I. Groeneveld

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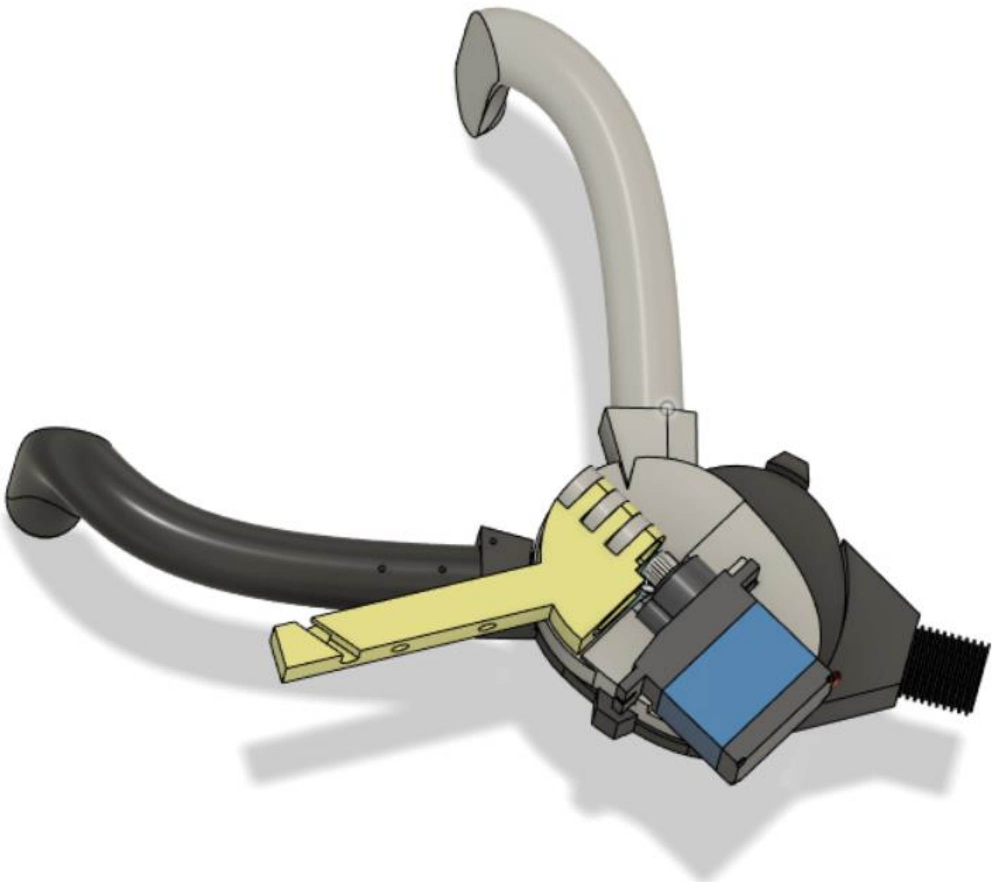
Realizing a proof-of-principle to validate feasibility of a hybrid hand prosthesis



Design of new hand prosthesis with two modes

Realizing a proof-of-principle to validate feasibility of a hybrid hand prosthesis

By

I. Groeneveld

in partial fulfilment of the requirements for the degree of

Master of Science
in Biomedical Engineering

at the Delft University of Technology,
to be defended publicly on Wednesday September 27, 2023 at 08:45 AM.

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Preface

This report marks my journey as a student at the TU Delft. During the writing of this thesis, besides being a student, I am a teacher at The Hague University, which has been a challenge to do both.

As I present this master thesis, I would like to thank some people who helped me to reach my goal.

First and foremost, I would like to thank my supervisor, Dick Plettenburg. His support and understanding of my situation helped me to finally complete my master.

Next, I would like to thank my boyfriend, Bas, who was always there for me and patiently explained the 3D printer to me.

My family, mom, dad and my sister, thank you for always believing in me, even when I didn't always believe in myself.

My colleagues always encouraged me to finish and not give up. And a special mention goes to Bianca, who encouraged and guided me through the final stages of writing this thesis.

As I reflect on this journey, I am reminded of all the good people around me who have supported me along the way. Thank you all!

I. Groeneveld
Hoogvliet, August 2023

Contents

Glossary

FDM printer	Fused Deposition Modeling print, most commonly used 3D printer.
Figure 9 harness	A commonly shoulder harness that controls the cable to the hand prosthesis. See figure 1.1
IoF	Index of Functionality
LIF	Linear Index of Functionality
SHAP	Southampton Hand Assessment Procedure – an outcome measure for hand prostheses.
Terminal device	Refers in this thesis to a hand prosthesis
VC	Voluntary closing
VO	Voluntary opening

Abstract

Background

An upper limb amputee currently has two choices for a body-powered prosthesis, a Voluntary Opening (VO) or Voluntary Closing (VC) hand prosthesis. Which type is best, depends on the task and the individual. Currently, there are no good options for VO and VC in one design.

Objectives

To design a proof-of-principle of a hand prosthesis and to validate the feasibility of the prosthesis. The hand prosthesis must have two different modes, the VO mode and the VC mode. Changing between these modes can be done without using the other hand..

Methods

First, a list of requirements and wishes was made, where cable forces are important because too much cable force can cause discomfort, fatigue or make the prosthesis difficult to control. A new design was created and a prototype was built for user testing. SHAP was used as the outcome measure.

Results

The prototype allowed the user to change between VO and VC and SHAP showed promising Linear Index of Functionality (LIF) values. The calculated cable forces were mostly within the requirements. However, because the prototype of this design was produced with an FDM-printer, not all the tests could be done and the calculated forces could not be verified.

Conclusions

A prototype of a hybrid hand prosthesis with VO and VC modes showed promise, with positive test results. However, limitations in the prototype's construction hindered some tests. The calculated cable forces mostly met requirements, except for a slightly high pinch grip force. Further development is needed, and there are material and design recommendations. This concept demonstrates feasibility but requires more work to become a functional hand prosthesis.

1. Introduction

1.1. Upper limb prosthesis

An upper limb amputee is a person who is missing part of at least one arm. This can be caused by disease, trauma, or a congenital defect [20]. An upper limb amputee has five prosthetic options:

1.1.1. *Passive prosthesis*

A passive prosthesis has no active movement, most of them are cosmetic prosthesis, but they can provide function. For example, when writing, a passive prosthesis can help hold down the paper. Passive prosthesis is usually the lightest.

1.1.2. *Body powered prosthesis*

A body-powered prosthesis is a device that can be moved with other parts of the body. In most cases, this is done with a shoulder harness that controls a cable to the terminal device. As the user moves his elbow and shoulder, the force on the cable changes, allowing the hand to be controlled. The figure shows a voluntary open hand. If the user applies force to the cable, the hand opens (figure 1.1b), and if the user does not apply force to the cable, the hand closes due to a spring or rubber band (figure 1.1a).

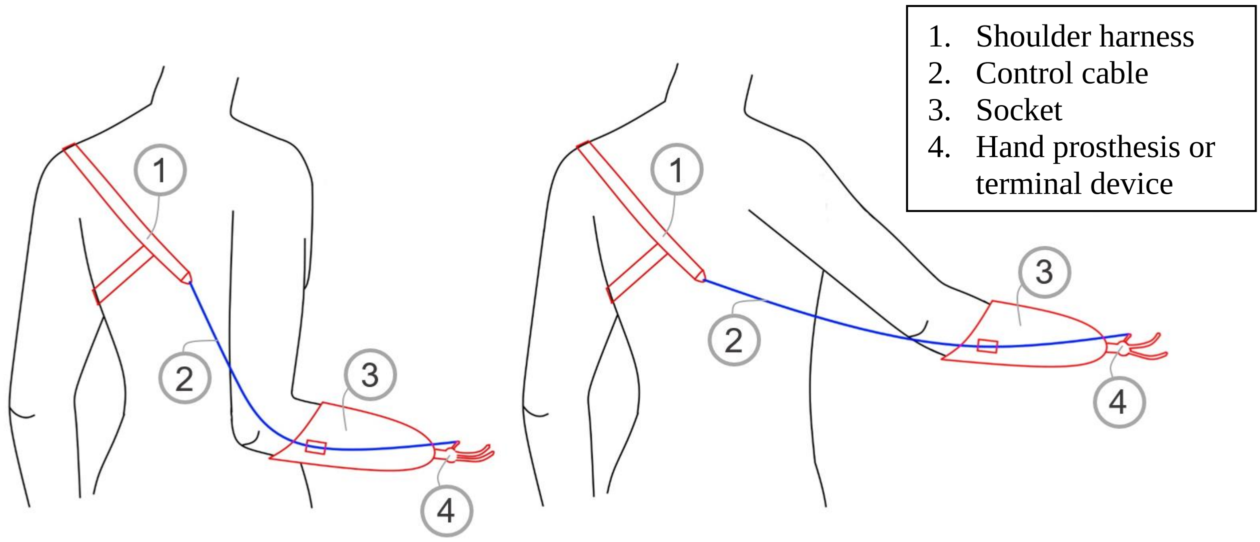


Figure 1.1: Body powered prosthesis (a) Cable relaxed (b) Force applied on cable

1.1.3. Myoelectric prosthesis

A myoelectric prosthesis is a prosthesis with an external power source that does the joint movements. Sensors use the electrical signals in the muscles of the stump to control the prosthesis. Electromyographic (EMG) electrodes pick up the EMG signals in the stump, which are processed in an EMG amplifier to control the motor that moves the joints in the hand prosthesis (see figure 1.2).

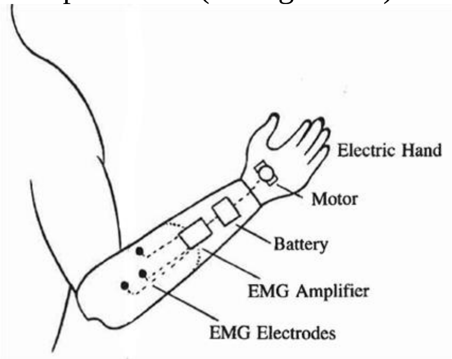


Figure 1.2: Myoelectric prosthesis [3]

1.1.4. Activity-specific prosthesis

The prosthesis an amputee uses for daily living is not always suitable for all activities, which is why there are activity-specific prostheses. This can be for sports, hobbies, or work tasks. It allows the amputee to grasp tools or assist with various specific activities. These prostheses can be passive, body-powered, or myoelectric.

1.2. Body powered prosthesis

The most commonly chosen prostheses are myoelectric and body-powered prostheses. This chapter will explain more about body powered prosthesis.

1.2.1. Hook vs hand

For a body powered prosthesis there is a chose between a hook (fig. 1.3a) or a hand (fig 1.3b). Both have different advantages [3]:

Advantage of a hook
- Lower weight
- Lower cable forces
- Better dexterity
- More durable
- Simple design

Advantage of a hand
- Looks more like a hand
- Cover protects internal mechanism

Figure 1.3: (a) Hosmer Prosthetic Model 5 Hook (VO), (b) Hosmer Male Soft Voluntary Opening (SVO) Hand

1.2.2. VO vs VC

There are two types of body-powered upper limb prostheses, voluntary opening (VO) and voluntary closing (VC). Voluntary closing (VC) means that when the cable between the shoulder harness and the socket is relaxed, the hand is open and when the cable is pulled, the hand closes. Voluntary opening (VO) is the opposite, so when the cable is relaxed, the hand is closed, and when the cable is pulled, the hand opens.

