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Industrial Electrical Engineering and Automation

The CB-hand

A Study of the Functions and Development of Modern Prosthetic Hands

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Abstract

The purpose of the thesis was to design and build an externally powered prosthetic hand. The hand should preferably have one or more new functionalities not found in other prostheses. The human hand is very complex, it contains over 30 muscles and at least 18 joints. In comparison, a complex and dexterous commercial prosthesis has five actuators and eleven joints, but only one or two control signals. All in all, making it essentially impossible to replace the human hand with an equal prosthesis.

The concepts were developed after literature study and interviews. The concept was 3D printed in plastic, tested, evaluated and improved in cycles until a final prototype could be constructed and manufactured. The final prototype was mainly 3D-printed in plastic because of the design, quickness and viability; the design was too complex to be manufacture in any other way. The exceptions are the gears, motors and shafts which were bought from suppliers.

In the end, the assembly of the final prototype did not go as well as expected. The reason was mainly because of poor accuracy of manufacture and the fitting of the gears to the shafts; the measurements of the parts was not accurate enough, and the gears came loose. Thus, it is very hard to draw any conclusions about the design from it. The conclusion that can be drawn is that the idea of the design seems to work, but it will probably require some rework. Finally, to get some real answers about its viability, it needs to be tested with a prototype of better build quality.

Sammanfattning

Syftet med detta arbete var att designa och bygga en externt driven proteshand. Handen ska helst ha en eller flera funktioner som inte finns hos andra protester. Den mänskliga handen är väldigt komplex, den innehåller över 30 muskler och minst 18 leder. Jämförelsevis har en komplex och rörlig kommersiell protes fem aktuatorer och elva leder, men endast en eller två kontrollsignaler. Allt som allt gör detta det i princip omöjligt att ersätta en mänsklig hand med en lika bra protes.

Koncepten fram togs efter litteraturstudie och intervjuer. Det valda konceptet 3D-printades i plast, testades, utvärderades och förbättrades i cykler till en slutgiltig prototyp kunde konstrueras och tillverkas. Prototypen var huvudsakligen 3D-printad i plast på grund av designen samt snabbheten och lättillgängligheten i att 3D-printa; designen var för komplex för att på ett smidigt sätt tillverkas på något annat sätt. Det ända som inte var printat var motorerna, kugghjulen och axlarna, vilka köptes av leverantörer.

Konstruktionen av den slutgiltiga prototypen gick inte så väl som förväntat. Anledningen var huvudsakligen att noggrannheten på tillverkningen var för dålig samt problem med att fästa kugghjulen på axlarna; måtten på de tillverkade delarna var inte tillräckligt noggranna, och kugghjulen lossnade. På grund av detta är det väldigt svårt att dra några slutsatser om designen. Den slutsats som kan dras är att det ser ut som om designen fungerar, men det är möjligt att det kommer krävas visst omarbete. För att dra några definitiva slutsatser om hur väl designen faktiskt fungerar, krävs en slutgiltig prototyp som är mer välbyggd.

Preface

We were interested in electromechanical aids that can enhance or replace the body function, e.g. an exoskeleton or a prosthesis. This is an application where we can use what we have learned in product development, mechanics, electronics and digital technology. At the same time, it is also a field where neither of us have worked before; thus, much more interesting. It does also have a big potential to provide people with a better life. We learned that Christian Antfolk, an associate professor at BME, wanted to build a prosthetic hand to develop and test new mechanical solutions. This gave us the opportunity to do our thesis in the area that we were interested in and it enabled us to actually build something, to work on the project from idea to a somewhat finished prototype.

The work of writing this thesis has been equally divided by the authors. It would not meaningful to separate what has been written by whom.

This report is available in the report number series of both the Department of Biomedical Engineering and the Department of Industrial Electronics and Automation.

