Chris P.A. van Houts
04-01-2021

TU Delft

Design of a multifunctional body powered prosthetic hand

Delft Institute of Prosthetics and Orthotics

DIPO

Design of a multifunctional body powered prosthetic hand

By

Chris P.A. van Houts

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 on Wednesday January 13, 2021 at 14:30 AM.

Daily supervisor:	Dr. ir. Dick H. Plettenburg,	TU Delft
Supervisor:	Prof. dr. Frans C.T. van der Helm,	TU Delft

TU Delft

TABLE OF CONTENTS

***Abstract*— Nowadays the design of prosthetic hands is mainly focused on myo-electric control for more functionality. And easy producible 3d printed prosthetics to lower the costs of a custom prosthesis. As a result of this change of focus, the body powered prosthetic hands currently on the market are mainly simple clamping mechanisms with no innovative functions. Looking back into the history of hand prosthetics many body powered prosthetic hands housed a couple of innovative design choices to increase the functionality. Some examples of this are the Pringle-Kirk arm and the Despinasse hand. As a counter reaction to this movement, a new body powered prosthetic hand is designed. The new prosthetic hand will be based on the innovative solutions of the past and will bring back more functionalities to the body powered prosthetics. The new design housed fingers made out of cylindrical springs, in combination with leaf springs. This is all actuated via a dependency mechanism in the hand palm, this combination allows for very flexible fingers that can grab complexly shaped objects and still offer a multi finger grip. The first tests revealed that the leaf springs limited the motion of the fingers and further testing without the leaf springs showed a setup with only cylindrical springs was a better solution. The second test was focused on pinch force, although the maximum acquired pinch force was not high, a sturdy grip should be possible based on literature, this does need further testing to validate. For the continuing of the prototyping testing of the dependency mechanism was done, initial testing at a larger scale showed promising results, little to no loss of force. The conclusion that can be drawn based on these tests is that there are certainly parts of prosthetic hands of the past that are worth taking a closer look at.**

I. INTRODUCTION

A. *Background*

In the mid 1800's till the late 1900's prostheses became more common among the people because of the many limb losses in wars. In these years a lot of prostheses were designed by different companies/designers for specific needs and most, if not all, of them were body powered or passive. Nowadays only a few major companies remain that develop prostheses. The most well known are the following, Ottobock, Ossur, Vincent Solutions and Steeper group. Once a small player with a good idea or concept rises in the market they quickly get bought up by these major players in the market in order to maintain their market share. Furthermore the focus of modern day prostheses is not on body powered anymore and a lot of the beautiful designs of the past are not used anymore, the focus has shifted to myo-electric prosthetic hands. These myo-electric prosthetic hands read out nerve ending in the remaining stump and use these signals to control a battery powered motorised prosthetic hand.

B. *Problem definition*

The main downsides of these motorised prosthetic hands is that they are heavy because of the motors and have a limited working time because of the battery power. By using body powered prosthetics both of these downsides no longer play a role, no motors are needed, only transmissions to obtain the desired movements and as a result also the battery becomes obsolete which brings down the weight. Another problem that arises with the shift from body powered to myo-electric is that most body powered prostheses on the market at the moment are mostly simple devices that allow for a single gripping motion that mostly resembles a simple clamping motion. This leaves a lot to be desired looking back at the innovative designs of the past. Some of the most inspiring designs of the past are, the prosthetic hand/arm of Carnes, the Despinasse hand, the Pringle-Kirk arm and the hand of Bethe [1], [2], [3], [4]. Looking at the big differences in functionality of the prosthetics of the past and the the body powered prosthetics on the market now a gap seems to exist. This is why there was chosen to design a body powered prosthesis.

C. *Goal*

This leads to the goal of this thesis, which is to design a new body powered prosthetic hand which is inspired by the smart design features of the prostheses from the 1800's and 1900's.
By designing a new body powered prosthetic hand which can do more than just simple clamping motion it is hoped that the body powered prosthetic hands become mainstream once again. In the end the goal of every prosthesis is to give back functionality to the fullest, which in many cases can be achieved by a more advanced body powered prosthetic hand. The prosthetic hand will give more intuitive feedback because not only visual feedback can be used but also the feedback

pathways of the muscles that are used, the applied force can be transferred back to the muscle strain. This increases the user experience in contrast to a myo-electric prosthesis where the force is predetermined and only visual feedback is given. By giving back muscle feedback besides the audio-visual feedback the usage of the prosthesis should become more intuitive after using it for a longer amount of time, and hereby increase the functionality and the comfort to the user.

D. Structure

This report guides through the design of a body powered hand prosthetic. In Section 2 the method and concept design are discussed, what steps are taken in the design process and to what outcome did this lead. In Section 3 the part design is presented, this section houses the individual design of the parts that the prosthesis consist out of. Section 4 brings together the full design, all parts are fitted together and a full design rolls out. In Section 5 the prototyping and the testing of several parts is presented. In Section 6 the test results and the overall design process are discussed. Section 7 concludes the thesis.

II. METHOD & CONCEPT DESIGN

The main objective of the thesis is to bring back the multifunctional body powered hand prosthetics. The newly designed prosthetic hand should allow for more than a simple clamping motion, unlike most of the body powered prostheses on the market at the moment. In this section the design approach, design inspirations and design criteria as well as the concept design will be discussed.

A. Design approach

The design approach started of with the gathering of body powered prosthetic hands/arm inspirations from which a few are discussed below. The mechanisms of these gathered prostheses are studied and the unique and main advantages are highlighted. From these main advantages and unique points a morphological map is created, expanding these points where possible. Next up is the creation of new concepts by drawing lines in the morphological map, combining some of the unique points and coming up with new ideas for the prosthetic hand. Afterwards these concepts will be described in further detail and the positive and negative points will be noted. These will then be judged on importance and a final score will role out. The concept with the highest score will be worked out in more detail. When scores are close together there may be chosen to combine 2 or more concepts to come up with the final design.

B. Concept inspiration

The idea is to implement some of the techniques used in prostheses designed in the 1800's & 1900's. The main prosthetic hands of the time span that stood out were the prosthetic hand/arm of Carnes, the Despinasse hand, the Pringle-Kirk arm and the hand of Bethe [1], [2], [3], [4]. Inspiration is gained from these prosthetics and their mechanisms will shortly be discussed one by one.
The first hand is the Carnes arm/hand, a full overview of the arm can be seen in figure 1. The figure shows two examples of the Carnes arm where there can be seen that each finger contains two articulated phalanges and the thumb only one but is angled inward by default. furthermore there can be seen that the wrist can be flexed and extended to allow for more natural grabbing positions in different situations. The wrist joint is coupled with the elbow joint and together they are moved by one of the two shoulders. The other shoulder is used to open and close the hand. The opening and closing of the hand can be done by a single cable because of the switching mechanism integrated into the palm of the hand. The mechanism of the fingers takes care of locking them in the most closed position reached during grabbing, the mechanism can be seen in more detail in figure 2. The mechanism consists out of an endless screw acting on a serrated arc which provides non reversible motion, the fingers will thus stay in their final position. The main advantage of such a mechanism is that there does not have to be a constant pulling force to hold an object which greatly increases the usability. Lastly the mechanism has proven to be very sturdy because of the metal components which replace the strings and springs compared to other prosthetics.

The second prosthesis is the Despinasse hand which originated in France. The four fingers have

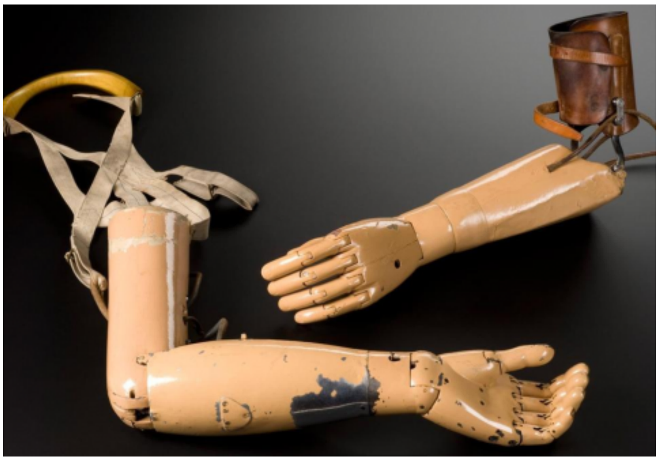


Fig. 1. Carnes arm [5]. The figure shows two examples of the Carnes arms, the right one is for long above-elbow amputees and contains the wrist and hand that are controllable by two separate bowden cables leading to the two shoulders. The left one is for short above-elbow amputees and contains the elbow, wrist and hand, in this prosthesis the elbow and wrist are controlled together with a single bowden cable and the hand uses the second bowden cable for control.

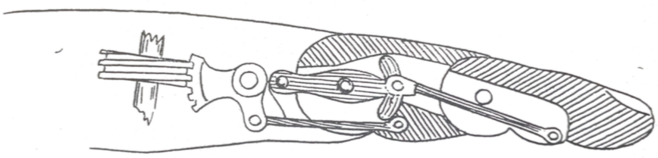


Fig. 2. Carnes detailed mechanism [3]. From the left to the right the figure shows the endless screw rotating on the serrated arc providing irreversible motion, the serrated arc then pushes a rod forward turning one of the disks in the joint which in it's turn then turns another disk hereby closing the fingers or opening then depending in the direction of the rotation of the endless screw at the start of the mechanism.

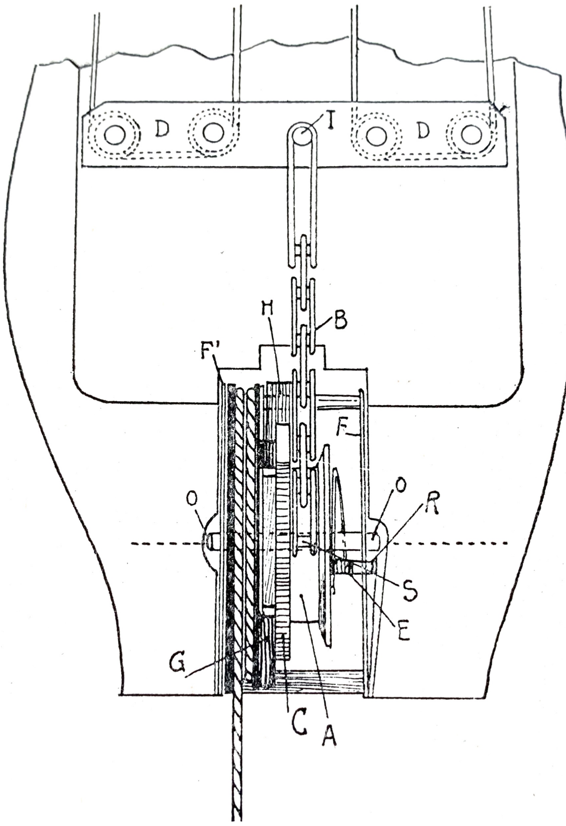


Fig. 3. Despinasse mechanism [3]. The figure shows a schematic overview of the mechanism of the Despinasse hand, a single cord is used to operate the opening of the four fingers. In more detail the cord rotates a wheel which then pulls on a chain, indicated by the letter B, connected to a pivot point in the center of the main board, indicated by the letter I, from this main board two sets of pulleys, indicated by the letter D, lead to two fingers each. Because of all these pulleys and strings the fingers move with respect to each other and can therefor be used to grab more complex shaped objects.

two articulated phalanges each and the thumb is a single piece. It is a voluntarily closing mechanism by means of a single cable pull. But although the flexion of the fingers is simultaneous the flexion is not the same in all fingers because of a pulley system integrated between the fingers, this system can be seen in figure 3. As a result of this pulley system a wider range of objects can be grasped successfully, the fingers can better form around objects, this is the main advantage of this prosthesis. The mechanism works as follows, the little fingers and the ring finger are controlled by a single string as well as the middle finger and the index finger. The two sets of two fingers are then connected again on sort of balance board which takes care of dividing the length of the strings between the two sets of fingers hereby connecting them all together. The force exerted on the single activation cable by the shoulder harness is transferred to the balance board in the palm of the hand where the dividing begins.

The third hand that is discussed is the Pringle-Kirk arm, this arm was invented in Ireland by an engineer and a surgeon. An overview of the hand can be seen in figure 4. The fingers consist of springs with wires running through them, by pulling the wires the fingers will flex and form around different shapes of objects. This way not a single joint is fixed and the hand can form around

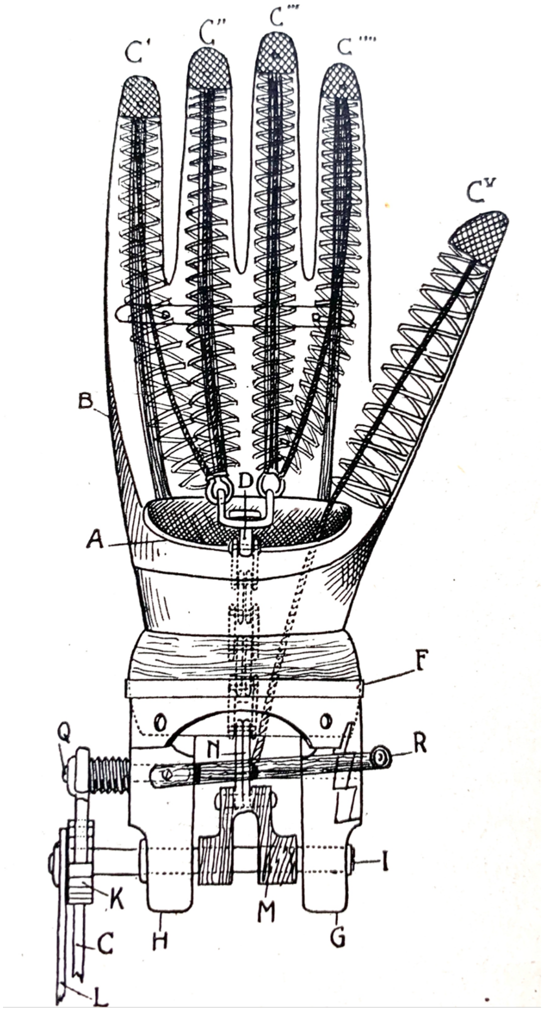


Fig. 4. Pringle hand [3]. The figure shows the internal mechanism of the wires inside the fingers, because of the spring construction of the fingers they can bend in any place and the wires therefore are connected in the finger tops. the closing of all five fingers happens simultaneously when the bar/cable indicated by the letter C is pulled.

all objects allowing the wearer to do manual work again. The fingers are elongated into the hand palm, this way the hand palm can also flex and allow for grasping of more objects. Unlike most prosthetic hands that have a certain number of joints in the fingers there can be said that the Pringle-Kirk arm has an infinite amount of joints because it can bend along its entire length, even extending into the hand palm. The main advantage of this prosthesis is that it has a flexible hand palm and has an infinite number of joints in the fingers which makes it usable for many tasks.

The fourth and final hand from which inspiration is drawn, is the hand of Bethe. It is designed

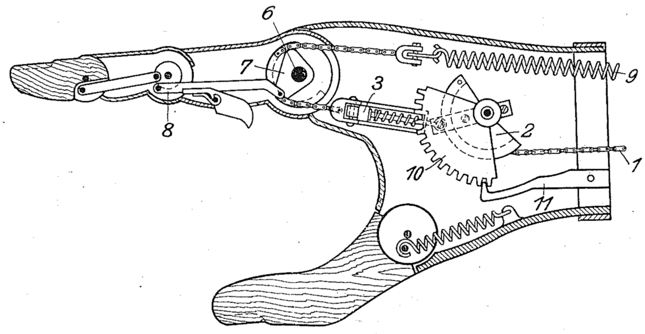


Fig. 5. Hand of Bethe. The figure shows the mechanism inside the hand that ensures the double grip function. The cable indicated by number one is the control cable used to close the hand, the springs indicated by number nine and three ensure the normal open position of the hand. the pal which sticks out of the finger near number eight is activated when an object in pressed into the hand and turns the wheel indicated by number eight and thereby changes the grip.