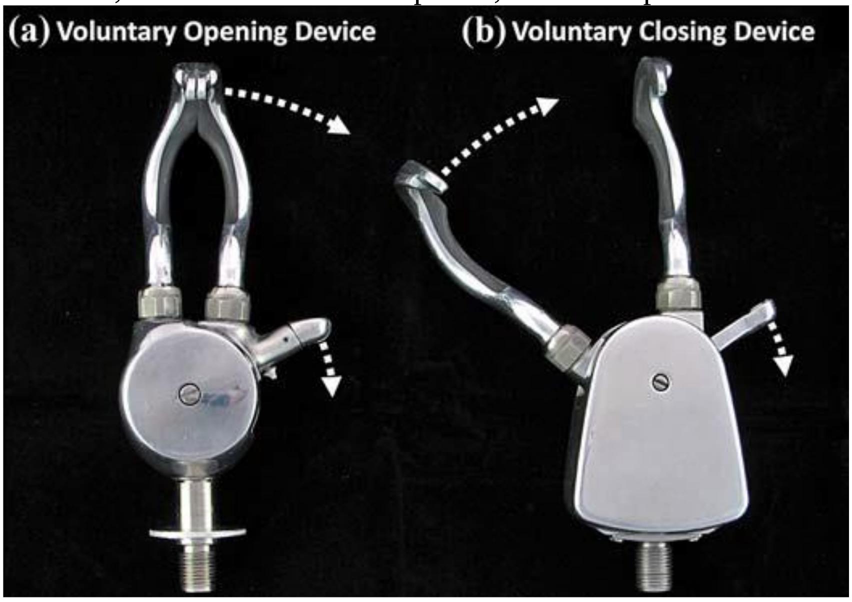


Figure 1.4: (a) VO device, (b) VC device [2]

1.3. Why this project

Some activities of daily living are better to do with a VO prosthesis, and others better with a VC prosthesis. So, if you only have one of the two, certain activities are harder to do. Previous research-projects, conducted at TU Delft, resulted in mulitple prototypes which used both VO and VC, but the prototypes didn't meet all the requirements. The pinch force was too low, the opening width was too small, or changing between the two modes did not work.

1.4. Goal

The goal is to design a proof-of-principle of a hand prosthesis and to validate the feasibility of the prosthesis. The hand prosthesis must be able to operate between two different modes, the VO mode and the VC mode. Changing between these modes can be done without using the other hand or pressing the prosthesis against a surface.

2. Requirements and wishes

The requirements for an upper limb prosthesis can be divided into three categories, the three C's: Comfort, Control, and Cosmetics [17].

2.1. Comfort

The prosthetic device should be as comfortable as possible, but at least not be hurting the user. For this research the socket isn't taking into account. But wearing the socket can give more irritation if the terminal device is heavy, so the terminal device should be as light as possible and the center of gravity of the terminal device should be as close as possible to the socket attachment. Next to that, a heavy prosthetic device can cause fatigue, which is another reason to make the device as light as possible.

According to Hari Krishnan [10], a normal human hand weighs 480 grams, but users said this was too heavy. According to Ford [7], 95% of the users are satisfied with the weight of the APRL hook. The weight of the APRL hook is 234 grams (8-1/4 ounces) [7]. The maximum weight for this new device will be 234 grams, but the wish is as low as possible.

In addition, the cable forces should be as low as possible to reduce irritation of the harness and socket. According to Hichert [11], cable forces can cause discomfort or pain, see figure 2.1 for an overview of where users can experience discomfort from high cable forces. The aim is to have low cable forces in this new design. In the next section, these forces will be specified in more detail.

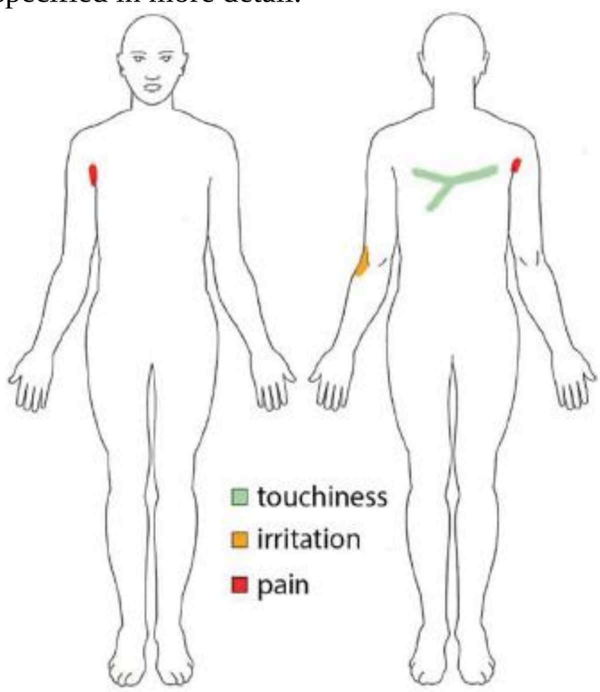


Figure 2.1: Body map colored by one subject indicating pain in the right armpit, irritation at the back of the left elbow, and touchiness on a stripe of his back [11].

2.2. Control

This research is mainly about the control of the hand prosthesis; to integrate two different modes in one prosthesis. But for the control there are more things important:

- Opening width of the hand
- Displacement of the cable
- Forces in the cable
- Pinch force

In addition, the prosthesis must be able to be used without the assistance of the other hand or a surface. Thus, to change between the two modes, VO to VC and vice versa, the user doesn't need to use the unaffected hand, a surface or anything else to change the mode.

2.2.1. Opening width of the hand

The width of the hand opening is important for good control because it determines the objects that can be picked up. Peeters did a literature search [16] on the opening width of upper limb prostheses and found out that 90% of the objects can be grasped with an opening width of 38 mm. However, she also found that an opening of at least 83 mm is needed to reach most of the other 10 percent.

2.2.2. Displacement of the cable

Cable excursion is the difference between the minimum and maximum length of the cable when using the prosthesis. There is a maximum of what it should be to be comfortable for the user and what the user is capable of doing. Therefore, it is important to know what the maximum displacement of the cable can be. Taylor et al. found that upper limb amputees can do 53 mm of cable excursion [19].

2.2.3. Forces in the cable

The user generates a cable force by moving the shoulder and elbow to control the prosthetic hand. There is a limit to what a person can do without fatigue. According to Hichert [11], cable forces should be less than 38 N for an average female user and less than 66 N for a male user for good control and no fatigue. Therefore, the cable force should be below 38 N. This must be measured with a 15 N pinch force in VC mode and 50 mm opening width in VO mode [11].

2.2.4. Pinch force

Pinch force is the force between the fingers when they are nearly closed, such as when holding a key to open a lock. The pinch force for the VC mode depends on the cable force, so it depends on what the user can do, the goal is to create a pinch force of 15 N with a maximum cable force of 38 N. The pinch force for the VO mode depends on the spring force. A pinch force of 14 N in VO is a good choice according to Berning et al [2].

2.3. Cosmetics

This research will mainly focus on the control of the prosthesis, it will not look into the appearance of the new design. However, the size will be taken into account so that the prosthetic hand will be about the same size as a normal hand.

The requirement will be a maximum size of an average hand, but the wish will be the average size minus the standard deviation. This is because it is usually harder to make something smaller than it is to make it bigger. Therefore, the prosthetic hand will be suitable for more people.

Table 2.1: Hand size, according to DINED [14]:

	Average	Average minus standard deviation
Hand width	103 mm	103 – 9 = 94 mm
Thickness of the hand	26 mm	26 – 6 = 20 mm
Length of the hand	187 mm	187 – 13 = 174 mm

2.4. Summary of requirements and wishes

Below is a table that lists all of the requirements and wishes.

Table 2.2 List of all requirements and wishes.

	Requirement	**Wish**
Comfort		
Weight	Maximum 234 gram	Low as possible and center of mass close to socket attachment
Cable forces	Maximum 38 N	Low
Control		
Modes	VO and VC (without needing the other hand, or a surface)	
Maximum opening width (VO and VC)	Minimum 83 mm	Minimum 100 mm
Cable excursion	Maximum 53 mm	
Cable forces (VO 15N pinch) (VC opening width of 50 mm)	Between 10 - 38 N	
Pinch force VO	14 N	
Cosmetics		
Width	Maximum 103 mm	Maximum 94 mm
Thickness (without thumb and fingers)	Maximum 26 mm	Maximum 20 mm
Length	Maximum 187 mm	Maximum 174 mm

3. Design

The aim is to create a proof-of-principle for a body-powered prosthetic hand that has two modes, voluntary opening and voluntary closing. The prosthesis must be able to be used without the assistance of the other hand or a surface.

3.1. Scope of research

There are two things that will not be looked at in this research; the first is the system that is going the be used: a cable driven system with a figure 9 harness on the non-affected side (see figure 1.1). The second is the finger shape: Peeters [15] has already done this. The finger shape that will be used is based on the Hosmer Prosthetic Model 5 Hook.

3.2. Overview of VO and VC in one design

There has been research on VO and VC in one design before, at TU Delft but also by other researchers. Research has concluded that there are three main categories:

1. Three fingers, with one active finger and two passive fingers. (See table 3.1)
   Two different ones found in the literature:
   - Coehoorn
   - Leblanc
2. Two fingers, with the handle on one side. (Handle is the part the cable is connected to.)
   One found in the literature and one new concept (See table 3.2)
   - Peeters
   - NEW(1)
3. Two fingers, but the handle moves sides. (See table 3.3)
   None found in literature and one new concept
   - NEW(2)

An overview of all the prostheses found in literature and the two new concepts can be found in the tables on the next pages.

Table 3.1: Design with three fingers

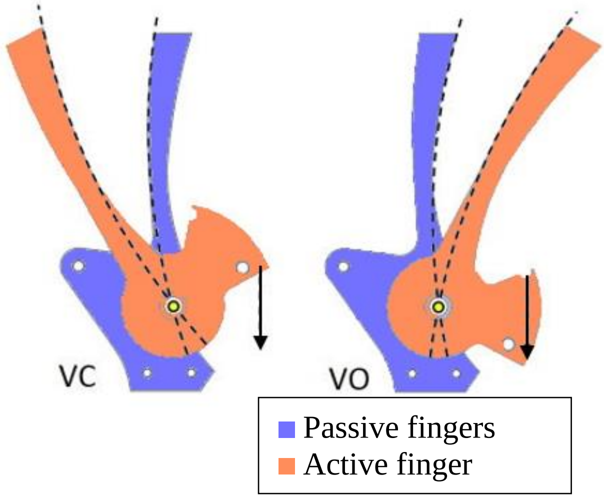
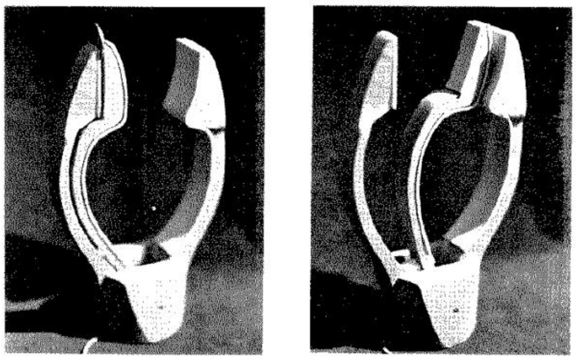
Three fingers	
Design by Coehoorn [6]	Design by LeBlanc [12]
This is a design has two passive fingers and an active finger, that can move in between them. When the active finger is one the left side it is in VC mode (fig 3.2a) and when the active finger is on the right side, it is in VO open mode.	This is a design has two passive fingers on the outside and active finger moves between them.
 Figure 3.1: Coehoorn's design  Figure 3.2: (a) VC mode, (b) VO mode	 Figure 3.3: LeBlanc's design in starting position and when closed bij the user.
There is not a switching mechanism, because it depends on the length of the cable and where the active finger is located.	There is not a switching mechanisme, because it depends on which side is used.
Advantages: + No complicated switching system + Easy design Disadvantages – Finger design – Not enough opening width (65 mm)	Advantages: + No complicated switching system + Easy design Disadvantages – Finger design – Small opening width

