tr>
<td>Total input displacement</td>
<td>( X_{input} )</td>
<td>53</td>
<td>mm</td>
</tr>
<tr>
<td>Input force before switching to stage 2</td>
<td>( F_{in-stage1} )</td>
<td>53.1</td>
<td>N</td>
</tr>
<tr>
<td>Input force at pinch force requirement</td>
<td>( F_{in-stage2} )</td>
<td>100.0</td>
<td>N</td>
</tr>
</tbody>
</table>
Realization of the input and MA cylinder:
The required diameter of the input cylinder is found in Table D.11. The stroke of the cylinder on the other hand is slightly larger than the value found in Table D.11. All calculations have been performed assuming a pinch grip, the prosthetic hand, however, is also able to perform a grasp grip. The requirements of this research say nothing about the maximum displacement for a grasp grip, but the design of the input cylinder must reckon the possibility of a grasp motion of designing the cylinder based on the pinch motion. The ratio between the grasp and pinch motion is indicated by Table D.9. In additional, the input cylinder would need an additional safety factor to compensate for differences between the simulation and practice, as well as the hydraulic losses due leakage and vaporization over time. A 3 month period would be a good basis for the hydraulic loss calculation as this time period would coincide with the periodic maintenance. The following formula shows the estimation of the stroke of the input cylinder.

\[
l_{\text{input}_\text{cyl}} = \frac{V_{\text{hand}} + V_{\text{MA}_\text{cyl}} + V_{\text{loss}} \sum_{j=1}^{N} \frac{1}{4} \pi d_{out,j}^2}{\frac{1}{4} \pi \left( d_{out,input}_\text{cyl}^2 - d_{in,input}_\text{cyl}^2 \right)}
\]

The O-rings used for the cylinders must have an integer value. Therefore instead of the calculated outer diameter of the input cylinder, the diameter of the actual design is chosen to be 12mm. To compensate for the difference between piston areas, the inner diameter of the actual design will be 5mm.

For the MA cylinder, the closest mechanical advantage difference in a real design compared to the calculation is by picking a smallest and biggest diameter of 10 and 11 mm respectively. This would result in a mechanical advantage of 5.76.

**D-4.2: Switch cylinder dimensions and configuration visualization**

The switch cylinder must be designed such that it would satisfy both the chosen concept (1,2) and the reference concept (2,2) from Appendix C. In fact there are two designed configurations which both apply to concept (1,2) and one that applies to concept (2,2). Figures D.9 shows the different configurations in schematic drawings. The drawings are slightly different from Table C.1 as the initial drawings were over simplified. For a reliable functioning of the cylinder, the O-rings may not go along the edge of the input and output stream. As a result, the pistons show 3 heads in contrary to the originally drawn 2 heads from Table C.1.
Each of the configurations could be expressed in formulas describing the switch behaviour. It is assumed there are no friction losses. The geometry of the cylinders is equal for each configuration, but the inlet and outlet are different. Table D.14 shows the variables used in the formulas for each configuration. Ideally the switch cylinder should be as small as possible since accumulation of the volume is undesirable. For practical reasons, the smallest O-ring dimension is 3x1 mm, followed by 4x1 mm and 5x1 mm for the other piston heads. The dimensions respectively represent the outer diameter and the thickness of the O-ring in millimetre. Figure D.10 shows a plot of the relation between the input pressure and output pressure for the different configurations. The behaviour is influenced by the spring of the switch cylinder. The function of the spring is to maintain a switch between stage 1 and stage 2 of the VMA mechanism at the exact switch pressure.
Equations:
Switch pressure, actual mechanical advantage of the MA cylinder:

\[ P_s = \frac{F_m}{0.25\pi \left(c_{m,d}^2 - c_{m,t}^2\right)} \]

\[ MA_T = \frac{c_{ia,A}}{c_{ib,A}} \]

\[ F_s = c_{ia,A}P_s \left(1 - \frac{1}{MA_T}\right) \]

Behaviour of configuration 1:

\[ F_{s,s} = P_s \left(MA_T \left(c_{s1a,A} - c_{s2b,A} + c_{s2a,A} - c_{s3b,A} + c_{s3a,A}\right)\right) \]

Phase 1: \[ F_s = \frac{F_{s,s}}{P_s}, \quad P_{out} = P_{in} \]

Phase 2: \[ F_s = P_{in} \left(MA_T \left(c_{s1a,A} - c_{s2b,A} + c_{s2a,A} - c_{s3b,A} + c_{s3a,A}\right)\right), \quad P_{out} = MA_T P_{in} \]

Behaviour of configuration 2:

\[ F_{s,s} = P_s \left(\frac{1}{MA_T} \left(c_{s1a,A} - c_{s2b,A} + c_{s2a,A} - c_{s3b,A} + c_{s3a,A}\right)\right) \]

Phase 1: \[ F_s = \frac{F_{s,s}}{P_s}, \quad P_{out} = P_{in} \]

Phase 2: \[ F_s = P_{in} \left(c_{s1a,A} - c_{s2b,A} + c_{s2a,A} - c_{s3b,A} + MA_T c_{s3a,A}\right), \quad P_{out} = MA_T P_{in} \]

Behaviour of configuration R:

\[ F_{s,s} = P_s \left(c_{s1a,A} - c_{s2b,A} + c_{s2a,A} - c_{s3b,A} + c_{s3a,A}\right) \]

Phase 1: \[ F_s = \frac{F_{s,s}}{P_s}, \quad P_{out} = P_{in} \]

Phase 2: \[ F_s = \left(P_{in} - \frac{F_s}{c_{ia,A}}\right) MA_T \left(c_{s1a,A} - c_{s2b,A} + c_{s2a,A} - c_{s3b,A}\right) + P_{in} c_{s3a,A}, \quad P_{out} = MA_T \left(P_{in} - \frac{F_s}{c_{ia,A}}\right) \]
<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Config 1</th>
<th>Config 2</th>
<th>Config 3</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right area of first piston head of switch cylinder</td>
<td>$c_{1a,A}$</td>
<td>21.2</td>
<td>21.2</td>
<td>21.2</td>
<td>mm$^2$</td>
</tr>
<tr>
<td>Right area of first piston head of switch cylinder</td>
<td>$c_{12a,A}$</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
<td>mm$^2$</td>
</tr>
<tr>
<td>Left area of second piston head of switch cylinder</td>
<td>$c_{2b,A}$</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
<td>mm$^2$</td>
</tr>
<tr>
<td>Right area of second piston head of switch cylinder</td>
<td>$c_{3a,A}$</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
<td>mm$^2$</td>
</tr>
<tr>
<td>Left area of third piston head of switch cylinder</td>
<td>$c_{3b,A}$</td>
<td>5.5</td>
<td>5.5</td>
<td>5.5</td>
<td>mm$^2$</td>
</tr>
<tr>
<td>Switch pressure (closing hand pressure)</td>
<td>$P_s$</td>
<td>0.56</td>
<td>0.56</td>
<td>0.56</td>
<td>MPa</td>
</tr>
<tr>
<td>Force at switch piston during switch</td>
<td>$F_{rs}$</td>
<td>38.8</td>
<td>11.8</td>
<td>15.8</td>
<td>N</td>
</tr>
<tr>
<td>Actual mechanical advantage of MA cylinder</td>
<td>$MA_A$</td>
<td>5.76</td>
<td>5.76</td>
<td>5.76</td>
<td>-</td>
</tr>
<tr>
<td>Maximum pressure at the input of the system</td>
<td>$P_{in}$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>MPa</td>
</tr>
<tr>
<td>Maximum pressure at the output of the system</td>
<td>$P_{out}$</td>
<td>5.76</td>
<td>5.76</td>
<td>3.10</td>
<td>MPa</td>
</tr>
<tr>
<td>Minimum pre-tension transmission spring</td>
<td>$F_l$</td>
<td>0</td>
<td>0</td>
<td>44.0</td>
<td>N</td>
</tr>
<tr>
<td>Bigger area of the piston head of the MA cylinder</td>
<td>$c_{in,A}$</td>
<td>95.0</td>
<td>95.0</td>
<td>95.0</td>
<td>mm$^2$</td>
</tr>
<tr>
<td>Smaller area of the piston head of the MA cylinder</td>
<td>$c_{in,A}$</td>
<td>16.5</td>
<td>16.5</td>
<td>16.5</td>
<td>mm$^2$</td>
</tr>
</tbody>
</table>
Figure D.10: Configuration behaviour plots. From top to bottom, configuration 1, configuration 2 and configuration R, with on the left relation between the switch force and the input pressure and on the right the relation between the output pressure and input pressure. On the left side the red dotted line represents the switch spring pretension and on the red side the red dotted line indicates which output pressures are plausible.
Spring dimensioning:
The goal of the spring is to withhold switching until the pressure increases above switch pressure (remaining fingers of the prosthetic hand fully closed). The required pretension and stiffness of the spring is different for each configuration. Therefore, the switch cylinder has a long tube that could fit an easily replaceable spring (see Appendix G). It is stated that the entire switching procedure must not contribute to a more than 5% increase in the initial switch pressure. The piston moves a 5 mm path to fully close of the initial inlet and open the other. The following formula defines the required spring dimensions. The outcome of the require spring compression is 111, 295 and 95 mm for configuration 1,2 and R respectively.