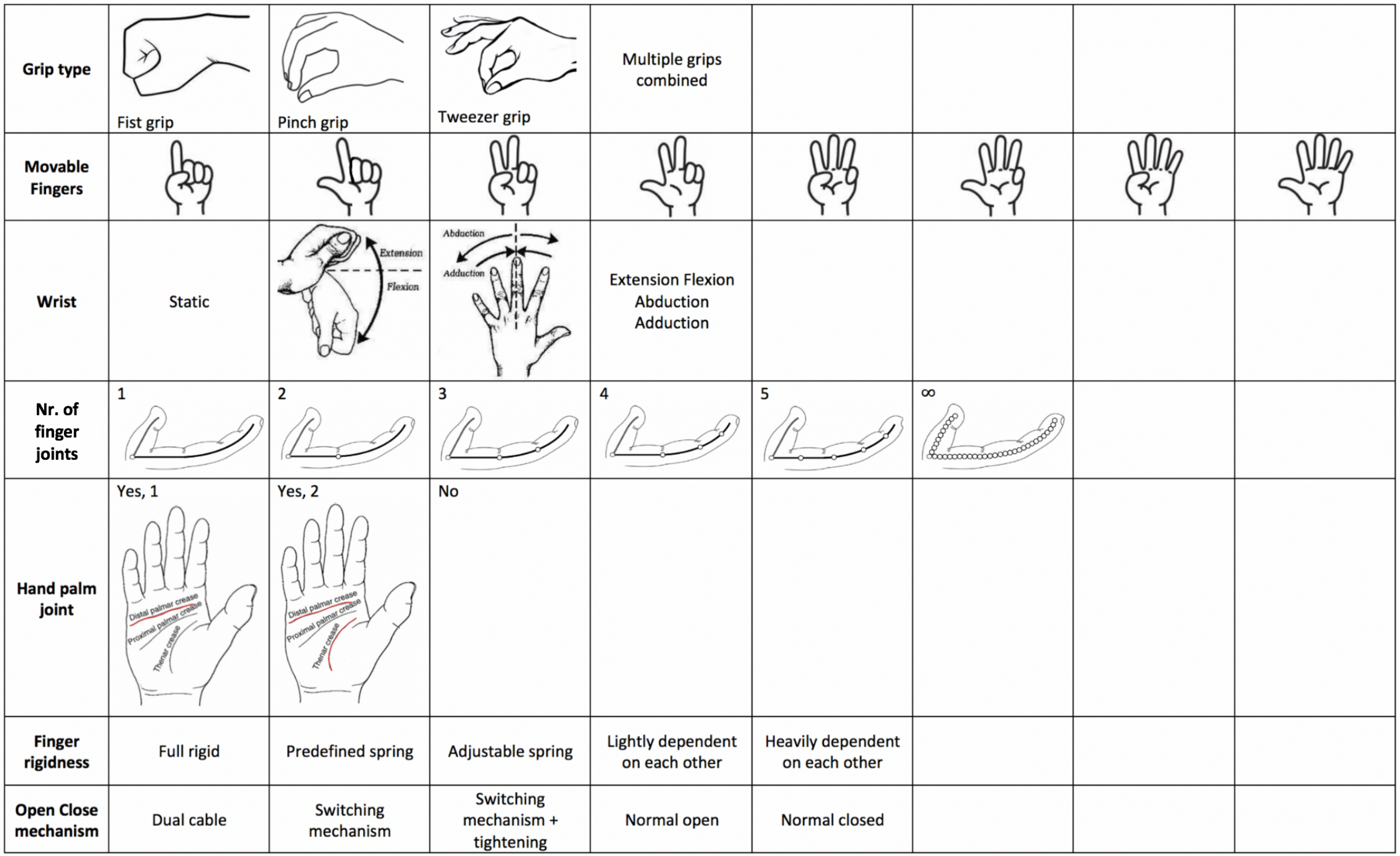
to have two different grips that can be used for specific tasks, normally a pinch grip is used but when an object is pressed against the palm of the hand a fist grip is created. The mechanism which allows for the change of grip is triggered by the little pal which is connected to the axis at number eight in figure 5. By triggering this pal the last two phalanges of the fingers move into a more closed position that resembles a fist grip. Though it is a great piece of engineering, reality proves it is a fragile piece to work with. The main advantage of this prosthesis is that is combines two often used grip positions and allows for easy switching between them.

C. Concept criteria

The new prosthetic hand that will be designed must fulfill the following criteria. First of all the prosthetic hand should be body powered, the second criteria is that the new prosthetic hand must provide an improvement on body powered prostheses currently on the market. These improvements may be on the following points, reduction of the weight of the hand, center of gravity closer to the body, less force required for grabbing objects, allow for the grabbing of a wider range of objects or increase the ease of operating the prosthetic hand.

D. *Morphological map*

Obtained from the design inspiration seven categories where created, these are represented in the morphological map in figure 6, the options that are available in these categories are listed on the horizontal axis.



Grip type	Fist grip	Pinch grip	Tweezer grip	Multiple grips combined				
Movable Fingers								
Wrist	Static	Extension / Flexion	Abduction / Adduction	Extension Flexion Abduction Adduction				
Nr. of finger joints	1	2	3	4	5	∞		
Hand palm joint	Yes, 1 (Distal palmar crease, Proximal palmar crease, Thenar crease)	Yes, 2 (Distal palmar crease, Proximal palmar crease, Thenar crease)	No					
Finger rigidness	Full rigid	Predefined spring	Adjustable spring	Lightly dependent on each other	Heavily dependent on each other			
Open Close mechanism	Dual cable	Switching mechanism	Switching mechanism + tightening	Normal open	Normal closed			

Fig. 6. Morphological map

E. Conceptual design

For the creation of the concepts lines were drawn through one option in each category resulting in five different concepts. The concepts are color coded as, red, yellow, purple, blue and green. The lines representing the concepts can be seen in figure 7. The next five subsections will describe the color coded concepts, a short explanation will be given for each chosen option to give a rough overview of the functions of the prosthesis, it's controls and looks.

1) Red: The red concept uses a fist grip with all fingers, including the thumb which creates a sturdier grip. The concept has a static wrist, assuming the arm can still pronate and supinate the hand can be positioned in the most common ways. The fingers will have four joints that allow for tight grips, this removes the need for a joint in the palm of the hand which decrease complexity and leaves space to integrate other mechanics, the forces exerted by the fingers lightly depend on each other to create a more natural grabbing action. Lastly a switching mechanism is used for opening and closing of the hand with a single cable. An additional second cable can then be used to control the elbow or pronate and supinate a mechanical arm.

2) Yellow: The yellow concept also uses a fist grip with a static wrist to decrease complexity. It does not have a movable thumb but it's fingers are made out of springs through which they have an unlimited number of joints, to increase the hand flexibility even more the hand palm also has two joints for an even tighter grip. The flexion of the fingers heavily depend on each other making grabbing of complex shaped objects possible. The prosthetic hand will be dual cable controlled to allow for more space inside the hand for mechanics because no switching mechanism needs to be placed inside.

3) Purple: The purple concept uses a pinch grip with all five fingers and a static wrist, the number of joints is increased to 5 to allow for a tighter grip. The hand palm also has a joint to decrease the range the fingers have to travel to reach the thumb or object between the fingers. The fingers heavily depend on each other making grabbing of more complex shaped objects easier, it is again controlled by a switching mechanism.

4) Blue: The blue concept also uses a pinch grip, with only two fingers plus the thumb, the wrist can flex and extend and therefor allow for a more natural grabbing position in more scenarios. The fingers have three joints just like a normal hand and no additional joints are added in the wrists. The fingers will have an integrated spring to allow for a bit of movement to mimic the stretch in the tendons of a normal hand. The hand is controlled by a switching mechanism with tightening mechanism. This allows for additional tightening when for example an object starts slipping between the fingers. This prosthesis should allow for more delicate work because of the integrated springs in the fingers and the additional possibility of tightening.

5) Green: In the green concept a tweezer grip uses the thumb and index finger, furthermore the wrist can flex and extend, abduct and adduct. Only two joints are added to the fingers to mimic a tweezer motion, to allow for a sturdy grip the fingers will be fully rigid. The control will be done by a single cable with switching and tightening mechanism. This prosthesis can best be used for picking up small objects with precision because of the freedom of movement in the wrist and the sturdiness of the fingers.

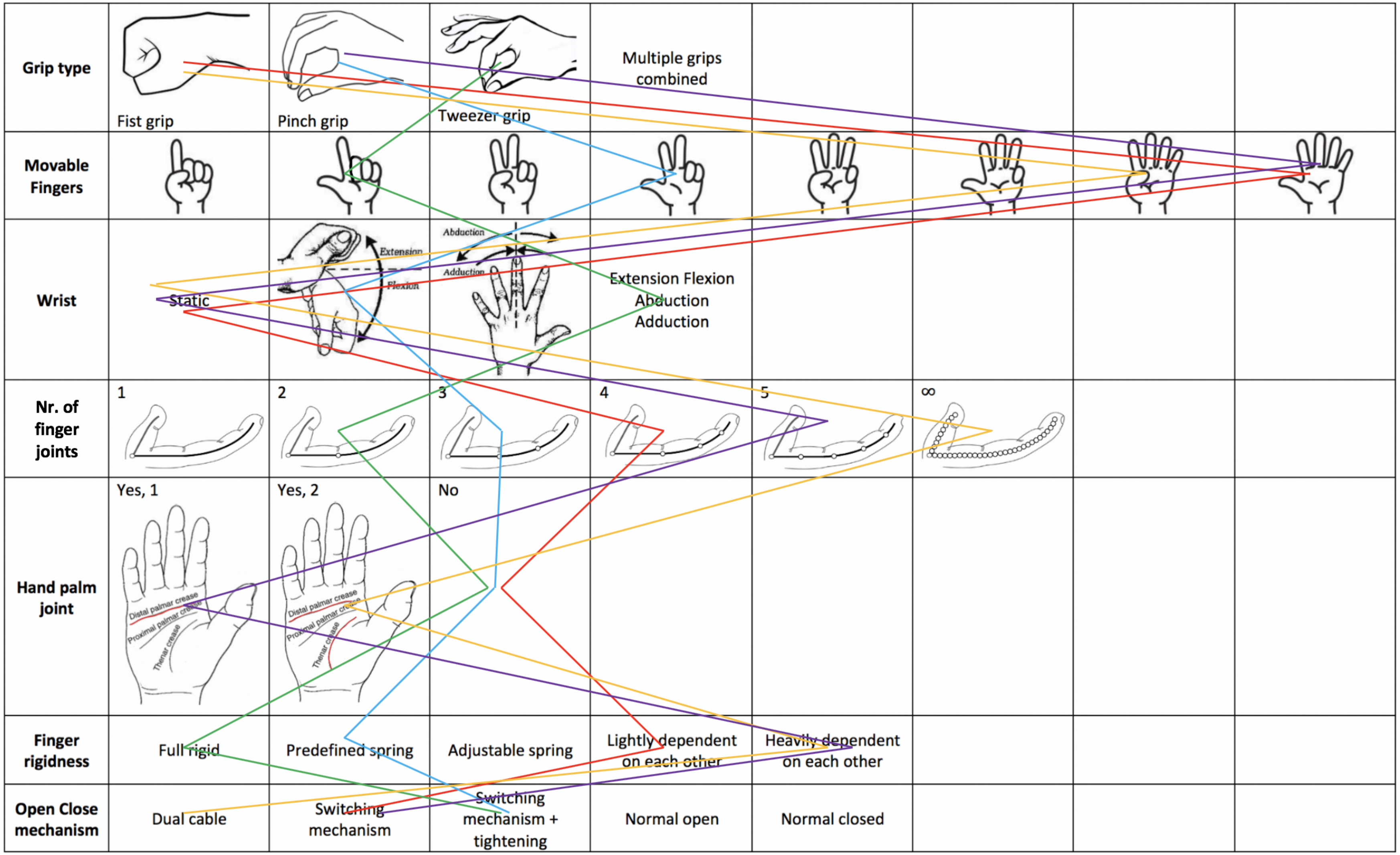


Fig. 7. Morphological map with the lines representing the concepts

F. *concept judgement*

The concepts needed to be judged on some criteria, these criteria needed to have a weight to be able to distinguish between the more important and less important criteria. The weight was created by comparing all the criteria against each other, if the criteria was more important it would get a point, adding up these points leaves all the criteria with a weight factor between one and nine which will later on be used to calculate the final score of the concepts. How the criteria weights came to be, can be seen in table I, the dividing of the points is explained in section 1 below.
The five concepts were then judged on the nine different criteria, grades between 1 and 5 were given because of the total of five concepts. The number of points that a concept was given on a particular criteria is explained in the subsections 2-10 located below.
The scores of the 9 criteria were then multiplied by the weight factor of the criteria and added together resulting in a final score per concept, the final judgement of the five concepts can be seen in table II.

1) Weight factors explained: The most important factor of the prosthetic hand is the increased functionality over other prosthesis, because the goal of this thesis is to design a new prosthetic hand. The second most important factor is the ease of control, when looking for improvements on prosthetic hands there is written that a lot of complex prostheses end up in the closet, not being used. The main reason for this is the complexity of the mechanisms causing a long learning time with too little progress for the prosthesis wearer. Next up is the weight of the prosthesis, to keep the prosthesis comfortable it is important to keep the weight down. Looking back at the older prosthetic hands some improvements can be made here with the use of new materials and new production techniques. When using the prosthetic hand, the main task the prosthesis will be used for will probably be picking up objects, the is why the grabbing of larger objects is next on the list. It is followed by the grabbing of smaller objects, the grabbing of smaller objects comes in afterward because smaller objects will most often be picked up by the remaining healthy hand instead of the prosthetic hand. Next up are the complexity of the different parts of the prosthesis, first comes the complexity of the fingers which is most important because multiple are needed and a limited space is available. Next up is the complexity of the hand, the hand also offers a limited space and will need to house some mayor components while accessibility might be limited. The complexity of the open and closing mechanism follows, again limited space is available but the many designs on market already may reduce the complexity of it. The least important was the wrist, this was chosen because the wrist is the most accessible area and the location allows for some freedom in the dimensions when needed, furthermore the weight of the wrist is the least important because of the location closer to the body it creates less momentum.

2) Grabbing large objects: The red concept gets five points because the hand will have the widest grip of all concepts, this is due to the fist grip and the usage of all fingers including the thumb. The yellow concept gets four point because it also uses a fist grip, the difference with red is that the thumb will not be actively controlled. This means the thumb will most likely be in a slightly bend position which can limit the maximum width of spreading between the thumb and the fingers. The purple concept get three points, the second best grip for large objects is the pinch grip, the purple again has an active thumb which makes it better at grabbing larger objects. In the blue concepts the ring finger and little finger are not actively controlled, this is why it gets two points. The last in this category is green with only 1 point, the hand only uses the thumb and index finger creating a precision grip not ideal for grabbing large objects.