Table 3.2: Two fingers, with the handle on one side

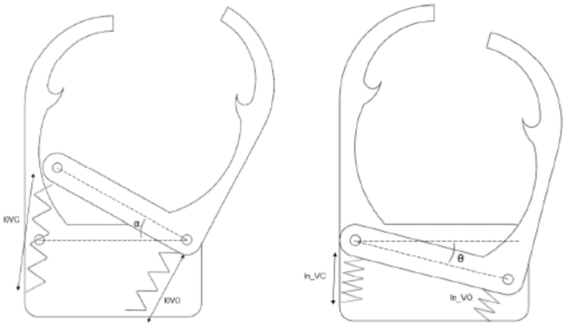
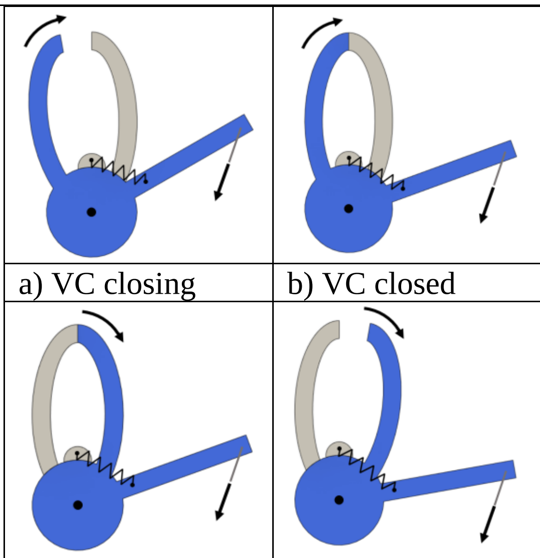
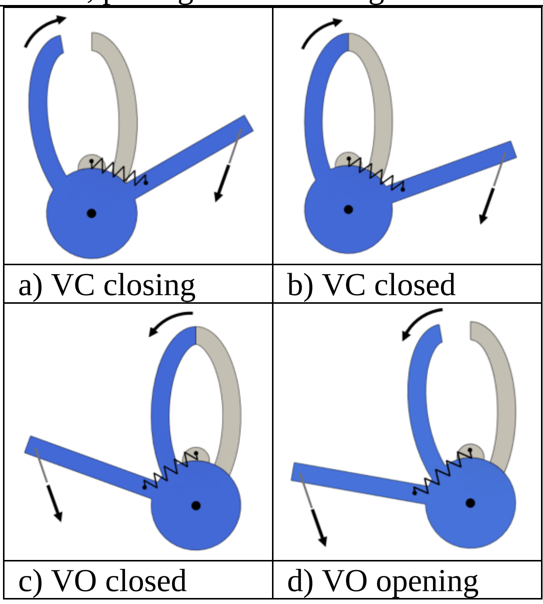
Two fingers, with the handle on one side	
Design by Peeters [15]	New concept: NEW(1)
It has two fingers, one active finger and one passive finger. The prosthesis uses a bi-stable system to change the rotation point from left to right. When the rotation point is on the right side, it is in VC mode (fig 3.4a) and when the rotation point is on the left side it is in VO mode (fig 3.4b).	This new concept has two fingers. The active and the passive finger change after changing modes.
 Figure 3.4: (a) VC, rotation point right (b) VO rotation point left	 a) VC closing b) VC closed c) VO closed d) VO opening Figure 3.5: NEW(1) Passive finger Active finger
Advantages: + All lot of finger design possible Disadvantages – Small opening width – Switching system didn't work always, has to align very precisely	Expected advantage: + Direction of rotation is the same + All lot of finger design possible + Large opening width possible Expected disadvantage: – Possible large cable force when fully open in open in VO mode. – Large cable displacement, between VO fully open and VC fully open.

Table 3.3: Two fingers, with the handle moves sides

Two fingers, with the handle moves sides

New concept NEW(2)

This new concept has two fingers. One active and one passive finger. The difference between VO and VC is that the handle rotates from one side to the other. When the handle rotates to the other side, the spring also moves, pulling the active finger to the other side.



a) VC closing	b) VC closed
c) VO closed	d) VO opening

Figure 3.6: NEW(2)

Passive finger
Active finger

Expected advantage:

+ Angle of hinge can change a lot in cable forces
+ All lot of finger design possible

Large opening width

– Expected disadvantage:
– Propably need an electric part to change the handle to the other side, because this is hard to do with the cable.

3.3. Options for changing between VO and VC

The two new concepts also require the addition of a changing modes mechanism, there are several ways to change between the two modes:

- Non (not necessary) – In the design of Leblanc (see table 3.1) it is not necessary to change between the modes, because there are always there.
- Length of cable – In the design of Coehoorn (see table 3.1) the position of the active finger determines the mode, which is determined by the length of the cable.
- Instable system – See the design of Peeters [15] in table 3.2.
- ‘Pushing’ with cable – The friction and stiffness of the Bowden cable make this is possible, but there can only be created a small force.
- Quick and short pull on the cable
- Electrical switch with a sensor
  - Electrically powered handle:
    - Servo
    - Magnet
  - Sensor:
    - Pull switch or pull sensor
    - Push with the cable: button or light-dependent resistor
    - Button control with elbow

3.4. Final choice

For this research, we will look at the concept with two fingers, where the handle rotates to the other side, because the ones that are found in the literature in the overview of chapter 3.2 are already made, and the biggest flaw was that the shape of the fingers are not the best shape, but necessary for the design. The concepts NEW(1) and NEW(2) are new concepts in which a variety of finger shapes are possible.

The NEW(1) will probably be easier to change modes because the handle does not have to move to the other side, but there are fewer options for spring connections and handle placement to meet all the requirements. Also, the forces will be higher because the spring will only get longer when closing in VC mode and then opening in VO mode. In addition, the cable displacement will be higher than the NEW(2) because the rotation of the handle will be more. The NEW(2) can have more different dimensions and angles to create a lot of different compositions. In the figure below are two examples of different angles of the hinge (orange line) of the handle, there are two different configurations. Where the cable forces will be different for each of these modes.

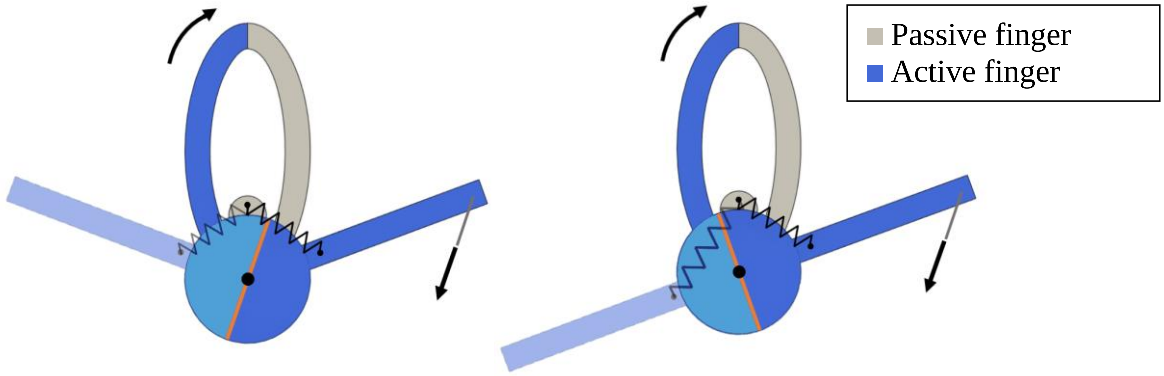


Figure 3.6: Two different compositions of NEW(2)

The NEW(2) will be harder to change modes because the spring is attached to the handle, so you have to overcome the force of the spring to rotate to the other side. Also, there needs to be a rotation of the handle around the hinge of 180 degrees. This can be solved with a combination of an electrically powered handle and sensor. Therefore, it is decided that NEW(2) would be the better option.

The electrically powered handle will be a small servo motor and the sensor will be a pull switch. The pull switch will be placed between the shoulders. The user will also have a shoulder harness on the other side. The pull switch between the shoulders is chosen because it allows the user to change modes, and if the user is good at controlling it, the prosthetic hand can stay in the same place.

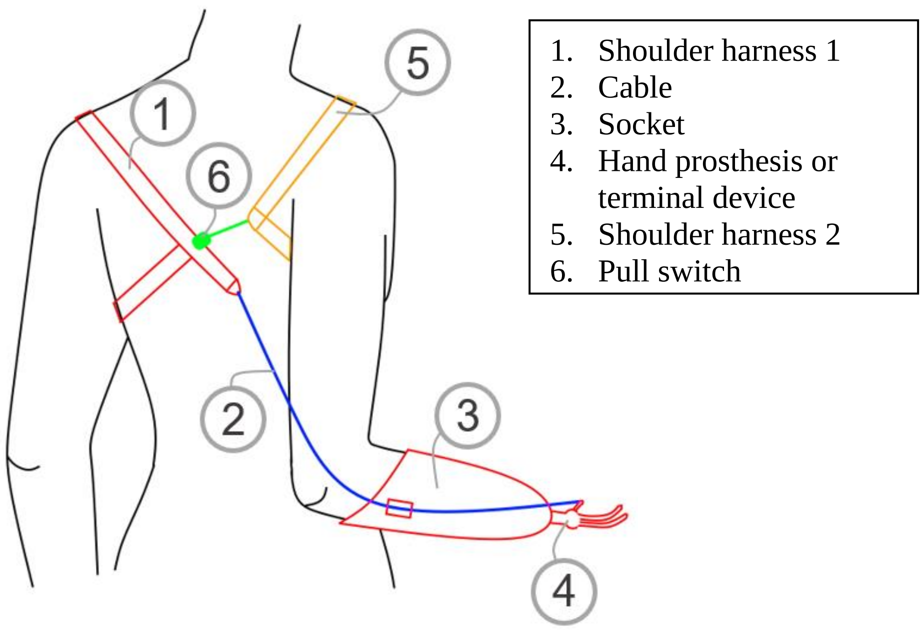


Figure 3.7 Place of pull switch and second shoulder harness

3.5. Strong and weak points

The expected strong and weak points are:
Strong points

- Terminal device can be compact and light weight.
- Simplicity in use: same as normal VO or VC device, except for the change modes part
- With one spring different force for VO and VC, depends on place and angle of the hinge of the handle.
- No other hand or object needed to change modes.
- Any shape of fingers can be used.

Weak points

- Uses a battery, which adds weight (somewhere, not necessary at the hand) and a battery can run out.
- Harness around both shoulders.

3.6. Final design

First, a quick prototype was made without the electrically powered handle, control cable and spring. Just to get a quick look at what would work. See figure 3.8 for the 3D printed model. The active finger is attached to the handle. On the left side (fig 3.8a) is in VC mode and when the handle is rotated 180 degrees the prototype is in VO mode (fig 3.8b).