Definitions & acronyms

Abduction - Outward pivoting motion, away from the palm

Adduction - Inward pivoting motion, towards the palm

Co-contraction - A simultaneous contraction of several muscles

DoF - Degree of freedom, a movement in one direction that an object is able to perform independently of other movements of the part and other parts. In an xy-diagram a point has two degrees of freedom, in the x- and y-directions.

DoC - Degrees of control, how many DoF: s or groups of DoF: s that can be controlled individually.

Extension - The outward or opening bending motion of a finger

Flexion - The inward or closing bending motion of a finger

NBDM – Non-back drivable mechanism

POM - Polyoxymethylene, a polymer

The name of the different joints and bones in the hand can be seen in figure 1

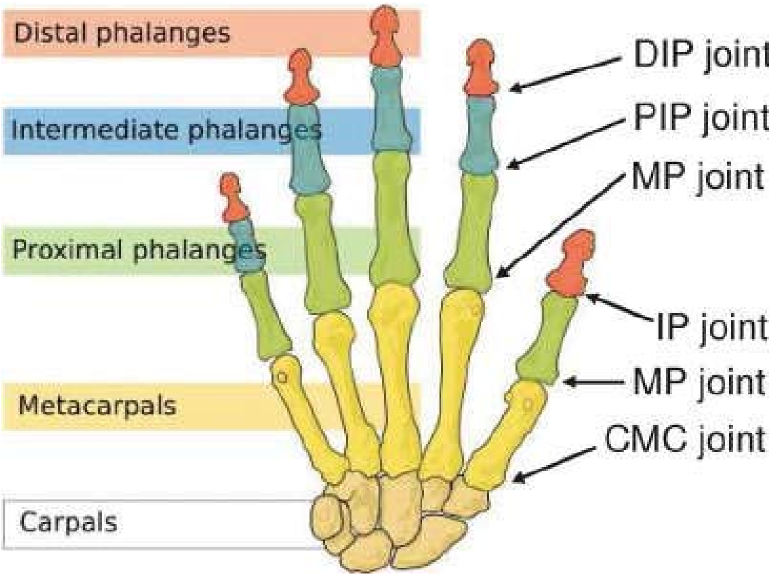

Figure 1, Joints of the thumb and the index finger (Sclabassi, 2009)

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1 Introduction

1.1 Background

Prostheses have been used by humans for a very long time. An example of an early prosthesis was found on a mummy in Egypt; a woman who had lost her big toe and, in its place, had a carved wooden prosthesis. (Lienhard, 2018)

During the 16th century, a German knight named Götz von Berlichingen lost his hand through a gunshot wound. As a replacement for his hand, he had a blacksmith make a quite advanced prosthesis. The fingers of this prosthesis could be passively closed and held in position until released with a lever. (Landesstelle.de, 2018)