3) Grabbing small objects: For grabbing smaller objects the story is almost switched, the green hand which is made for precision work is the best for grabbing small objects and gets five points. The stiff fingers and limited usage of fingers makes it ideal. The blue concept comes next with four point, the three fingers still allow for precision and the predefined spring in the fingers makes it adjustable for precision work when necessary. Next up is the purple concept with three points, the dependency in the fingers makes It score lower because mostly two fingers will be used for grabbing smaller object which means the fingers need to close further for a sturdy grip. The red concept scores two points, lighter finger dependency makes it more suitable for grabbing small objects but the fist grip is not ideal. Yellow comes is last with only one point, control over the thumb is essential when grabbing small objects.

4) Complexity of the wrist: Red, yellow and purple all get five points because they have a static wrist so the least complexity. Blue gets 3 points because the wrist has to allow flexion and extension increasing the complexity of the wrist. The green concept gets only one point because both flexion extension as well as abduction and adduction need to be integrated into the wrist joint

5) Complexity of the hand palm: The red hand gets four points because the hand does not have joints in the palm of the hand but the fingers do depend on each other lightly. The blue and green concepts both do not have a joint in the hand palm but do have a switching mechanism which allows for additional tightening. Because both hands have movable wrists the mechanism will probably be mainly based in the palm of the hand. The purple concepts gets two points, a single joint is integrated into the hand palm and the fingers heavily depend on each other again. Yellow gets only one point because the hand palm has two integrated joints, furthermore the fingers heavily depend on each other which greatly increases the complexity of the hand palm.

6) Complexity of the fingers: The green concept gets five points because it has only two movable fingers with two joints, the fingers will also be rigid so no further springs involved. The blue concept gets three points, it has three movable fingers and joints. The fingers do have a predefined spring integrated increasing the complexity. The red concept uses all five fingers and has four joints, the fingers also lightly depend on each other's bending increasing the complexity leading to a total of three points. The yellow and purple concepts only get a point each because the fingers have a lot of joints in them and the fingers also heavily depend on each other, greatly increasing the complexity of them.

7) Complexity of open and closing mechanism: The yellow hand gets five point because the opening and closing is operated by two single cables which makes for an easy mechanism. The red and purple concepts both get three points because they have a switching mechanism for operating with a single cable, though it removes the need for a second cable the mechanism is quite complex. The green and blue concepts both have the switching mechanism with tightening which adds another complex feature to this already complex part. That is why they both get only one point.

8) Approximated weight: The red concept gets three points, it has five movable fingers and a switching mechanism, furthermore the fingers lightly depend on each other increasing the weight further. The blue concept also gets three points although it only has three movable fingers it has a more complex wrist mechanism and the switching mechanism plus tightening. The green concept gets two points because it has a complex wrist mechanism which ought to be quite heavy and also a switching mechanism plus tightening. The yellow and purple concept both have a lot of finger joints and some more joints in the palm of the hand. These joints are suspected to increase the weight quite a bit that is why they both get only one point.

9) Increased functionality over other prosthesis: The yellow concept gets five points because of the joints in the palm of the hand in combination with the infinite joint fingers and the heavy dependency between fingers. The purple concept get also five points, again because of the joint in the palm of the hand but this time in combination with a switching mechanism removing the need for two control cables. The green concept gets four points, the high precision obtained by the manoeuvrability of the wrist and the usage of only two fingers should allow for a lot of new possibilities in usage. The red concept gets two points because of the dependency between fingers in combination with the switching mechanism. The blue concept gets also two points, it has only three movable fingers in combination with a wrist that can flex and extend.

10) Ease of control: The yellow concept gets five points, the dual cable control should allow for easier learning of the controls because they are separated. The red concept gets four points cause the switching mechanism does need some time to get used to. The blue concepts gets three points because of the integration of the flexion and extension possibility in the wrist this increases the number of movements in the hand so it increases the effort needed to control it. The purple concept also gets three points, this is due to the integration of the extra joint in the palm of the hand. The green concept gets two points, the switching mechanism plus tightening in combination with the wrist that can flex, extend, abduct and adduct may require a lot of getting used to because of the freedom of movement.

	Grabbing larger objects	Grabbing smaller objects	Complexity of the wrist	Complexity of the hand	Complexity of the fingers	Complexity of open & closing mechanism	Approx. weight	Increased functionality over other prosthesis	Ease of control
Grabbing larger objects	1	0	0	0	0	0	1	1	1
Grabbing smaller objects	1	1	0	0	0	0	1	1	1
Complexity of the wrist	1	1	1	1	1	1	1	1	1
Complexity of the hand	1	1	0	1	1	0	1	1	1
Complexity of the fingers	1	1	0	0	1	0	1	1	1
Complexity of open & closing mechanism	1	1	0	1	1	1	1	1	1
Approximated weight	0	0	0	0	0	0	1	1	1
Increased functionality over other prosthesis	0	0	0	0	0	0	0	1	0
Ease of control	0	0	0	0	0	0	0	1	1
Weight factor	**6**	**5**	**1**	**3**	**4**	**2**	**7**	**9**	**8**

TABLE I

WEIGHT FACTOR DISTRIBUTION OF THE CONCEPT CRITERIA

	Red	Yellow	Purple	Blue	Green
[6] Grabbing larger objects	5	4	3	2	1
[5] Grabbing smaller objects	2	1	3	4	5
[1] Complexity of the wrist	5	5	5	3	1
[3] Complexity of the hand	4	1	2	3	3
[4] Complexity of the fingers	2	1	1	3	5
[2] Complexity of open and closing mechanism	3	5	3	1	1
[7] Approximated weight	3	1	1	3	2
[9] Increasement in functionality over other prosthesis	2	5	5	2	4
[8] Ease of control	4	5	3	3	2
Total number of points:	**145**	**143**	**130**	**121**	**129**

TABLE II

GRADING OF THE CONCEPTS

G. Choosing the final concept

Looking at the results in table II there can be seen that two concepts have significantly more points as the other three concepts, the yellow concept and the red concept come out on top. To choose a final concept it is interesting to see what the main differences are between these two concepts and if it is worth combining specific points to create an even better concept. There was looked at two different things, the differences in points and the differences in design, these will be shortly discussed in the next two sections. Afterwards the final design choice is discussed in the third section.

1) Differences in points: The main differences in points between the red and yellow concepts are in the complexity of the hand, the approximated weight and the increased functionality over other prosthesis. The complexity of the hand is mainly a challenge in the yellow concept because of the hinges integrated into the palm and the heavy dependency integrated between the fingers. The red concept has only a light dependency between fingers and no further complex hinges in the palm of the hand. Because of the hinges in the palm of the hand the yellow concept is also rewarded less points on the approximated weight. Finally the Yellow concept surpasses the red concept on the increased functionality over other prosthesis, while the red concept only integrates light dependency into the fingers the yellow concept gets extra hinges in the palm of the hand, heavy dependency between fingers and the fingers will have an infinite amount of joints because of the spring construction.

2) Differences in design: The Red hand uses four fingers plus the thumb, the yellow uses only the four fingers. The red concept has four joints, while the yellow hand has infinite joints because of the spring construction. The red concept has a static hand palm but the yellow one has two joints integrated into the palm of the hand increasing the closing range of the hand. Furthermore the red concept has light dependency between fingers while the yellow concept has heavy dependency and finally the red hand uses a switching mechanism with one cable to control the opening and closing of the hand while the yellow hand uses a dual cable system in an effort to save some space for all the mechanics inside the hand.

3) Final concept choice: The final concept that is chosen is the yellow concept, although it was rewarded a few points less as the red concept the yellow design integrates many features which make the design stand out more from prosthetic hand designs currently on the market. The design of the yellow concept can be described as a combination of the Despinasse hand with the Pringle-Kirk arm. The dependency between fingers is inspired by the Despinasse hand, while the spring fingers in the yellow concept and also the idea of integrating hinges into the palm of the hand came from the spring fingers which extend into the hand in the Pringle-Kirk arm. For the control of the prosthetic hand there has been chosen for a dual cable system this choice was made because the spring fingers and the hinges inside the hand palm will probably take up a lot of space. Some more room is needed to integrate the dependency between the fingers and an additional switching mechanism for single cable control would take up even more room which is probably not available. When during the development phase of the control mechanism enough room is available or the switching mechanism does not take more space as the dual cable system this option will certainly be explored further.

III. Part design

In this section the final concept will be divided into different parts which will be worked out into further detail one part at a time following the design order. The next step will then be to bringing the separately designed parts back together into a full design.

A. Design order

To ease the design process there has been chosen to split the concept up into different parts. These parts and their mechanisms will be studied individually and worked out till a rough estimation of the space and the complexity can be made. The next step of the final design process will then be to integrate the different parts of the design into a single hand prosthetic design. This will mean designing the connections between the different parts and working out the fitting in the overall prosthesis. The design order of the prosthesis parts is starting from the fingers and moving down step by step until the wrist is reached. The first design part will therefore be the fingers, next up will be the dependency mechanism for the fingers, followed by the hinges in the hand palm. These two might be switched in the final design but from a design standpoint the dependency mechanism is a closer match to the fingers as the hand palm joints. After finishing these parts there will be looked into the control mechanism, to hold open the option of the switching mechanism as well as the dual cable control both of the options will be worked out into detail so a deliberate decision can be made on the final open and closing mechanism.

B. The fingers

For the fingers mechanism there has been chosen for an infinite amount of hinges, this can be created by using springs in the fingers just like the Pringle-Kirk arm. A more recent example of a prosthetic hand that uses springs in the fingers is the Becker mechanical hand which is still on the market.

1) Existing design/inspiration: To get a clear overview of both existing prosthetic hands, the patents were consulted [6] & [7]. After going through the patent documents the prosthesis were compared, the Becker hand versus the Pringle-Kirk hand. They look similar though there a few major differences. For one, the most used Pringle-Kirk hand has the springs extend into the palm of the hand allowing for even more flexion while the springs in the Becker hand only wrap the fingers. Another major difference is that the Becker mechanical hand uses the springs for a more aesthetic purpose. The springs make sure a natural look is kept in every open or closed position, but the actual hinges that allow for the motion of the fingers are located inside the springs. This means the Becker hand does not have a infinite amount of hinges but only a set amount that is internally integrated. As where the Pringle-Kirk hand allows for bending of the fingers in each possible place, this does however reduce the natural look of the hand when grabbing objects but makes the grabbing complex objects easier.

2) New design: For the design of the prosthetic hand with infinite joints the mechanism incorporated in the fingers of the hand of the Pringle-Kirk arm gives the best results. Another closer look at the patent documents of the Pringle-Kirk arm shows that a couple of different techniques can be used to achieve the flexible fingers. These techniques are described below.

1) The first option is a mechanism that uses coiled springs as fingers with control cables inside, this leaves the full freedom of movement which is not desirable because a natural movement is preferred. The movement can be limited to bending movement to the front by for example, using guide loops in the bottom side of the coiled springs.
2) Leaf springs are the second option, they will use a control cable on the top or bottom. The benefit of leaf springs is that the direction of bending is already predefined, a downside however is that the finger aesthetics, the round shape, of the fingers has to be made in a different way. This can for instance be done by casting a rubber like substance around the leaf spring.
3) The third option is a hybrid of the two options mentioned above. This hybrid uses the coiled spring for a better aesthetic look while remaining flexible in all directions, and limits the freedom of movement by a small pre-bend leaf spring to make sure the fingers only flex forward and not backward or sideways.

Looking at the three options mentioned above the third option seems the best. The hybrid option uses the benefits of both while eliminating the downsides of them, making it the ideal solution for the fingers. The coiled spring and leaf spring will both be attached to the top of the finger that is made out of a rubber substance for better grip, and attached to the bottom of the hand palm. A rough representation of the assembly of the fingers can be seen in figure 8

3) finger length: The next step was defining the length of the fingers and the ratio between the thumb and the fingers. The dimensions for the prosthetic hand were taken from an average dutch male student between 17-27 years, taken from DINED on the 1st of July 2020 [8]. According to this data, the index finger has a length of 74

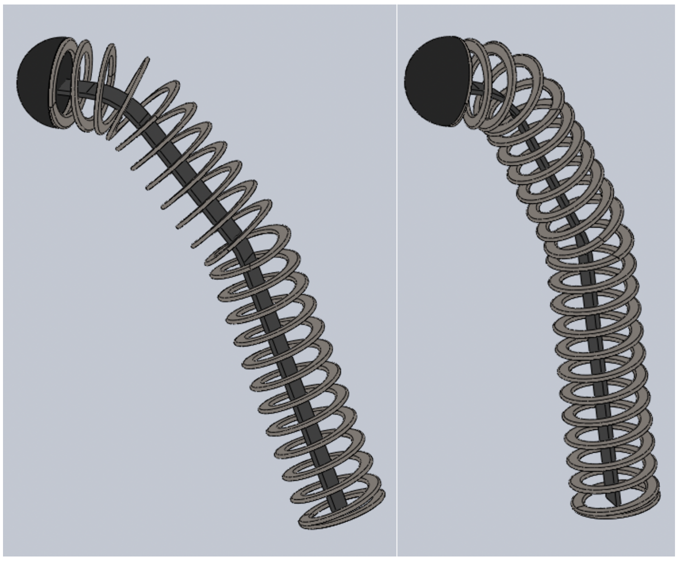


Fig. 8. Finger assembly. The figure show a rough representation of how the finger assembly will look, the rubber finger top with the coiled spring and the leaf spring extending out till the palm of the hand.

mm, a width of 16 mm and the total with of the hand without the thumb is 85 mm. The total length of the hand, from the start of the wrist to the top of the middle finger, is 191 mm and the thickness of the average hand is 27 mm. So now the rough dimensions are known but not the dimensions of the individual fingers, another important measurement is the length of the thumb [9]. In this article the ratio between the finger sections and the ratio between the fingers and the thumb is investigated. The optimal ratio was calculated based on the WS(Work Space) and GMI(Global Manipulation Index). For an average human hand the WS is 0.0253 and the GMI is 0.0170, for the optimal hand that came out of the research the WS is 0.0295 and the GMI is 0.0198. Comparing the ratio's, the thumb to finger ratio of a human hand is 0.661, the ratio of the optimal hand that was found during their research has a thumb to finger ratio of 0.720. Because the prosthetic hand should have the most optimal proportions for the best result there was decided to take the ratio of the optimal hand, so 0.720 as the thumb to finger ratio. This leads to a index finger with a length of 74 mm obtained from DINED, and the associated thumb length 53.28 mm, which is obtained by multiplying the ratio with the length of the index finger. For the length of the ring finger the 2D:4D ratio was used, the 2D:4D ratio is the result of dividing the length of the index finger by the length of the ring finger, for the average male the 2D:4D ratio is 0.947 [10]. This results in a ring finger length of 78.14 mm, the same ratio for the distance between joints is used for the pre-bending of the leaf spring. In the average human hand the middle finger is slightly larger as the index finger and the ring finger. This lead to the length of the middle finger to be defined as 80 mm, the ratio between the finger sections is maintained throughout all fingers. The final finger that needs to be defined is the little finger, there was decided to scaled the little finger to 84% of the index finger. There was chosen for scaling in all directions instead of only adjusting the length because of the overall smaller size on average.