$$\Delta_s = \frac{F_{s,t}}{c_{s,k}}$$

Table D.15: Variables used for spring compression calculation

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring compression</td>
<td>$\Delta_s$</td>
<td>mm</td>
</tr>
<tr>
<td>Spring force at switch pressure</td>
<td>$F_{s,t}$</td>
<td>N</td>
</tr>
<tr>
<td>Spring stiffness</td>
<td>$c_{s,k}$</td>
<td>N/mm</td>
</tr>
</tbody>
</table>

A suitable spring for each configuration has been picked selected with guidance of the TEVEMA spring search engine. Table D.16 shows the spring choice, its dimensions and the alterations. The last column shows that the required spring compression is lower than the maximum spring compression.

Table D.16: Chosen springs from TEVEMA based on calculated attributes

<table>
<thead>
<tr>
<th>Configuration</th>
<th>$c_{s,k}$</th>
<th>$\Delta_s$</th>
<th>Spring</th>
<th>Original Length</th>
<th>Original Stiffness</th>
<th>Cutted Lenght</th>
<th>Cutted stiffness</th>
<th>Max compression</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.35</td>
<td>111</td>
<td>DL30028</td>
<td>500</td>
<td>0.14</td>
<td>200</td>
<td>0.35</td>
<td>120</td>
</tr>
<tr>
<td>2</td>
<td>0.04</td>
<td>295</td>
<td>DL30017</td>
<td>500</td>
<td>0.04</td>
<td>500</td>
<td>0.04</td>
<td>373</td>
</tr>
<tr>
<td>R</td>
<td>0.16</td>
<td>99</td>
<td>DL30018</td>
<td>500</td>
<td>0.06</td>
<td>200</td>
<td>0.15</td>
<td>123</td>
</tr>
</tbody>
</table>
Appendix E: Simulation analysis

Using the dimensions of the prototype as defined by Appendix D, a system behaviour analysis can be performed. The goal of this analysis is to determine any overseen design criteria and to identify the risk of the system. The analysis is done by a simulation of pinching an object with the required pinch force $F_{\text{pinch}}$ by initially moving towards this object and subsequently releasing the object, moving back to its initial position. The simulation is done by calculations done in MATLAB, while the visualization is made by hand using the outcomes of the calculations. The calculations are done in section E-1, while the setup of the system can be observed in section E-2.

E-1: Calculations per step for the configuration

Aside from the detailed design components (the input cylinder, MA cylinder and switch cylinder from Appendix D), the setup includes two testing cylinders simplifying the prosthetic hand. One cylinder (Object cylinder, $c_o$) is used to hold an object representing the pinch motion of the hand, the other cylinder (Remaining cylinder, $c_r$) moves freely until its maximum piston stroke, representing the closing hand motion of the remaining fingers of the hand. Both testing cylinders work against a linear spring, mimicking the stiffness of the prosthetic hand. The dimensions of the testing cylinders are designed such that the piston total volume is comparable to that of the prosthetic hand cylinders. The diameter of the test cylinders are chosen to be 10 mm, in line with the diameters of the other cylinders. A conversion factor is required between the output force of the object cylinder and the actual pinch force of the prosthetic hand. The stiffness of the linear springs will also be chosen accordingly.


c_{o,\Delta} = c_{r,\Delta} = 0.25\pi(10^2)

c_{o,t} = c_{r,t} = \frac{V_t}{c_{o,\Delta} + c_{r,\Delta}}

F_{\text{pinch}} = \frac{a_{pp} c_{pp,\Delta}}{l_{pp} c_{o,\Delta}} \cdot F_{\text{object}} = \text{con} \cdot F_{\text{object}}

\frac{c_{o,k}}{c_{r,k}} = P_s \frac{c_{o,\Delta}}{c_{o,t}}
With,

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piston area of object cylinder</td>
<td>( c_{o,A} )</td>
<td>100</td>
<td>( \text{mm}^2 )</td>
</tr>
<tr>
<td>Piston area of remaining cylinder</td>
<td>( c_{r,A} )</td>
<td>100</td>
<td>( \text{mm}^2 )</td>
</tr>
<tr>
<td>Piston stroke of object cylinder</td>
<td>( c_{o,s} )</td>
<td>20</td>
<td>( \text{mm}^2 )</td>
</tr>
<tr>
<td>Piston stroke of remaining cylinder</td>
<td>( c_{r,s} )</td>
<td>20</td>
<td>( \text{mm}^2 )</td>
</tr>
<tr>
<td>Stiffness of the testing cylinder springs</td>
<td>( \text{obj}_k )</td>
<td>115.4</td>
<td>( \text{Nm}^{-1} )</td>
</tr>
<tr>
<td>Conversion factor</td>
<td>( \text{con} )</td>
<td>0.1331</td>
<td>-</td>
</tr>
<tr>
<td>Area of piston head of input cylinder</td>
<td>( c_{m,A} )</td>
<td>93.5</td>
<td>( \text{mm}^2 )</td>
</tr>
</tbody>
</table>

The object that is hold by the object cylinder has an unknown stiffness. The object stiffness \( \text{obj}_k \) is assigned a value of 50 times the spring stiffness \( c_{s,k} \), in line with Figure D.4. The variables used for the calculations are shown in Table E.1, Table E.2 and the calculated cylinder dimensions in Appendix D.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piston displacement of input cylinder</td>
<td>( c_{m,x} )</td>
<td>mm</td>
</tr>
<tr>
<td>Piston displacement of switch cylinder</td>
<td>( c_{s,x} )</td>
<td>mm</td>
</tr>
<tr>
<td>Piston displacement of MA cylinder</td>
<td>( c_{i,x} )</td>
<td>mm</td>
</tr>
<tr>
<td>Piston displacement of object cylinder</td>
<td>( c_{o,y} )</td>
<td>mm</td>
</tr>
<tr>
<td>Piston displacement of remaining cylinder</td>
<td>( c_{r,y} )</td>
<td>mm</td>
</tr>
<tr>
<td>Pressure at the input of the system</td>
<td>( P_{in} )</td>
<td>MPa</td>
</tr>
<tr>
<td>Pressure at the output of the system</td>
<td>( P_{out} )</td>
<td>MPa</td>
</tr>
<tr>
<td>The delivered force to the object</td>
<td>( F_{\text{object}} )</td>
<td>N</td>
</tr>
</tbody>
</table>

The prototype has 3 configurations based on the input and output connections used. Two configurations mentioned as configuration 1 and configuration 2 are based on the chosen concept from Appendix C, the last configuration, called configuration R is a design of the reference concept. The simulation of pinching an object is done step by step, starting from the neutral position. For each step the position of the cylinders and the pressure in the system can be calculated. Combining all steps gives the system behaviour of the cylindrical position and hydraulic of the VMA mechanism. The system behaviour visualization of each configuration is shown in the Figures of section E-1. The calculations done for only the first configuration is shown with the following equations.
Step i=1 – Initial position

\[ c_{x,x(i)} = 0 \quad P_{in(i)} = \frac{c_{r,y(i)} c_{r,k}}{c_{r,A}} \]
\[ c_{z,z(i)} = 0 \quad P_{out(i)} = P_{in(i)} \]
\[ c_{o,y(i)} = 0 \quad c_{m,x(i)} = 0 \]
\[ c_{r,y(i)} = 0 \]

