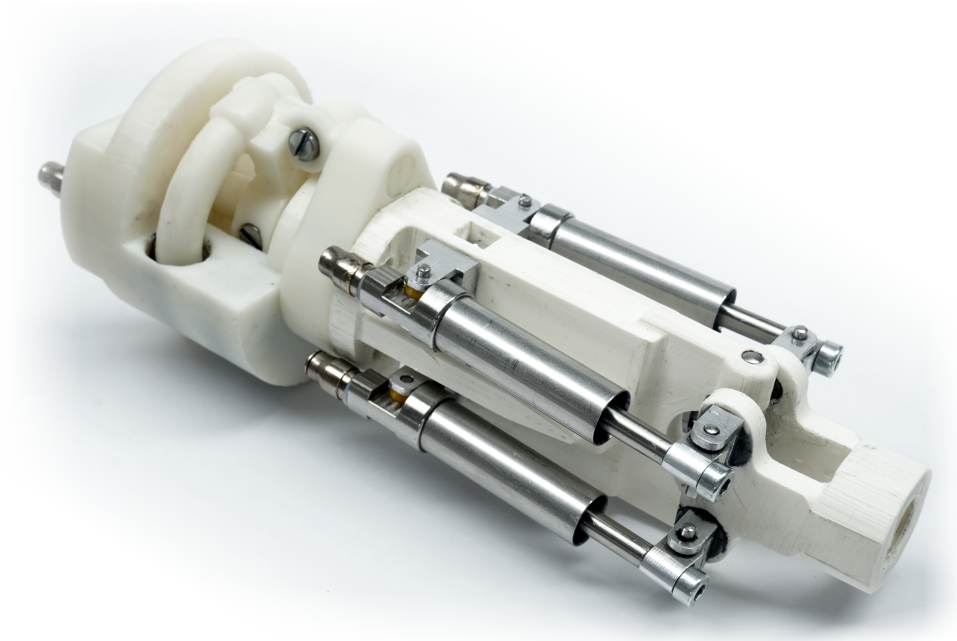


A New Take on Prosthetic Wrists

**The Development of a 3 DoF, Hydraulically Powered Wrist
Prosthesis**

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**In partial fulfillment of the requirements for the degree of
Master of Science in BioMedical Engineering**

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February 11th, 2020

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Preface

Two major things happened during the past year. I got the opportunity to do an internship at the University of Salford (UK), which was my first time abroad for longer than 2 weeks, and I completed my thesis. My thesis perfectly describes what I want to do since I was young: help people using technological knowledge and engineering.

My journey in BioMechanics started at the Hague University, where I studied Human Kinetic Motion Technology. I decided to continue studying, this time a master at the Delft University of Technology. The master BioMedical Technology tries to bridge the gap between living organisms and technology, often combining knowledge of both areas. My thesis project, developing a wrist that could replicate the motions of the human wrist, matched that ideology very well. There were tons of different experiences throughout my master thesis project. Although the main part of my project was to design a wrist, evaluation and manufacturing were also part of the process. During my project, I met multiple people who helped me create and test my final prototype. I would like to use this opportunity to thank everyone who helped me.

First and foremost, I would like to thank Gerwin Smit for his supervision and guidance throughout the project. I would like to thank Jan Frankenhuyzen for his advice during the design phase, as well as the 3D printing of most of the parts and Jos van Driel for the materials and advice during the evaluation phase. Finally, I want to thank my friends, girlfriend, and family for supporting me not only during my graduation project but throughout my whole academic period.

Contents

1	Introduction	1
1.1	Prosthetic Wrists	1
1.2	Current 3 DoF Wrists	2
1.3	Problem Definition	2
1.4	Goal	2
1.5	Overview	2
2	Design requirements	2
2.1	Movement Requirements	2
2.2	Functional Requirements	3
2.3	Size and Mass Requirements	3
2.4	Non-significant Requirements	3
3	Final Design	4
3.1	Design process	4
3.2	Front Half Design	4
3.3	Back Half Design	4
3.4	Prototype Development	5
3.5	Control	6
4	Evaluation	7
4.1	Variables	7
4.2	Test Setup	7
4.3	Protocol	7
5	Results	9
5.1	Weight and Size	9
5.2	Force	9
5.3	RoM and Stability	10
5.4	Static Friction	10
6	Discussion	10
6.1	Observations	10
6.2	Recommendations	11
7	Conclusion	12
	Appendix A Early Sketches	15
	Appendix B Concepts	17
	Appendix C Revising Pro-/supination	21
	Appendix D Technical Drawings	22
	Appendix E Matlab Code	22

A New Take on Prosthetic Wrists: The Development of a 3 DoF, Hydraulically Powered Wrist Prosthesis

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Abstract

Background: While new prosthetic hands are developed to increase functionality and allow more complex movements, prosthetic wrists are researched less. Although there are wrists available, primarily featuring 1 degree of freedom (DoF), only a few prototype 3 DoF wrists are currently known. These 3 DoF wrists usually have sufficient range of motion (RoM), but they fail in delivering high torques while being lightweight and compact, which can increase chances of rejecting the prosthesis.

Objectives: The purpose of this study is to design and evaluate a conceptual 3 DoF wrist that is capable of replicating the RoM of the human wrist while keeping the size and mass as low as possible. Furthermore, the wrist needs to be able to deliver more torque than existing 3 DoF wrists.

Results: A functional 3 DoF prototype was created. The design is actively controllable using three motors and pumps but can also adapt to different surroundings if the motors are off. The prototype is capable of a total range of motion of 142° for flexion/extension and 90° for ulnar/radial deviation and can provide estimated torques of 4.52 Nm and 7.29 Nm respectively. Pro-/supination was not measured, but can provide a theoretical RoM of 134° and torque of 8.9 Nm. The complete wrist has a length of 150 mm and a diameter of 50 mm at the thickest part, and a mass of 166 g (including fluid).

Conclusion: A 3 DoF wrist that is theoretically able to provide more torques than previously researched wrists is successfully designed and tested. The available RoM approaches the required RoM, except for pro-/supination. Future research should primarily focus on measuring the front part of the wrist using higher pressure. The 3D printed pro-/supination part of the wrist should be further researched to improve RoM and remove leakage while pressurized.

1 Introduction

1.1 Prosthetic Wrists

The forearm and hand are capable of four general movements. The hand can be used for grasping or pinching objects, the wrist for rotating the hand up and down (flexion/extension) or from side to side (ulnar/radial deviation) and everything between the wrist and elbow rotates the hand around the forearm (pronation/supination). Upper limb deficiency, often caused by accidents, removes some or all of the functions (degrees of freedom) of the forearm and hand. Functional prostheses are devices that can be attached to the remaining part of the limb, replacing some of the functions of the missing part of the upper limb. A prosthesis replacing the forearm often has a functional terminal device, such as an artificial hand or a hook. Due to the complex nature of the hand, with multiple articulating fingers that can adapt to different objects and situations, more complex ter-

minal devices are developed to make up for the loss of function. One of these examples is the Delft Cylinder Hand, using hydraulic cylinders to actuate the fingers.¹ However, development of prosthetic wrists is advancing more slowly, while research suggests that the wrist function is important and sometimes prioritized as research goal by users.^{2,3}

Users of prostheses without wrists can perform most activities of daily living (ADL) tasks by using other body parts. Other joints, such as the shoulder and upper back, are used to compensate for the loss of degrees of freedom (DoF) of the wrist.⁴⁻⁶ However, this causes an increase in muscle activity of the muscles of the shoulder and upper back, which can lead to muscle fatigue and joint injury.^{7,8} Re-introducing one or more DoF using prosthetic wrists improves the use of the prosthesis by decreasing compensatory motions of the shoulder and upper back, and improving the natural movement of the user.⁹⁻¹¹ Furthermore, com-

fort and appearance increase subjectively for the user.^{10,12}

1 DoF wrists^{13,14} are the most abundant of the currently available wrists and often support pro-/supination or flexion/extension. 3 DoF wrists¹⁵ are scarce but support all movements of the wrist and forearm combined. The available wrists are either rigid, passive or actuated. Actuated wrists are moved using a harness around the shoulder (body-powered), or using motors and batteries (electrically powered).

In the end, upper limb deficiency, especially regarding the forearm, causes loss of function. This loss can cause fatigue and injury of the (over)used muscles, which can be partly compensated by implementing a wrist with at least 1 DoF.

1.2 Current 3 DoF Wrists

Few wrist prostheses are capable of 3 DoF.¹⁶ While they show promising and innovative features, the prostheses are still heavy (>500g).^{17,18} Moving a heavy prosthesis requires more force, causing fatigue. The materials used, like motors and large metal cylinders, contribute to this mass. Moreover, they also increase the overall size of the wrist in length and diameter. Furthermore, these wrists are not yet capable of achieving the same parameters as the healthy wrist. For example, torques that the wrists can generate are lower than those generated by the healthy wrist. Lastly, healthy wrists can adapt to the environment, while prosthetic wrists are usually incapable of doing that and need to be actively actuated to move. Ultimately, lowering the mass and increasing the torque can improve the functionality. Furthermore, facilitating control, partly by incorporating a flexible mode, can improve ease of use and reduce fatigue.

1.3 Problem Definition

Current 3 DoF prosthetic wrists do not allow the user to make use of the full potential of a healthy human wrist in terms of torque while maintaining a low profile and low mass. Furthermore, few 3 DoF wrists incorporate a flexible mode.