4) finger strength: Another important aspect in the prosthetic hand is the grip strength, it needs to be able to become high enough without causing too much strain on the wearer. The force that will be delivered to the fingers has to travel through quite a lot of mechanisms to get there and this causes additional effort that needs to be delivered. All this effort has to be delivered by the shoulder in the case of a shoulder harness. To get an idea of the force that the hand needs to be able to put out, the maximum force that can be delivered by an average human hand is consulted. This data was found in an article by C.A. Crosby published in 1994, it describes the pulp pinch strength that the dominant and non-dominant hand can deliver for both the left and the right hand and for both males as well as females, an example of the pulp pinch can be seen in figure 9 [11]. For the prosthetic hand that is designed the sizes of the hand were obtained from a data set concerning a male between 17-27 years of age, so there is looked at the male data set. Furthermore another article describes that the prosthetic hand is mainly used as the non-dominant hand[12]. This results in a maximum pulp pinch strength value of a male non-dominant hand in the range between 6.35 and 10 kilogram that transfers to a value between 62 and 98 newtons, which matches with the values found in other articles [13]. To get an idea of the acceptable losses inside a hand prosthetic there was looked at an article named "Efficiency of

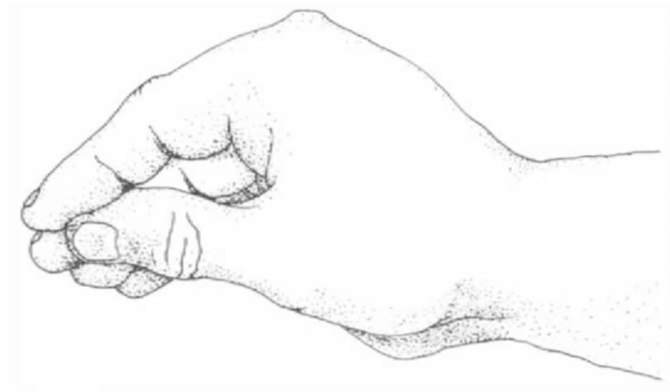


Fig. 9. Pulp pinch, the figure shows an example of a pulp pinch. The thumb and other fingers act in a pinching motion till touching each other or the object in between.

Voluntary Closing Hand and Hook Prostheses" [14]. In figure 10 the power in/out put can be seen of a few hand prosthetics. Furthermore the maximum power that can be delivered by the shoulder of a male is important, this data was found on an online source that had a test group of 23 prosthesis users [15]. The maximum force that a male could deliver to the shoulder harness during the testing was between 215 and 449 newtons.

When looking further into these numbers the maximum losses can be calculated. The non-dominant hand has a maximum pulp strength of minimal 62 newtons, comparing this to the maximum force delivered by the shoulder of minimal 215 newtons an excess is present of approximately 250%. Looking at the maximum values a 98 newton force can be exerted by the non-dominant hand, and 449 newtons can be delivered by the shoulder harness, this results in a excess force of approximately 350%. This seams to be a lot but as mentioned by Mona Hichert, the operating power of the current body powered prostheses is too high for comfortable use. That is why the maximum operating power should only rarely be requested. This might be possible because the operating power is compared to the maximum pinch strength and this is also rarely used, in daily life the average force required is about 20% of the maximum force that can be delivered [15]. This in combination with a locking mechanism should allow for a more comfortable use of the prosthesis all day round. The operating power that is required is lower and it only has to be delivered for a short amount of time each action because the locking mechanism will take over the constant force required to hold objects.

C. Dependency mechanism for the fingers

With a possible finger mechanism in place the next part is the dependency mechanism. This mechanism will allow the different fingers to bend further or less with respect to each other, hereby the grabbing of complex shaped objects will become easier. The mechanism should allow for a decent amount of difference in the bending between fingers but should not limit the closing range.

1) Existing design/inspiration: The inspiration behind the dependency mechanism came from the book artificial limbs[3], in this book the Despinasse hand is brought forward that was developed in France 3. The two main design features of this prosthetic hand are the locking mechanism that holds the hand in the most closed position, so no effort needs to be delivered to hold an object. And the dependency mechanism that would allow for the better grabbing and holding of objects. The increased grip would be achieved by wrapping the fingers around an object, instead of only one finger touching when all fingers move the same amount in a standard prosthetic hand.

2) New design: For the new design there was chosen to replicate the Despinasse hand but try to make the mechanism more compact to allow for the placement of other components in the palm of the hand, this led to the design that can be seen in figure 11. The dependency mechanism consists out of multiple pulleys, some of which can move up and down and some are connected. These pulleys are then ordered in a way that a few cables connect the bowden cable all the way up the the top of the fingers. In further detail, starting from the bowden control cable which is represented by the orange arrow. The cable wraps around a pulley and then connects to the center of the smaller blue pulley. The smaller blue pulley can move up and down with a total range of 25 mm, and is shown in the other final position by the dotted

	Prosthesis	Mass (gr)	Opening width (mm)	Maximum cable excursion (mm), $n=4$	Work closing (Nmm), $n=4$	Cycle hysteresis (Nmm), $n=4$	Work closing and pinching 15 N (Nmm), $n=4$	Required cable force for a 15 N pinch (N), $n=4$	Pinch force at a cable force of 100 N (N)	Pinch force drop at a 15 N pinch (N), $n=4$
1	Hosmer APRL hand, 52541 (L) size 8	347	44 (70*)	37 ± 0.1	1058 ± 4	298 ± 8	831 ± 1	61 ± 0.6	41	7.3 ± 0.4
2	Hosmer APRL hook, 52601 (R)	248	73 (33**)	38 ± 0.1	720 ± 6	138 ± 3	687 ± 2	62 ± 0.0	30	10 ± 1.5
3	Hosmer soft hand, 61794 (R) size $7\frac{3}{4}$	366	71	38 ± 0.3	2292 ± 12	1409 ± 37	2176 ± 16	131 ± 0.7	5	14 ± 1.7
4	Otto Bock, 8K24 (L) size $7\frac{3}{4}$, frame	220	100	60 ± 0.5	1624 ± 8	389 ± 19	1545 ± 1	78 ± 0.3	28	6.7 ± 0.5
5	Otto Bock, 8K24 (L) size $7\frac{3}{4}$, frame + inner glove	350	69	41 ± 0.2	1639 ± 24	672 ± 8	1694 ± 16	90 ± 0.9	19	5.9 ± 0.4
6	Otto Bock, 8K24 (L) size $7\frac{3}{4}$, frame + inner glove and cosmetic glove	423	57	38 ± 0.5	1710 ± 20	681 ± 23	1636 ± 29	98 ± 0.5	14	6.5 ± 0.3
7	TRS hook, Grip 2S	318	72	49 ± 0.1	284 ± 3	52 ± 1	243 ± 3	33 ± 0.2	58	–

*Thumb positioned in 'wide' position. **Hook adjusted to small range.

Fig. 10. Prostheses closing force overview. The figure shows an overview of the forces that are required or need to be delivered to get a specific force output, this is given for a couple of hand prosthetics to create an overview. [14]

lines. This movement can extend or shorten the cable connected to the pulley system of the fingers and contract or extend the fingers. The yellow pulleys are connected in pairs and guide the cables that extend into the fingers. When the blue cable shortens, the yellow pulley pairs are pulled down and hereby the cable extending into the finger shortens and contracts the fingers. Furthermore the grey dots inside the circles represent the pulleys that can move up, down and rotate, the black dots represent the fixed pulleys that can only rotate. The dependency in the finger is guaranteed by the pulleys guiding a single cable, for example the cable connecting the index- and middle-finger that runs through the yellow pulleys on the left. This allows for the index or middle finger to flex further in respect to the other finger. The two sets of fingers are then connected by the blue pulleys and cable that allow for the sets of fingers to move with respect to each other. By these two pulley constructions it is possible to have one finger contract fully while the other fingers are barely bend and the other way around. This will allow for a more natural grip on non symmetrical objects that require different bending in the fingers. The prosthetic hand will form to the object instead of the worst case scenario of only one finger connecting to the object that is grasped.

The up and down movement of the blue pulley decides the max shortening of the cable and thereby the max contraction if the fingers. To acquire the range needed for the fingers to bend to a certain angle a schematic was made from which the length of the cable could be obtained, the schematic overview can be seen in figure 12. The fingers are bend at each joint respectively 110 & 110, 130 & 130, 150 & 150, 170 & 170 degrees, taking that fully extended is 180 degrees. By drawing the boxes that extend 8 mm from the middle of the finger the shortest cable length can be approximated. The distance from the bottom to the top of the middle of the fingers is 66 mm, when bend 170 degrees at both joints it slinks to 63.2 mm, at 150 degrees it slinks to 57.4 mm, at 130 degrees it slinks to 51 mm and at 110 degrees it is only 43.5 mm. Taking that 110 degrees bend at the two joints counts as fully flexed the cable should be able to pull 66 - 43.5 = 22.5 mm. To leave a little wiggle room and account for some stretch in the cable there was decided to allow for a movement if 25 mm.

When building a dependency mechanism consisting out of pulleys and wire rope it is important to look at the loss of strength in a given wire because of the repetitive bending around the pulley. The formula used to calculate the loss of strength

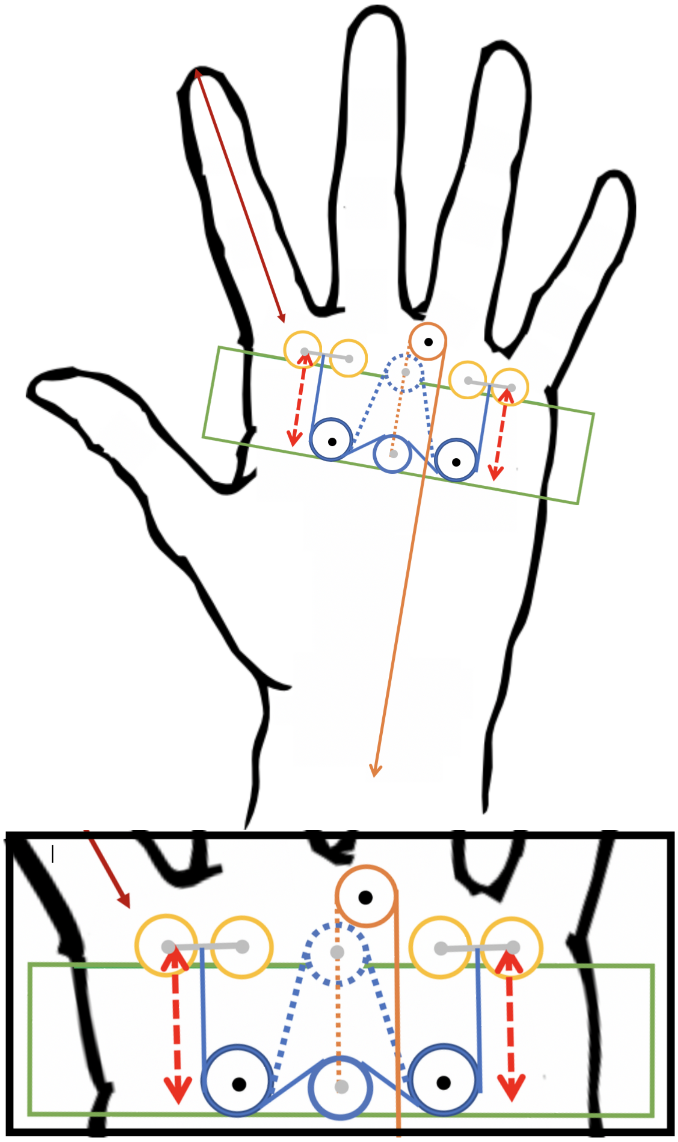


Fig. 11. Dependency mechanism, the figure shows the dependency mechanism positioned in the hand and a zoomed in version of the gears. Starting from the bowden control cable represented by the orange arrow, it wraps around a pulley and then connects to the center of the blue pulley. The smaller blue pulley can move up and down, as is shown by the dotted lines, and hereby extend or shorten the cable connected to the pulley system of the fingers and contract or extend them. The yellow pulleys are connected in pairs and guide the cables that extend into the fingers, when the blue cable shortens the yellow pulley pairs are pulled down and hereby the cable extending into the finger shortens and contracts the fingers. Furthermore the grey dots inside the circles represent the pulleys that can move up, down and rotate, the black dots represent the fixed pulleys that can only rotate.

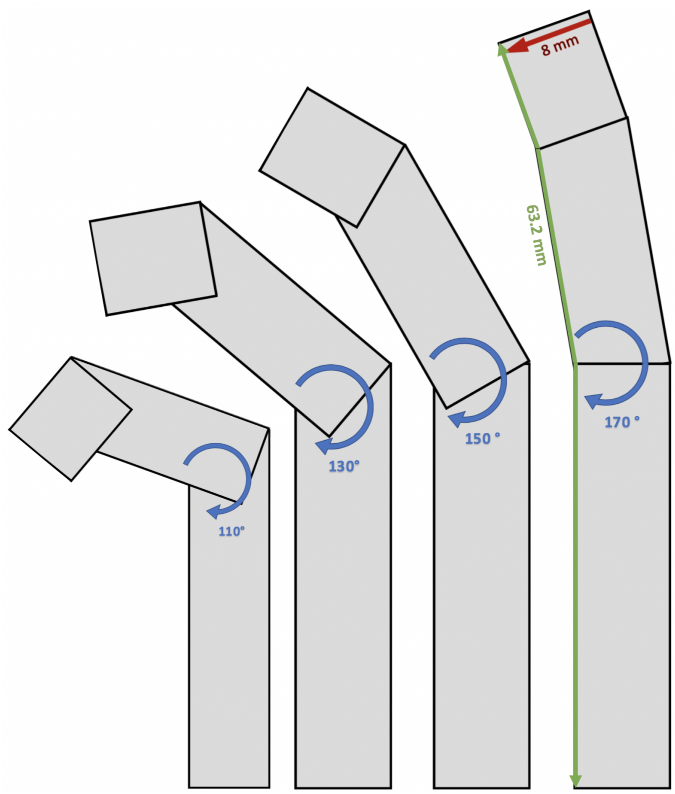


Fig. 12. Bending length, the figure shows a schematic overview of the middle finger in four different bend states. The right side of the fingers represents the middle of the finger and the boxes of 8 mm around them represent the thickness of the finger. By measuring the shortest distance to from top to bottom finger is all four cases the shortening of the cable that actuates the finger can be estimated.

in the given wires is as follows, $P = \frac{\pi (d)^4 EG}{16 R r_S \left[2G\left(1+\sin^2\alpha\right)+E\cos^2\alpha\right]}$ [16]. In Attachment A the calculations for the minimal wire ropes that are required are performed. The results of the calculations that came out were of a 1 mm thickness and a 2 mm thickness wire rope with both 19 strands, with respectively a residual strength of 396 Newton and 632 Newton. A helpful guideline that can be followed for choosing the right wire rope is, the more strands a wire rope consists our of the more flexible it is. Though the formula gives an estimate, actual testing of the wire ropes with the pulleys should point out the real life cycle and strength that is manageable.

D. *Hinges in the hand palm*

Next up are the hinges in the palm of the hand, fitting one or two and in which location will they be most beneficial.