Step i=2 – Hitting the object at halfway displacement

\[ c_{x,x(i)} = 0 \quad P_{in(i)} = \frac{c_{r,y(i)} c_{r,k}}{c_{r,A}} \]
\[ c_{z,z(i)} = 0 \quad P_{out(i)} = P_{in(i)} \]
\[ c_{o,y(i)} = \frac{1}{2} c_{o,x} \quad c_{m,x(i)} = \frac{c_{o,y(i)} c_{o,A} + c_{r,y(i)} c_{r,A}}{c_{m,A}} \]
\[ c_{r,y(i)} = \frac{1}{2} c_{r,x} \]

Step i=3 – Increasing pressure to switch pressure

\[ c_{x,x(i)} = 0 \quad P_{in(i)} = P_s \]
\[ c_{z,z(i)} = 0 \quad P_{out(i)} = P_{in(i)} \]
\[ c_{o,y(i)} = c_{o,y(i-1)} + \left( P_s - P_{in(i-1)} \right) \frac{c_{o,A}}{obj_k} \quad c_{m,x(i)} = \frac{c_{o,y(i)} c_{o,A} + c_{r,y(i)} c_{r,A}}{c_{m,A}} \]
\[ c_{r,y(i)} = P_s \frac{c_{r,A}}{c_{r,k}} \]

Step i=4 – Increasing pressure while phase 1 port is closing

\[ c_{r,x(0)} = 2 \quad P_{a(0)} = 1.02 P_s \]
\[ c_{r,x(0)} = c_{r,x(i)} \frac{c_{o,A} - c_{2h_A}}{c_{h_A}} \quad P_{aout(0)} = P_{a(0)} \]
\[ c_{o,y(0)} = c_{o,y(i-1)} + \left( P_{a(i)} - P_{a(i-1)} \right) \frac{c_{o,A}}{obj_k} \quad c_{m,x(0)} = c_{m,x(i-1)} + \frac{c_{o,x(i)} \left( c_{2h_A} - c_{2h_A} + c_{3h_A} \right) + c_{o,x(i)} c_{o_A} + c_{e,x(i)} - c_{e,x(i-1)} c_{r_A}}{c_{m_A}} \]
\[ c_{r,y(0)} = P_{a(i)} \frac{c_{r,A}}{c_{r,k}} \]

Step i=5 – Increasing pressure while both ports are closed
\( c_{s,\Delta t} = 1 \)

\[
c_{s,t(i)} = c_{s,t(i-1)} + c_{s,\Delta t}
\]

\[
c_{r,s(i)} = c_{r,s(i)} + \frac{c_{r,\Delta t} \left( c_{s1a,d} - c_{s2b,d} \right)}{c_{b,b,d}}
\]

\( P_{in(i)} = 1.03 P_s \)

\[
P_{out(i)} = \frac{c_{r,s(i)} c_{r,b}}{c_{r,d}}
\]

\[
c_{o,y(i)} = c_{o,y(i-1)} - \frac{c_{r,k} c_{s,\Delta t} \left( c_{s2a,d} - c_{s3b,d} \right)}{\left( c_{r,k} + obj \right) c_{s,d}}
\]

\[
c_{m,s(i)} = c_{m,s(i-1)} + \frac{c_{r,\Delta t} c_{s2a,d} + \left( c_{s,t(i)} - c_{s,t(i-1)} \right) c_{m,a}}{c_{m,a}}
\]

\[
c_{r,y(i)} = \frac{c_{r,y(i-1)} \left( c_{s2a,d} - c_{s3b,d} \right)}{\left( c_{r,k} + obj \right) c_{r,d}}
\]

**Step i=6 – Increasing pressure while phase 2 port is opening**

\( c_{s,\Delta t} = 2 \)

\[
c_{s,t(i)} = c_{s,t(i-1)} + c_{s,\Delta t}
\]

\[
c_{r,s(i)} = c_{r,s(i)} + \frac{c_{r,\Delta t} \left( c_{s1a,d} - c_{s2b,d} \right) + c_{s,d} \left( c_{o,y(i)} - c_{o,y(i-1)} \right) + c_{r,d} \left( c_{r,y(i)} - c_{r,y(i-1)} \right)}{c_{b,b,d}}
\]

\( P_{in(i)} = 1.05 P_s \)

\[
P_{out(i)} = MA_P m_{in(i)}
\]

\[
c_{o,y(i)} = c_{o,y(i)} + \left( P_{out(i)} - P_{m(2)} \right) \frac{c_{o,d}}{obj}
\]

\[
c_{r,y(i)} = \min \left( c_{r,s(i)}, \frac{c_{r,d}}{c_{r,b}} \right)
\]

**Step i=7 – Increasing input pressure until to 1.5 the switch pressure**

\( c_{s,t(i)} = c_{s,t(i-1)} \)

\[
c_{r,s(i)} = c_{r,s(i)} + \frac{c_{r,\Delta t} \left( c_{o,y(i)} - c_{o,y(i-1)} \right) + c_{r,d} \left( c_{r,y(i)} - c_{r,y(i-1)} \right)}{c_{b,b,d}}
\]

\( P_{in(i)} = 1.5 P_s \)

\[
P_{out(i)} = MA_P m_{in(i)}
\]

\[
c_{o,y(i)} = c_{o,y(i)} + \left( P_{out(i)} - P_{m(2)} \right) \frac{c_{o,d}}{obj}
\]

\[
c_{r,y(i)} = \min \left( c_{r,s(i)}, \frac{c_{r,d}}{c_{r,b}} \right)
\]
Calculation of switch spring stiffness and return pressure:
The stiffness was chosen such that the whole switch movement would result in an increase of 5% of the initial switch force. As a result, the input pressure would be 1.05 times the switch pressure when the switch has moved 5 millimetres. Since the relation of the system pressures are different while moving back, this means that the full switch procedure of 5 millimetres does not go together with a 5% decrease of the initial switching back pressure.

\[ F_s = P_s \left( MA_T \left( c_{s1a,a} - c_{s2b,a} \right) + c_{s2a,a} - c_{s3b,a} + c_{s3a,a} \right) \]

\[ F_{s,b} = 1.05 P_s \left( MA_T \left( c_{s1a,a} - c_{s2b,a} \right) + c_{s2a,a} - c_{s3b,a} \right) + P_{out(5)} \left( c_{s2a,a} - c_{s3b,a} \right) \]

\[ P_{s,b} = \frac{F_{s,b}}{MA_T \left( c_{s1a,a} - c_{s2b,a} + c_{s2a,a} - c_{s3b,a} \right) + c_{s3a,a}} \]

\[ c_{s,k} = \frac{1}{3} \left( F_{s,b} - F_s \right) \]

Step i=8 – Lower the pressure, to the 1.05 of the initial switch pressure

\[ c_{s,x(i)} = c_{s,x(i-2)} \]
\[ P_{in(i)} = P_{in(i-2)} \]

\[ c_{t,x(i)} = c_{t,x(i-2)} \]
\[ P_{out(i)} = P_{out(i-2)} \]

\[ c_{o,y(i)} = c_{o,y(i-2)} \]
\[ c_{m,x(i)} = c_{m,x(i-2)} \]

\[ c_{r,y(i)} = c_{r,y(i-2)} \]