1.4 Goal

The purpose of this study is to design and evaluate a conceptual 3 DoF wrist (primarily for the

Delft Cylinder Hand) that is capable of replicating the movements and torques of a healthy, human wrist while keeping the size and mass as low as possible. The wrist should be able to adapt to surroundings without active control.

1.5 Overview

This paper will first describe the design requirements used throughout the design phase. Next, the final design, material selection, and manufacturing methods will be explained. Reported next are the evaluation and results, followed by the discussion and conclusion of the paper.

2 Design requirements

2.1 Movement Requirements

Degrees of freedom: There are few prosthetic wrists with 2+ DoF. The goal of this project is to allow all DoF of the healthy wrist and forearm. Therefore, the design of the wrist has to accommodate pro-/supination, flexion/extension, and ulnar/radial deviation.

Range of motion: The range of motion (RoM) of the healthy hand is used in an attempt to mimic the same range of motion of the wrist. Previously conducted literature research collected the mean of the maximum values of the 3 DoF. The results show that the minimum RoM for all movements are: 75° flexion and 65° extension, 20° radial deviation and 35° ulnar deviation, 80° pronation and 80° supination (Table I).¹⁹ The prosthetic wrists that are currently documented provide more RoM than required, with exceptions like in the wrist developed by Mahmoud, Ueno, and Tatsumi (2010), which provides a total RoM of 18.6° for ulnar/radial deviation.²⁰

Table I: The RoM of the healthy wrist. All values are the mean of different maximum values found in literature.

Movement	Healthy wrist (°) ¹⁹
Pro-/supination	80/80
Flexion/Extension	75/65
Ulnar/radial deviation	35/20

2.2 Functional Requirements

Actuation: The wrist should be actively controlled, either using body-powered control or using electronics. The movement of the wrist can be actuated using electrically powered components such as motors but also using pneumatics or hydraulics.

Torques: It is preferred that the prosthetic wrist can produce the same maximum torque as a healthy wrist. The maximum possible torque of males was investigated to take all possible users of the wrist into account. However, these values were high and it was deemed unfeasible to generate those torques during the design process. Therefore, the revised requirement states that the torque generated by the prosthetic wrist should be equal to or more than current wrists found in literature. Table II shows the maximum torque for the healthy wrist and prosthetic wrists that can be found in literature, where the underlined values are used as a requirement.

Flexibility of the wrist: One feature that seems to be missing from almost every prosthetic wrist, is adaptability. Healthy wrists can adapt to the environment, for example, bending the wrist when pressed against a wall. Incorporating this into a prosthetic wrist shows that this is especially useful during reaching phases, where the subject reaches out to grab an object.²¹ Therefore, the design should be equipped with the possibility to implement a flexible mode. By keeping in mind a system that can allow the user to switch between two modes, ease of use may be improved.

2.3 Size and Mass Requirements

Diameter: The diameter of the wrist is important for improving the appearance. A wrist that is proportionally too large will attract attention, which is often unwanted by the user and can cause

rejection of the prosthesis. The mean diameter for the healthy wrist (50mm^{22,23}) is used in previous design studies for prosthetic wrists. This diameter gives some working room during the design process but is narrow enough to fit most of the population. Therefore, this study will use a circle with a diameter of 50mm as a boundary for the thickness of the wrist.

Mass: Mass is an important factor in prostheses. More mass, especially distally from the elbow, could cause fatigue due to the momentum needed to bend the elbow. This could cause rejection of the prosthesis. Of the 12 wrists investigated by Bajaj et al. with an established mass, 7 wrists weigh equal to or more than 200 g regardless of the number of DoF. Because this wrist is mainly designed to work together with the Delft Cylinder Hand which is around 300 g, the mass of the wrist has to be equal to or lower than 500g-300g = 200g. However, in literature, the maximum mass for a prosthetic hand is 500 g.^{24,25} Subtracting the mass of a healthy hand, which is roughly 400 g,²⁶ leaves 100 g for the prosthetic wrist. Ideally, the wrist should weigh less than 100 g.

2.4 Non-significant Requirements

The following requirements are important for later iterations of the design. Although they will not have a high priority in this early stage of the design process, they play an important role in the final product phase when the design is prepared for commercial release. These requirements are therefore included.

Stability: The stability of the wrist is important to prevent unwanted movements when using the wrist. Stability translates to the number of degrees that the wrist can freely move due to slack in the joints. Ultimately, there should be no slack in the

Table II: The maximum torques of the healthy wrist compared to those of researched prosthetic wrists. Underlined values are used as requirement.

Movement	Healthy wrist ¹⁹	Prosthetic wrists ^{18*}
Pro-/supination	8 Nm	<u>4.2 Nm</u>
Flexion/Extension	12 Nm	<u>4.5 Nm</u>
Ulnar/radial deviation	10 Nm	<u>4.5 Nm</u>

* Theoretical values, have yet to be proven in literature.

wrist joint at all, whether the wrist is actively actuated or not.

Part count: The part count of the prosthetic wrist should be kept as low as possible. This improves manufacturing, assembling and wear and tear when the wrist is in use. Furthermore, it should decrease the difficulty of replacing parts.

3 Final Design

3.1 Design process

The design process consisted of multiple stages. Appendix A shows the early design phase where 11 simple sketches were formed, Appendix B shows the final choice of concept and Appendix C shows the problem that arose during designing the pro-/supination part of the wrist and the found solution. Lastly, the technical drawings are addressed in Appendix D.

3.2 Front Half Design

Figure 1 shows the final design for the flexion/extension and ulnar/radial deviation part of the wrist. The design consists of the main body, a hinge that connects the main body to the hand connector and four single-acting hydraulic cylinders that actuate the hand connector. The design bears a resemblance to the flexible wrist developed by Montagnani et al. (2017) due to the parallel setup of the cylinders.²⁷

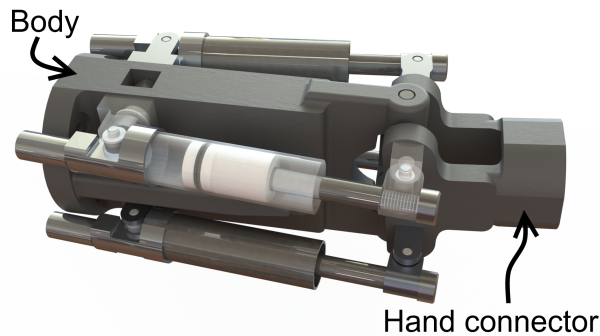


Figure 1: The final concept for flexion/extension and ulnar/radial deviation. One transparent cylinder (including hinges) shows the inside. A hinge connects the body and hand connector.

The four hydraulic cylinders are also the largest change compared to the first design, as this used two double-acting cylinders. However, four single-acting hydraulic cylinders were deemed more vi-

able as these had a smaller length and diameter. Hinges that can rotate around two axes connect the hydraulic cylinders to the body and the hand connector, resulting in eight hinges total. The hinges are connected to the body and hand connector using bolts.

The single-acting hydraulic cylinders are placed in a parallel setup, which increases stability and control. An optimization program, written in MATLAB²⁸ (Appendix E.1), used the desired moment and flexion/extension movement to determine the optimal placement of the hydraulic cylinders and the minimal diameter of the piston. The cylinders have an inside diameter of 8mm and a wall thickness of 1mm. An O-ring of 6x1mm is placed around the piston. The cylinders are placed in such a way that the piston is blocked in the extreme positions without extending beyond the length of the cylinder. The bases of the cylinders are custom made and provide the connection to a fluid tube.

The body is reinforced using multiple ridges to prevent it from bending and breaking. The ridges are formed in such a way that they do not interfere with the movements of the hand connector and cylinders. The body has four M3 threaded holes on the back that allow a connection to the pro-/supination design using standard bolts. The hand connector has a standard M12 threaded hole for connecting the hydraulic hand. The connection between the body and the hinge is made using 3 mm pins, while the connection between the hinge and the hand connector is done using an M3 bolt. The cylinders are connected to the body and hand connector using 2 mm pins and a variety of bolts, nuts, and bearings.

3.3 Back Half Design

Figure 2 shows the design for pro-/supination, which is placed behind the body of the front part. This design consists of two curved pistons and a base with two curved cylinders (single-acting). The idea of curved cylinders was first investigated by Nieuwendijk (2010) and later by Sooryanarain (2016).^{29,30} Karthaus (2019) conducted research with a similar design simultaneously.³¹

The two curved pistons connect to a rotating disk that provides the connection to the front part. The

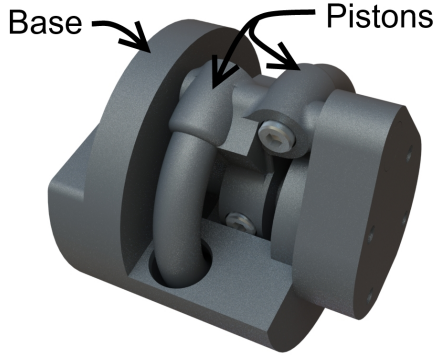


Figure 2: The final concept for pro-/supination using curved cylinders (inside the base) and curved pistons. The pistons are connected to a rotating disk.

base does not only contain the two curved cylinders, but also an internal system that connects the backside of the base to the cylinders. This system removes the need to install fittings on the side of the base, which makes this design more compact and allows the fittings to be installed at the back of the base.