Fig. 13. Bebionic hand, myoelectic prosthetic hand by Ottobock, the black material between the thumb and the palm of the hand is flexible and the thumb can bend around this joint. [17]

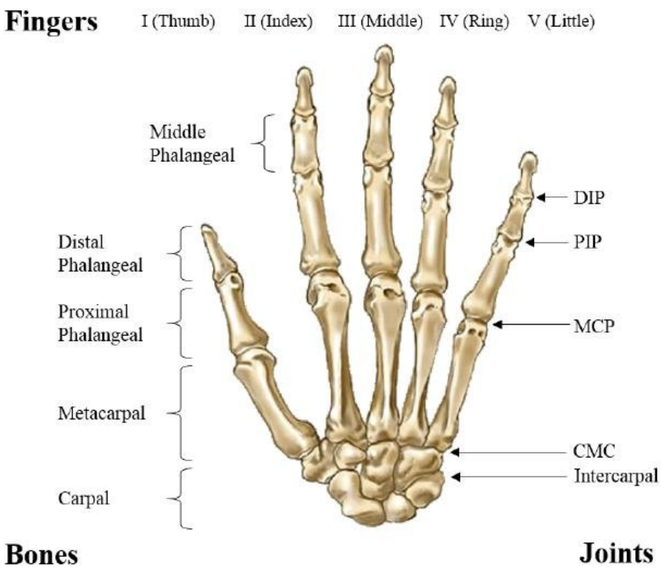


Fig. 14. Bones and joints, the figure shows the bones and joints of the human hand. The CMC (CarpoMetaCarpal) joint is the joint of interest for the extra hinge that is integrated into the palm of the hand of the prosthesis [17]

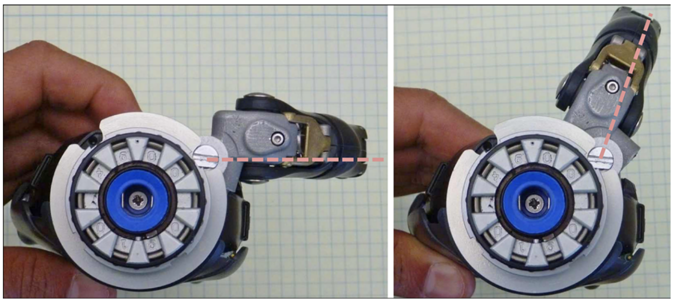


Fig. 15. Bebionic V2, the figure shows the bottom view of the prosthetic hand at the wrist and the location and rotation axis of the CMC (CarpoMetaCarpal) joint that is used in the bebionic V2 and will also be used in the new prosthetic hand that is designed. The orange line starts at the center of rotation and stops at the end of the thumb joint viewed from below.[18]

1) Existing design/inspiration: The idea of a flexible hand palm comes for the Pringle-Kirk hand shown in figure 4. In this design the fingers which consist our of springs extend into the palm of the hand, hereby making the palm of the hand flexible. Another example of a movable hand palm is the Bebionic hand of Ottobock, the joint between the thumb and the palm of the hand is movable this can be seen by the black material at the base of the thumb in figure 13.

2) New design: In the new design not the whole palm will be flexible because the area of the palm should house more components. So instead there is chosen to integrate hinges into the palm of the hand, hereby leaving room for other important components in the palm but still offer some of the benefits of a flexible hand palm. Looking at the anatomy of the human hand in figure 14 the joint that would add the most benefits to the prosthesis grip is the CarpoMetaCarpal (CMC) joint of the thumb. This joint helps with squeezing something in the hand palm and can help forming a fist grip with the hand prosthetic, following the same principle as the Bebionic hand of Ottobock. The CMC joint takes care of the movement of the base of the thumb inward to the palm of the hand and outwards, this movement can be mimicked by a single strategically placed hinge that moves the whole thumb as can be seen in figure 15. The thumb will consist of the same winded spring and leaf spring construction as the rest of the fingers and will be controlled by a branch that comes of the main actuation cable.

Fig. 16. The Equilux by ToughWare, the figure shows the clamp respectively in its voluntary closing and voluntary opening position. By flipping the large metal lever from one side to the other the modes can be switched, the actual switching happens because of the repositioning of the elastic band pulling force from one side of the joint to the other side of the joint. [19]

E. The control mechanism

To hold open the option of the switching mechanism as well as other options, the switching mechanism will be worked out into detail so a deliberate decision can be made on the final open and closing mechanism.

1) Existing design/inspiration: The Carnes arm has a sort of switching mechanism integrated in the palm of the hand, it consists out of an endless screw mechanism that gets winded up by pulling the cable that closes the hand. The mechanism that releases the break and reverses the movement of the winded endless screw is controlled by the shoulder. This way the speed and distance the hand will open can then be decided by the same shoulder used to open the hand.
A second mechanism that is the found is the Equilux by ToughWare, it works by means of a physical switch that is controlled by the healthy hand [19]. It is a rigid design with an elastic band that provides the opening/closing force. It works by reordering the elastic band to the other side of the joint hereby changing the direction of the pull of the elastic band, the difference between the two modes of the hand can be seen in figure 16. Another published design for the clamp switch mechanism works in a similar way as the Equilux [20]. Instead of the elastic band it works with mechanical links that move the opening force to the opposite site of the joint, these mechanical links further increase the already heavy mechanism although it does improve the longevity.

2) New design: For the new design there has been chosen not to use a switching mechanism because of the size and weight that needs to be limited. Instead a voluntary closing setup is chosen, this is easily implementable because of the coiled springs and leaf springs already present in the fingers. These two springs in every finger will take care of the extension of the fingers while the cable connected to the dependency mechanism takes care of flexing the fingers. By using this technique the weight needed for the control mechanism is minimal and no space is required because the cable coming out of the dependency mechanism can directly be coupled to the bowden cable going to the shoulder.

A downside to the voluntary closing mechanism that is chosen, instead of a switching mechanism, is that a lock needs to be implemented to keep the hand in it's closed position when needed. The locking mechanism is preferred in the prosthetic hand because it takes away a lot of strain from the shoulder muscles, that only need to contract when grabbing an object, but no longer need to remain strained when holding an object steady.

The locking mechanism can be integrated into the hand so a abrupt strong pull will release the cable and with normal pulling the cable will stay in its mot retracted position thus holding the hand at it's most closed position. Another option could be to use an external cable locking mechanism. This is for example mounted on the arm and is basically a switch that can be operated by the other hand. Activating the switch will hold the hand in it's current position and deactivating the switch will release the control cable back to the user. An good example of this lock is the SURE-LOK CABLE LOCK CONTROL SYSTEMS of TRS [21].

IV. Full Design

In this section the four parts that have been designed and described in the previous sections will be combined into one full hand prosthetic design. Just like the part design the assembly will be approached from the top of the fingers toward the wrist connection and will start off with a quick overview.

A. *Overview*

First a quick overview will be given of the connections that need to be made before they will be worked out into further detail. The first connection needed is the connection of the finger top out of a rubbery material or something coated with a rubbery material to the leaf spring, the coiled spring. It should also provide a secure connection for the cable that will flex the finger. This connection is needed five times, in all fingers. The second connection that is needed is the connection of the leaf spring and the coiled spring to the palm of the hand. The palm of the hand will most likely be an open construction because it will house multiple components. The cables from the top of the four fingers will run into the dependency mechanism in the hand palm where the forces will be distributed to the single cable coming out of the bottom part. As said the hand palm will house the dependency mechanism that consists out of eight pulleys, from which three are stationary and can thus be directly connected to the open hand palm construction. A single pulley which needs to be able to move up and down on a slider of some sort, and two sets of pulleys which also need to be able to move up and down by means of a sliding mechanism. The next connection that is needed is the one that connects the thumb to the hinge, this connection can be similar to the one that fixes the other four fingers. The other side of the thumb hinge needs to be connected to the open hand palm construction. The cable coming out of the thumb can then meet the other single cable coming out of the dependency mechanism and form the main actuation cable. The voluntarily closing mechanism does not need extra components besides the locking mechanism. This mechanism is located between the main actuation cable, consisting out of the two combined cables of the thumb and the dependency mechanism, and the bowden cable that is coming from the shoulder harness. The locking mechanism itself again is connected inside the open hand palm construction or can be a separate component outside of the hand.

B. *Finger top*

The first connection is made in all the five tops of the fingers, because these will all be similar only one will be discussed. The finger top needs to connect to the cable that flexes the finger and to the winded spring and the leaf spring that extend the full length of the finger. The idea is to attach the leaf spring at the top and bottom and hereby enclose the coiled spring so it will stay in place. A small circle on the finger top that falls into the coiled spring can be used to make sure it stays in the right place. The control cable is looped at the top and will slide into a slot in the top of the finger together with the leaf spring and will be locked in place with a small screw, fixating both the cable and the leaf spring and locking the coiled spring on top. The whole finger top then gets covered with a rubbery layer that assures better friction for picking up and holding objects.

C. *Finger to hand palm*

The finger connection to the hand palm can use the same idea as the finger top with the circle protruding from the hand palm and falling into the coiled spring, locking the spring in place. It could also use the reverse of the protrusion, a circle cutout in the hand palm in which the whole spring sits secure. The leaf spring can fall into a slot and get locked in place with a small screw. The control cable on the other hand should be able to pass through a hole into the open hand palm construction to be able to actuate the finger.

D. *Hand palm*

The hand palm will be a hollow construction housing the dependency mechanism and possibly the locking mechanism, it will be connected to the fingers and to the wrist. At the top four circles are protruding or cut out to hold the coiled spring in place, furthermore four slots will be created in a thickened section of the hollow construction to allow for the leaf springs to slide in and get locked in place by small screws. Ideally the hollow hand palm consists our of 2 parts that can be clicked together after placing all the components of the dependency mechanism and the locking mechanism inside. This would allow for easier manufacturing and assembly.

E. *Thumb hinge*

The top part of the hinge in the thumb can use the same techniques as the hand palm to secure the fingers, so a circle which allows the coiled spring to fall into and a slot with screw fixation for the leaf spring. The bottom part of the hinge needs to be connected to the hand palm but allow for a cable to run through for the flexing of the thumb so an open structure is ideal.

F. Wrist connection

The final connection needed is the connection of the wrist to the rest of the arm. This connection will variate a lot based on the needed connection. With a connection to a prosthetic arm the cable could run internally and a screw fixation can be used. When the hand will connect to healthy arm the control cable should be outside and will be guided closely to the arm towards the shoulder harness. Because of these variations an easy adaptable end piece should be designed that can be switched out when desired.

V. Prototype & Testing

In this section there will be discussed what parts were made for the prototype and why and how these part were made. The goal was to deliver a full working prototype, but there was decided to start of with individual parts for testing purposes.

A. Finger prototype

The finger prototype was needed to acquire the needed pulling force for bending the five fingers. This was done by fully working out one finger and putting it on a testing bench and performing pulling force measurements on the control cable. The finger was worked out into detail in the final design, the components were then ordered or made at the university. The cylindrical spring was the limiting factor in the finger so it was the first part that was worked out. The cylindrical spring was found and ordered from TEVEMA, a company specialized in tension springs, the spring has a diameter of 15.95 mm and a length of 65.4 mm. This spring was available with two different spring constants so additional testing was required for choosing the right one.

The next part was the cable, it should be as thin as possible while remaining strong enough to handle the maximum force that will be exerted on it. Furthermore it should consist out of as many wires as possible as this increases the flexibility of the cable, which is needed because the cable runs over a few small pulleys. The cable was found at Carlstahl in the techno cable section, it has 8x19 + 7x7 wires so a total of 201 wires and is available in different thicknesses. The thickness will depend of the force needed for the closing of the five fingers, the two options are, a 0.76 mm thick cable with a minimum break load of 400N and a 0.95mm thick cable with a minimum break load of 800N.

The finger top needs to be sturdy but it is so small it is very hard to make by means of turning and milling. Instead there was chosen to 3d printed it out of PLA but full solid for extra strength, testing will reveal if it is strong enough this way.

The 0.5mm thick leaf spring is cut to size on location to gain the ideal size.

The finger needs an end stop to rest against and needs a means of fixing it to the testing bench. A single part was created that has circular cutouts for the spring to fall into and different slot holes to easily fix it to the testing bench. This part is also 3d printed at the university.

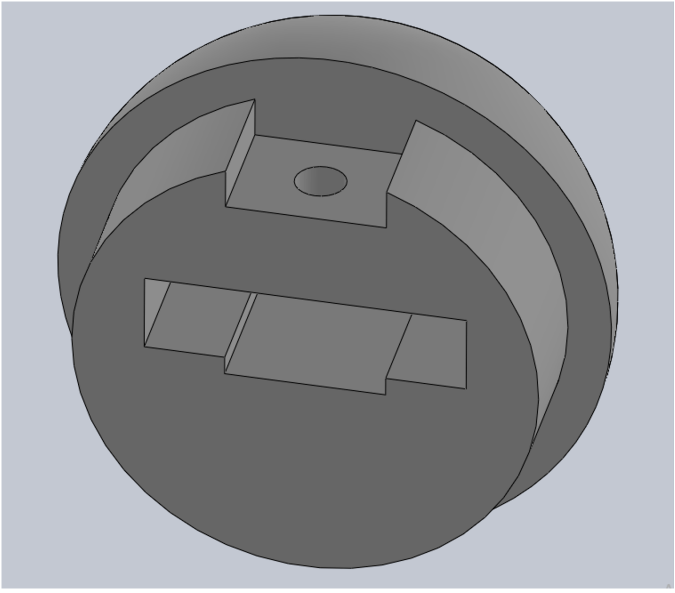


Fig. 17. The finger top is 3D printed and forms the end point of all the fingers, it is a half sphere on one end, and cylindrical on the other end where the cylindrical spring will slide over, furthermore it features a slot in which the cable loop and leaf spring can be inserted and fixed in place by a small screw.

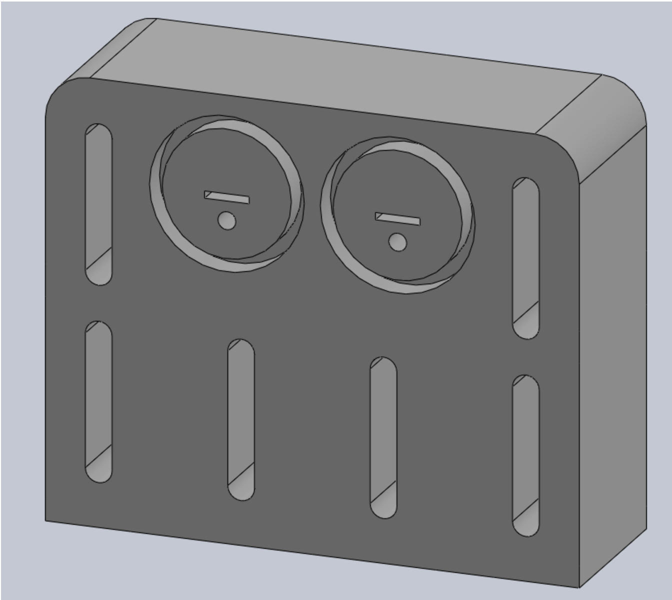


Fig. 18. The finger test block is also 3D printed and is used to fixate the fingers to the testing bench, the slots allow for some movement up and down while the testing bench houses slots that allow for movement forward, backward and to the left and right. The cylindrical springs fall into grooves in the block to fix the in place and the control cable will be fed through the small hole that is positioned off center to the bottom to force the finger to bend this way.

B. Testing setup single finger

The testing was performed on a preexisting testing bench for testing grip strength and pull force, it can be seen in figure 19. The testing bench consists out of a slotted plate that allows for variable placing of the finger or hand setup, a hook to which the control cable of the finger or hand needs to be fixed, the wheel for moving the hook to the left and thereby exerting force on the cable and the small sensor that can measure pinch force. The output values that were used are the time, displacement, pull force, and pinch force.