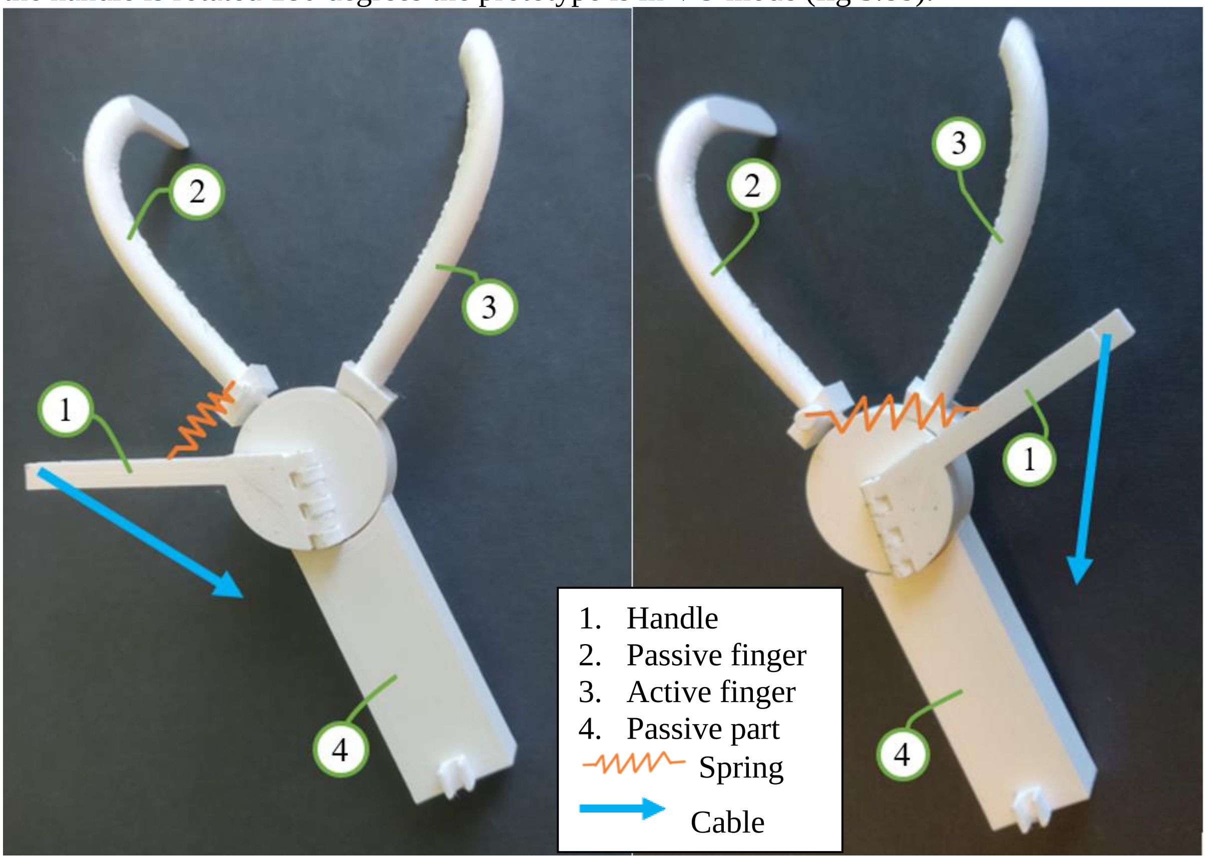


Figure 3.8: First quick prototype (a) VC mode (b) VO mode

3.6.1. *Calculations*

A Matlab script was written for all calculations, see Appendix A for the code. This was done to get the optimal measurements and angles of the prosthesis and to calculate what the expected forces are in the cable. In figure 3.9 is a diagram of what is calculated in the Matlab script for each angle.

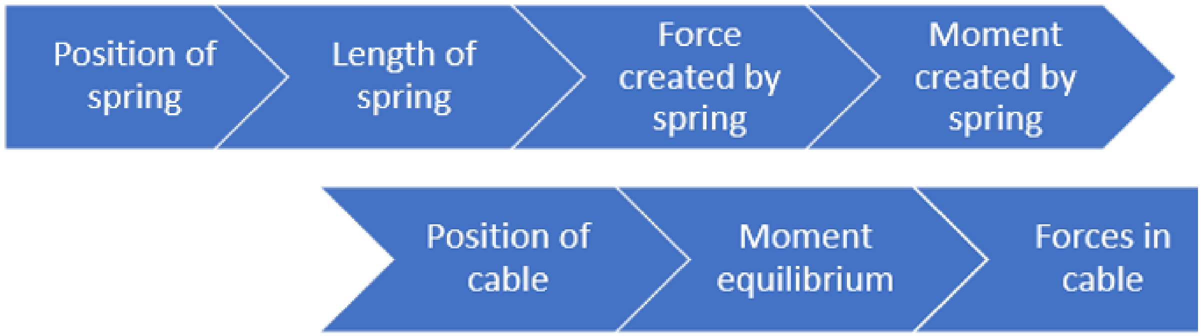


Figure 3.9: Diagram of Matlab script.

The inputs for the calculations are:

- Spring characteristics:
    - Resting length
    - Stiffness
    - Placement on the handle
    - Placement on the passive part
- Cable attachments:
    - End placement of inner cable on the handle
    - Placement of cable housing on the socket
- Angles
    - VO angle of handle for closed position
    - VC angle of handle for closed position

The outputs of the Matlab script are:

- Graphs with cable forces in every position (figure 3.10)
- Maximum cable displacement (fig 3.11)
- Checks for all the cable force requirements (fig 3.11)
- Check for pinch force (fig 3.11)
- Graph of cable forces and pictures of position in VC (fig 3.12) and VO (fig 3.13)

The graph below shows the forces in the cable, calculated for each position. These must remain above 10 N and below 38 N to meet the requirements. The black dashed lines show these limits. The inputs for these graphs can be found in Appendix A.

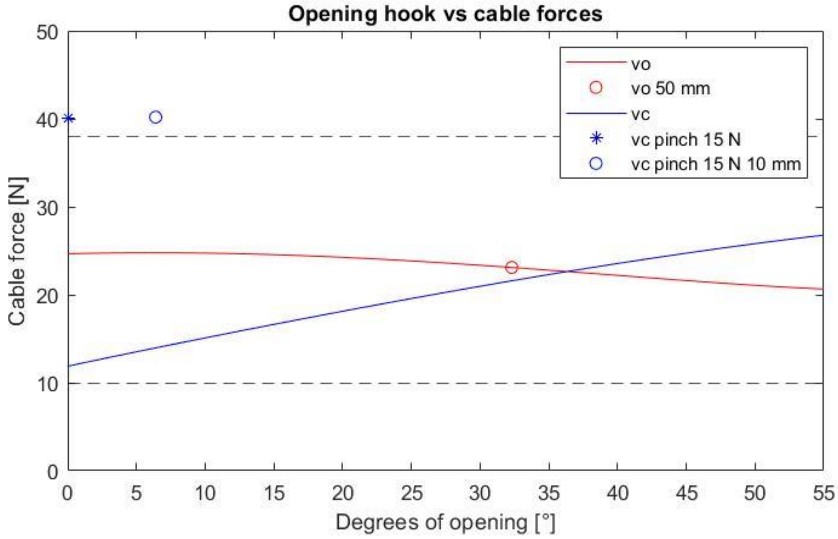


Figure 3.10: Cable forces in every position for VO and VC

```
The lowest cable force (VC) is 11.8797 N. This cannot be lower then 10 N.
The cable force (VC) when 15 N pinch is 40.0411 N.
The cable force (VC) when 15 N pinch is 40.1905 N with an object of 10 mm object.
The cable force (VC) when closed is 11.8797 N.
This can be maximal 38 N.
.
The lowest cable force (VO) is 20.6536 N. This cannot be lower then 10 N.
The cable force (VO) when opening width is 50 mm is 23.102 N. This can be maximal 38 N.
The pinch force (VO) is 13.5774 N. This has to be 14 N.
.
The maximal cable displacement is 51.6085 mm. This cannot be higher than 53 mm.
The maximal opening width is 83.1148 mm. This needs be at least 83 mm.
```

Figure 3.11: Text output of Matlab script

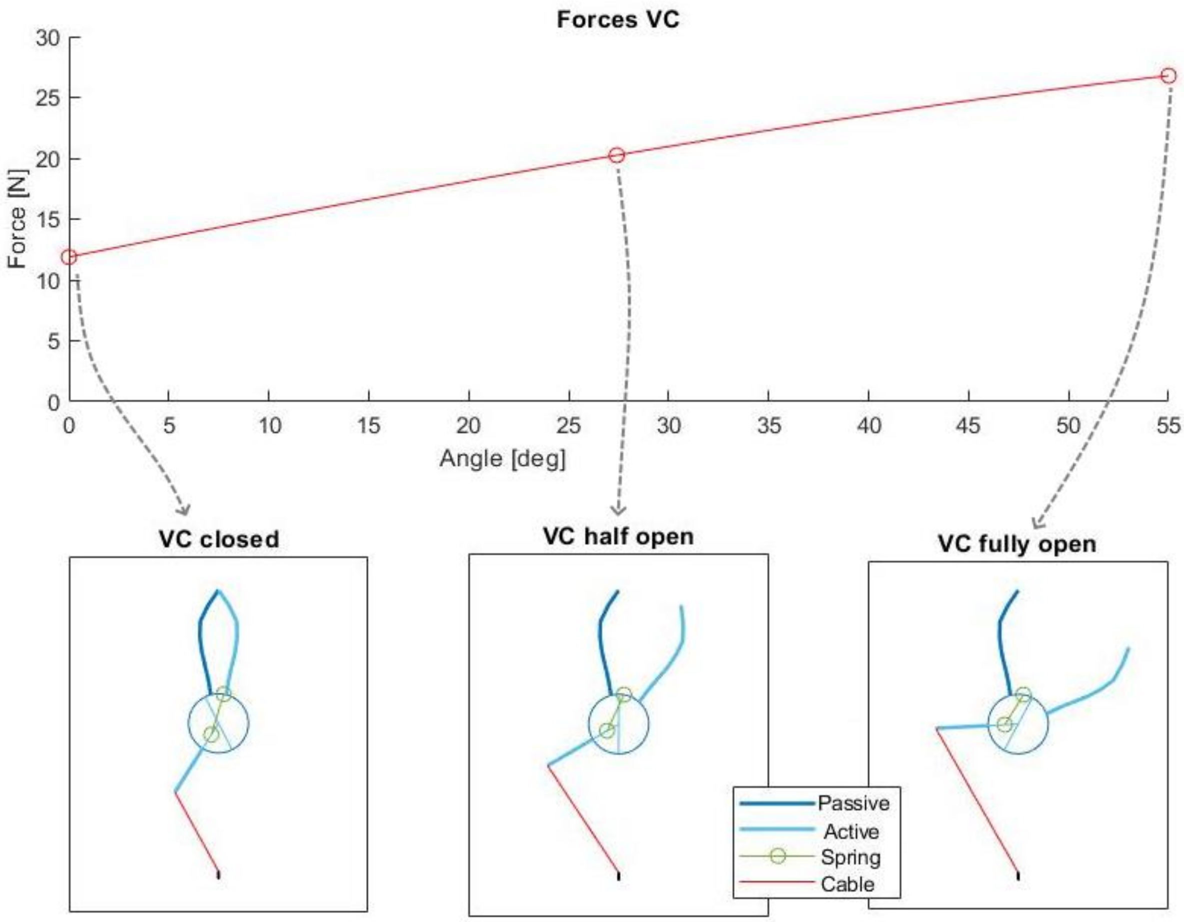


Figure 3.12: Cable forces and pictures of position in VC

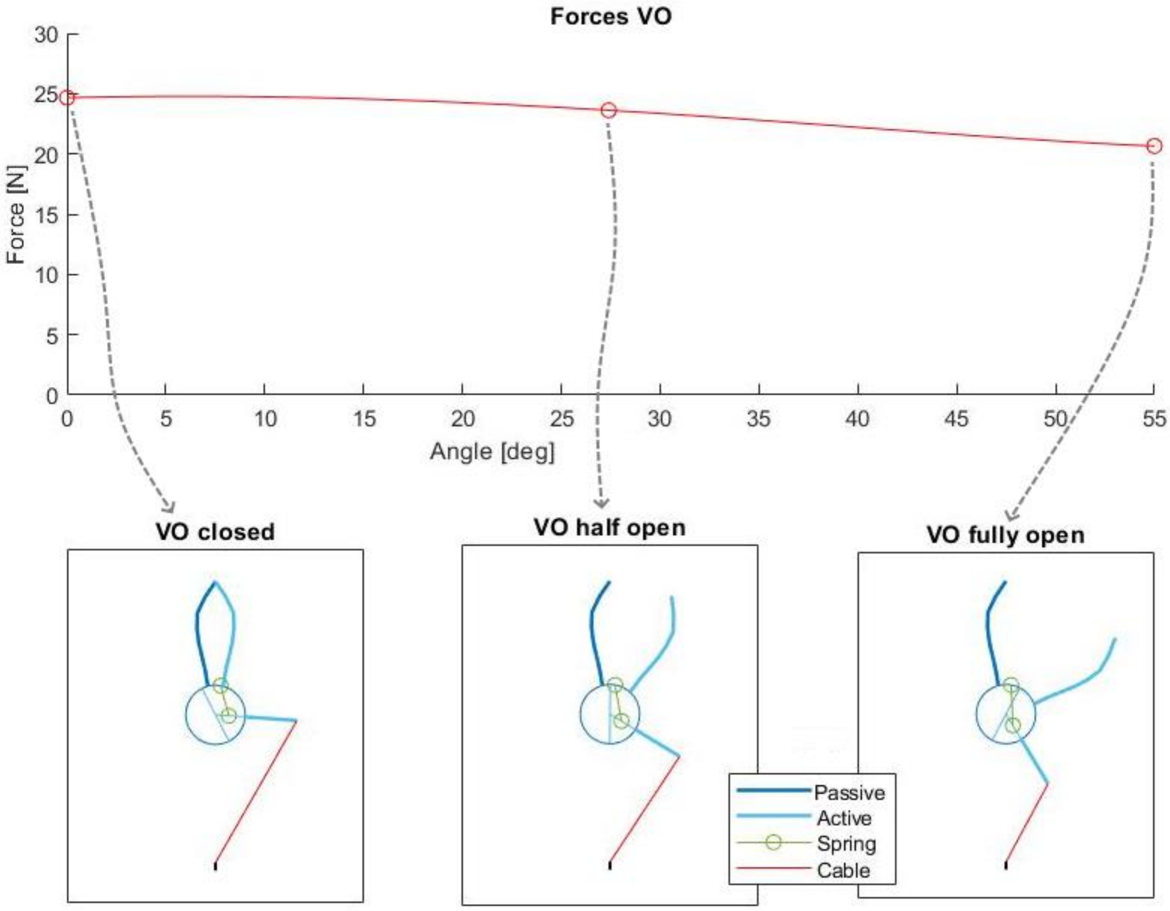


Figure 3.13: Cable forces and pictures of position in VO

3.6.2. Drawing final design for 3D printing

After calculating the right dimensions and angles, a prototype is designed with Fusion 360, see figures 3.14 and 3.15 on the next page.