Step i=9 – Lower the pressure, until switching back pressure (Fs,b)

\[ c_{s,x(i)} = c_{s,x(i-1)} \]

\[ P_{in(i)} = P_{s,b} \]

\[ c_{t,x(i)} = \frac{c_{s,x(i-1)} + \left( c_{o,y(i)} - c_{r,y(i-1)} \right) + c_{r,\Delta} \left( c_{r,y(i)} - c_{r,y(i-1)} \right)}{c_{2b,a}} \]

\[ P_{out(i)} = MA_T P_{in(i)} \]

\[ c_{o,y(i)} = c_{o,y(2)} + \left( P_{out(i)} - P_{m(2)} \right) \frac{C_{o,B}}{obj_k} \]

\[ c_{m,x(i)} = c_{m,x(i-1)} + \frac{\left( c_{s,x(i-1)} - c_{s,x(i-1)} \right) c_{m,a}}{c_{m,a}} \]

\[ c_{r,y(i)} = \min \left( c_{r,x} P_{out(i)} \frac{c_{s,\Delta}}{c_{r,k}} \right) \]

Step i=10 – Lower the pressure, while phase 2 port is closing

\[ c_{s,\Delta x} = 2 \]
\[ c_{r,t(i)} = c_{r,t(i-1)} - c_{r,t} \]
\[ c_{s,\Delta t} = c_{s,t(i)} + c_{s,t} \left( c_{r,t(i)} - c_{r,t(i-1)} \right) \]
\[ p_{m(i)} = \frac{c_{s,t(i)} - c_{s,t(i-1)}}{5} + \frac{(5 - c_{s,t(i-1)})}{5} p_{s,b} \frac{F_{i}}{F_{s,b}} \]
\[ p_{out(i)} = MA_{p} c_{o,t} \]
\[ c_{m,t(i)} = c_{m,t(i-1)} + \frac{1}{c_{m,t}} \left( c_{r,t(i-1)} - c_{r,t(i)} \right) \left( c_{r,t(i)} - c_{r,t(i-1)} \right) \]

**Step i=11 – decrease pressure, both ports closed**

\[ c_{s,\Delta t} = 1 \]
\[ c_{s,t(i)} = c_{s,t(i-1)} - c_{s,t} \]
\[ c_{s,t(i)} = c_{s,t(i-1)} + \left( c_{r,t(i)} - c_{r,t(i-1)} \right) \]
\[ c_{s,t(i)} = c_{s,t(i-1)} + \left( c_{r,t(i)} - c_{r,t(i-1)} \right) \]
\[ c_{r,t(i)} = \min \left( \frac{c_{r,t} + p_{out(i)} c_{o,t}}{c_{o,t}} \right) \]

**Step i=12 – decrease pressure, while port 1 is opening**

\[ c_{s,\Delta t} = 2 \]
\[ c_{s,t(i)} = 0 \]
\[ c_{s,t(i)} = c_{s,t} \left( c_{r,t(i)} - c_{r,t(i-1)} \right) \]
\[ p_{m(i)} = p_{m(i-1)} \]
\[ p_{out(i)} = p_{out(i-1)} \]
\[ c_{m,t(i)} = c_{m,t(i-1)} + \left( c_{r,t(i)} - c_{r,t(i-1)} \right) \]
\[ c_{r,t(i)} = \frac{p_{out(i)} c_{o,t}}{c_{o,t}} \]

**Step i=13 – decrease pressure, until object is dropped**

\[ c_{s,t(i)} = 0 \]
\[ p_{m(i)} = p_{m(i-1)} \]
\[ c_{s,t(i)} = c_{s,t(i-1)} \]
\[ c_{s,t(i)} = c_{s,t(i-1)} + \left( c_{r,t(i-1)} - c_{r,t(i)} \right) \]
\[ c_{r,t(i)} = c_{r,t(i-1)} \]
Step i=14 – Return to starting position

\[ c_{x,t(i)} = 0 \]
\[ P_{0(i)} = P_{m(i)} \]
\[ c_{y,t(i)} = c_{x,t(i-1)} \]
\[ P_{out(i)} = P_{out(i-1)} \]
\[ c_{o,x(i)} = c_{o,y(i)} \]
\[ c_{m,x(i)} = c_{m,y(i-1)} + \frac{(c_{o,y(i)} - c_{o,y(i-1)}) c_{o,d} + (c_{r,y(i)} - c_{r,y(i-1)}) c_{r,d}}{c_{m,d}} \]
\[ c_{r,y(i)} = c_{r,y(i)} \]

**E-2: Outcome per step per configuration**

The outcome of each step of the calculations from the previous section is stored in different tables. For each configuration a high and low system pressure is given. The high system pressure corresponds to the requirements, while the low system pressure is used as a reference to compare it with the testing phase.

**E-2.1: High pressure**

Table E.3 to E.14 show the values of each of the cylinders for each step at the different configurations at high pressure. The tables show a distinction between the two different load cases; pinching a large object with stretched fingers (Tables E.3 to E.8) and when pinching a small 10 mm object (Tables E.9 to E.14). Note that immediate pinching occurs for the large object, while for the small object the prosthetic hand first needs to be moved towards that object. Figures E.1 to E.6 show graphs of the outcome. The values for the 10 mm object pinching at high pressure are processed in to schematic drawings of each of the cylinders in section E-3.

**Table E.3: Simulation of configuration 1 – high system pressure – large object- pinching phase**

<table>
<thead>
<tr>
<th>Steps</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>( c_{x,t(i)} )</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>( c_{y,t(i)} )</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.048</td>
<td>1.571</td>
<td>15.75</td>
<td>20.45</td>
</tr>
<tr>
<td>( c_{o,x(i)} )</td>
<td>0</td>
<td>0</td>
<td>0.381</td>
<td>0.389</td>
<td>0.387</td>
<td>2.305</td>
<td>3.293</td>
</tr>
<tr>
<td>( c_{r,x(i)} )</td>
<td>0</td>
<td>0</td>
<td>19.05</td>
<td>19.43</td>
<td>19.34</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>( P_{m(i)} )</td>
<td>0</td>
<td>0</td>
<td>0.56</td>
<td>0.571</td>
<td>0.576</td>
<td>0.588</td>
<td>0.839</td>
</tr>
<tr>
<td>( P_{out(i)} )</td>
<td>0</td>
<td>0</td>
<td>0.56</td>
<td>0.571</td>
<td>0.568</td>
<td>3.386</td>
<td>4.837</td>
</tr>
<tr>
<td>( c_{m,x(i)} )</td>
<td>0</td>
<td>0</td>
<td>16.33</td>
<td>18.14</td>
<td>18.81</td>
<td>33.49</td>
<td>38.27</td>
</tr>
<tr>
<td>( F_{input(i)} )</td>
<td>0</td>
<td>0</td>
<td>52.31</td>
<td>53.35</td>
<td>53.88</td>
<td>54.92</td>
<td>78.46</td>
</tr>
<tr>
<td>( F_{pinch(i)} )</td>
<td>0</td>
<td>0</td>
<td>5.85</td>
<td>5.967</td>
<td>5.94</td>
<td>35.39</td>
<td>50.56</td>
</tr>
</tbody>
</table>
Table E.4: Simulation of configuration 1 – high system pressure – large object- opening phase

<table>
<thead>
<tr>
<th>Steps</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{x,x(i)}$</td>
<td>5</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$c_{L,x(i)}$</td>
<td>15.75</td>
<td>12.14</td>
<td>10.11</td>
<td>9.582</td>
<td>8.535</td>
<td>8.535</td>
<td>8.535</td>
</tr>
<tr>
<td>$c_{h,y(i)}$</td>
<td>2.305</td>
<td>1.547</td>
<td>1.519</td>
<td>1.609</td>
<td>0.25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$c_{r,y(i)}$</td>
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<td>20</td>
<td>20</td>
<td>20</td>
<td>12.48</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$P_{in(i)}$</td>
<td>0.588</td>
<td>0.394</td>
<td>0.387</td>
<td>0.367</td>
<td>0.367</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$P_{out(i)}$</td>
<td>3.386</td>
<td>2.273</td>
<td>2.232</td>
<td>2.364</td>
<td>0.367</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$c_{m,x(i)}$</td>
<td>33.49</td>
<td>29.82</td>
<td>27.48</td>
<td>26.82</td>
<td>17.87</td>
<td>7.172</td>
<td>7.172</td>
</tr>
<tr>
<td>$F_{input(i)}$</td>
<td>54.92</td>
<td>36.86</td>
<td>36.21</td>
<td>34.27</td>
<td>34.27</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$F_{pinch(i)}$</td>
<td>35.39</td>
<td>23.75</td>
<td>23.33</td>
<td>24.71</td>
<td>3.832</td>
<td>0</td>
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</tbody>
</table>