Another optimization program (Appendix E.2) was used to provide the optimal diameter of the pistons and cylinders using the required moment. The cylinders have an inside diameter of 10 mm with a wall thickness of 1 mm. One O-ring of 8x1 mm is used per piston. M3 bolts provide the connections between the pistons and the rotating disks. Earlier iterations of this concept had a higher range of motion. However, due to structural errors, the concept was enforced with ridges, espe-

cially around the base of the pistons where a bolt connected both pistons. Therefore, the concept is less optimized for RoM but does show the working principle without breaking.

3.4 Prototype Development

Figure 3 shows the complete design, without bolts and O-rings. The different colors show the different materials and techniques used to manufacture the prototype.

Yellow: These parts are developed using an FDM (Fused Deposition Modeling) 3D printer, the Ultimaker 3. This printer melts and extrudes solid material and builds a CAD (Computer-Aided Design) model layer by layer. The material immediately solidifies after extrusion. The material used for these parts was PLA, while PVA created the support, a material that can be dissolved in water. The components were printed using a layer thickness of 0.1 mm and an infill of 60% or 70%. The components were printed on their sides as this increased strength in the direction of force. A hand drill was used to enlarge the holes in the prints, as well as additional sanding for smoothing.

Red: This material is 3D printed as well, but using a different 3D printer, the SLA (Stereolithography) Formlabs Form 2 printer. This printer was chosen mainly because of the ability to print without internal support, which allowed the cylinders inside the base to be printed. The printing technique used involves a liquid resin that is solidified layer by layer using a laser. After completion, the model is cured (dried). The model is ready to use

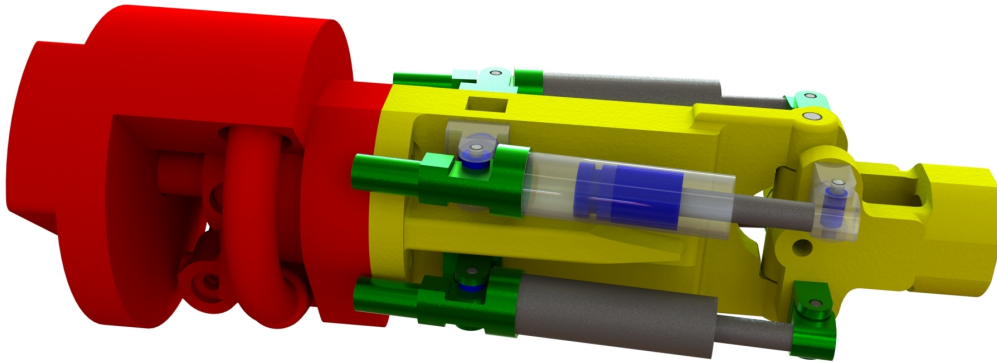


Figure 3: The final concept (without bolts, nuts or O-rings) showing the different materials used for each colored part. The red parts are 3d printed using SLA, the yellow parts are 3D printed using PLA. Connected to the yellow parts are the custom made green parts (aluminum), grey parts (stainless steel) and blue parts (Teflon).

after curing. Selecting a resolution of $50\text{ }\mu\text{m}$ created a smooth surface, which was required for the cylinders and pistons. The material is strong but brittle. It was, therefore, necessary to reinforce the design, increasing the overall strength while decreasing the RoM.

Green: Parts in green were custom made using aluminum in the workshop available for staff members at the TU Delft. The parts used for the base of the cylinders were already custom made and could be used right away. The rest of the parts were created using subtractive manufacturing (e.g. drilling, milling). Some post-processing was necessary for the front hinges, as these did not fit perfectly.

Grey: All grey parts were custom made in the workshop as well, but the material used was stainless steel. The cylinders and tubes in front of the pistons were cut from a larger pipe, while the axles used in the hinges were pre-cut and only required additional cutting if necessary.

Blue: These parts were manufactured using Teflon tubes. This material is suitable for moving parts, to act as a bearing. The flanged bushings inside the back hinges have a double function: they allow smooth rotation between the bolt to the body and the hinge, as well as preventing that the bolt pushes against the hinge. The bearings in the front

hinges and the rings in the back hinges were tight enough to hold the axles in place, without need for additional fixation.

The final prototype, developed using the aforementioned methods, can be seen in Figure 4.

3.5 Control

The design can theoretically be controlled using three motors and pumps. The design for pronation/supination can be controlled by one motor and pump that is connected to both outputs. The flow can be reversed by reversing the current, meaning that reversing the current will determine whether the design pronates or supinates. The design for flexion/extension and radial/ulnar deviation can be controlled using two motors and pumps. Each motor+pump has to be connected to the diagonally opposite cylinders since those never extend or retract at the same time. Actuating both motors will result in a certain movement, determined by the flow directions of each pump. This does not only allow flexion/extension or ulnar/radial deviation but combinations of the two as well (also known as "dart thrower's motion"³²). It is possible to move the pump passively in this configuration, allowing the wrist to be moved using an external force, such as the other hand or pushing the hand against the wall.

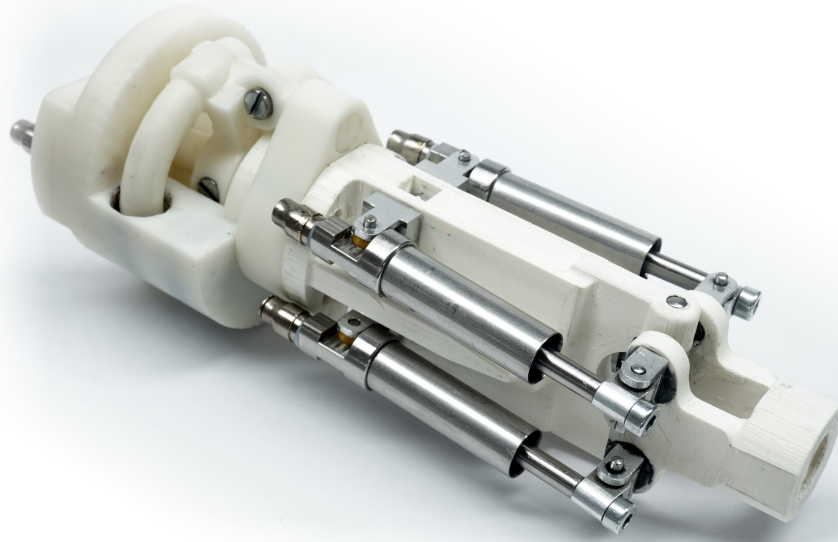


Figure 4: The final, functional prototype.

4 Evaluation

Three types of measurements were performed to evaluate the performance of the front part of the developed wrist. The first evaluation involved measuring the maximum force of the wrist, the second evaluation determined the RoM of the wrist and the third and final evaluation determined the static friction in the system. The Delft Cylinder Hand can withstand 6 MPa (6 MPa).¹ Technically, the wrist prototype should be able to handle similar amounts of pressure as it uses the same hydraulic system, including the same hoses and similar cylinders which differ only in length. However, the available pumps for this experiment were able to generate only 2.5 MPa consistently, as they overheated quickly and could become unreliable when generating more pressure. The pro-/supination part was not measured, as there was not enough time after developing a working prototype.

4.1 Variables

4.1.1 Dependent variables

Pressure (bar): The pressure of the hydraulic system was measured for different voltages. 1 bar is equal to 0.1 MPa.

Force (N): The force was measured in a static situation using different voltages.

RoM (deg): The RoM was measured using a predefined voltage and measured using manual input.

4.1.2 Independent variables

Voltage (V): The voltage was changed by the conductor of the experiment.

Current (A): The current was set on the maximum value of 11 A.

4.2 Test Setup

The pressure of the system was measured using a pressure sensor (Gems Sensors 3100 series, max 40 bar) that was connected closely to one of the hydraulic cylinders of the prototype. To measure the force of the system, a load cell (FUTEK LSB200, maximum force of 445 N) was placed perpendicular to the hand connector using 3D printed parts, which allowed the force to be measured under the most optimal angle (Figure 5). An F-clamp fixated the prototype. The angle was measured using the same setup but by removing the force sen-

sor and inserting a potentiometer (Feteris Potentiometer CP22E). A motor and pump controlled the prototype, using a power source (Power Supply ES 030-5, maximum voltage of 30 V and a maximum current of 11 A). MAGOM oil was used as fluid during testing. A LabVIEW³³ program collected the data of all sensors.

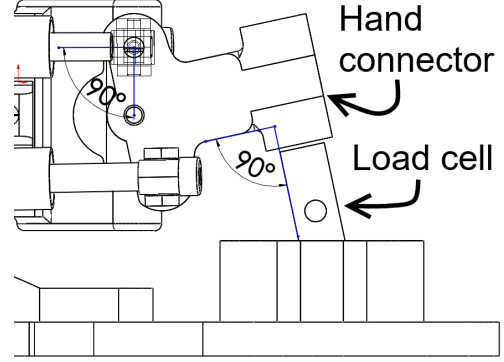


Figure 5: The load cell is perpendicular to the hand connector and the angle between the cylinder and hand connector is optimal. The gap between the hand connector and the load cell is to take into account the extra thickness while 3D printing.

4.3 Protocol

4.3.1 Measuring Weight and Size

The weight and size of both parts of the wrist were measured independently and together. The weight was measured using a digital kitchen scale, with and without fluid. The size of the parts (diameter and length) was measured with a caliper. The hand connector was positioned in the neutral position (as seen in Figure 3) during these measurements.