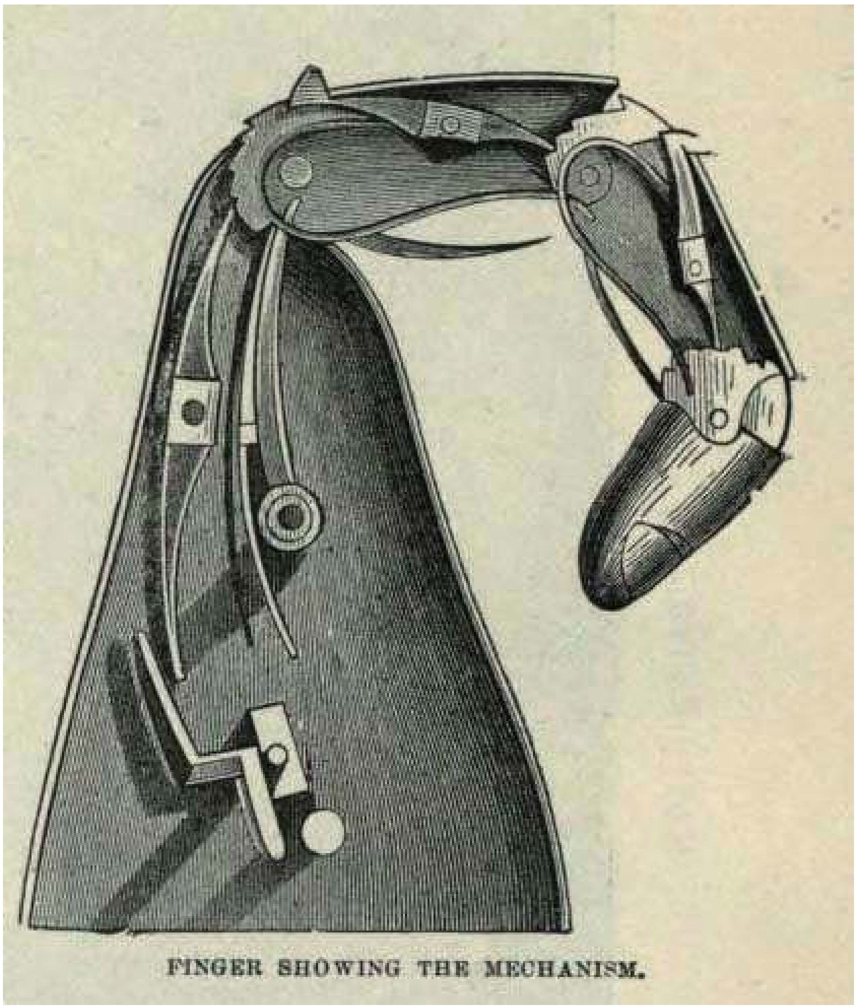


Figure 2, The mechanism of von Berlichingen's hand (Wikimedia, 2018)

The first body powered prosthesis was created by Peter Baliff in 1818. It was used by wounded French soldiers and allowed them to flex the thumb or fingers by using the muscles in the shoulder and trunk.

An electrically powered prosthetic hand was suggested in “Ersatzglieder und Arbeitshilfen” (Limb Substitutes and Work Aids) in 1919. However, due to technological limitations it was not possible to build the hand. Reinhold Reiter built the first myoelectrically controlled prosthetic hand in 1948, but it never gained clinical or commercial acceptance. The first myoelectrical hand that was sold commercially was made by Alexander Kobrinski in 1960. As he was a Russian scientist, it was known as the Russian hand. It had many drawbacks however, as being weak and heavy.

By the 1980's myoelectrical prostheses were more practical, with advancements in technology making them lighter. Today there are several commercial and experimentational prostheses such as iLimb by Touch Bionics and the Michelangelo hand by Otto Bock. The technology is progressing, and we are coming closer to developing an artificial hand that can largely replace a lost one, although there is yet a very long way to go.

This thesis tries to be a part of this development and to contribute in some small way to the field of prosthetic hands.

Source for the entirety of this paragraph is the evolution of functional hand replacement: From iron prostheses to hand transplantation. (Zuo and Olson, 2014)

1.2 Issue and aim

The purpose of this thesis is to determine which functionality exists in modern prosthetic hands and to try to come up with one or more new functions. Finally, these functions are to be implemented in a working prosthetic hand if possible.

The following questions are treated:

1. What functions exist in current prostheses?
2. What functions are requested by the prosthesis users?
3. What functions can be added to fulfil the user needs?
4. Which functions should be developed?
5. How will these functions be realised?

1.3 Limitation of scope

This thesis is concerned with developing the mechanics of the actual hand part of a prosthetic hand, i.e. the design of the fingers, motors, torque transmission and the frame to which everything else is attached as well as a basic control of the motors and through that the movement of the fingers. A program for torque control, to ensure that the motors would not be overloaded, as well as for stop control, when the endpoint for finger movement is reached, was considered but not implemented. It will not be concerned with anything exterior to this, which would be necessary to develop a functioning prosthesis. The reason for this is the limited time in which a master thesis is written.

The parts not developed that would be necessary for a functioning prosthesis include but may not be limited to the following.