Table E.5: Simulation of configuration 2 – high system pressure – large object- pinching phase

<table>
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<th>Steps</th>
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<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{x,x(i)}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>$c_{L,x(i)}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-0.18</td>
<td>-0.27</td>
<td>13.95</td>
<td>18.65</td>
</tr>
<tr>
<td>$c_{h,y(i)}$</td>
<td>0</td>
<td>0</td>
<td>0.381</td>
<td>0.389</td>
<td>0.385</td>
<td>2.305</td>
<td>3.293</td>
</tr>
<tr>
<td>$c_{r,y(i)}$</td>
<td>0</td>
<td>0</td>
<td>19.05</td>
<td>19.43</td>
<td>19.25</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>$P_{in(i)}$</td>
<td>0</td>
<td>0</td>
<td>0.56</td>
<td>0.571</td>
<td>0.576</td>
<td>0.588</td>
<td>0.839</td>
</tr>
<tr>
<td>$P_{out(i)}$</td>
<td>0</td>
<td>0</td>
<td>0.56</td>
<td>0.571</td>
<td>0.566</td>
<td>3.386</td>
<td>4.837</td>
</tr>
<tr>
<td>$c_{m,x(i)}$</td>
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<td>0</td>
<td>16.33</td>
<td>17.11</td>
<td>17.18</td>
<td>31.98</td>
<td>36.76</td>
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<tr>
<td>$F_{input(i)}$</td>
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<td>0</td>
<td>52.31</td>
<td>53.35</td>
<td>53.88</td>
<td>54.92</td>
<td>78.46</td>
</tr>
<tr>
<td>$F_{pinch(i)}$</td>
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<td>0</td>
<td>5.85</td>
<td>5.967</td>
<td>5.913</td>
<td>35.39</td>
<td>50.56</td>
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</tbody>
</table>

Table E.6: Simulation of configuration 2 – high system pressure – large object- opening phase

<table>
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<tr>
<th>Steps</th>
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<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{x,x(i)}$</td>
<td>5</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$c_{L,x(i)}$</td>
<td>13.95</td>
<td>5.542</td>
<td>3.994</td>
<td>4.085</td>
<td>4.267</td>
<td>4.267</td>
<td>4.267</td>
</tr>
<tr>
<td>$c_{h,y(i)}$</td>
<td>2.305</td>
<td>0.539</td>
<td>0.534</td>
<td>0.713</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$c_{r,y(i)}$</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$P_{in(i)}$</td>
<td>0.588</td>
<td>0.137</td>
<td>0.136</td>
<td>-0.4</td>
<td>-0.4</td>
<td>-0.4</td>
<td>0</td>
</tr>
<tr>
<td>$P_{out(i)}$</td>
<td>3.386</td>
<td>0.792</td>
<td>0.785</td>
<td>1.048</td>
<td>-0.4</td>
<td>0.6</td>
<td>0</td>
</tr>
<tr>
<td>$c_{m,x(i)}$</td>
<td>31.98</td>
<td>23.43</td>
<td>21.52</td>
<td>21.44</td>
<td>3.585</td>
<td>3.585</td>
<td>3.585</td>
</tr>
<tr>
<td>$F_{input(i)}$</td>
<td>54.92</td>
<td>12.85</td>
<td>12.73</td>
<td>-37</td>
<td>-37</td>
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### Table E.7: Simulation of configuration R – high system pressure – large object- pinching phase

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### Table E.8: Simulation of configuration R – high system pressure – large object- opening phase

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<td>0.571</td>
<td>0.56</td>
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### Table E.9: Simulation of configuration 1 – high system pressure – small object- pinching phase

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<td>5</td>
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### Table E.10: Simulation of configuration 1 – high system pressure – small object- opening phase

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<td>0</td>
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### Table E.11: Simulation of configuration 2 – high system pressure – small object- pinching phase

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<td>54.92</td>
<td>78.46</td>
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<td>0</td>
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<td>4.352</td>
<td>4.271</td>
<td>48.57</td>
<td>71.37</td>
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<td>0</td>
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<td>4.271</td>
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### Table E.12: Simulation of configuration 2 – high system pressure – small object- opening phase

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Table E.13: Simulation of configuration R – high system pressure – small object- pinching phase

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<td>19.23</td>
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<td>0.576</td>
<td>0.588</td>
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<td>53.88</td>
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Table E.14: Simulation of configuration R – high system pressure – small object- opening phase

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Figure E.1: Pinch force to input force relation (top) and input force to input displacement relation (bottom) for configuration 1 simulation (high pressure, large object)
Figure E.2: Pinch force to input force relation (top) and input force to input displacement relation (bottom) for configuration 2 simulation (high pressure, large object)

Figure E.3: Pinch force to input force relation (top) and input force to input displacement relation (bottom) for configuration R simulation (high pressure, large object)
Figure E.4: Pinch force to input force relation (top) and input force to input displacement relation (bottom) for configuration 1 simulation (high pressure, small object)
Figure E.5: Pinch force to input force relation (top) and input force to input displacement relation (bottom) for configuration 2 simulation (high pressure, small object)

Figure E.6: Pinch force to input force relation (top) and input force to input displacement relation (bottom) for configuration R simulation (high pressure, small object)
**E-2.2: Low pressure**

Table E.15 to E.26 show the values of each of the cylinders for each step at the different configurations at low pressure. The tables show a distinction between the two different load cases; pinching a large object with stretched fingers (Tables E.15 to E.21) and when pinching a small 10 mm object (Tables E.21 to E.26). Note that immediate pinching occurs for the large object, while for the small object the prosthetic hand first needs to be moved towards that object. Figures E.7 to E.12 show graphs of the outcome.

**Table E.15: Simulation of configuration 1 – low system pressure – large object- pinching phase**

<table>
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<td>0.413</td>
<td>0.411</td>
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<tr>
<td>$P_{out(i)}$</td>
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**Table E.16: Simulation of configuration 1 – low system pressure – large object- opening phase**

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69
### Table E.17: Simulation of configuration 2 – low system pressure – large object- pinching phase

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### Table E.18: Simulation of configuration 2 – low system pressure – large object- opening phase

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### Table E.19: Simulation of configuration R – low system pressure – large object- pinching phase

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<td>20.04</td>
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<td>0.206</td>
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<tr>
<td>$P_{out(i)}$</td>
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<td>19.64</td>
<td>19.83</td>
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<td>2.175</td>
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### Table E.20: Simulation of configuration R – low system pressure – large object- opening phase

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<td>$P_{in(i)}$</td>
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### Table E.21: Simulation of configuration 1 – low system pressure – small object- pinching phase

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<td>0.21</td>
<td>0.209</td>
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### Table E.22: Simulation of configuration 1 – low system pressure – small object- opening phase

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<td>$c_{m,x(i)}$</td>
<td>37.52</td>
<td>33.62</td>
<td>31.28</td>
<td>30.61</td>
<td>22.27</td>
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<td>2.65</td>
</tr>
<tr>
<td>$F_{input(i)}$</td>
<td>20.22</td>
<td>13.57</td>
<td>13.33</td>
<td>12.64</td>
<td>12.64</td>
<td>9.52</td>
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<tr>
<td>$F_{pinch(i)}$</td>
<td>17.98</td>
<td>11.54</td>
<td>11.31</td>
<td>12.03</td>
<td>0.525</td>
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</table>
### Table E.23: Simulation of configuration 2 – low system pressure – small object- pinching phase