4.3.2 Measuring force

The force was measured using the setup shown in Figure 6. The top two cylinders were actuated by an open-loop hydraulic circuit with an oil reservoir, while the two cylinders at the bottom were not connected. The measurement started by making sure the hand connector was floating just above the load cell to prevent a starting load. Furthermore, the hand connector was positioned in such a way that it was in a top-down neutral position as much as visibly possible. After positioning the hand connector, the LabVIEW program was started and

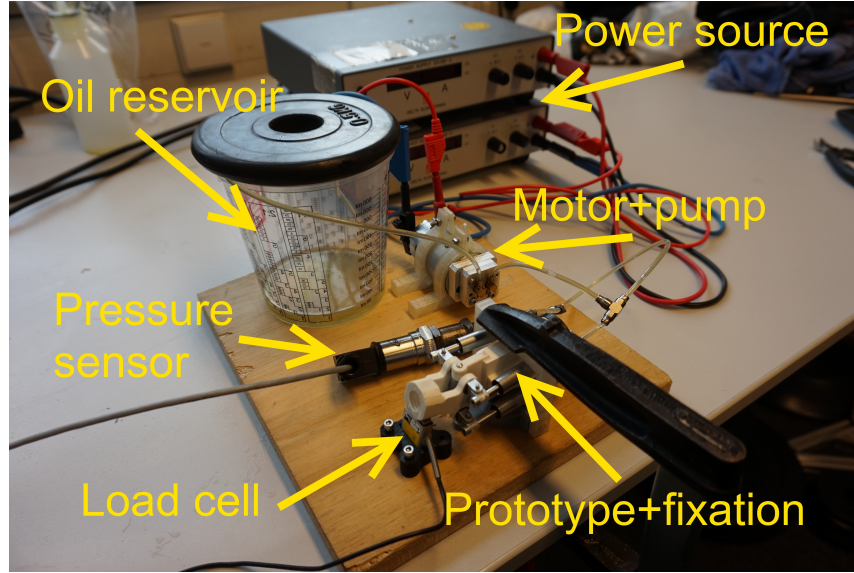


Figure 6: The setup for measuring force. The power source powers the motor, which activates the pump. The pump transfers oil from the oil reservoir to the fixated prototype. The hand connector pushes against the load cell. The pressure is measured using the pressure sensor.

the voltage was slowly manually increased until the pressure reached 26 bar (this made sure that the measurement recorded at least 25 bar). The speed at which this happened was not strictly defined, because the main purpose of this test was to test the linearity of the relation between the pressure and the force. After the 26 bar was reached, the voltage was slowly reduced to zero. Due to the symmetry of the design, the force for both movements could be measured by rotating the wrist 90° . This measurement was repeated 10 times for both movements.

4.3.3 Measuring RoM and Stability

The load cell was removed and the potentiometer added to measure the angle (Figure 7). Five new parts were created using the FDM 3D printer to hold the potentiometer and connect the rotating part to the wrist.

The fixation of the wrist remained the same. Two similar measurements were done to measure the angle. The first measurement involved the motor and pump in a closed-loop circuit (the input in both left cylinders, the output in both right cylinders) to rotate the hand connector as much as possible. The current was reversed after about 3 seconds, which switched the input and output, caus-

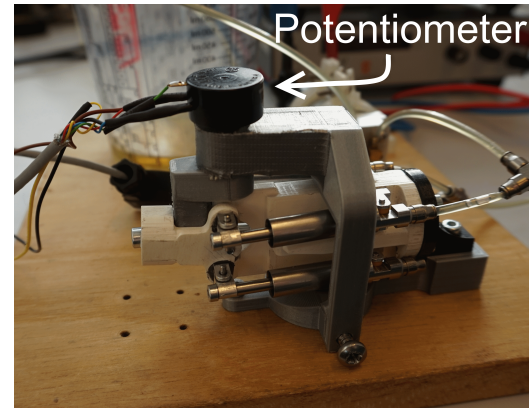


Figure 7: The setup for measuring the angle. The black object on top of the structure is the potentiometer.

ing the wrist to rotate the other way. A voltage of 7 V was used to activate the motor and pump. The back and forth motion of the wrist was performed 5 times during one measurement. The same measurement was repeated but without using the motor and pump. Instead, the hand connector was moved manually. This second measurement was executed to confirm whether the motor could achieve the full range of motion of the design. The prototype could be rotated 90° and the brace to hold the potentiometer replaced to measure movement in the other direction. The stability of the wrist

was measured using the same setup. The wrist was rotated manually with and without actuation of all cylinders. The goal was to measure the slack in the hinges, therefore care was taken that the pistons did not move during this test. The wrist was actuated using 7 V.

4.3.4 Measuring Static Friction

Low static friction improves the responsiveness of the system and allows for better adaptability of the wrist. The same setup as the measurement for RoM was used, except only the left two cylinders are connected to an open-loop hydraulic circuit. The hand connector was positioned in the neutral position. After starting the measurement in LabVIEW, the voltage was slowly increased, until movement occurred. After that, the voltage was reduced to zero, the measurement was stopped and the hand connector was returned to its neutral position. After repeating this measurement 5 times, the prototype was rotated 90° and the same measurements were performed. This was repeated until the prototype was rotated 4 times, which resulted in $4 \times 5 = 20$ total measurements.

5 Results

5.1 Weight and Size

The front part of the prototype weighs 92 g and 94 g with and without fluid respectively. This is 68 g and 72 g for the back part. The front part

has a length of 91 mm and a diameter of 48 mm, while the back part is 59 mm long and has a diameter of 50 mm. The total weight of the prototype is 160 g without fluid and 166 g with fluid. The prototype has a diameter of 50 mm at the thickest point, which is the pro-/supination part of the design. The entire length of the prototype is 150 mm.

5.2 Force

The force in both directions shows linear behavior (Figure 8). From this linearity, the expected torque around 6 MPa (60 bar) can be derived by extending the red and blue lines shown in the same figure. The value found at 6 MPa can be used in the following formula to calculate the moment around the joint.

$$M = F * a \quad (1)$$

Where M is the moment in Nm, F is the force in N and a is the distance between the center of the joint and the point of application of the force in m. Because the exact point of application is difficult to determine due to the thickness of the load cell, different moment arms are used that show the worst-case (the shortest moment arm) and best case (the longest moment arm) scenario. Figure 9 shows the polynomials extended to 6 MPa so that the values of the maximum moments can be determined. The worst-case scenario moment in

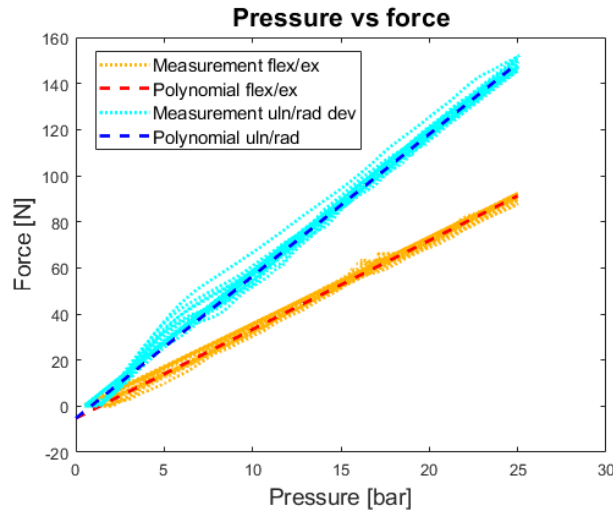


Figure 8: The linear relation of pressure and force for both movements.

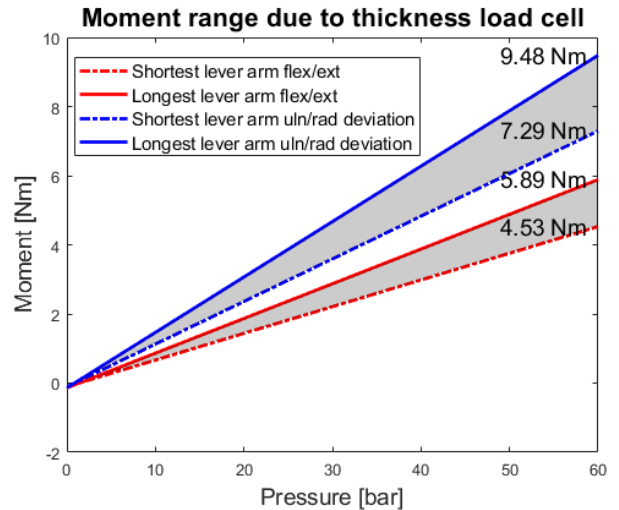


Figure 9: The extended polynomials so that the value around 6 MPa can be determined.

the flexion/extension direction is 4.53 Nm, while the worst-case scenario moment in the ulnar/radial deviation direction is 7.29 Nm. Both torques are likely higher than the minimum values presented due to the thickness of the load cell.

The moment in the pro-/supination direction is not measured. Using the dimensions of the cylinders and pistons, the theoretical force of the cylinders can be derived using the formula:

$$F = P * A \quad (2)$$

F is the force in N, P is the pressure in MPa and A is the surface of the piston in mm². Using a pressure of 6 MPa and an area of 78.5 mm² (using a diameter of 10 mm), the maximum force is 471.2 N. Multiplying this with the moment arm (19 mm) gives a theoretical maximum moment of 8.9 Nm.