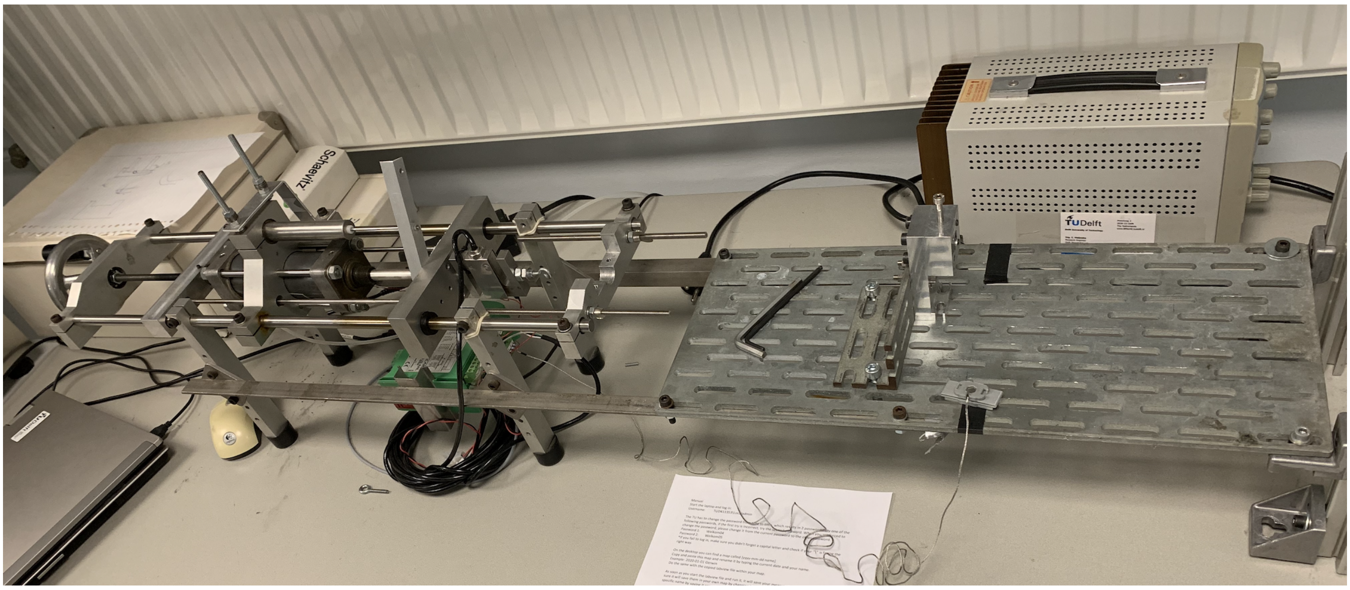


Fig. 19. The custom testing bench (developed by Delft Institute of Prosthetics and Orthotics, DIPO) consists out of a slotted plate that allows for variable placing of the finger or hand setup, a hook to which the control cable of the finger or hand needs to be fixed, the wheel for moving the hook to the left and thereby exerting force on the cable and the small sensor that can measure pinch force. The output values that were used are the time, displacement, pull force, and pinch force

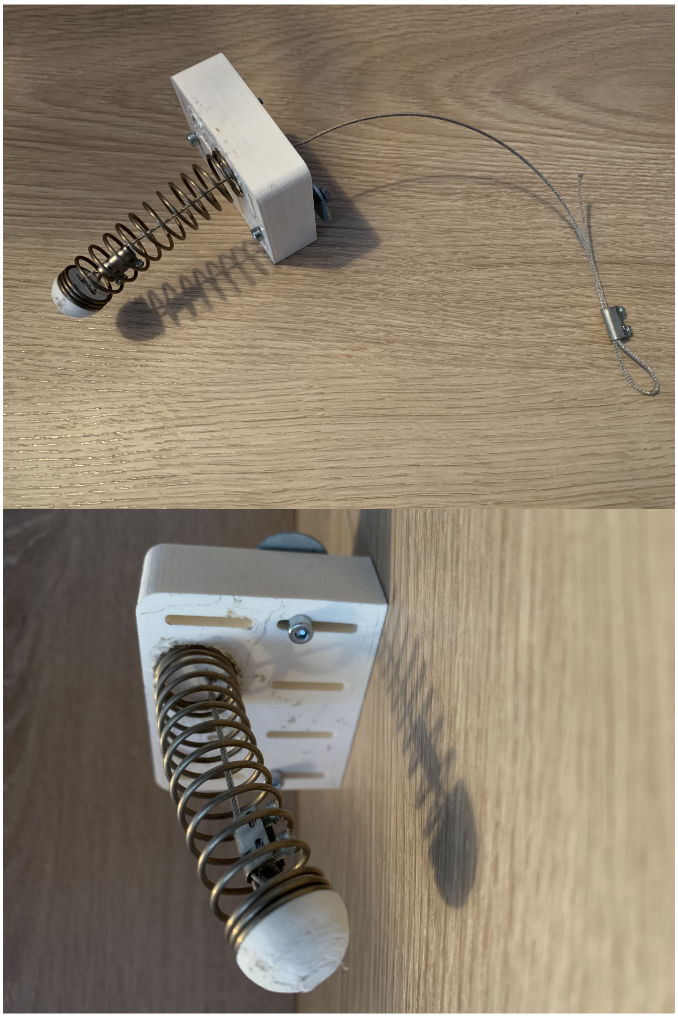


Fig. 20. The finger test assembly, the cylindrical spring is pushed into the groove in the test block and slid around the cylindrical end at the finger top. The cable is looped on both ends, one end that is fixed by means of a nut in the finger top and the other side can be hooked on to the testing bench to exert the pulling force on.

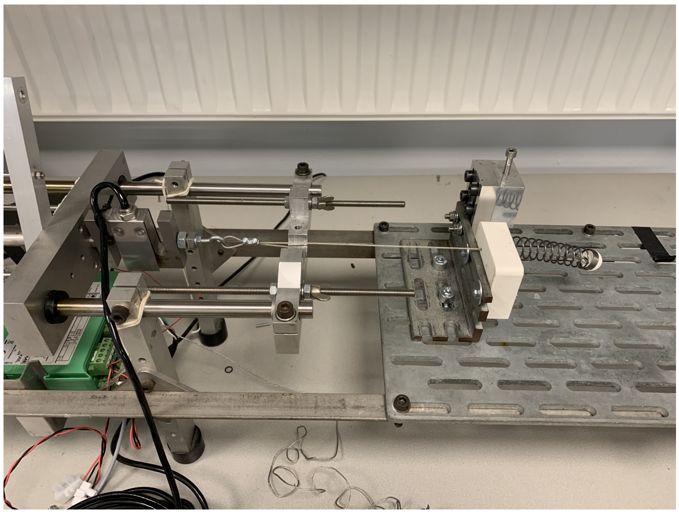


Fig. 21. The full testing setup, the finger test assembly is fixed to the testing bench with the use of two slots with nuts and bolts and the cable coming out the back of the finger test assembly is hooked onto the hook.

The finger test assembly is shown in figure 20, the cylindrical spring is under slight tension between the test block and the finger top. This tension is created by the cable that is locked in the finger top and passed through the hole in the testing block and fastened on the testing hook by the loop in the cable.

The full setup can be seen in figure 21. The finger test assembly is fixed to the testing bench with the use of two slots with nuts and bolts. The cable coming out the back of the finger test assembly is looped around the hook. The testing can now start by running the Labview software, the data will be outputted in text format. As the Labview script is running, the wheel at the left of the testing bench can be turned to slowly move the hook backwards, exert force onto the cable, and hereby bend the finger. The pinch sensor can be moved around and place exactly between the top of the finger and the test bench for measuring the pinch force.

C. Results single finger test

For the testing there were two cylindrical spring options, so in between the tests the cylindrical spring needed to be changed. During the first test however it seemed the leaf spring was limiting the motion, so the finger could not bend as far as was desired. The leaf spring was added for securing the direction of the bending of the cylindrical spring, because it was limiting the motion there was decided to also test without the leaf spring in place. This resulted in 4 different options for the test setup, the cylindrical spring (0.12 N/mm) with and without the leaf spring, and the cylindrical spring (0.10 N/mm) with and without the leaf spring. In figure 22 the full bending cycle of a finger with just the cylindrical spring can be seen, in the top left corner the finger is fully extended and in the bottom right corner the finger in fully flexed against the testing block. The amount of flexing that is possible with the finger with only

the cylindrical spring is sufficient to pinch things between the finger and the thumb as well as grab larger objects as was suspected.
The cable pulling forces required for the flexing can be seen in figure 23, the graph shows the displacement in millimeters on the x-axis and the pull force in Newton on the y-axis. The blue line stops around the 16 mm displacement point which is the point where the maximum bending that is possible for the leaf spring construction is reached. The orange line that represents the lighter spring continues on because there was tested if some parts of the finger would fail at higher pull forces, this was not the case.
The results of the tests with only the cylindrical spring can be seen in figure 24, again the graph shows the displacement in millimeters on the x-axis and the pull force in Newton on the y-axis. The blue and orange lines stop around the 32 mm displacement point, this is the point where the maximum bending is reached. The yellow and purple lines that represent the lighter spring continue till 35 mm displacement, this again was done to test if a point of failure would exist, which is not the case.
After the bending test the pinch test was performed, using the same setup but now the pinch sensor was placed between the top of the finger and a heightened spot of the test bench to be able to pinch the sensor in between. The pinch force of the finger with only the cylindrical spring did not meet the expectations and stayed around the 3 Newton maximum pinch force. Therefor it was decided to also test with the leaf spring attached again to see the results. It was expected that the pinch force would be able increase because the pull force can use the leaf springs limited bending to apply force across. The results of this can be seen in figure 25, the graphs all have a lot of spikes which can be explained by the exact point that needed to be pressed for the pinch force measurement and the finger that could move around this spot easily. Looking at the top of the spikes there can be seen that the cylindrical spring can reach a maximum pinch force of around 3 Newton but does this at only 12 Newton pulling force. The cylindrical spring with the leaf spring only fixed at the top of the finger has spikes between 4 to 6 Newton. A specific bending angle is ideal for the pull force to exert force over the leaf spring at 18 Newton pulling force. The cylindrical spring with leaf spring fixed at both ends performs best with a steady 6 Newton pinch force starting from 22 Newton pulling force.

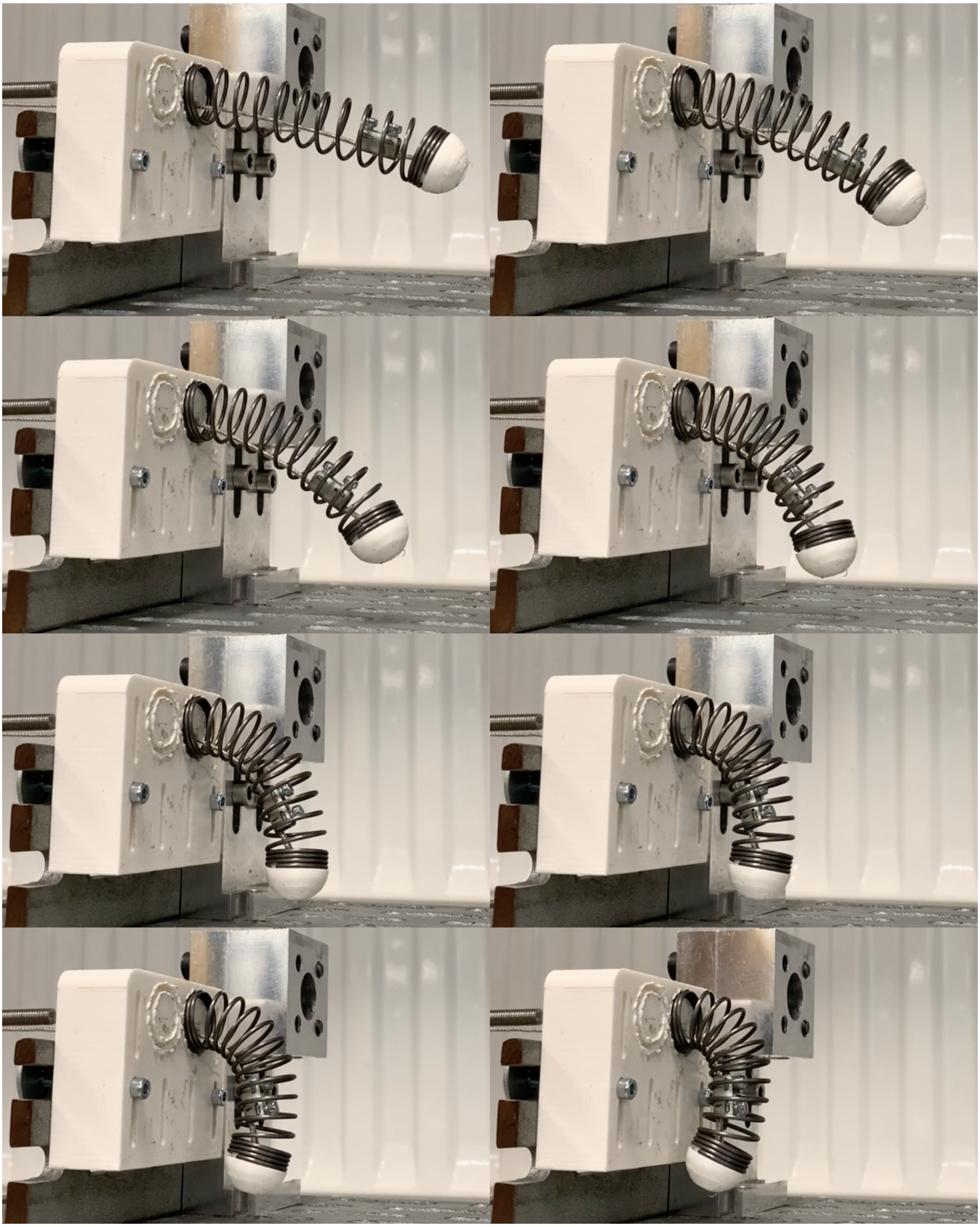


Fig. 22. Finger bending cycle, in the top left the maximum extended position and in the bottom right the maximum flexed position.

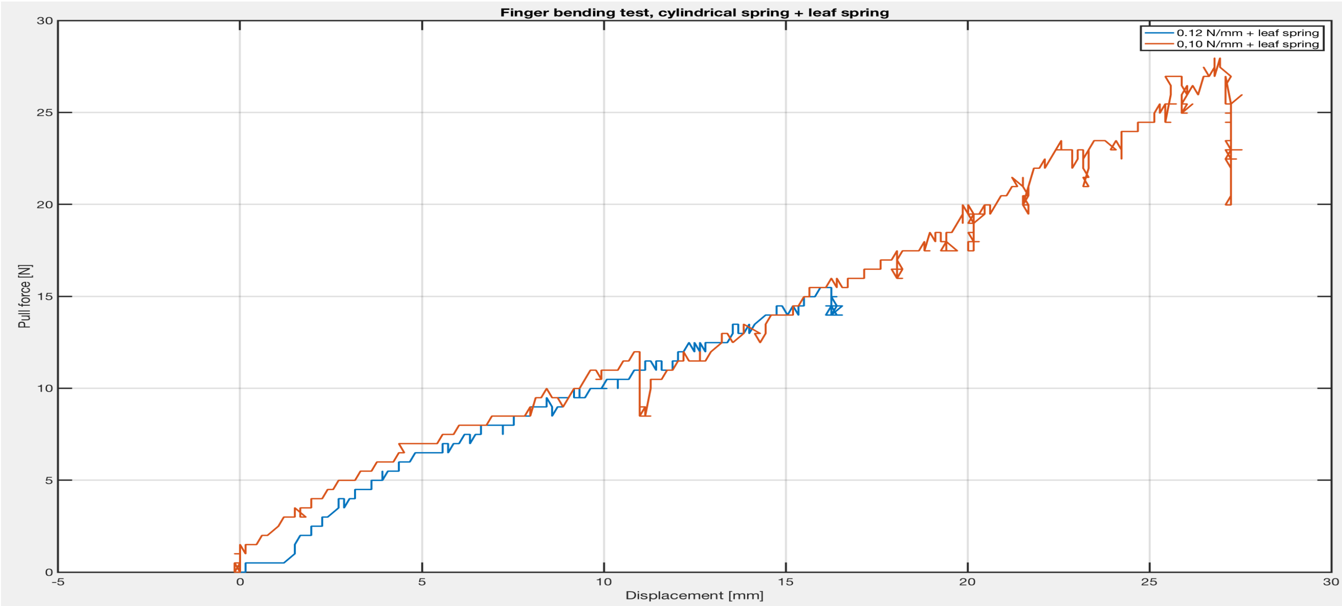


Fig. 23. Finger bending test results of the assemblies with leaf springs and cylindrical springs, the graph shows the displacement in millimeter on the x-axis and the pull force in Newton on the y-axis. The blue line stops around the 16 mm displacement point, this is the point where the maximum bending, that is possible for the leaf spring construction, is reached. The orange line that represents the lighter spring continues on because there was tested if some parts of the finger would fail at higher pull forces, this was not the case.