A way to attach the prosthesis to an arm sleeve which allows fitting it to the body. Such a sleeve would also usually contain batteries and myoelectric sensors for control of the prosthesis.

A latex glove to mimic the appearance of a real hand, protect the prosthesis and enhance the grip.

A control program that allows for switching between multiple grips, providing more versatility than just the palmar prehension performed by, for instance, Otto Bock VariPlus Speed.

Furthermore, body-powered prostheses are outside of this thesis' scope, as such it will be acknowledged but not discussed in any depth in this report.

2 Methodology

The first part of the thesis was spent on a literature study and information gathering. The purpose was to get an understanding of, and background to, the problems of designing a hand prosthesis. Part of this was also to see how today's commercial prostheses solve these problems. The main articles were Mechanical design and performance specifications of anthropomorphic prosthetics hand: a review (Belter et al., 2013), Advances in the design and control of dexterous artificial hands for functional substitution (Controzzi, 2013) and Design of artificial arms and hands for prosthetic applications (Weir, 2003). Another source of information was the hand surgeon in Malmö where the researcher Ulrika Wijk and two people who use prosthetic hands were interviewed.

The second part was concept research and generation. Part of this was looking at current commercial prostheses and see how what could be improved. Another part was to try to come up with new ideas and concepts and see if they solved the problem any better. When looking at different prostheses, the areas of interests were what type of actuator to use, and how many of them, and the design of the fingers and the thumb.

The prostheses looked at were:

- iLimb by Touch Bionics
- iLimb Pulse by Touch Bionics
- Bebionic hand by RSL Steeper
- Bebionic hand v2 by RSL Steeper
- Vincent hand by Vincent Systems
- Michelangelo hand by Otto Bock.
- VariPlus Speed by Otto Bock (Professionals.ottobockus.com, 2018)
- Smart Hand by the Biorobotics Institute
- IH2 Azzurra by Prensilia Srl

The third step were prototype development. Here the strengths of the generated concepts were identified and incorporated into a first prototype. The prototype was tested and evaluated. After the evaluation different concepts for improving the prototype were developed. These improvements were evaluated and subsequently implemented and tested though rapid prototyping. After a couple of prototypes, one final prototype was designed, build and test. All the previous prototypes served to get an idea of the finger and thumb design while the last prototype was the only one to contain transmission and motors.

For components that were bought rather than manufactured, the strengths and weaknesses of different alternatives were identified, such that the best solution for the final prototype could be picked.

3 The problem with prostheses

There are over 30 muscles acting on the forearm and hand. The hand has 27 major bones and at least 18 joints articulations. (Weir, 2003) All in all, this results in the human hand having 22 or more DoF: s. (Controzzi, 2013) To compare, the most advanced commercial myoelectric prostheses, e.g. iLimb or Bebionic, only have six actuators and eleven joints; simpler myoelectric prostheses have one or two actuators and two to six joints. In addition to this the number of DoC: s in today's prostheses range from one to two, making it a low input, high output problem. Normally people only have one hand amputated, and thus the natural hand will become the dominant hand. (Wijk, 2018) Because of this the prosthesis will mainly be used as a support when one hand is not enough. The reason for the prosthesis becoming the non-dominant hand is mainly because the user has full control over the natural hand; the natural hand is also more dexterous, more precise and faster than today's prostheses.

One of the most important things with prostheses is that it should look natural, especially when used around people; the prosthesis should not be noticed. (Wijk, 2018) There is also the cost, an advanced and highly dexterous prosthesis will be expensive while a simpler prosthesis is cheaper but may not fulfil the role that is required. As such, a lot of people choose to use a purely cosmetic prosthesis. A lot of the time it may not even be required to have a powered prosthesis; a cosmetic is in many cases enough.

When designing a prosthetic hand, it is important to know how the human hand grasps objects, what makes a good grip etc., so that the prosthetic hand might do the same. Broadly speaking, the hands movement can be subdivided into two groups; prehensile movement - "movements in which an object is seized and held partly or wholly within the compass of the hand" and non-prehensile movements – "movements in which no seizing or grasping is involved". (Controzzi, 2013, p. 14) Henceforth only prehensile movement will be looked at because the goal is to know how to design the grasp of the prosthesis.