<table>
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<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{s, x(i)}$</td>
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<tr>
<td>$c_{z, x(i)}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-0.18</td>
<td>-0.27</td>
<td>8.799</td>
<td>13.79</td>
</tr>
<tr>
<td>$c_{p, y(i)}$</td>
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<td>10</td>
<td>10.2</td>
<td>10.21</td>
<td>10.21</td>
<td>12.25</td>
<td>13.3</td>
</tr>
<tr>
<td>$c_{p, y(i)}$</td>
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<td>10</td>
<td>20.22</td>
<td>20.63</td>
<td>20.45</td>
<td>20</td>
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</tr>
<tr>
<td>$p_{in(i)}$</td>
<td>0</td>
<td>0.102</td>
<td>0.206</td>
<td>0.21</td>
<td>0.212</td>
<td>0.216</td>
<td>0.309</td>
</tr>
<tr>
<td>$p_{out(i)}$</td>
<td>0</td>
<td>0.102</td>
<td>0.206</td>
<td>0.21</td>
<td>0.208</td>
<td>1.246</td>
<td>1.78</td>
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<tr>
<td>$c_{m, x(i)}$</td>
<td>0</td>
<td>16.81</td>
<td>25.57</td>
<td>26.37</td>
<td>26.44</td>
<td>36.01</td>
<td>41.08</td>
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<td>19.25</td>
<td>19.64</td>
<td>19.83</td>
<td>20.22</td>
<td>28.88</td>
</tr>
<tr>
<td>$F_{pinch(i)}$</td>
<td>0</td>
<td>0</td>
<td>1.636</td>
<td>1.701</td>
<td>1.672</td>
<td>17.98</td>
<td>26.37</td>
</tr>
</tbody>
</table>

### Table E.24: Simulation of configuration 2 – low system pressure – small object- opening phase

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<th>Steps</th>
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<th>13</th>
<th>14</th>
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</thead>
<tbody>
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<td>$c_{s, x(i)}$</td>
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<td>5</td>
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<td>0</td>
</tr>
<tr>
<td>$c_{z, x(i)}$</td>
<td>8.799</td>
<td>-0.13</td>
<td>-1.68</td>
<td>-1.59</td>
<td>-1.4</td>
<td>-1.4</td>
<td>-1.4</td>
</tr>
<tr>
<td>$c_{p, y(i)}$</td>
<td>12.25</td>
<td>10.37</td>
<td>10.37</td>
<td>10.55</td>
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<td>0</td>
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<tr>
<td>$c_{p, y(i)}$</td>
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<td>20</td>
<td>20</td>
<td>20</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$p_{in(i)}$</td>
<td>0.216</td>
<td>0.051</td>
<td>0.05</td>
<td>-0.13</td>
<td>-0.13</td>
<td>-0.13</td>
<td>0</td>
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<tr>
<td>$p_{out(i)}$</td>
<td>1.246</td>
<td>0.292</td>
<td>0.289</td>
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<td>-1.18</td>
<td>-1.18</td>
</tr>
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<td>$F_{input(i)}$</td>
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<td>4.73</td>
<td>4.685</td>
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<td>-12.6</td>
<td>-12.6</td>
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<tr>
<td>$F_{pinch(i)}$</td>
<td>17.98</td>
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<td>2.937</td>
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</table>

### Table E.25: Simulation of configuration R – low system pressure – small object- pinching phase

<table>
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<th>Steps</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{s, x(i)}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
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<tr>
<td>$c_{z, x(i)}$</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4.641</td>
</tr>
<tr>
<td>$c_{p, y(i)}$</td>
<td>0</td>
<td>10</td>
<td>10.2</td>
<td>10.21</td>
<td>10.21</td>
<td>10.2</td>
<td>11.22</td>
</tr>
<tr>
<td>$c_{p, y(i)}$</td>
<td>0</td>
<td>10</td>
<td>20.22</td>
<td>20.63</td>
<td>20.43</td>
<td>20.04</td>
<td>20</td>
</tr>
<tr>
<td>$p_{in(i)}$</td>
<td>0</td>
<td>0.102</td>
<td>0.206</td>
<td>0.21</td>
<td>0.212</td>
<td>0.216</td>
<td>0.309</td>
</tr>
<tr>
<td>$p_{out(i)}$</td>
<td>0</td>
<td>0.102</td>
<td>0.206</td>
<td>0.21</td>
<td>0.208</td>
<td>0.204</td>
<td>0.721</td>
</tr>
<tr>
<td>$c_{m, x(i)}$</td>
<td>0</td>
<td>16.81</td>
<td>25.57</td>
<td>26.52</td>
<td>26.66</td>
<td>26.93</td>
<td>31.64</td>
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<tr>
<td>$F_{input(i)}$</td>
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<td>19.64</td>
<td>19.83</td>
<td>20.22</td>
<td>28.88</td>
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<tr>
<td>$F_{pinch(i)}$</td>
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<td>1.636</td>
<td>1.701</td>
<td>1.669</td>
<td>1.606</td>
<td>9.725</td>
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</table>
Table E.26: Simulation of configuration R – low system pressure – small object – opening phase

<table>
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<tr>
<th>Steps</th>
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<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C_{x,i}(i))</td>
<td>5</td>
<td>5</td>
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<td>(C_{y,i}(i))</td>
<td>4.641</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(C_{p,y}(i))</td>
<td>11.22</td>
<td>10.2</td>
<td>10.21</td>
<td>10.21</td>
<td>10.2</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>(C_{r,y}(i))</td>
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<td>20.04</td>
<td>20.43</td>
<td>20.63</td>
<td>20.22</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>(P_{in}(i))</td>
<td>0.309</td>
<td>0.216</td>
<td>0.212</td>
<td>0.21</td>
<td>0.206</td>
<td>0.102</td>
<td>0</td>
</tr>
<tr>
<td>(P_{out}(i))</td>
<td>0.721</td>
<td>0.204</td>
<td>0.208</td>
<td>0.21</td>
<td>0.206</td>
<td>0.102</td>
<td>0</td>
</tr>
<tr>
<td>(c_{m,i}(i))</td>
<td>31.64</td>
<td>26.93</td>
<td>26.66</td>
<td>26.52</td>
<td>25.57</td>
<td>16.81</td>
<td>0</td>
</tr>
<tr>
<td>(F_{input}(i))</td>
<td>28.88</td>
<td>20.22</td>
<td>19.83</td>
<td>19.64</td>
<td>19.25</td>
<td>9.52</td>
<td>0</td>
</tr>
<tr>
<td>(F_{pinch}(i))</td>
<td>9.725</td>
<td>1.606</td>
<td>1.669</td>
<td>1.701</td>
<td>1.636</td>
<td>0</td>
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</tr>
</tbody>
</table>

Figure E.7: Pinch force to input force relation (top) and input force to input displacement relation (bottom) for configuration 1 simulation (low pressure, large object)
Figure E.8: Pinch force to input force relation (top) and input force to input displacement relation (bottom) for configuration 2 simulation (low pressure, large object)
Figure E.9: Pinch force to input force relation (top) and input force to input displacement relation (bottom) for configuration R simulation (low pressure, large object)

Figure E.10: Pinch force to input force relation (top) and input force to input displacement relation (bottom) for configuration 1 simulation (low pressure, small object)

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Figure E.11: Pinch force to input force relation (top) and input force to input displacement relation (bottom) for configuration 2 simulation (low pressure, small object)
**E-3: Visualization (High pressure, small object)**

The following images visualize the movement of the cylinders for the case of pinching a small object on high pressure. The piston of the input cylinder is shown by x-in, for the piston for the MA cylinder this is shown by x-t, for the switch cylinder by x-s and for the testing cylinders by y-o for the object and y-r for remaining fingers of the hand. The hydraulics is indicated by a blue colour, grey for the pistons and cylinder housings and red for the springs used.
**Configuration 1 steps:**

1. Initial position
2. Hitting the object
3. Switching pressure
4. Port 1 closes (port 2 still closed)
5. Both ports closed
6. Port 2 opens
7. Increasing pinch force
**Configuration 1 steps:**