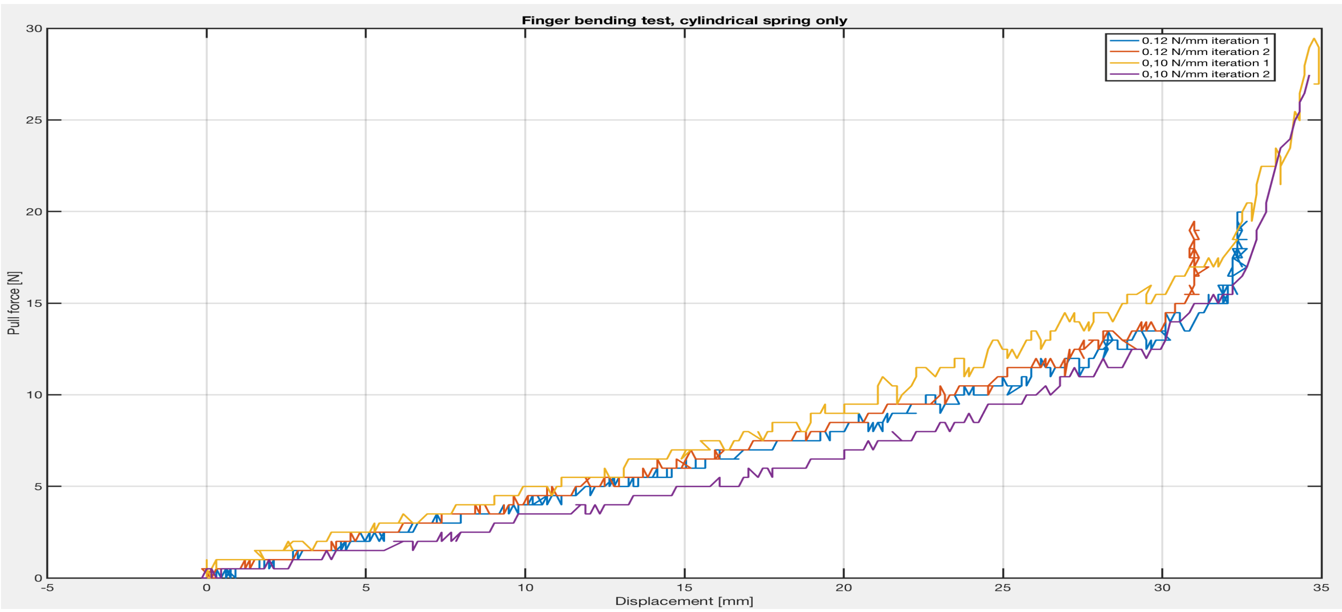


Fig. 24. Finger bending test results of the assemblies with only the cylindrical springs, the graph shows the displacement in millimeter on the x-axis and the pull force in Newton on the y-axis. The blue and orange lines stops around the 32 mm displacement point, this is the point where the maximum bending is reached. The yellow and purple lines that represent the lighter spring continue till 35 mm displacement, this again was used to test if a breaking point would exist, which is not the point.

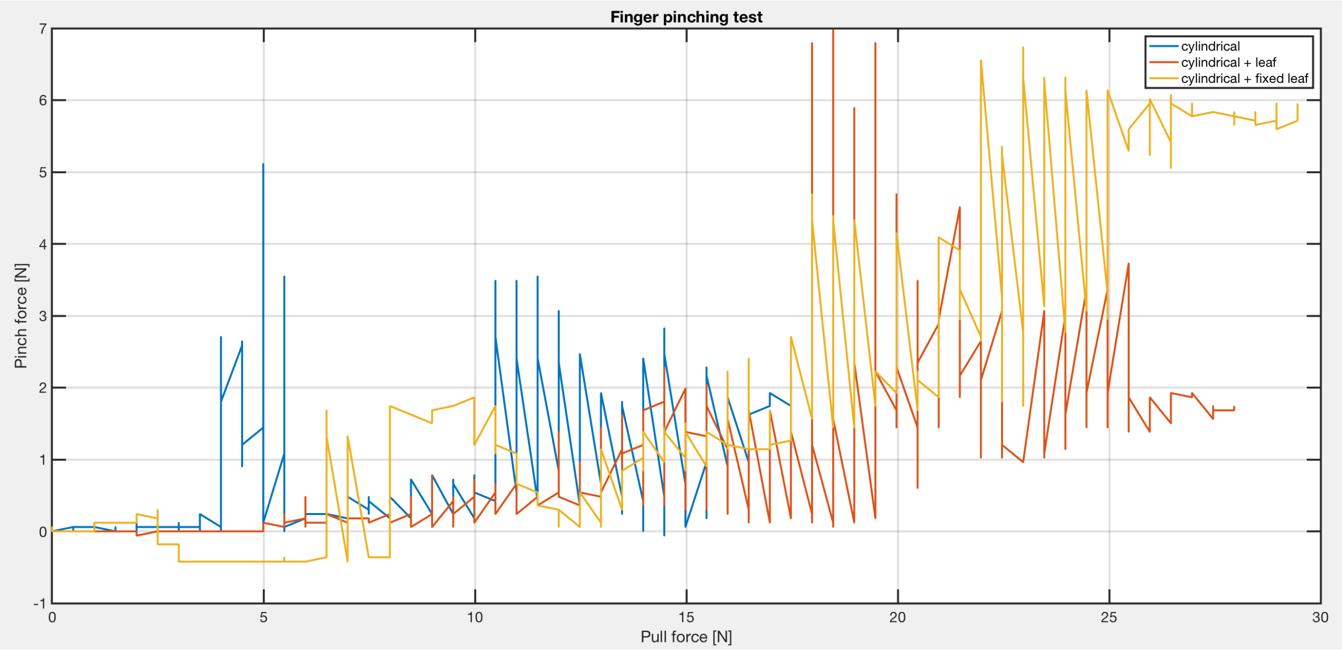


Fig. 25. Finger pinch test results of the assembly with only the cylindrical spring, and the one with a free leaf spring and a locked leaf spring. The graph shows the pulling force in Newton on the x-axis and the pinch force in Newton on the y-axis. The graphs all have a lot of spikes which can be explained by the exact point that needed to be pressed for the pinch force measurement and the finger can move around this spot easily.

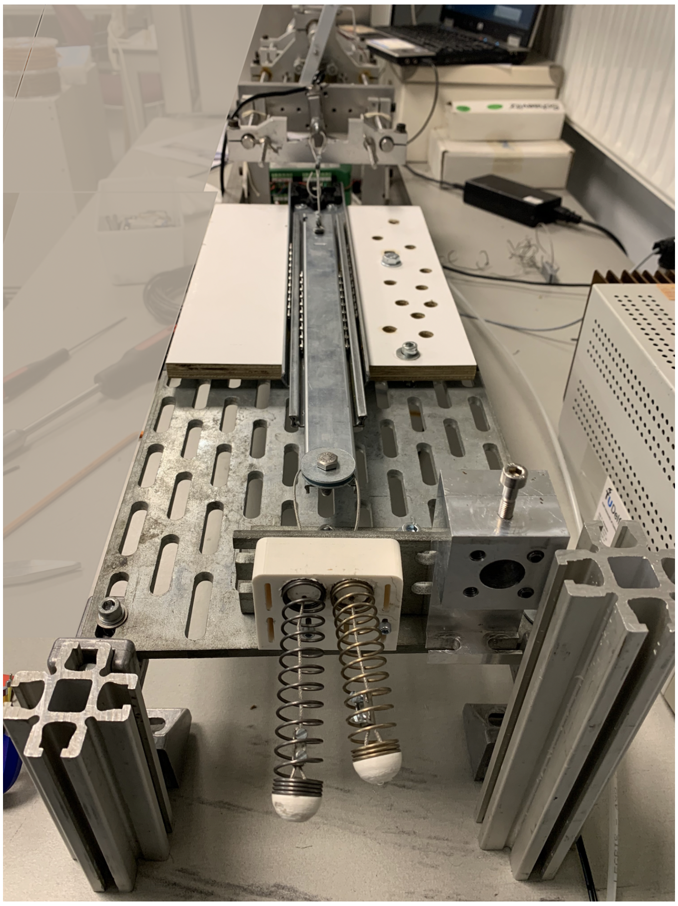


Fig. 26. Dual finger test setup, two fingers mounted to the test block with a single actuation cable connecting both to the slider mounted on the white board. Another cable on the end of the slider connects to the hook of the testing bench.

D. Testing setup dual finger

For the testing of the dependency mechanism two fingers were used, the same test bench was used and a similar setup with a few add-ons as can be seen in figure 26. Now both fingers are mounted on the test block and a single actuation cable connects both to the pulley on the slider. Another cable at the end of the slider is connected to the testing bench hook. Using this setup there can be tested how much force is needed to close two fingers at the same time and how much force it takes to close one finger while the second is blocked from bending.

E. Results dual finger test

The test consisted out of two parts, the first part being the bending two fingers at the same time and the second part, bending one finger while keeping the other extended. The first part of the test should point out if the relation between the pull force and the number of fingers is linear.
Figure 27 shows the results of two iterations of the test with two fingers, as can be seen the force needed to bend both fingers fully, doubles as expected. The means little to no energy gets lost in the dependency mechanism.
Figure 28 show the results of the two iterations where one finger is locked in the fully extended position. The two graphs are roughly the same but during the second iteration the pulling force is increased more to see what the effect of would be, the effect can be seen in figure 29. By applying more pulling force the extended finger is pulled together, packing the windings closer together, because of this the extra applied force gets dissipated in the finger. The packing together of the windings starts having a bigger effect after the other finger is fully bend.

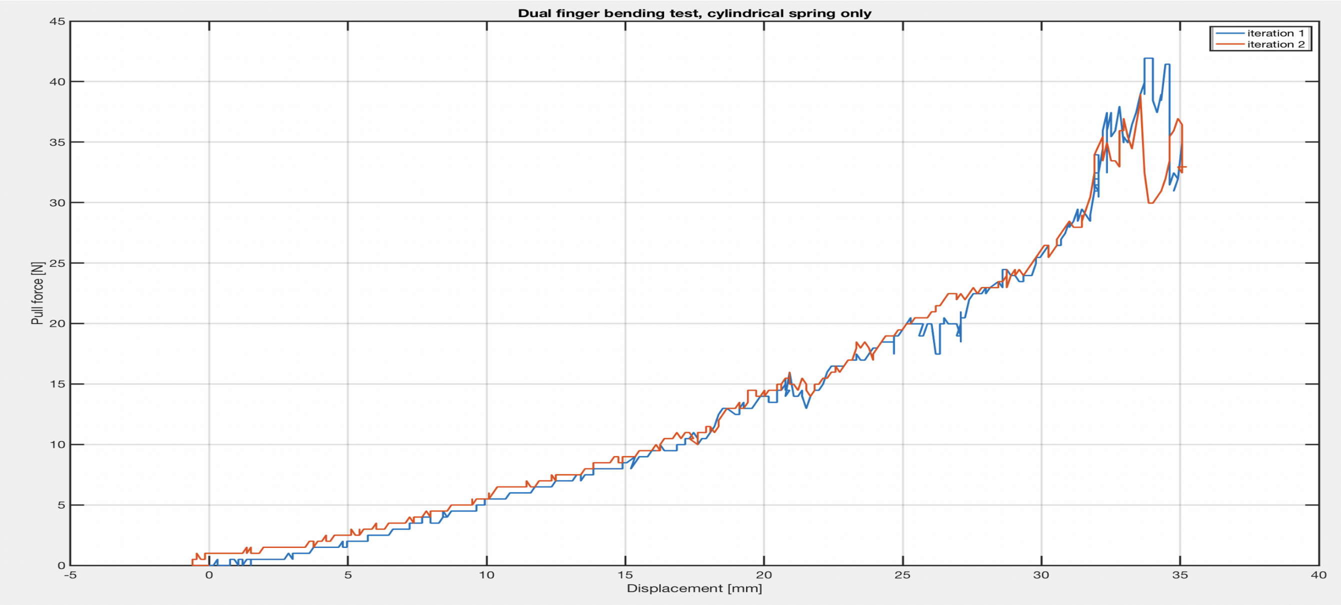


Fig. 27. Finger bending test results of the assembly with two fingers, the graph shows the displacement in millimeter on the x-axis and the pull force in Newton on the y-axis. The blue and orange lines start rising steep around the 32 mm displacement point, this is the point where the maximum bending is reached. The pulling force at 32 mm displacement is 30 Newton which is double the force of a single finger.

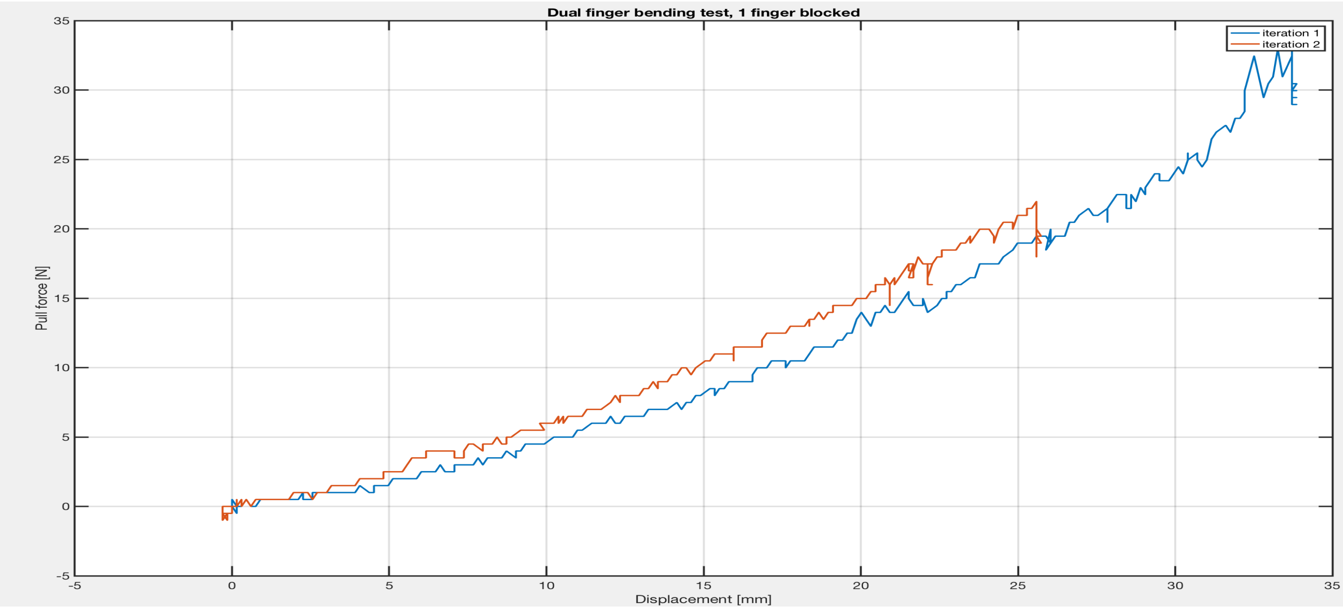


Fig. 28. Finger bending test results of the assembly with two fingers, with one blocked. The graph shows the displacement in millimeter on the x-axis and the pull force in Newton on the y-axis. The blue and orange lines are roughly the same till the 26 mm displacement, after this point only the pull force is increased during the second iteration.