5.3 RoM and Stability

The total RoM of both movements is shown in Table III. The angles divided by 2 are the RoM for the individual movements, as the design is symmetrical. This shows that flexion and extension achieved an angle of roughly 71° if moved by motor and pump, and roughly 78.5° while being moved manually. Ulnar and radial deviation reached about 45° while being actuated by motor and pump. Moving by hand caused a rotation of about 44.5°. The RoM of the pro-/supination is measured using SolidWorks³⁴ and is 134.7°.

Table III: The angles of the prototype, tested with a motor+pump and by moving the hand connector manually.

Movement	Motor (°)	Manual (°)
Flexion/Extension	142.4	157.1
Ulnar/radial deviation	90.5	89.3

There is no slack if the wrist is actuated due to the force exerted by the hydraulic cylinders. There is some slack when the wrist is not actuated, although this varies between 1° and 3°.

5.4 Static Friction

The minimal pressure that is needed to move the system is 1.48 bar or 0.148 MPa. The pressure can be used to calculate the amount of friction inside the system with equation 2, where F is the static

friction and A is the surface of both actuated pistons. This results in a static friction force of 14.8 N.

6 Discussion

6.1 Observations

The presented designs offer two parts of a prosthetic wrist that can be used separately or can be combined. Combining both designs creates a 3 DoF wrist with decent torque and RoM. A comparison between the requirements and results can be seen in Table IV. Although the weight of the wrist is higher than the proposed maximum value of 100 g, it is still lighter than most current 2 DoF and 3 DoF wrists. Furthermore, the wrist and the Delft Cylinder Hand V3 combined weigh less than 500 g. The wrist fits inside a circle with a diameter of 50 mm. The entire prototype consists of 103 parts, including bolts and nuts. This is quite a lot of parts, especially considering how small they are. The amount and size of parts increase the production time.

The RoM of ulnar/radial deviation (~45°) and extension (~71°) are higher than the desired RoM while using the motor and pump. The RoM of flexion (~71°) is slightly lower than the desired RoM using the motor and pump, but slightly higher (~78°) when manually moved. The overall stability of the wrist for flexion/extension was high when the wrist was actuated, as there was no slack in the hinges. When the wrist was not actuated, there was some slack (between 1° and 3°), mainly due to some room between the hinge, bolt and hand connector. The RoM of pro-/supination (~67°/~67°) is less than desired as well, caused by the added support to prevent the prototype from breaking.

Controlling all DoF can be done using three motors and pumps. The flow direction determines the specific movements and is changed by reversing the current of the motors. The pro-/supination movement is done separately while the flexion/extension and ulnar/radial deviation movements are combined and controlled using two motors and pumps. Other movements, such as the dart thrower's motion, can also be created using the combined control. If the motors are not supplied with any current, the wrist is flexible and can be moved us-

Table IV: A comparison between the design requirements and results. Values in green meet the requirements, values in red do not. The part count is neither green nor red, as there was no quantitative requirement.

	Requirements	Results
Degrees of freedom	All 3 DoF	✓
Range of motion (flex/ex, uln/rad dev, pro-/sup)	75°/65°, 35°/20°, 80°/80°	71°/71°, 45°/45°, 67°/67° (theoretical)
Torques (flex/ex, uln/rad dev, pro-/sup)	4.5 Nm, 4.5 Nm, 4.2 Nm	4.52 Nm, 7.29 Nm, 8.9 Nm (theoretical)
Flexibility of the wrist	Flexible mode optional	✓
Diameter	50 mm	50 mm
Mass	100 g	166 g (including fluid)
Stability	0° while actuated and not actuated	0° while actuated, 1°-3° while not actuated
Part count	As low as possible	103

ing external forces, such as the other hand or surroundings.

The system could withstand a minimum pressure of over 3 MPa (30 bar) during testing but should be able to withstand at least 6 MPa, considering it uses the same hydraulic system as the Delft Cylinder Hand. Using the linear relation between pressure and force, it can be assumed that the criteria for the moments around all movements are met around 6 MPa. The wrist should be able to generate a torque of at least 4.52 Nm in the flexion/extension direction, and 7.29 Nm in the ulnar/radial deviation direction. This is higher than the mentioned 3 DoF wrists. The criterion for ulnar/radial deviation is already met using a lower pressure of 3.8 MPa (38 bar). The pro-/supination direction is theoretically able to provide a torque of 8.9 Nm at 60 bar, which is higher than the desired torque as well as the torque of the healthy wrist. However, this design is not yet able to withstand 6 MPa, as leakage occurred around 1.6 MPa using the most optimal tested O-ring and groove design. It is likely that the cylinder wall is not smooth enough, causing the fluid to spill through small gaps between the rough surface and the O-ring. After using the prototype a few times, the amount of pressure it could handle decreased until leakage occurred before movement. This was caused by the O-ring slipping out of the groove. Furthermore, black residue on the inner cylinder walls sug-

gests the rough surface of the cylinder could also cause wear on the O-ring.

The static friction of the flexion/extension and ulnar/radial deviation directions is around 14.8 N. An increase of 0.5 bar is needed to move the wrist using the hydraulic cylinders, considering the already present atmospheric pressure of roughly 1 bar. This static friction allows easier adaptation using the environment, as adjustment requires little force.

6.2 Recommendations

Although the prototype is lightweight, the mass can still be improved. The metal parts, mainly the base of the cylinders of the front part, are the heaviest. The mass of these parts could be reduced by using a different material. A suggested method is 3D printing, as this produces lightweight parts. However, the question remains if 3D printed material is strong enough. Besides the weight, a part count of 103 parts is quite high and increases complexity. Reducing the part count might decrease manufacturing time and simplify construction.

It is not known whether the prototype can withstand the amount of pressure (6 MPa) needed to reach the desired moments. Future research should increase the pressure as much as possible to test the limits of the design. The 3D printed parts can be printed using a higher infill (70%+) in case of failure, as these are most likely the weakest.

One recommendation regarding the test setup is to connect the load cell to the hand connector using a string so the load cell measures pulling force instead of pushing force. This removes the variability due to the thickness of the load cell, as the exact point of attachment of the string (and thus the moment arm) can be defined. A different test setup can be used to measure the maximum pressure, where the two working cylinders are connected and weights are added to the end of the cylinder. The maximum pressure can be determined this way.

The flexion/extension direction suffers from an instability in the most extreme positions due to the awkward angle between the cylinder and the direction of the force. The motor and pump can therefore not utilize the full possible RoM. This could be solved by moving the back hinges of the cylinders on the side closer to each other, increasing the range of motion capable by the motor and removing the instability. However, there is a possibility that this hinders the mechanism due to the cylinders colliding. The RoM for pro-/supination can be increased by removing the extra support. It is recommended to investigate different materials to increase the strength and smoothness of the design so that the design can handle more pressure and is less prone to wear.

The wrist is stable while being actively actuated, but there is a slight instability if the wrist is not actuated due to the slack in the hinges. This can be solved by using a different method to connect the front hinges to the hand connector, as the current method causes the bolts to loosen over time.

Another recommendation is to test different kinds of O-rings, such as a U-cup. Although there was no leakage present during the evaluation, this could still happen if the pressure is increased. A U-cup could prevent this from happening and could decrease the static friction.

Finally, the control of the wrist should be re-defined and developed using all three motors and pumps. It is recommended to use a micro-controller like Arduino for control as this allows the different movements to work in conjunction. Disconnecting the pumps while the wrist is flexible would be another improvement, as this would lessen the strain on the unpowered motors.

7 Conclusion

Two designs were presented during this study. Combining these designs created a functional, hydraulic 3 DoF wrist. The movements of the combined wrist include flexion/extension, ulnar/radial deviation and pro-/supination. All movements can be actively controlled using three motors and pumps, or passively adjusted by either using the sound hand or using the environment when the wrist is not powered. The wrist comes close to the healthy wrist in terms of RoM regarding flexion/extension (142°) and radial/ulnar deviation (90°), but can be improved in terms of pro-/supination (134°). The moment measured during the evaluation is linearly related to the pressure. It can be derived that the maximum torques deliverable by the prototype are higher than existing 3 DoF wrists. However, these torques are not fully tested using the required amount of pressure (6 MPa). The torques are 4.52 Nm for flexion/extension, 7.29 Nm for ulnar/radial deviation and a theoretical 8.9 Nm for pro-/supination. Although the manufactured wrist is lightweight, it is still heavier than recommended (100 g). Future research should focus on testing the wrist with higher pressure, making the wrist lighter, and improving the wrist in terms of RoM.

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Appendices

A Early Sketches

A brainstorm session using the requirements resulted in a total of 11 sketches. These sketches are shown in Figure 10. The sketches were compared using a Harris profile to determine the best three ideas. These could be either a single sketch or a combination of two sketches. The scores given in the Harris profile are an estimation of how well a certain sketch would comply with the requirement. A score of -2, -1, 0, 1, 2 is used, where -2 is negative and 2 is positive. The final score determines which Harris profile is the best. Table V shows the Harris profile.