The colors are there to indicate the different parts:

- Black: the passive part and the passive finger
- Gray: the part that rotates, i.e. the active part and the active finger,
- Yellow: the handle
- Blue/black: the servomotor

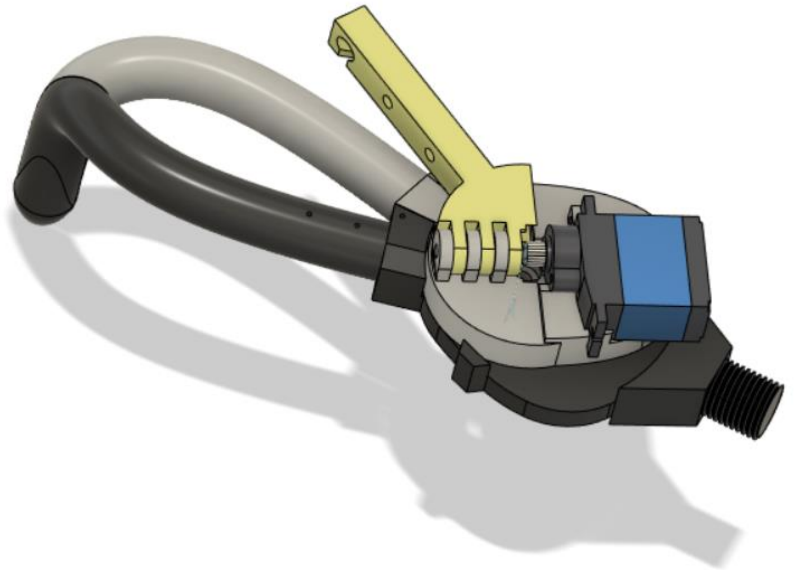


Fig 3.14 Render of prototype (VO closed) (Black: the passive part and the passive finger Gray: the part that rotates, i.e. the active part and the active finger, Yellow: the handle, Blue/black: the servomotor)

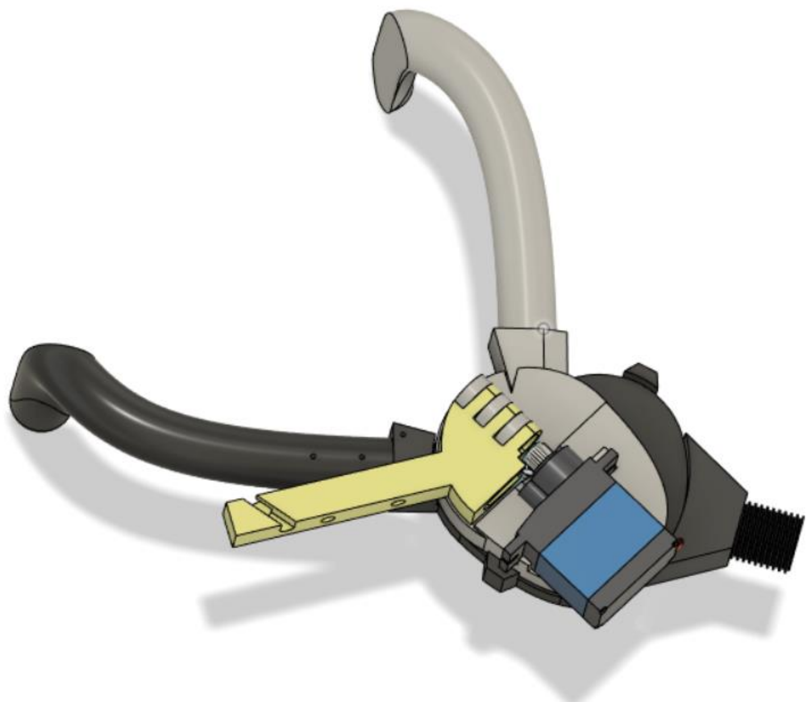


Fig 3.15 Render of prototype (VC open) (Black: the passive part and the passive finger Gray: the part that rotates, i.e. the active part and the active finger, Yellow: the handle, Blue/black: the servomotor)

3.6.3. *Design for electrically powered handle and pull switch*

For this proof of principle, it was decided to work with materials that were readily available and that would work for this proof of principle.

A servomotor was chosen for the rotation of the handle: Tower Pro MG92B [13], this is a small and lightweight servo motor, but powerful, which can turn 360 degrees. Although 180 degrees would be enough, in practice servos that turn 180 degrees on paper, do not work ideally in situations they need to turn exactly from 0 to 180 degrees.

The pull switch [8] will be place between two shoulder harnesses, see figure 3.7. When the user makes a hollow back (arches his spine), the pull switch will be pulled.

The signal from the pull switch is sent to a microcontroller, the Arduino Nano [1], which controls the servo, see the connection diagram in figure 3.16. Each time the pull switch is pulled, the servo rotates 180 degrees to rotate the handle to the other side and change modes, between VO and VC. The Arduino code can be found in the Appendix B.

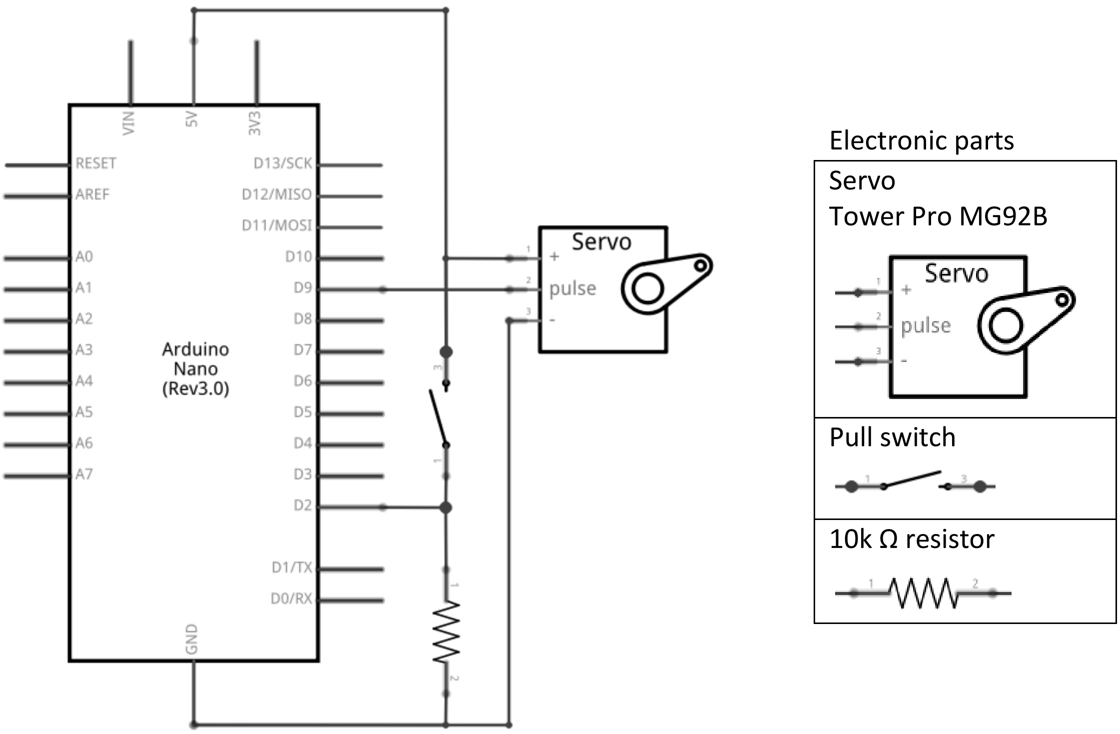


Figure 3.16: Connection diagram of the pull switch

The pull switch works like a normal switch, when the switch is pulled the circuit closes and when the switch is pulled again the circuit opens. The 10kΩ resistor acts as a pull-down resistor for the pull switch.

4. Prototype

An FDM printer (most common type of 3D printer) was chosen to produce the proof-of-principle prototype. This is because it is the fastest way to make the prototype instead of giving the design to an external manufacturer.

The FDM printer used to create the prototype is a Creality Ender 3 S1. For the sake of printing a prototype fast and easy, the material used is PETG. This was in this case the strongest material available.

Besides to that, the prototype needs to fit on a body powered prosthetic simulator (fig 5.1) for testing. The prototype can be attached to the simulator through a 5 inch (½-20 UNF) thread connection.

4.1. Prosthetic hand

The parts are 3D-printed, see figure 4.1 and then assembled together with cyanoacrylate glue and a nut, bolts and a spring, see figure 4.2 and 4.3.

Figure 4.1: 3D-printed parts

Figure 4.2: 3D printed parts assembled, VC mode

Figure 4.3: 3D printed parts assembled, VO mode

4.2. Electronic part

The connection diagram from chapter 3.6.3 was built and soldered together, see figure 4.4. The black wires go to the pull switch and the red, yellow and brown wires go to the servo motor. To make it more robust and able to be connected to the body powered prosthetic simulator, a black casing was designed and printed, see figure 4.5. To power the Arduino Nano and the servomotor, a small power bank will be used.