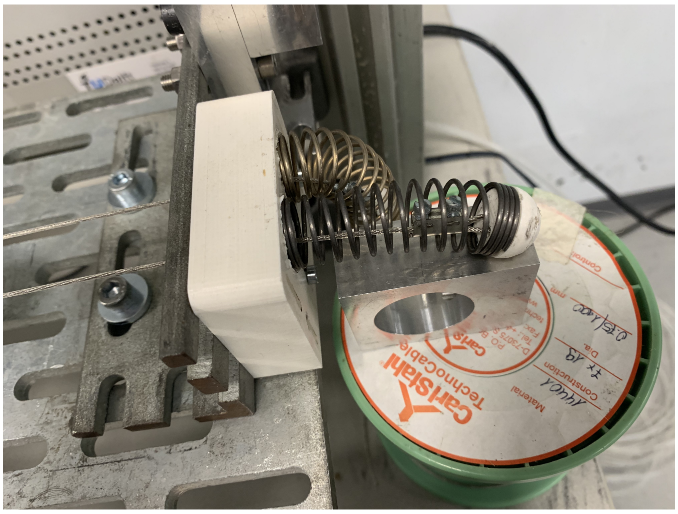


Fig. 29. Finger bending test picture. In the picture there can be seen that one finger is bend and the other finger is extended, when taking a closer look it is visible that the windings of the extended finger are closer together because of the pulling force excerted on the cable.

VI. Discussion

The first evaluation that was done was the evaluation of the bending cycle, is the bending of the finger sufficient? The combination of the leaf spring and the cylindrical spring was inspired by the Pringle-Kirk arm, in the book Artificial limbs [3] there was stated that both a design with cylindrical springs as well as a design with a leaf spring were achievable. During the first test is came forward that the finger with the leaf spring could not flex enough, the finger would only bend around 90 degrees. There was decided to continue testing with just the cylindrical spring, this turned out to be a good option. The finger with only the cylindrical spring could bend the full 180 degrees and even a bit further as could be seen in figure 22. This is more than sufficient for the hand to become functional. Furthermore, at the end of all the lines there can be seen that the pull force goes up exponentially with respect to the displacement, this means the finger has reached it's most closed position. So more displacement in the final parts of the graph do not represent bending the finger further, but represent the increasing the pressure that is exerted on the testing bench or against the testing block of the fingers.

The second part that was evaluated was the pulling force required for the finger to bend a full cycle, the results of this are visible in the graph in figure 24. The two slightly different springs that were tested performed very similar, this is probably due to the stretching of the windings of the spring. With both of the springs the finger reaches its maximum flexion around 30-32 millimeters, with a corresponding pulling force between 15 and 17 Newton. Looking back at figure 10 the closing force can be calculated from the work and the maximum cable excursion. The average of all the prosthetic hands that were tested is 32 Newton, a few outliers exist requiring a force of 60 Newton but also a mere 6 Newton for another. Judged by these numbers the 15-17 Newtons for a single finger is quite high, it should also be noted that some of the tested hands were fitted with a cosmetic glove increasing the required closing force. Further testing with two fingers and the dependency between them, showed that the closing force increases linear with the amount of fingers, the two fingers with the dependency mechanism needed 30 Newton of pulling force to both fully close. This does however show that the dependency mechanism takes little to no force to operate, making it possible to implement it in other prosthetics. The results of preventing one of the fingers from bending were acceptable, a little force gets lost because the extended finger also contracts but this is minimal during the bending face of the other finger. The force that gets dissipated in the contraction of the extended finger only starts playing a major role when the other finger is fully bend, because of this it does not cause issues in the usage of the prosthetic hand.

The next part that was evaluated was the pinch force, there was tested how much pinch force could be delivered and how much pulling force it takes to achieve this pinch force. The results that can be seen in figure 25, it shows that the maximum pinch force that can be achieved by the cylindrical spring finger is 3 Newton, this is quite low comparing it to the values that are seen in 10 again. This can be explained by the way the pinch force is tested on the testing bench, the finger should squeeze a force sensor between the bench and the top of the finger. This kind of force might be hard to apply for the spring finger because of the lack of a point over which leverage can be given to apply the pressing force downward. The spring finger will just contract or bend in a different way because of it's freedom in movement.

In figure 25 there can be seen that tests were also executed with the leaf spring. This construction gives the finger a lot less freedom of movement and makes for a point to apply force across. The figure shows that the pinch force that can be created is twice as high.

But although the pinch force is low in the finger with only the cylindrical spring the working grip should be good, it will be comparable to the Pringle-Kirk arm and according to the book Artificial Limbs [3] that hand was suitable for manual labour which needs a sturdy grip on handles. This can be explained by the flexible fingers that can form around objects and thereby not having to apply a lot of force but have a lot of surface touching. To confirm that the grip is suitable for manual labour as is indicated in the book Artificial Limbs [3], another test setup should be created that can test the grip force of a full prosthetic hand on different objects mimicking manual labour.

VII. Conclusion

The new hand prosthetic design was inspired by the prosthetics of the past, these inspirations were used to create a new body powered design that shows some advantages over the prosthetic hands currently on the market. The main advantage is the dependency mechanism that was inspired by the Despinasse hand. In comparison to other prosthetic hands in which the fingers all bend an equal amount, only one finger will sometimes connect with the object that is grasped. The dependency mechanism housed inside the hand palm divides the pulling force evenly over all fingers, because of this all the fingers bend individually and will all make contact with a object this allows for grabbing of complex shaped objects. The tests of the dependency mechanism for two fingers showed little to no extra pulling force was needed because of the mechanism and the flexion indeed switched between fingers when resistance was met.

Another possible advantage, inspired by the Pringle-Kirk arm, being the flexibility of the fingers that is no longer limited by a set number of joints but can flex over the entire length. The advantage of this is that the hand can now form to a specific object hereby increasing the surface of the grip on the object. Although testing showed a only limited pinch force could be achieved by the fingers, the increased surface area with the object that is grasped could make up for this. This does however need to be tested with a different test setup.

Furthermore, the spring setup of the fingers takes care of the extension of the fingers, thereby allowing a voluntary closing mechanism controlled by a single cable. This does however create the need for a locking mechanism which can be an off the shelf component, for example the Sure-Lok cable lock control system of TRS.

Looking at the possible benefits of these separate parts the new body powered prosthetic hand will add a number of functions and increase the ease of use with respect to other body powered prosthetic hands. The conclusion that can be drawn from this is that there are certainly parts of prosthetic hands from the past that are worth bringing back to the current days, although more testing is required for the grip strength of the fingers, the first tests of the dependency mechanism show promising results.

References

[1] W. T. Carnes, “Artificial hand mechanisms,” patent 1,402,476, 1922.

[2] ——, “Artificial arm and hand,” patent 999,484, 1911.

[3] D. F. Martin, *Artificial limbs*. Georges Thone, 1924.

[4] F. Puschel, *Künstliche Hande Künstliche Arme*. Walter de Gruyter & co, 1954.

[5] W. Schweitzer. (2010) Carnes arm - history and current status. [Online]. Available: https://www.swisswuff.ch/tech/?p=243

[6] A. Pringle, “Artificial hand,” patent 1,324,564, 1919.

[7] D.B.Becker, “Artificial hand,” patent 2,301,009, 1942.

[8] J. Molenbroek. (2017) DINED anthroprometric database. [Online]. Available: https://dined.io.tudelft.nl/en/database/tool

[9] D. Hu, C.-H. Xiong, and M.-J. Liu, “Exploring the existence of better hands for manipulation than the human hand based on hand proportions,” *Journal of Theoretical Biology*, vol. 440, p. 100–111, Mar 2018. [Online]. Available: http://dx.doi.org/10.1016/j.jtbi.2017.12.026

[10] S. M. van Anders, P. A. Vernon, and C. J. Wilbur, “Finger-length ratios show evidence of prenatal hormone-transfer between opposite-sex twins,” *Hormones and Behavior*, vol. 49, no. 3, pp. 315–319, Mar. 2006. [Online]. Available: https://doi.org/10.1016/j.yhbeh.2005.08.003

[11] C. A. Crosby and M. A. Wehbé, “Hand strength: Normative values,” *The Journal of Hand Surgery*, vol. 19, no. 4, pp. 665–670, Jul. 1994. [Online]. Available: https://doi.org/10.1016/0363-5023(94)90280-1

[12] C. M. Fraser, “An evaluation of the use made of cosmetic and functional prostheses by unilateral upper limb amputees,” *Prosthetics and Orthotics International*, vol. 22, no. 3, pp. 216–223, 1998, pMID: 9881609. [Online]. Available: https://www.tandfonline.com/doi/abs/10.3109/03093649809164486

[13] J. Belter, J. Segil, A. Dollar, and R. Weir, “Mechanical design and performance specifications of anthropomorphic prosthetic hands: A review,” *Journal of rehabilitation research and development*, vol. 50, pp. 599–618, 08 2013.

[14] G. Smit and D. H. Plettenburg, “Efficiency of voluntary closing hand and hook prostheses,” *Prosthetics and Orthotics International*, vol. 34, no. 4, pp. 411–427, Dec. 2010. [Online]. Available: https://doi.org/10.3109/03093646.2010.486390

[15] M. Hichert. (2017) Arm prostheses require too much force. [Online]. Available: https://www.delta.tudelft.nl/article/arm-prostheses-require-too-much-force

[16] D. M. Stewart, “Behavior of stationiry wire ropes in tension and bending,” *Fritz Laboratory Reports*, vol. 102, no. 9, pp. 606–650, 1937. [Online]. Available: https://preserve.lehigh.edu/engr-civil-environmental-fritz-lab-reports/1181

[17] I. Ben Abdallah, Y. Bouteraa, and C. Rekik, “Design and development of 3d printed myoelectric robotic exoskeleton for hand rehabilitation,” *International Journal on Smart Sensing and Intelligent Systems*, vol. 10, pp. 341–366, 06 2017.

[18] J. T. Belter, J. L. Segil, A. M. Dollar, and R. F. Weir, “Mechanical design and performance specifications of anthropomorphic prosthetic hands: A review,” *The Journal of Rehabilitation Research and Development*, vol. 50, no. 5, p. 599, 2013. [Online]. Available: https://doi.org/10.1682/jrrd.2011.10.0188

[19] ToughWare. (2017) Partnership with toughware prosthetics. [Online]. Available: https://zh-cn.facebook.com/InfiniteBiomed/photos/a.342741025786360/1605452966181820/?type=3&theater

[20] J. W. Sensinger, J. Lipsey, A. Thomas, and K. Turner, 2015. [Online]. Available: https://www.rehab.research.va.gov/jour/2015/521/jrrd-2014-03-0087.html

[21] “Sure-lok cable lock control systems.” [Online]. Available: https://www.trsprosthetics.com/product/sure-lok-cable-system/

Attachments

Attachment A: Wire rope strength calculations

In this attachment the calculations of the wire ropes that run over the pulleys are discussed. When a wire rope runs over a pulley it stretches on one side and compresses on the other side and the middle remain neutral. This stretching and compressing causes stress in the wires and hereby decreases the strength of the wire. To calculate the loss of strength in a wire running over a couple of pulleys there was chosen to use equation 1 which was obtained from the article of D. M. Stewart [16].

$$P = \frac{\pi(d)^4 EG}{16Rr_S\left[2G\left(1+\sin^2\alpha\right)+E\cos^2\alpha\right]} \quad (1)$$

$$P = \frac{mm^4 * N/mm^2 * N/mm^2}{mm * mm\,(N/mm^2)} = \frac{N^2}{N} = N \quad (2)$$

P = loss of strength in a given wire [N];
d = diameter of a given wire; $[\mathrm{mm}]$
E = modulus of elasticity of a given wire; $1570\mathrm{N/mm2}$
μ = Poisson's ratio; 0.27
R = radius of a sheave $[\mathrm{mm}]$

$$G = \frac{E}{2(1+\mu)} \quad (3)$$

$$G = \frac{1570}{2(1+0.27)}$$

G = modulus of rigidity of a given wire; $618\mathrm{N/mm2}$
r_s = radius trom the center of the strand to the center of the wire in question;
α = the angle between the perpendicular to the axis of a rope and the tangent to the center line of the wire.
when $r_S = 0$; substitute r_r which is defined as the radius from the center of a wire rope to the center wire of a strand.

Using these known values the formula can be filled in for the most part, leaving the values that need to be found as characters:

$$P = \frac{\pi(d)^4 * 1570 * 618}{16^* R^* r_S\left[2^*618\left(1+\sin^2\alpha\right)+1570^*\cos^2\alpha\right]} \quad (4)$$

The values are based of cables on Fabory, one that is 1 mm thick with 19 strands and one of 2 mm thickness with also 19 strands. Both the wires are made out of stainless steel and are build up out of 12 outer strands 6 middle strands and 1 inner strand. The cables have a breaking force of 830 Newton and 3300 Newton respectively.
Looking at the first cable in the dependency mechanism, the cable that needs to be able to sustain the full 449 Newton a shoulder can deliver. The cable of 2mm was chosen, filling in the remaining numbers in the first formula and trying a couple of sizes for the pulleys the ideal pulley size of 13mm in found, the calculations can be seen in equations 5-7. The loss of strength for this first cable with the 13mm pulleys is 2668 Newton. this leaves 3300 - 2668 = 632 Newton which is more that sufficient for the maximum load of 449 Newton.
The two cables that run into the fingers do not need to be able to sustain the full force of 449 Newton from the shoulder, but do however need to be able to handle a large portion of it. A force of 75 percent of the maximum should be manageable which comes roughly down to 370 Newton. The wire therefor can become thinner so the 1mm thick cable was chosen. Running this through the first formula with multiple pulley diameters returns an ideal pulley diameter of 10mm with a strength loss of 434 Newton, the calculations can be seen in equations 8-10. Subtracting the loss of 434 Newton from the 830 Newton the cable can handle, 396 Newton is left which is a bit more than 75 percent of the maximum the shoulder can deliver.

$$P1 = \frac{\pi(2)^4 1570^* 618}{16^*13^*0.8\left[1236\left(1+\sin^2(30)\right)+1570^*\cos^2(30)\right]} \quad (5)$$

$$P1 = 107.6556364$$

$$P2 = \frac{\pi(2)^4 1570^* 618}{16 * 13 * 0.4\left[1236\left(1+\sin^2(60)\right)+1570^*\cos^2(60)\right]} \quad (6)$$

$$P2 = 229.3817022$$

$$\sum P = 12 * P1 + 6 * P2 \quad (7)$$

$$\sum P = 2668\mathrm{N}$$

$$P1 = \frac{\pi(1)^4 1570^* 618}{16^* 10^* 0.4 \left[1236 \left(1 + \sin^2(30)\right) + 1570^* \cos^2(30)\right]} \tag{8}$$

$$P1 = 17.49404091N$$

$$P2 = \frac{\pi(1)^4 1570^* 618}{16^* 10^* 0.2 \left[1236 \left(1 + \sin^2(60)\right) + 1570^* \cos^2(60)\right]} \tag{9}$$

$$P2 = 32.27452661N$$

$$\sum P = 12 * P1 + 6 * P2 \tag{10}$$

$$\sum P = 434N$$