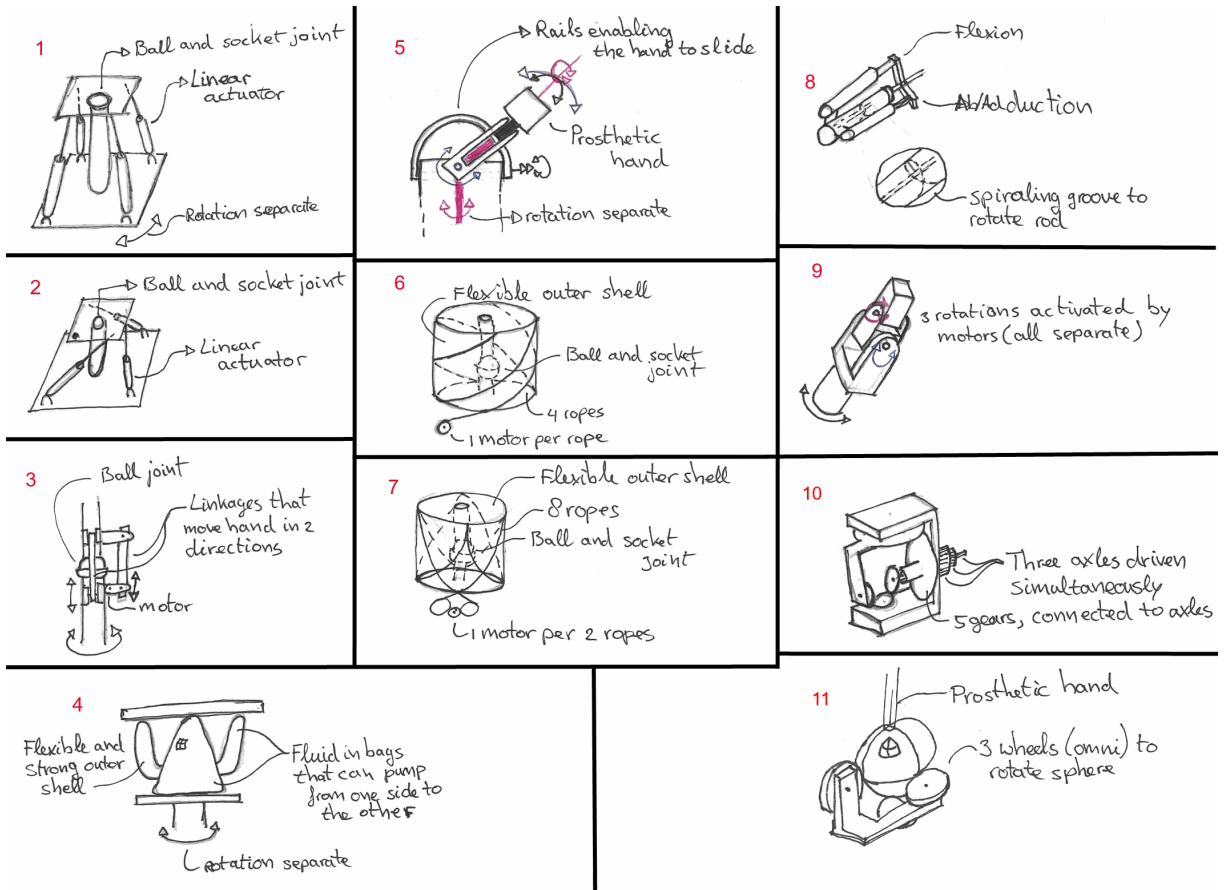


Figure 10: All the eleven sketches.

Sketch 1

A simple ball joint that is actuated with hydraulic linear actuators. The position of the actuators allows two movements, rotation is not included in this concept. There is limited material needed and the torque is high due to the two actuators per movement, but RoM is limited. Stability is greater because of the number of actuators.

Sketch 2

Similar to sketch 2, but the configuration of the hydraulic linear actuators allows all 3 DoF. Not much material is needed, but the RoM is limited. Torques are high but lower than sketch 1, as the angles between the actuators and the working force are less ideal. Hydraulic linear actuators require

maintenance and are susceptible to leakage.

Sketch 3

A ball joint connects two rods, where two linkages can move the hands in two directions. The linkages are powered by electric servos. Rotation is not included in this sketch. The servos are bulky and heavy, depending on the required torque. The linkages allow this mechanism to have a higher RoM than sketch 1 and 2.

Sketch 4

Two plates are connected using a joint (e.g. ball joint), while multiple bags of fluid are placed on the outsides. The fluid inside these bags can be pumped from one side to the other, just like hydraulic linear actuators. Rotation is done separately. The shell of the bags should be flexible and strong but is still susceptible to damage. Stability would be an issue, as there is no rigid structure due to the flexibility of the bags.

Sketch 5

This mechanism incorporates two rails that guide a pin to which the prosthetic hand is attached. The rails themselves can be moved, causing the pin to move. While rotation is separately actuated, the mechanism for rotating the hand is incorporated into the design. Hydraulic linear actuators would move the rails, while a servo motor would rotate the hand. This mechanism is capable of a large RoM, but involves complex parts and movements.

Sketch 6

This design is based on a flexible outer shell with ropes wrapped around it. These ropes are connected to servos, where there is one servo per rope. Multiple servos acting together cause a movement in a certain direction. Rotation is integrated but only powered in one way. The flexible shell returns the mechanism to its original position. While the design itself is lightweight, the servo motors increase the weight. However, it is not needed to have the servo motors mounted on the mechanism itself.

Sketch 7

This design is similar to sketch 6 but uses 8 strings instead of 4. Movement in every direction is powered this way. Four motors are used in total, which increases the weight. However, just like sketch 6, the motors do not have to be close to the mechanism.

Sketch 8

This mechanism uses two hydraulic actuators to perform flexion/extension and radial/ulnar deviation. Rotation is also done via a hydraulic actuator but uses a curved groove. The actuator extends, causing a rod perpendicular to the actuator to move forward. The rod is forced to rotate due to a groove in an outer shell. Around this shell is another shell that can rotate with the rod. Although this design is compact, it causes friction.

Sketch 9

This is a very simple mechanism that is based on three servo motors. These servos are connected in sequence. Each motor represents a movement, resulting in 3 DoF. The ROM of this design can be quite large, but the three motors make it heavy. Furthermore, the stacked motors increase the size of the wrist and cause the movements to be misaligned compared to the healthy wrist.

Sketch 10

This design uses a complex set of gears to allow all DoF that the healthy wrist has. This design is compact but complex in both fabrication and control. Three different axles, powered by servo motors, need to move together to create movement. The gear system will likely introduce slack which decreases the reliability of this design.

Sketch 11

Three wheels, powered by servo motors, rotate a sphere. The wheels only provide friction in the spinning direction, allowing the sphere to rotate freely in the other direction. The servo motors increase the weight, and holding the sphere in place while still allowing a large RoM is difficult.

Table V: The Harris profile comparing all 11 sketches. The underlined total values are the sketches used for the concepts, sketch 5 and 8 are combined into one concept.

	Concept number										
Requirement	1	2	3	4	5	6	7	8	9	10	11
The DoF of the wrist	2	3	2	2	3	3	3	3	3	3	3
Weight of the wrist	1	1	0	1	-1	2	0	2	-1	1	0
RoM of the wrist	0	0	1	0	2	0	0	1	2	2	2
Torques of the wrist	2	1	-1	1	0	0	0	1	0	0	-1
Stability of the wrist	2	2	0	-1	1	-1	-1	1	-1	1	1
Size of the wrist	1	1	0	2	1	2	2	0	-1	2	2
Part count of the wrist	1	1	0	1	-2	1	-1	1	1	0	-2
Total	<u>7</u>	<u>6</u>	0	4	<u>1</u>	4	0	<u>6</u>	0	<u>6</u>	2

B Concepts

B.1 Concept 1

Concept 1 (Figure 11) consists of three rotating tubes that are connected to different outputs. It is based on sketch 10. Each output controls 1 DoF. The possible RoM of pronation/supination is 360° , while being slightly lower than 180° for both flexion/extension and ulnar/radial deviation. The torques of the wrist of this design are the same as the input torques. However, this can be changed by changing the ratios of the gears, sacrificing speed or torque depending on the ratio. The torques remain constant as long as the input torques are constant but are dependent on the torque of the actuation. The design is compact and reliable due to the casing that locks the gears. Actuation can be done by electrical or hydraulic motors. The two possible types of hydraulic motors suitable for this concept are gerotor and external/internal gear motors, although implementing hydraulic motors might prove difficult. This concept requires different gears to work together to require a single movement, which makes control more difficult to implement. Furthermore, gears are susceptible to backlash, which causes small, unwanted movements that could affect stability. Connecting this design to the affected arm is difficult as the design needs to be placed in some kind of brace to function. Although the concept is compact, it is also dense. The tightly packed gears could impact the smoothness of the rotation, and the gears and sturdy frame could cause a higher weight, relative to the other concepts. There are no calculations made for this concept, due to high variability in gear and motor size.

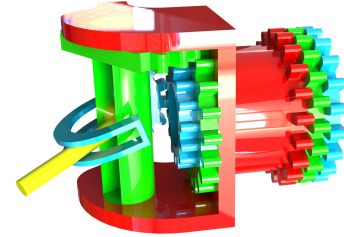


Figure 11: The first concept, based on sketch 10.