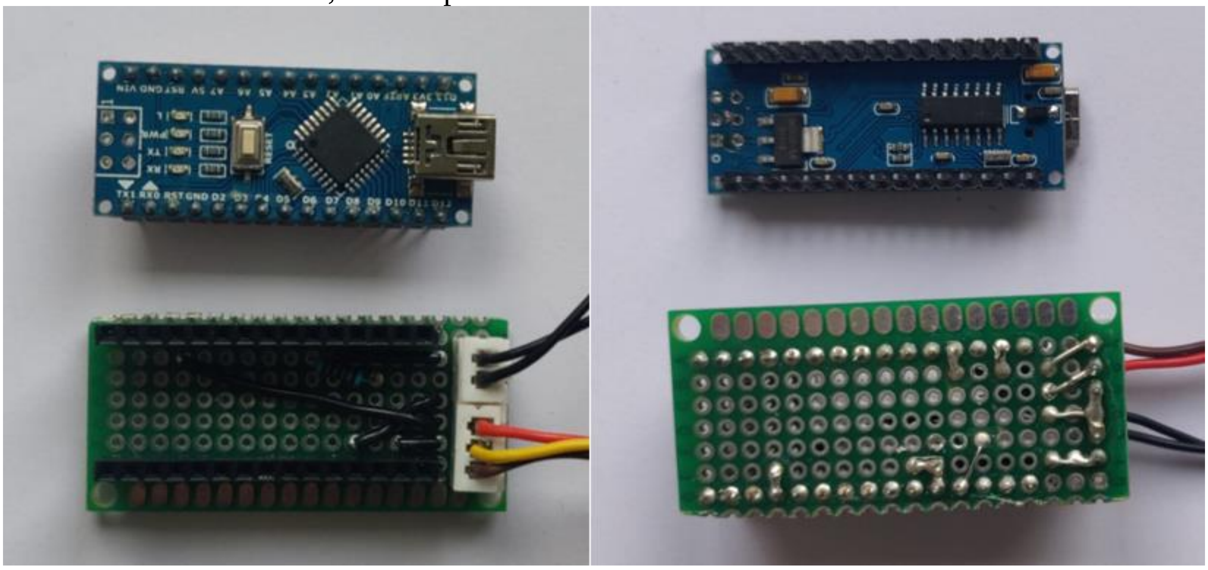


Figure 4.4: Arduino Nano and Electric circuit (a) Topside (b) Bottom side

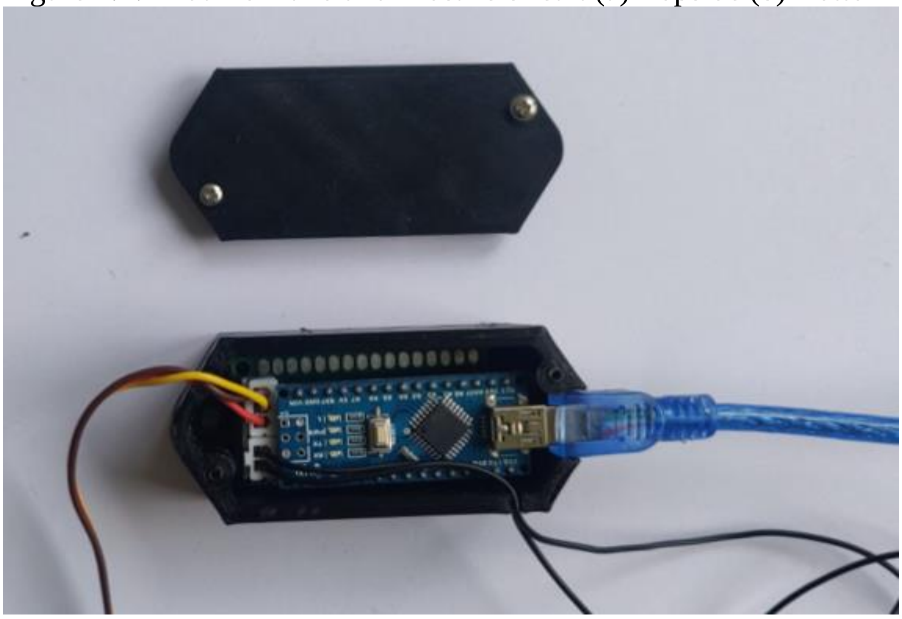


Figure 4.5: Black casing with electric circuit and Arduino Nano

To connect the pull switch to the existing harness (non-affected side), a housing was made to connect the pull switch to the ring on the back of the harness. A second shoulder strap was also made to connect the pull switch to the other shoulder (affected side).

Figure 4.6: Harness with pull switch

4.3. Finger surface

When the hand prosthesis was assembled and some quick tests were performed, it turned out that the surface of the 3D printed fingers was too hard and slippery to get grip on objects.

The surface of the fingers, the part where the touch, is flat and very smooth, too smooth to get grip on objects. Although it was decided to not look at the finger design, this had to be fixed. Otherwise the tests, in order to evaluate the design, could not be conducted properly. Different options were tried:

First fix: A silicon strip was added on the fingers, but the glue connection could not sufifce properly.
Second fix: 3D printed surface, with ridges, did stay on, but still a slippery, and softer surface that can deform a bit would be better. See figure 4.7a.
Final fix: Neoprene material that is also used in foot prostheses to have grip and protect the foot prosthesis. Cut to size and glued on the fingers. See figure 4.7b.

Figure 4.7: Different surface of the finger (a) 3D printed (b) Neoprene

4.4. Break downs

The prosthesis has broken a few times during training and testing:

- **Problem**: Hinge of the handle broke (See figure 4.8)
  Solution: The hinge was made bigger, so the surface area of break point was bigger.
- **Problem**: 3D printed bolt that connects the hand with the simulator broke (See figure 4.9)
  Solution: This part was not printed with a 100% infill, so next protype was printed with 100% infill. This was still the weakest part of the design, but the dimensions could not be changed, so at the end there was decided to only do the lighter tests.
- **Problem**: During training the hand delaminated, this was probably a fault with the printer, this did not happen with the hands that were printed afterwards.

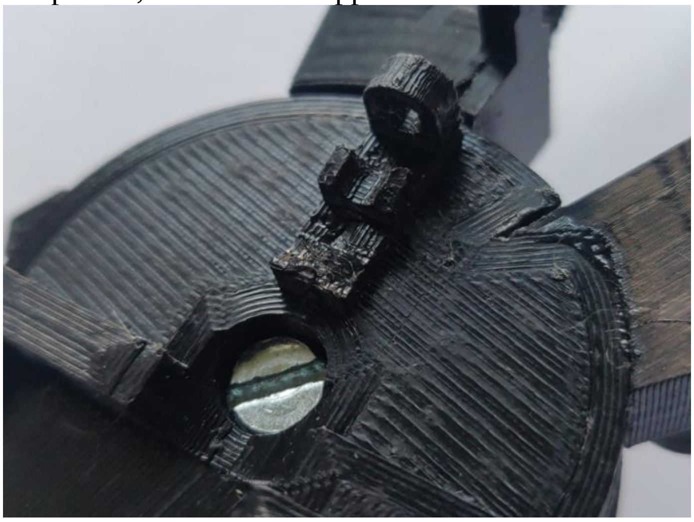


Figure 4.8: Broken hinge of handle

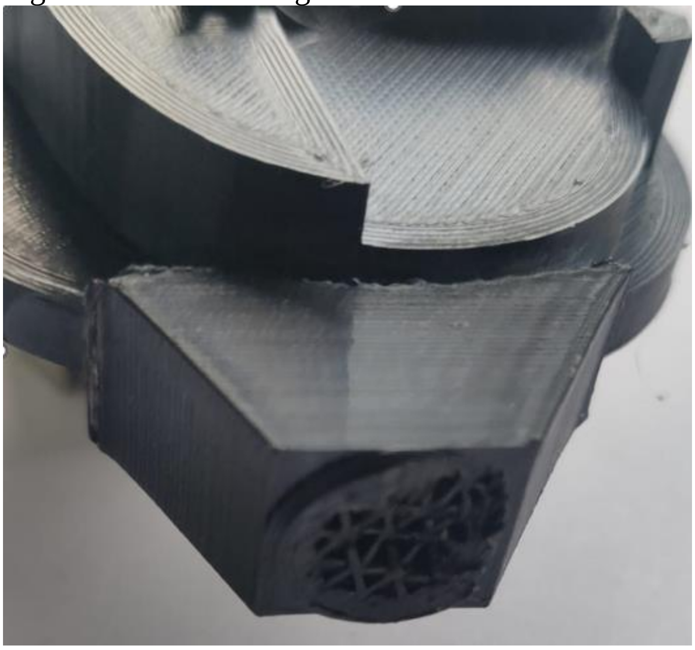


Figure 4.9: Broken bolt

5. Testing

SHAP (Southampton Hand Assessment Procedure) was used as the outcome measure. According to the literature study [9] SHAP is the best test for a functional test, which also gives good test results for able-bodied people with a simulator (figure 5.1).

Figure 5.1 The body powered prosthetic simulator [4]

As mentioned in Chapter 4.2, the 3D printed prosthesis broke a few times, so for the final tests it was decided to do only the light abstract objects of the SHAP, so there would at least be some test results.

Five participants did the tests. All five participants are right-handed able-bodied persons and thus used the simulator. All had no experience with hand prosthesis. Each participant practiced first and then did everything in VC mode and then in VO mode. The fastest times from VO and VC were used for the hybrid times.

All test results and information about the test persons can be found in the Appendix C.

The LIF (Linear Index of Functionality) was calculated from the test scores. According to Burgerhof [5], the LIF is similar to the IoF (Index of Functionality) and has a high correlation with the IoF scores that can be calculated from the SHAP website. The LIF was chosen over the SHAP website's IoF scores because the SHAP website's underlying equations are not public. The LIF has a value between 0 and 100, where 100 indicates a very good performance compared to an abled bodied person. The results of the test can be found in the next chapter.

6. Results

6.1. User test results

In table 6.1 are the mean LIF scores of all the test persons. The calculation can be found in Appendix D.

Table 6.1: LIF scores

Grip	VC Mean ± SD	VO Mean ± SD	Hybrid Mean ± SD
Sphere	50.4 (± 18.2)	60,5 (± 12.0)	64.0 (± 12.7)
Tripod	58.1 (± 10.2)	66,3 (± 7.3)	69.0 (± 6.4)
Power	22.6 (± 22.7)	68,6 (± 6.6)	68.6 (± 6.6)
Lateral	53.7 (± 5.2)	49,6 (± 19.0)	57.8 (± 6.3)
Tip	40.1 (± 14.5)	39,9 (± 7.9)	45.1 (± 10.4)
Extension	46.1 (± 23.6)	45,4 (± 4.9)	55.4 (± 8.0)

In table 6.2 are the hybrid LIF scores of this prototype compared to the IoF scores of a previous VO/VC device. On average, the prototype scores are 15.4 points higher, which is a better score.

Table 6.2: Compared to the hybrid IoF scores to earlier new designs [15]

Grip	This prototype	Previous design [15]	Difference
Sphere	64.0	61.7	+2.3
Tripod	69.0	26.0	+43.0
Power	68.6	21.2	+47.4
Lateral	57.8	62.1	-4.3
Tip	45.1	37.8	+7.3
Extension	55.4	58.7	-3.3

6.2. Checking requirements and wishes

In this chapter, the requirements and wishes are compared with the results of designing, calculating, prototyping and testing.

Table 6.3, on the next page, lists the requirements and wishes from Chapter 2.4. The last two columns list the results.

The cable forces were not measured, because this was not possible with this prototype, so these are the calculated cable forces from the Matlab script.

Table 6.3 List of requirements and wishes with results

	Requirement	Wish	Verification method	Result	Findings
Comfort					
Weight	Maximum 234 gram	Low as possible and center of mass close to socket attachment	Fusion 360	**170 grams (Material aluminum 7075 T6 + servo) and center of mass is 61 mm of the socket attachment**	**Good**
Cable forces	Maximum of 38 N	Low	Matlab calculation	**40.0 N**	**A little too high**
Control					
Modes	VO and VC (without needing the other hand, or a surface)		Test of proof-of-principle	**Yes**	**Good**
Maximum opening width (VO and VC)	Minimum 83 mm	100 mm	Measurement	**Opening width: 83 mm**	**Good**
Cable excursion	Maximum 53 mm		Matlab calculation	**Max cable excursion: 51.6 mm**	**Good**
Cable forces (VC 15N pinch) (VO opening width of 50 mm)	Between 10 - 38 N		Matlab calculation	**Forces: VC closed: 11.9 N VC 15N pinch: 40.0 N VO 50 mm open: 23.1 N**	**Only VC 15N pinch is little too high, otherwise good**
Pinch force VO	14 N		Matlab calculation	**Forces: 13.6 N**	**Good Not exactly 14N**
Cosmetics					
Width	Maximum 103 mm	Max 94 mm	Measurement	**53 mm**	**Good**
Thickness (without thumb and fingers)	Maximum 26 mm	Max 20 mm	Measurement	**23 mm (without fingers)**	**Good**
Length	Maximum 187 mm	Max 174 mm	Measurement	**150 mm**	**Good**

Most results are good. Only when the user uses the prosthesis in VC mode and wants a 15 N pinch force, the cable forces are a little higher than desired. The maximum cable force that is comfortable is 38 N, and the cable force is 40.0 N.

7. Discussion

7.1. Calculated forces

7.1.1. No mechanical testing

All forces in this research are calculated forces and the prosthesis is not mechanically tested. This was for several reasons. The proof-of-principle was not made to withstand high forces because of the material it's made of. The real forces are probably a little different from what is calculated, the expectation is that the real cable forces are a little higher because of friction.