8. Initial switch pressure (no switching)
9. Return switch pressure
10. Port 2 closes, IMA cylinder is stuck
11. Both port closed
12. Port 1 opens
13. Release object
14. Return to initial position, Input cylinder cannot move back further
Configuration 2 steps:
1. Initial position
2. Hitting the object
3. Switching pressure
4. Port 1 closes (port 2 still closed)
5. Both ports closed
6. Port 2 opens
7. Increasing pinch force
Configuration 2 steps:
8. Initial switch pressure (no switching)
9. Return switch pressure
10. Port 2 closes, IMA cylinder is stuck
11. Both port closed, IVery low input pressure, due relatively high output pressure
12. Port 1 opens, IImmediate drop in output pressure
13. Release object (step 12 = step 13)
14. Return to initial position, IInput cylinder cannot move back further
**Configuration R steps:**

1. Initial position
2. Hitting the object
3. Switching pressure
4. Port 1 closes
5. Port 1 closed, MA cylinder not moving
6. MA cylinder starts moving
7. Increasing pinch force
Configuration R steps:

8. MA cylinder on return position
9. Initial switch pressure (start switching)
10. Return switch (step 10 = step 9)
11. Port 1 opens
12. Switch on return position
13. Release object
14. Return to initial position
Appendix F: Risk Analysis

The main risk of the VMA mechanism is the occurrence of a leakage. The consequence of this occurrence is failure of achieving the required pinch forces, or pinch all together. The appendix focuses on the main risk, leakage, by means of a tree diagram showing the different causes for leakage in Figure F.1.

![Tree diagram showing the risk of the different leakage causes](image)

Figure F.1: Tree diagram showing the risk of the different leakage causes

Table F.1 indicates which of the causes has occurred (shown in red) and proposes a solution for each cause. In addition, successful solutions are shown in green, failed solutions are shown in red and partly successful solutions are shown in orange colour.

<table>
<thead>
<tr>
<th>Occurrence</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sharp edges near O-ring movement</td>
<td>The O-ring moves near sharp edging during the assembly of the input and switch cylinder. Since both cylinders were designed with a cylindrical pipe, the pipe could easily be cleared of sharp edges.</td>
</tr>
<tr>
<td>Weak sealing design</td>
<td>Limiting the number of parts would greatly improve a weak sealing design.</td>
</tr>
<tr>
<td>Low O-ring compression</td>
<td>By choosing a low O-ring compression (8%) the risk of leakage enlarges. The solution would be to increase the O-ring compression, but it is chosen not to do so due to otherwise increased friction</td>
</tr>
<tr>
<td>Wrong dimensions</td>
<td>Automatic dimensioning software would solve the risk of forwarding wrong dimensions</td>
</tr>
<tr>
<td>Wrong or missed tolerance</td>
<td>External drawing checks of a professional as well as good communication between designer and manufacturer about the function of the prototype would greatly reduce the risks of wrong and missed tolerances</td>
</tr>
<tr>
<td>Fabrication</td>
<td>Too big O-ring Chambers</td>
</tr>
<tr>
<td>-------------</td>
<td>------------------------</td>
</tr>
<tr>
<td></td>
<td>Too small shaft fitting</td>
</tr>
<tr>
<td></td>
<td>Too big shaft fitting</td>
</tr>
<tr>
<td></td>
<td>Concentricity</td>
</tr>
<tr>
<td></td>
<td>Wrong dimensions</td>
</tr>
<tr>
<td></td>
<td>Bad surface roughness</td>
</tr>
<tr>
<td></td>
<td>Sharp edges</td>
</tr>
<tr>
<td>Assembly</td>
<td>Scratchy cylinder housing</td>
</tr>
<tr>
<td></td>
<td>Ripping O-ring by sharp edges</td>
</tr>
<tr>
<td></td>
<td>Ripping coupling O-ring by metal reinforced hoses</td>
</tr>
<tr>
<td></td>
<td>Overused m3 sealing rings</td>
</tr>
<tr>
<td></td>
<td>Incomplete Adhesive padding</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>O-ring misalignment</td>
</tr>
<tr>
<td></td>
<td>O-ring outside tolerance region</td>
</tr>
<tr>
<td></td>
<td>Hose failure by overpressure</td>
</tr>
<tr>
<td></td>
<td>Bad hose surface roughness</td>
</tr>
</tbody>
</table>
Sometimes a solution to one of the risk of leakage occurrence could in cause or influence another risk. It is important to take these situations in to account. Some have been briefly mentioned in table F.1, others have not. All situations are listed below.

- The design of cylindrical pipes is not mainly done against the sharp edges, but it turned out to be a good solution. On the other hand, by increasing the amount of parts, the risk on leakage is increased. The same counts for the use of 2 different for the O-ring chambers.
- The thin copper sheet to reduce the risk of leakage could potentially increase the risk if not done correctly. The sheet should not overlap itself and only have a small gap between the start and the end that could be filled up with glue. Another risk not related to leakage would be the increase of friction, such that the VMA requirement might not be met.
- The use of the metal reinforced hoses greatly reduced the risk on friction caused by a high pressure, but in turn increased the risk of damaging the O-rings in the couplings, thus yet an additional solution had to be performed.
- The sealant which was used to make the cylindrical pipe leak proof was curing at unwanted places as well. The cured glue acted as a sharp edge damaging the O-rings and needed to be removed, risking scratching of the cylinder housing as well.
Appendix G: Technical Drawings

The following pages are a sum up of all the different cylinders designed into a prototype. It shows 3D rendered images as well as the construction drawings of the main part of the cylinder.

G-1: Assembly

Figure F.1 shows the cylinders attached on a metal plate, hydraulic tubes are not shown. Cube in the background represents the weight which is used instead of the transmission spring for the configuration 1S (Figure E.X). The weight is attached with a rope to the bolted piston of the transmission cylinder. The sensor to measure the output force is indicated by the green rectangle. The input cylinder is not shown in this assembly as it is not to the metal plate. Figure F.2 shows a cross-section of the assembly. On the left, the test cylinder is shown, mimicking the behaviour of the Delft Prosthetic Hand. The spring shown in the hollow tube acts as the stiffness of the prosthetic glove and the green bar symbolizes the pinched object.

![Figure F.1: Assembly of the cylinders, excluding the input cylinder, on a metal plate](image)

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Figure F.2: Assembly of the cylinders, cross-section view
G-2: Input cylinder
G-3: Switch cylinder
Switch Hole - part 1
SwitchCylinder
**G-4: Mechanical advantage (MA) cylinder**
G-5: Testing cylinders
G-6: Valve
G-7: Assembly plate
Appendix H: Test procedure

This appendix describes the different testing configurations that have been used during the testing phase. Aside from the prototype described by Appendix G, the testing face uses a testing machine that could measure the motion and force of the input cylinder. The motion is controlled by a manual wheel handle, the output force is measured by placing a metal rod in line with one of the testing cylinders connected to a force sensor and the pressure in the system is measured by a pressure sensor, all shown in Figure H.1.

![Testing setup showing the prototype as well as the different sensors and testing machine](image)

Figure H.1: Testing setup showing the prototype as well as the different sensors and testing machine
The testing plan consists of 2 sections.
- Testing individual cylinders
- Using each testing configuration on a low pressure

The thoughts and details behind each section will be explained briefly in this paragraph. This will be done using schematic drawings of the configurations. The drawings represent the different objects of the design as well as sensors used for the testing. Figure H.2 shows the different drawings used to represent the configurations. Because the practical testing is done for a lower pressure, the stiffness of the springs are adjusted to a lower stiffness accordingly.

![Symbols used for the testing configurations drawings](image)

*Figure H.2: Symbols used for the testing configurations drawings*
**H-1: Part: Testing individual objects.**

The goal of the testing of individual objects is to check if all objects behave as intended (e.g. having the correct transmission ratio). The testing is explained by a schematic drawing of the set up.

**Input cylinder and test cylinders:**

**Setup:**

![Testing setup for input cylinder and testing cylinder](image)

**Procedure:**

Actuate the input cylinder by three different weights (0.5, 1.0, 1.5 and 2.0 kg)

Repeat 2 more times

**Measure:**

Output pressure, Output force

**Theoretical Outcome & Results:**

Figure H.4 shows that the cylinders are behaving as expected. Expected values exclude friction, so measured values could be slightly lower than the expected value. The odd thing is that the measured pressure is more similar to the expected value than the output force.