B.2 Concept 2

This concept (Figure 12) is less compact than concept 1 but allows for independent movement of all DoF. It uses the actuation methods of sketch 8, but the hinge of sketch 5. This makes control easier. The RoM for flexion/extension and radial/ulnar deviation is slightly lower than 180° due to the movement axis interfering with the hydraulic cylinder. The RoM of pro/-supination can be increased at the cost of torque. Pro/-supination is done via an extending hydraulic cylinder that is forced to rotate due to a curved slot in the outer shell. The order of movements is the same as concept 10, with pronation/supination before flexion/extension and ulnar/radial deviation. The reliability of the concept is dependent on the hydraulic cylinders, which are susceptible to leakage. While this concept is quite compact, it still needs some length for the hydraulic cylinders. However, this also means an increase in stability, and the cylinders are able to generate a higher torque (or moment) due to the moment arm. The torques for flexion/extension and ulnar/radial adduction are non-linear, because of the rotating moment arm. The torque for pro/supination is constant but is dependent on the angled groove. The working principle for rotation causes friction and could lead to early wear, as well as the sliding motion along the grooves.

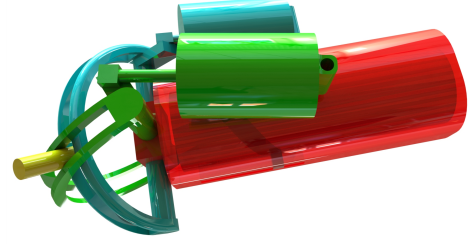


Figure 12: The second concept, which is a combination of sketch 5 and 8.

Some rough calculations were made to compare the concepts. First, the needed inside diameter of the cylinder for flexion/extension of ulnar/radial deviation (depending on which one needs to most force) is calculated. This is done for the ideal position, where the cylinder is in the same working direction as the force.

$$F = \frac{M}{a} \rightarrow F = \frac{4.5Nm}{0.0065m} = 693N \quad (3)$$

Where F is the force [N], M is the moment [Nm] and a [m] the moment arm. This force leads to the following diameter:

$$A = \frac{F}{P} \rightarrow A = \frac{693}{6} = 115.4mm^2 \quad (4)$$

$$d = 2 * (\sqrt{\frac{A}{\pi}}) \rightarrow d = 2 * (\sqrt{\frac{115.4}{\pi}}) = 12.1mm \quad (5)$$

Here, A [mm²] is the area of the piston, P [MPa] the pressure and d [mm] the diameter of the piston or inside diameter of the cylinder, which is 12.1 mm for this concept. For the rotational part, the angle of the used helix needs to be considered.

$$F = \frac{4.2Nm}{0.006m} = 647N \quad (6)$$

$$FCyl = \frac{F}{\sin(angle)} \rightarrow FCyl = \frac{647N}{\sin(57.5)} = 767N \quad (7)$$

$$A = \frac{FCyl}{P} \rightarrow A = \frac{767}{6} = 127.7mm^2 \quad (8)$$

$$d = 2 * (\sqrt{\frac{A}{\pi}}) \rightarrow d = 2 * (\sqrt{\frac{127.7}{\pi}}) = 12.8mm \quad (9)$$

Where angle [°] is the angle of the helix. The cylinder for the rotational part needs to have an inside diameter of at least 12.8 mm.

B.3 Concept 3a

This concept (Figure 13), based on sketch 2, can be quite compact and lightweight but prone to leakage and blockage. The control is done by controlling all three double-acting cylinders at once to create a single motion. This makes control difficult but precise and stable. The order of rotations is different than the previous concept, as there is no specific order. This could potentially lead to uncertainties in control, impeding easy control. The RoM of all DoF of this concept are relatively low compared to the previous concepts and highly dependent on the configuration of the cylinders. However, torques are higher due to the three cylinders that all act on the same joint. This concept is the lightest relative to the other concepts because there is less material needed. Simple calculations show that this concept needs at least 3 cylinders with an inside diameter of 6.8 mm (equations 10-13).

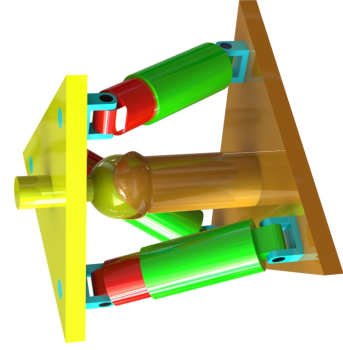


Figure 13: The third concept, which is based on sketch 2.

$$F = \frac{4.5Nm}{0.03m} = 150N \quad (10)$$

$$FCyl = \frac{150N}{\sin(44)} = 215N \quad (11)$$

$$A = \frac{767}{6} = 35.9mm^2 \quad (12)$$

$$d = 2 * (\sqrt{\frac{115.4}{\pi}}) = 6.8mm \quad (13)$$

Note: The angle in equation 11 represents the angle between the cylinder and the working direction of the force.

B.4 Concept 3b

Inspired by the anatomy of the human arm, this concept (Figure 14) uses the same pro-/supination technique as a healthy lower arm. The activation of the pro-/supination is done with a double-acting hydraulic cylinder. This rotates an artificial radius around an artificial ulna. Two double-acting hydraulic cylinders make flexion/extension and ulnar/radial deviation possible, like sketch 1. Both cylinders act on the same joint, which allows for greater generated moments. The RoM of this concept are similar to the healthy wrist, although pro-/supination is limited. The weight of this concept is relatively low, because of the small volume of the materials used. The shapes of the concept are unconventional and may cause problems while manufacturing. While there is not much material needed to produce the parts, the concept is relatively long and thin. Problems may occur with the stability of the pro-/supination part. The other two movements are made possible by the same hinge, which could cause instability as well. Lastly, to make the pro-/supination possible, a rod needs to slide through a ball joint. This can build up friction, which makes this concept prone to wear. Using calcula-

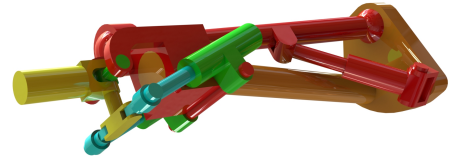


Figure 14: The fourth concept, which is primarily based on sketch 1. However, this is an anatomical approach in an effort to mimic the human bones and muscles, and has a different mechanism for pro-/supination.

tions, a rough estimation of the size of the cylinders for the front part (equation 14-16) and back part (equation 17-20) can be defined.

$$FCyl = \frac{4.5Nm}{0.015m} = 300N \quad (14)$$

$$A = \frac{767}{6} = 50mm^2 \quad (15)$$

$$d = 2 * (\sqrt{\frac{115.4}{\pi}}) = 8mm \quad (16)$$

The most optimal position requires in an inside diameter of 8 mm for the front two cylinders.

$$F = \frac{4.2Nm}{0.028m} = 161N \quad (17)$$

$$FCyl = \frac{150N}{\sin(43.3)} = 235N \quad (18)$$

$$A = \frac{767}{6} = 39.1mm^2 \quad (19)$$

$$d = 2 * (\sqrt{\frac{115.4}{\pi}}) = 7.1mm \quad (20)$$

The cylinder responsible for pro-/supination is always at an angle and never in the same direction as the working direction of the force. The cylinder requires an inside diameter of 7.1 mm.

B.5 Final Concept

The calculations show that concept 2 has the largest cylinders and is, therefore, the bulkiest. Besides the size, the pro-/supination mechanism is prone to friction and can lead to early wear. Concept 1 is compact but reliant on gears, which introduce slack. This is unwanted, as this increases instability. Furthermore, this concept would be difficult to control because of the complex interaction between the gears. Concept 3a is promising in weight and size but has decreased RoM, especially regarding pro-supination. The variant of this concept does have higher RoM for flexion/extension and ulnar/radial deviation. Ultimately, concept 3b is the final concept, although the pro-/supination part is explored further.

Iteration 1

The first iteration was significantly changed compared to the original concept. Where concept 3b consists of two double-acting cylinders, the new iteration consisted of four single-acting cylinders, mainly because single-acting cylinders can be shorter and smaller. The new iteration was symmetrical as well.

Iteration 2

The second iteration was to experiment with different connections between the 3D printed parts and the metal parts. Different bolts were tested, as well as using threaded holes in the 3D print or using nuts. The connection between the hinge and the part that connected the hand to the wrist was changed as well, from a standard metal pin to a bolt, to prevent the 3D printed part to flex.

Iteration 3 The last iteration introduced several ridges to improve the durability of the wrist. Furthermore, it prevented the 3D parts to flex under high loads. The ridges were not only included on the main body, but the hand connector part was improved as well. Lastly, a threaded M12 hole was tapped in the hand connector, allowing the hand to be attached.

C Revising Pro-/supination

During the evolution of the final concept, the rotation methods shown in the design process were ultimately deemed unfeasible. The amount of force needed was high because of irregular angles between the direction of the force and the direction of movement in concept 2 and concept 3b. The available RoM in concept 3a was too little. It was, therefore, necessary to revisit the designs capable of performing pro-/supination. For this reason, another brainstorm resulted in three alternate concepts.

C.1 Concept 1 (pro-/supination)

This concept uses two hydraulic cylinders to rotate a wedge (Figure 15). The wedge is connected to a smaller rod via a belt. This belt is made from a soft material that is sturdy, easy to bend and non-elastic. Because the wedge has a larger outside diameter than the rod, the wedge does not have to move as much as the rod, which provides more convenient angles for the hydraulic cylinders. The belt does not cause any friction but is loaded heavily due to the hydraulic cylinders that are required. This means that the internal forces are high, which causes friction in the axles and puts the entire mechanism under stress.