7.1.2. Little too high cable force

One of the calculated forces is slightly too high, when the user is creating a 15 N pinch force, as shown in Table 6.3. The required maximum force was 38 N and the calculated force is 40.0 N. According to Hichert [15], when a user wants to apply a force of 40 N, the average error is about 4 N. Probably a user doesn't feel the difference between a force of 38 N and a force of 40 N.

7.2. User testing

The user test results are promising. The proof-of-principle works, but there were also some shortcomings due to the material and manufacturing method used.

During the test, the prosthesis broke a few times. Therefore, the participant had to be careful when using the prosthesis.

For this research, only the light abstract tasks of SHAP were tested, this is because the proof-of-principle was made of PETG instead of aluminum, where it was designed for. This meant that only the lighter tasks could be performed.

In addition, when the fingertips were used and force was applied, the fingers bent. See figure 7.1. As a result, it was more difficult to pick up small things with the tip of the fingers.

Another thing to keep in mind is that the test subjects are not people who use a prosthesis in everyday life and have not been trained in the use of a hand prosthesis.

Figure 7.1: Fingers bending

8. Recommendations

There are some recommendations for future research:

Stronger material

The first thing to do is to make the prototype out of aluminum 7075 T6 so that the correct spring can be used and all the SHAP tests can be done. When the prototype is made of a stronger material, it can also be tested to verify the calculated cable forces.

Design optimization

It is possible that this design is not the optimal design, ideas to make the design possibly better are:

- Use an optimization program on Matlab script for best parameters
- New design with spring in another place
- Hinge of the handle not in the middle of the circle
- Look at different shapes of the handle, only looked at straight design, but maybe it is better to have an arc.
- For longer use, it would be nice if the battery was smaller and not attached to the arm, but somewhere else. Perhaps when the battery is flat, it could be placed on the back or in the socket.

Sensor

Pull switch on the back can be annoying when users want to sit on a chair with a backrest, this can be solved in multiple ways:

- Sensor from Ottobock: Harness pull switch or Cable pull switch. These are flatter than the pull switch which is used in the prototype.
- Sensor in different place, for example use the elbow as input.

Other points

- Consider the possibility of making the prosthesis waterproof.
- Consider the look of the hand

9. Conclusion

In conclusion, a new hand prosthesis with VO and VC mode was designed and a prototype was created. The prototype allowed the user to change between VO and VC and SHAP was used to test the prototype. The outcomes of the test were good, the LIF scores were better than previous designs. However, it was not possible to do all the tests because of the way the prototype was made, with an FDM printer. The prototype was not strong enough to do de heavier test.

The calculated cable forces mostly met the requirements. Only the cable force for the pinch grip was a bit high, 40 N instead of the required maximum of 38 N, but it's expected that a user won't feel the difference.

The fact that the prototype worked is a good sign, there are material and design recommendations for future research to improve the concept. These can be found in the previous chapter.

Overall, this new concept showed that it is feasible to have a hybrid hand prosthesis that is able to change between VO and VC. The concept needs further work to make it into a hand prosthesis.

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Appendices

A. Matlab code
B. Arduino code
C. User test results
D. LIF calculations

A. Matlab code

```
%% Graduation project
%Iris Groeneveld

close all
clear variables

%% Constants

% Spring
k = 13;                 % Spring stiffness [N/mm]
l_0_spring = 10;        % Rest length spring [mm]
r = 20;                 % Radius [mm] r=15


% Locked finger
angle_locked = [-15 -13 -13 -13 -12 -10 -5 0];      % Angles locked finger
angle_free = -angle_locked;
r_finger = [r r+10 r+20 r+30 r+40 r+50 r+60 r+70 ];


% position cable and spring
cable_start = [0,-100]; % place on socket/terminal device where Bowden cable

spring_start_r = 20;
spring_start_angle= 10;
spring_start = [spring_start_r*sind(spring_start_angle);spring_start_r*cosd↙
(spring_start_angle)]; % position spring on locked finger [x;y]

r_cable= 55;
r_spring = 9;
r_s_c = r_cable-r_spring; % distance between attachment of spring and cable on thumb

% Voluntary opening
l_arm_vo = r_cable;       % length of thumb VO [mm]
angle_open = 55;          % total amount degrees opening
angle_vo_start = 94;      % start position
step_size= 0.1;           % stepsize between angles
angle_vo = (angle_vo_start:step_size:angle_vo_start+angle_open);     % angle VO, from↙
close to open [degrees]

% Voluntary closing
l_arm_vc = l_arm_vo;            % length of thumb VC [mm]
angle_vc_start = 212;
angle_vc = (angle_vc_start:step_size:angle_vc_start+angle_open);   % angle VC, from↙
close to open [degrees]


%% Calculations VO
```

```
% Spring
spring_end_vo = [(l_arm_vo-r_s_c)*sind(angle_vo); (l_arm_vo-r_s_c)*cosd(angle_vo)]; %
position of spring on thumb [x;y in mm]
spring_vector_vo = [spring_start(1)-spring_end_vo(1,:);spring_start(2)-spring_end_vo
(2,:)]; % vector from spring end to spring start [x;y in mm]
l_spring_vo = sqrt(spring_vector_vo(1,:).^2+spring_vector_vo(2,:).^2); % length
spring [mm]
F_spring_vo = (l_spring_vo-l_0_spring)*k; % force in spring [N]


% Cable
cable_end_vo = [l_arm_vo*sind(angle_vo); l_arm_vo*cosd(angle_vo)]; % position of
cable on thumb [x;y in mm]
cable_vector_vo = [cable_end_vo(1,:)-cable_start(1);cable_end_vo(2,:)-cable_start
(2)]; % vector from cable end to cable start [x;y in mm]
l_cable_vo = sqrt(cable_vector_vo(1,:).^2+cable_vector_vo(2,:).^2); % length cable
[mm]


%% Calculations VC

% Spring
spring_end_vc = [(l_arm_vc-r_s_c)*sind(angle_vc); (l_arm_vc-r_s_c)*cosd(angle_vc)]; %
position of spring on thumb [x;y in mm]
spring_vector_vc = [spring_start(1)-spring_end_vc(1,:);spring_start(2)-spring_end_vc
(2,:)]; % vector from spring end to spring start [x;y in mm]
l_spring_vc = sqrt(spring_vector_vc(1,:).^2+spring_vector_vc(2,:).^2); % length
spring [mm]
F_spring_vc = (l_spring_vc-l_0_spring)*k; % force in spring [N]

% Cable
cable_end_vc = [l_arm_vc*sind(angle_vc); l_arm_vc*cosd(angle_vc)]; % position of
cable on thumb [x;y in mm]
cable_vector_vc = [cable_end_vc(1,:)-cable_start(1);cable_end_vc(2,:)-cable_start
(2)]; % vector from cable end to cable start [x;y in mm]
l_cable_vc = sqrt(cable_vector_vc(1,:).^2+cable_vector_vc(2,:).^2); % length cable
[mm]


%% Moment equilibrium VO

% Moment created by spring
%M_spring_vo = spring_end_vo(1,:).*F_spring_vo.*(spring_vector_vo(2,:)./l_spring_vo)-
spring_end_vo(2,:).*F_spring_vo.*(spring_vector_vo(1,:)./l_spring_vo);

% Shortest distance from [0,0] to spring

distance_spring_vo = zeros(1,length(spring_end_vo));
```

```
for i=(1:1:length(spring_end_vo))
    v1=[spring_end_vo(1,i),spring_end_vo(2,i),0];
    v2=[spring_start(1),spring_start(2),0];

    pt=[0,0,0];
    a=v1-v2;
    b=v1-pt;

    d=norm(cross(a,b))/norm(a);

    distance_spring_vo(i) = d;
end

M_spring_vo=F_spring_vo.*distance_spring_vo;

% M_spring + M_cable = 0, so M_spring = -M_cable
% Force in cable [N]
%F_cable_vo = M_spring_vo./(cable_end_vo(1,:).*cable_vector_vo(2,:). ↙
/l_cable_vo+cable_end_vo(2,:).*cable_vector_vo(1,:)./l_cable_vo);

% Shortest distance from [0,0] to cable

distance_cable_vo = zeros(1,length(cable_end_vo));


for i=(1:1:length(cable_end_vo))
    v1=[cable_end_vo(1,i),cable_end_vo(2,i),0];
    v2=[cable_start(1),cable_start(2),0];

    pt=[0,0,0];
    a=v1-v2;
    b=v1-pt;

    d=norm(cross(a,b))/norm(a);

    distance_cable_vo(i) = d;
end

F_cable_vo = M_spring_vo./distance_cable_vo;

%% Moment equilibrium VC

% Moment created by spring
%M_spring_vc = spring_end_vc(1,:).*F_spring_vc.*(spring_vector_vc(2,:)./l_spring_vc)- ↙
spring_end_vc(2,:).*F_spring_vc.*(spring_vector_vc(1,:)./l_spring_vc);

% Shortest distance from [0,0] to spring

distance_spring_vc = zeros(1,length(spring_end_vc));
```

```
for i=(1:1:length(spring_end_vc))
    v1=[spring_end_vc(1,i),spring_end_vc(2,i),0];
    v2=[spring_start(1),spring_start(2),0];

    pt=[0,0,0];
    a=v1-v2;
    b=v1-pt;

    d=norm(cross(a,b))/norm(a);

    distance_spring_vc(i) = d;
end

M_spring_vc=F_spring_vc.*distance_spring_vc;


% M_spring + M_cable = 0, so M_spring = -M_cable
% Force in cable [N]
%F_cable_vc = M_spring_vc./(cable_end_vc(1,:).*cable_vector_vc(2,:). ↙
/l_cable_vc+cable_end_vc(2,:).*cable_vector_vc(1,:)./l_cable_vc);

distance_cable_vc = zeros(1,length(cable_end_vc));

for i=(1:1:length(cable_end_vc))
    v1=[cable_end_vc(1,i),cable_end_vc(2,i),0];
    v2=[cable_start(1),cable_start(2),0];

    pt=[0,0,0];
    a=v1-v2;
    b=v1-pt;

    d=norm(cross(a,b))/norm(a);

    distance_cable_vc(i) = d;
end

F_cable_vc = M_spring_vc./distance_cable_vc;
%% Plot forces
tiledlayout(2,4)

nexttile
plot(angle_vo, F_spring_vo)
hold on
plot(angle_vo,F_cable_vo)
title('Forces VO')
ylabel('Force [N]')
xlabel('Angle [deg]')
legend('Spring','Cable')
hold off
```

```
nexttile
plot(angle_vo, M_spring_vo)
title('Moment spring VO')
ylabel('Moment [Nmm]')
xlabel('Angle [deg]')

nexttile
plot(angle_vc, F_spring_vc)
hold on
plot(angle_vc,F_cable_vc)
title('Forces VC')
ylabel('Force [N]')
xlabel('Angle [deg]')
legend('Spring','Cable')
hold off

nexttile
plot(angle_vc, M_spring_vc)
title('Moment spring VC')
ylabel('Moment [Nmm]')
xlabel('Angle [deg]')


%% Plot picture VO

for i=[1,length(angle_vo)]

    nexttile
    % Circle
    angle_c = (0:5:360);
    plot(r*sind(angle_c), r*cosd(angle_c),'b', 'LineWidth',2)
    hold on
    plot(0,0,'bo')

    % Thumb
    plot([0;l_arm_vo*sind(angle_vo(i))], [0;l_arm_vo*cosd(angle_vo(i))], 'k',↙
'LineWidth',2)

    % Spring
    plot([spring_start(1);spring_end_vo(1,i)],[spring_start(2);spring_end_vo(2, ↙
i)],'ro-')

    % Cable
    plot([cable_start(1);cable_end_vo(1,i)],[cable_start(2);cable_end_vo(2,i)], 'k')
    rectangle('Position',[cable_start(1)-0.5 cable_start(2)-5 1 5])

    % Locked finger
    plot(r_finger.*sind(angle_locked), r_finger.*cosd(angle_locked), 'b', 'LineWidth',↙
```

```
2)

    % Free finger
    plot(r_finger.*sind(angle_free+angle_vo(i)-angle_vo(1)), r_finger.*cosd
(angle_free+angle_vo(i)-angle_vo(1)),'k','LineWidth',2)
    angle_switch = (angle_vc(1)+angle_vo(1))/2+angle_vo(i)-angle_vo(1);
    plot([r*sind(angle_switch);0],[r*cosd(angle_switch);0],'k','LineWidth',2)
    plot([0;r*sind(180+angle_switch)],[0;r*cosd(180+angle_switch)],'k','LineWidth',2)

    ylim([-65 max(r_finger)+r+5])
    axis equal
    title(['VO ',num2str(angle_vo(i)),' degrees'])
    hold off

end

%% Plot pictue VC
for j=[1,length(angle_vc)]

    nexttile

    % Circle
    angle_c = (0:5:360);
    plot(r*sind(angle_c), r*cosd(angle_c),'b', 'LineWidth',2)
    hold on
    plot(0,0,'bo')

    % Thumb
    plot([0;l_arm_vc*sind(angle_vc(j))], [0;l_arm_vc*cosd(angle_vc(j))],'k',
'LineWidth',2)
     % Spring
     plot([spring_start(1);spring_end_vc(1,j)],[spring_start(2);spring_end_vc(2,
j)],'ro-')

     % Cable
     plot([cable_start(1);cable_end_vc(1,j)],[cable_start(2);cable_end_vc(2,j)], 'k')
     rectangle('Position',[cable_start(1)-0.5 cable_start(2)-5 1 5])

     % Locked finger
     plot(r_finger.*sind(angle_locked), r_finger.*cosd(angle_locked),'b', 'LineWidth',
2)

     % Free finger
     plot(r_finger.*sind(angle_free+angle_vc(j)-angle_vc(1)), r_finger.*cosd
(angle_free+angle_vc(j)-angle_vc(1)),'k','LineWidth',2)
     plot([r*sind((angle_vc(1)+angle_vo(1))/2+angle_vc(j)-angle_vc(1));0],[r*cosd
((angle_vc(1)+angle_vo(1))/2+angle_vc(j)-angle_vc(1));0],'k','LineWidth',2)
     plot([0;r*sind(180+(angle_vc(1)+angle_vo(1))/2+angle_vc(j)-angle_vc(1))],[0;
```

```
r*cosd(180+(angle_vc(1)+angle_vo(1))/2+angle_vc(j)-angle_vc(1))], 'k','LineWidth',2)

    ylim([-65 max(r_finger)+r+5])
    axis equal

    title(['VC ',num2str(angle_vc(j)),' degrees'])
    hold off

end
%% Calculation opening width

%open_width_x = r_finger(end)*sind(angle_locked(end))-r_finger(end)*sind(- ↙
angle_locked(end)+angle_vo(end)-angle_vo(1));
%open_width_y = r_finger(end)*cosd(angle_locked(end))-r_finger(end)*cosd(- ↙
angle_locked(end)+angle_vo(end)-angle_vo(1));
%open_width_max = sqrt(open_width_x^2+open_width_y^2);

% 50 mm index 324, 10 mm index 65
open_width_x = r_finger(end)*sind(angle_locked(end))-r_finger(end)*sind(-angle_locked ↙
(end)+angle_vo-angle_vo(1));
open_width_y = r_finger(end)*cosd(angle_locked(end))-r_finger(end)*cosd(-angle_locked ↙
(end)+angle_vo-angle_vo(1));
open_width = sqrt(open_width_x.^2+open_width_y.^2);
open_width_max = max(open_width);

% 50 mm
index_50mm=find(open_width>=50, 1 );
degree_50mm=angle_vo(index_50mm)-angle_vo(1);
% 10 mm
index_10mm=find(open_width>=10, 1 );
degree_10mm=angle_vo(index_10mm)-angle_vo(1);

%% Calculations requirements

cable_ex = max([l_cable_vo, l_cable_vc])-min([l_cable_vo, l_cable_vc]);
F_pinch_VO = M_spring_vo(1)/r_finger(end);

% cable force VO opening width 50 mm 62.3 degrees (index =324)
F_cable_VO_50 = F_cable_vo(index_50mm);

% Pinch force of 15N
%F_cable_vc_15 = (M_spring_vc(1)-r_finger(end)*15)/(cable_end_vc(1,1)*cable_vector_vc ↙
(2,1)/l_cable_vc(1)+cable_end_vc(2,1)*cable_vector_vc(1,1)/l_cable_vc(1));
%F_cable_vc_15_10mm = (M_spring_vc(index_10mm)-r_finger(end)*15)/(cable_end_vc(1, ↙
index_10mm)*cable_vector_vc(2,index_10mm)/l_cable_vc(index_10mm)+cable_end_vc(2, ↙
index_10mm)*cable_vector_vc(1,index_10mm)/l_cable_vc(index_10mm));
F_cable_vc_15 = (M_spring_vc(1)+r_finger(end)*15)/distance_cable_vc(1);
F_cable_vc_15_10mm = (M_spring_vc(index_10mm)+r_finger(end)*15)/distance_cable_vc ↙
(index_10mm);
```

```matlab
%% plot force spring en angle

figure()
plot((angle_vo-angle_vo_start), F_cable_vo)
hold on
plot((angle_vc-angle_vc_start), F_cable_vc)

hold off


%% plot force in cable en angle opening

angle_opening_vo = angle_vo-angle_vo_start;
angle_opening_vc = angle_vc-angle_vc_start;
plot(angle_opening_vo,F_cable_vo,'r')
hold on
plot(angle_vo(index_50mm)-angle_vo_start, F_cable_VO_50, 'ro')
plot(angle_opening_vc,F_cable_vc,'b')
plot(angle_vc(1)-angle_vc_start,F_cable_vc_15,'b*')
plot(angle_vc(index_10mm)-angle_vc_start,F_cable_vc_15_10mm, 'bo')
yline(38)
yline(10)
title('Opening hook vs cable forces')
legend('vo', 'vo 50 mm', 'vc', 'vc pinch 15 N', 'vc pinch 15 N 10 mm')

%% Displays

disp(['The lowest cable force (VC) is ',num2str(min(F_cable_vc)),' N. This cannot be lower then 10 N.'])
disp(['The cable force (VC) when 15 N pinch is ',num2str(max(F_cable_vc_15)),' N.'])
disp(['The cable force (VC) when 15 N pinch is ',num2str(max(F_cable_vc_15_10mm)) ' N with an object of 10 mm object.'])
disp(['The cable force (VC) when closed is ',num2str((F_cable_vc(1))),' N.'])
disp('This can be maximal 38 N.')
disp('.')
disp(['The lowest cable force (VO) is ',num2str(min(F_cable_vo)),' N. This cannot be lower then 10 N.'])
disp(['The cable force (VO) when opening width is 50 mm is ',num2str(F_cable_VO_50),' N. This can be maximal 38 N.'])
disp(['The pinch force (VO) is ',num2str(F_pinch_VO),' N. This has to be 14 N.'])
disp('.')
disp(['The maximal cable displacement is ', num2str(cable_ex), ' mm. This cannot be higher than 53 mm.'])
disp(['The maximal opening width is ', num2str(open_width_max), ' mm. This needs be at least 83 mm.'])

if min(l_spring_vo)<l_0_spring
    disp("Attention: spring VO is smaller then resting length!")
```

```
end

if min(l_spring_vc)<l_0_spring
    disp("Attention: spring VC is smaller then resting length!")
end
```