![Measured and expected results of the input cylinder input pressure and testing cylinder output force](image)

**Test cylinder spring**

**Setup:**
Procedure:
Actuate the test cylinder until the spring is fully compressed (testing closing fingers)

Measure:
Input force

Results:
17 N for the weak spring (low pressure)
Thus the switching pressure should be at 95% of the compressed spring force:
16 N for the weak spring (low pressure)
MA cylinder – no weight:

**Setup:**

![Diagram of MA cylinder setup]

**Procedure:**
Actuate the input cylinder by three different weights (0.5, 1.0, 1.5 and 2.0 kg)
Repeat 2 more times

**Measure:**
Output pressure

**Theoretical Outcome & Results:**
Figure H.7 shows that the measured values are lower than the expected values. The expectation is not wrong, as the slope of the 4 dots clearly shows that the resulting mechanical advantage is correct. The friction in the MA cylinder is causing the measured value to be much lower.
Figure H.7: Measured and expected results of the pressure while using the MA cylinder

MA cylinder –weight:

Setup:
Procedure:
Actuate the input cylinder by a weight at the switch pressure, $P_s$ (see Switch cylinder – spring test)
The valve must be open.

$$M_{actuated} = \frac{P_s \cdot 0.25\pi \left(12^2 - 5^2 \right)}{g}$$

Required weight to actuate input cylinder at low switching pressure: 1.96 kg

Measure:
The required weight

Theoretical Outcome:

$$F_i = c_{w, f} P_s \left(1 - \frac{1}{\alpha_1} \right) = 1.65 \text{ kg}$$

Results:
The tests have been performed with known weights (Table H.1) on the MA cylinder. Interpolation
between the weights is required to calculate the actual outcome.

$$F_i = 1.5(kg) - \frac{(2.4(bar) - 2.06(bar)) \cdot (1.5(kg) - 1(kg))}{2.4(bar) - 1.8(bar)} = 1.2 \text{ kg}$$

The outcome is lower than the expected value due to the large friction in the MA cylinder.

Table H.1: Test results of the required input pressure for a giving weight on the MA cylinder

<table>
<thead>
<tr>
<th>Weight</th>
<th>pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 kg</td>
<td>1.8 bar</td>
</tr>
<tr>
<td>1.5 kg</td>
<td>2.4 bar</td>
</tr>
<tr>
<td>2 kg</td>
<td>3 bar</td>
</tr>
</tbody>
</table>

Switch cylinder – no spring

Setup:

Figure H.9: Testing setup including switch cylinder without spring
**Procedure:**
Actuate the input pressure by means of a compressor, until switching occurs.
Repeat 2 more times

**Measure:**
Input Pressure, Output pressure

**Results:**
Switching occurs at 1 bar for each test. This is the minimum friction of switch cylinder.

<table>
<thead>
<tr>
<th>Switch (bar)</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

Switch cylinder - spring

**Setup:**

*Figure H.10: Testing setup including switch cylinder including spring*

**Procedure:**
Actuate the input pressure by means of a compressor, gradually increase and then decrease until the switch moves back. Repeat until switch occurs at the converted switch pressure $P_{s,c}$.

**Measure:**
Input Pressure, Output pressure, Tightened distance
Theoretical Outcome:

\[ P_s = \frac{95\% \cdot \text{spring compression}}{0.25\pi \cdot 10^2} \]

\[ P_s = \frac{16}{0.25\pi \cdot 10^2} = 2.06 \text{ [bar]} \] (Low pressure)

For configuration 1: \( F_s = P_s \left( MA_T \left( c_{s1a,a} - c_{s2a,A} + c_{s2b,a} - c_{s3b,A} + c_{s3a,A} \right) \right) \)

For configuration 2: \( F_s = P_s \left( \frac{1}{MA_T} \left( c_{s1a,a} - c_{s2b,A} + c_{s2a,a} - c_{s3b,A} + c_{s3a,A} \right) \right) \)

\[ P_{s_c} = \frac{F_s}{c_{s2a,a} - c_{s3b,A} + c_{s3a,A}} \]

\( P_{s_c} \) (Low pressure, configuration 1) = 7.2 [bar]

\( P_{s_c} \) (Low pressure, configuration 2) = 2.2 [bar]

Results:
The results show the required pretension of the spring for low pressure switching. It is used for the setup of part 2 of the testing phase. The theoretical outcome switch pressure \( P_s = 2.06 \text{ bar} \), will be evaluated in part 2. The required pretension for the different configuration can be found in table

Table H.3: Required pretension of the configuration 1 switch spring at low pressure

<table>
<thead>
<tr>
<th>Switch (bar)</th>
<th>Tightening distance (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2</td>
<td>0</td>
</tr>
<tr>
<td>2.4</td>
<td>1.5 mm (1 stroke)</td>
</tr>
<tr>
<td>2.6</td>
<td>3 mm</td>
</tr>
<tr>
<td>2.8</td>
<td>4.5 mm</td>
</tr>
<tr>
<td>7.2</td>
<td>37.5 mm (extrapolation)</td>
</tr>
<tr>
<td>7.2</td>
<td>4.5 mm (+33mm adapter)</td>
</tr>
</tbody>
</table>

Table H.4: Required pretension of the configuration 2 switch spring at low pressure

<table>
<thead>
<tr>
<th>Switch (bar)</th>
<th>Tightening distance (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>2.2 bar</td>
<td>4 mm</td>
</tr>
<tr>
<td>2.4</td>
<td>8 mm (max)</td>
</tr>
</tbody>
</table>

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Valve Cylinder

Setup:

![Testing setup including MA cylinder and Valve cylinder](image)

Procedure:
Actuate the input cylinder with the valve closed until the MA-cylinder is at half way position. Open the valve and return the testing cylinder to initial position. Close the valve and try to move back the input cylinder, note if the pressure drops below 0. Open the valve.

Measure:
Output pressure, input displacement, check of the MA cylinder moving back

Results:
Pressure did not drop below zero, because the sensor is unable to measure below 0.4 bar. The MA getting stuck when the valve is closed and able to move when the valve is opened was observed optically.
**H-2: Part 2: Testing of the different configurations on low pressure**

By testing the different configurations of the design it can be tested if the variable mechanical advantage mechanism actually works. Since the different configurations have each a different switching pressure, it is important to calibrate the switch spring such that the switching pressure for each configuration is approximately the same. The different testing setup configurations are shown below.

**Configuration 1**

![Figure H.12: Testing setup for configuration 1](image)

**Configuration 2**

![Figure H.13: Testing setup for configuration 2](image)
Calibrating of the switch spring

Procedure:
Extract and retract input cylinder and tighten spring such that it switches at 2.06. Validate the results with part 1: testing of the individual switch cylinder.

Measure:
Tightened distance, output pressure

Results:
Figure H.15 shows the graph showing the occurrence of a switch around 22 seconds. The switch pressure is approximately the same as the intended switch pressure of 2.06 bar, therefore the results of the individual spring from section G-3 has been validated.
Testing of the different configurations:

Procedure:
Gradually increase pressure until switch switches, continue up to 5 bar for the output pressure, then gradually recover. During recovery be careful for under pressure, if this occurs, open the valve.

Measure:
Input force, output pressure, displacement, output force

Results:
The testing of the different configuration has not been successful. Figure H.16 how the pressure does not increase after switching to stage 2 of the VMA mechanism around 2.06 bar. A leakage has been identified in the switch cylinder which presumably is causing the issue. One other thing could be observed just before system failure, which is the exceptionally high required input force during the switch procedure, shown by Figure H.17. The spike is caused by the choice of the spring stiffness. Originally the pressure while switching should not exceed more than 5% as determined by the spring calculation of Table D.15. Due to testing at a lower pressure, a different spring was used.
Figure H.16: System pressure during configuration 2 testing. Closing the hand is indicated with the blue line and opening the hand is indicated with the red line.

Figure H.17: Input force during configuration 2 testing. Closing the hand is indicated with the blue line and opening the hand is indicated with the red line.