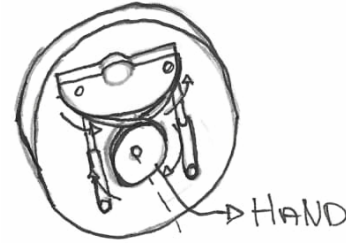


Figure 15: The first concept for pro-/supination.

C.2 Concept 2 (pro-/supination)

This concept (Figure 16) uses two straight hydraulic cylinders to rotate a rod in the middle. The cylinders are attached to two levers, extending from the side of the boom. The cylinders are double-acting, meaning that they can both extend and retract. Unfortunately, this idea creates inconvenient angles between the cylinder and the needed force direction. Therefore, the system comes close to an unstable state, where the hydraulic cylinders are under such sharp angles that the forces needed to move the system are high. Furthermore, the total angle that this system can achieve is not the desired angle.

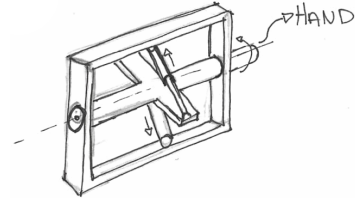


Figure 16: The second concept for pro-/supination.

C.3 Concept 3 (pro-/supination)

This concept is a variation on concept 2 but uses curved cylinders instead of straight (Figure 17). Moreover, these cylinders are single-acting, meaning they can only extend using the fluid pressure. Retracting happens while the other cylinder extends. This concept solves a few, earlier mentioned problems. Because the cylinders are curved, the force is always perpendicular to the levers, which is the optimum position. Therefore, there are no unfortunate angles. This concept is capable of a higher RoM.

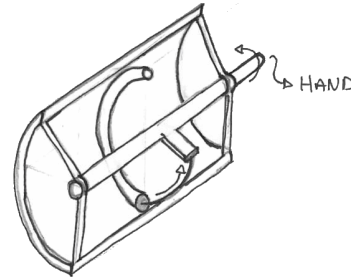


Figure 17: The third concept for pro-/supination.

C.4 Final Concept Pro-/supination

The final concept chosen for rotation is concept 3. Although concept 1 is promising and can be manufactured, it is not possible to design it in such a way that it stays within the size requirement due to the hydraulic cylinders. Furthermore, the internal forces are high due to the short moment arms of the pulley system. This makes it difficult to find a suitable material for the flexible band that connects the

pulleys. Concept 2 suffers from inconvenient angles between the hydraulic cylinders, which increases the forces that the cylinders need to provide. The most theoretical advantageous concept is concept 3. The forces are always the same due to the constant 90-degree angle with the rod. It is also possible to keep this concept compact and within the requirements. Therefore, this is chosen as the final pronation/supination concept.

Iteration 1

The first iteration involved the 'base' part, consisting of two circular curved cylinders with attached extensions that were able to hold the rotating disk. The base had an integrated system that directed the fluid from the back of the base to the start of the cylinder. Two pistons with the same curvature and diameter as the cylinders were inserted in the cylinders and connected to the rotating part using bolts. Different dimensions for the pistons and sizes for the O-ring grooves were tried until they aligned with the walls of the cylinder and the O-rings provided enough compression.

Iteration 2

The second iteration kept the same base but improved the pistons. The piston head, containing the O-ring, was separated from the piston body. The first iteration suffered from friction which caused the piston to get stuck or not move at all while still applying pressure. Therefore, the diameter of the piston body was reduced. The diameter of the piston head stayed the same, except for the dimensions of the O-ring groove, which were varied for testing. The separation of the piston body and head allowed for an adaptable system using a bolt where the piston heads could be switched. This reduced material usage.

Iteration 3 The third and last iteration primarily changed the body. The inlets, where the fluid entered the body, consisted of two round protrusions. These were damaged quickly and were therefore replaced by a protrusion that not only improved durability but also allowed the prototype to be clamped using a vise. Furthermore, the base of the pistons were slightly widened as they tended to break easily.

D Technical Drawings

The technical drawings can be requested by emailing Tom Belet using the email address tom.belet@hotmail.com.

E Matlab Code

E.1 Flexion/extension

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Created by Tom Belet %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%% Clear workspace

clear all
close all
clc

%% Initial values

plotgraph = 0; % Determines whether an animation of the movement is
               % plotted
Maxmoment = 6000; % A moment of 6 Nm (6000 Nmm) is required
```



```

Origin = [0; 0; 0]; % The origin of the hinge between body and hand
                % connector

% The values below are initial values that are used later in the
% program
Dmax0 = inf;
ForceCylReqDiff0 = inf;
i = 1;

%% Creating a virtual model
% The values behind 'for' are predetermined now. The values were
% slowly changed to check whether they were viable. The 'perfect'
% values were not used, as these introduced geometry problems
for OriginCylx = -60
    for OriginCyly = 10
        OriginCyl = [OriginCylx; OriginCyly; 0];
        for r = 10
            ReqForce = Maxmoment/r;
            for AngleMomArm = -12
                for alpha = 75:-1:-65 % Range of motion of
                                        % flexion/extension

                    % The three lines below calculate different angles
                    VFlex = rotz(alpha+AngleMomArm)*[0; r; 0];
                    VHand = rotz(alpha)*[20; 0; 0];
                    VForce = VFlex+rotz(alpha+AngleMomArm)*[r; 0; 0];

                    if plotgraph == 1
                        % These lines plot the movement
                        plot3([Origin(1) VFlex(1)], [Origin(2)...
                            VFlex(2)], [Origin(3) VFlex(3)])
                        hold on
                        plot3([VFlex(1) OriginCyl(1)], [VFlex(2)...
                            OriginCyl(2)], [VFlex(3) OriginCyl(3)])
                        plot3([VFlex(1) VForce(1)], [VFlex(2)...
                            VForce(2)], [VFlex(3) VForce(3)])
                        plot3([Origin(1) VHand(1)], [Origin(2)...
                            VHand(2)], [Origin(3) VHand(3)])

                        xlim([-80 40])
                        ylim([-30 30])
                        zlim([-1 1])
                        view([0 90])
                        pbaspect([2 1 1])
                        pause(0.1)
                        clf('reset')
                    end
                end
            end
        end
    end
end

```

```

% The lines below calculate the angle between the
% direction of the force and the direction of
% movement and determine the required force
VecForce = VForce-VFlex;
VecCyl = OriginCyl-VFlex;
AngleCyl1Hor(i) = 180-CalculateVecorAngle(...
    VecForce,VecCyl);
ForceCyl(i) = (ReqForce/cosd(AngleCyl1Hor(i)))/2;

% Determines the lenght of the cylinder+piston. If
% the previous length exceeds the current length,
% the piston shortened which is unwanted
LCyl(i) = norm(VecCyl);
if i >= 2
    if LCyl(i-1) >= LCyl(i)
        Incorrect = 1;
        break
    else
        Incorrect = 0;
    end
end
i = i+1;

end

% Determine the diameter of the cylinder using the
% previously calculated required force
Circlemax = (min(abs(ForceCyl)))/6;
Dmax = sqrt(Circlemax/(pi/4));

% Calculate whether the piston extends beyond the
% limit of the cylinder. If that is the case, stop the
% loop
LCylDiff = max(LCyl)-min(LCyl);
if LCylDiff+20 > min(LCyl)
    Incorrect = 1;
else
    Incorrect = 0;
end

% Calculate the difference between the min required
% and max required force. The smallest difference is
% taken as the 'best' option. This line (110) can be
% adapted using own requirements
ForceCylReqDiff = max(ForceCyl)-min(ForceCyl);

i = 1;

```

```

% Save values in 'best' option
if Incorrect == 0 && ForceCylReqDiff <...
    ForceCylReqDiff0
    FinalDmax = Dmax;
    FinalForceCyl = ForceCyl;
    FinalAngleCyl1Hor = AngleCyl1Hor;
    FinalOriginCyl = OriginCyl;
    Final_r = r;
    FinalAngleMomArm = AngleMomArm;
    FinalLCylDiff = LCylDiff;
    FinalLCyl = LCyl;
    Dmax0 = Dmax;
    FinalForceCylReqDiff = ForceCylReqDiff;
    ForceCylReqDiff0 = ForceCylReqDiff;
end
end
end
end
end
end

```

E.2 Pro-/supination

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Created by Tom Belet %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

%% Clear workspace

```

clear all
close all
clc

```

%% Setup initial values

```

ReqMoment = 8000; % A moment of 8 Nm (8000 Nmm) is required
Dmax0 = inf; % An initial value to allow comparison in the next part

```

%% Calculating the best values for designing the pro-/supination part

```

for r = 1:25 % The available radius for the curved cylinder
    ForceCylReq = ReqMoment/r; % The required force

    % Calculate the needed area and diameter of the piston, and the
    % outer diameter of the cylinder

    Circlemax = (min(abs(ForceCylReq))/1)/6;
    Dmax = sqrt(Circlemax/(pi/4));

```

```

DOutMax = Dmax+1;

% Calculate the distance to the maximum diameter of the design
% (25 mm)
DistanceShell = 25-(r+DOutMax/2);

% Determine whether the previously changed radius makes for better
% or worse results. If better, save results
if Dmax < Dmax0 && DistanceShell > 0
    FinalDistanceShell = DistanceShell;
    FinalDmax = Dmax;
    Final_r = r;
    DistanceShell0 = DistanceShell;
    Dmax0 = Dmax;
end
end

```