B. Arduino code

```
#include <Servo.h>            //include libary for servo
int const pull_switch = 2;    // pin of the switch
int switch_state = 0;         // state of the switch 0 = VC and 1 = VO

Servo hinge;          // object to control servo
int pos_vc = 0;       // position of hinge when VC
int pos_vo = 180;     // position of hinge when VO
int pos = 0;          // position of hinge

void setup() {
      hinge.attach(9);                  // pin of the servo
      pinMode(pull_switch, OUTPUT);     // initialize pull_switch as output
}

void loop() {
      switch_state = digitalRead(pull_switch);  // read state of switch,
one side is 0 other side is 1

      if (switch_state == 0) {
            // 0 = VC
            pos = pos_vc;    // Change current position to VC position
      }
      else {
            // 1 = VO
            pos = pos_vo;    // Change current position to VO position
      }

      hinge.write(pos); // Send current postion to the servo, the servo
will turn to current position
}
```

C. User test results

Test person	1	2	3	4	5
Male/Female	F	M	F	M	F
Age	28	55	62	26	30

VC (time in s)

Light Sphere	5.90	4.65	9.12	6.52	10.25
Light Tripod	5.38	7.25	8.03	7.07	4.90
Light Power	7.00	12.20	14.15	9.31	21.03
Light Lateral	8.28	7.51	8.19	6.71	6.87
Light Tip	7.69	7.21	11.06	6.43	8.88
Light Extension	8.26	6.81	14.40	6.53	6.63

VO (time in s)

Light Sphere	4.60	6.68	8.50	5.83	5.09
Light Tripod	4.54	5.25	6.68	4.94	6.47
Light Power	5.00	6.13	7.05	5.31	4.84
Light Lateral	6.50	7.50	12.56	5.94	7.59
Light Tip	7.50	8.50	9.88	8.03	7.50
Light Extension	7.50	8.50	9.21	9.13	8.59

Hybrid (time in s)

Light Sphere	4.60	4.65	8.50	5.83	5.09
Light Tripod	4.54	5.25	6.68	4.94	4.90
Light Power	5.00	6.13	7.05	5.31	4.84
Light Lateral	6.50	7.50	8.19	5.94	6.87
Light Tip	7.50	7.21	9.88	6.43	7.50
Light Extension	7.50	6.81	9.21	6.53	6.63

D. LIF Calculations

$$LIF = \frac{8 \cdot mean\ time - time}{7 \cdot mean\ time} \cdot 100 \quad [5]$$

If the time is higher than the time limit ($8 \cdot mean\ time$) the LIF score is 0.

	Mean time (s)	Time limit (s)
Light Sphere	1.63	13.04
Light Tripod	1.66	13.28
Light Power	1.77	14.16
Light Lateral	1.77	14.16
Light Tip	1.59	12.72
Light Extension	1.78	14.24

LIF scores

VO	1	2	3	4	5	Average	Standard deviation
Light Sphere	62.58	73.53	34.36	57.14	24.45	50.41	18.22
Light Tripod	67.99	51.89	45.18	53.44	72.12	58.12	10.21
Light Power	57.79	15.82	0.08	39.14	0.00	22.57	22.70
Light Lateral	47.46	53.67	48.18	60.13	58.84	53.66	5.24
Light Tip	45.19	49.51	14.91	56.51	34.50	40.13	14.49
Light Extension	47.99	59.63	0.00	61.88	61.08	45.86	24.10

VC	1	2	3	4	5	Average	Standard deviation
Light Sphere	73.97	55.74	39.79	63.19	69.68	60.47	12.04
Light Tripod	75.22	69.10	56.80	71.77	58.61	66.30	7.30
Light Power	73.93	64.81	57.38	71.43	75.22	68.56	6.64
Light Lateral	61.82	53.75	12.91	66.34	53.03	49.57	19.00
Light Tip	46.90	37.92	25.52	42.14	46.90	39.87	7.92
Light Extension	54.09	46.07	40.37	41.01	45.35	45.38	4.91

Hybrid	1	2	3	4	5	Average	Standard deviation
Light Sphere	73.97	73.53	39.79	63.19	69.68	64.03	12.72
Light Tripod	75.22	69.10	56.80	71.77	72.12	69.00	6.40
Light Power	73.93	64.81	57.38	71.43	75.22	68.56	6.64
Light Lateral	61.82	53.75	48.18	66.34	58.84	57.79	6.31
Light Tip	46.90	49.51	25.52	56.51	46.90	45.07	10.39
Light Extension	54.09	59.63	40.37	61.88	61.08	55.41	8.00