Within the prosthetic field there are six grasping patterns which are the most widely accepted and was adopted by Keller (Keller et al.,1947, cited in Weir, 2003, 32.4.1 Anatomical design considerations), derived from the 12 patterns by Schlesinger. (Schlesinger et al., 1919 cited in Weir, 2003, 32.4.1 Anatomical design considerations) These are shown in figure 3.

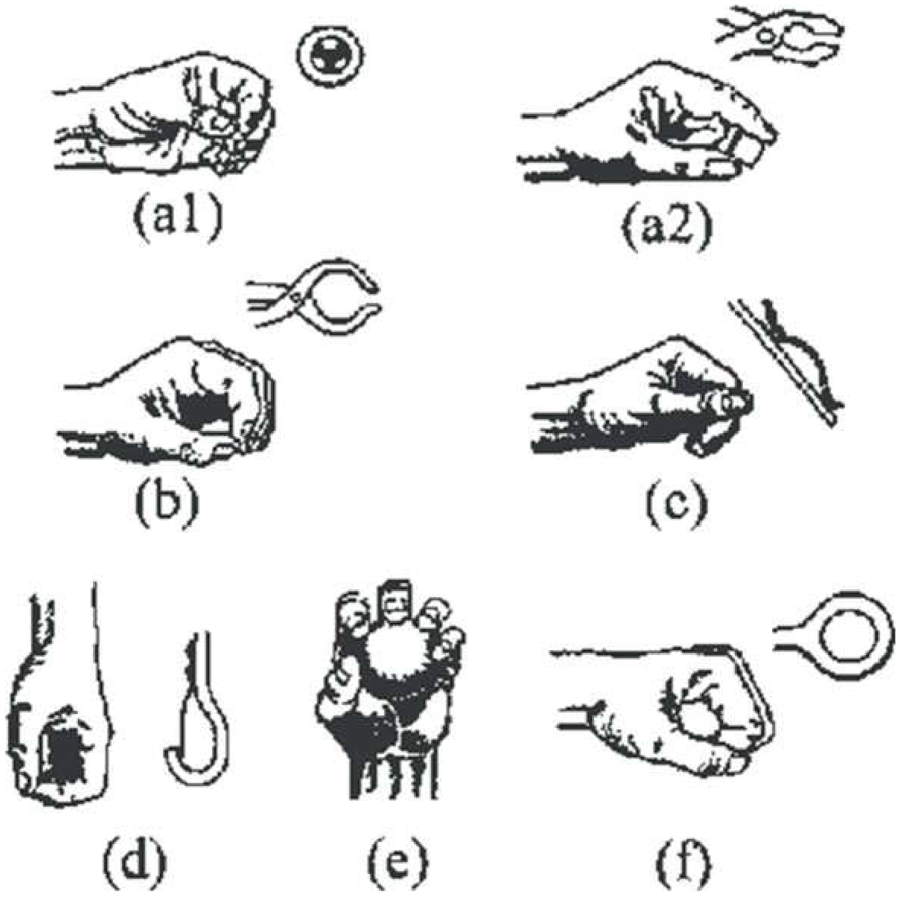


Figure 3, Schematic of the prehension patterns of the hand. (a1) palmar prehension (three-jaw chuck), (a2) palmar prehension (two finger), (b) tip prehension, (c) lateral prehension, (d) hook prehension, (e) spherical prehension, (f) cylindrical prehension. (Weir, 2004)

Generally, the grasps of the hand fall into two categories, power grasps and precision grips. Power grasps use all fingers to achieve an encompassing grasp to firmly stabilise the object. Precision grips on the other hand primarily involves the thumb working in opposition to the index and/or middle finger. Napier described tip prehension, palmar prehension, and lateral prehension as precision grips and spherical and cylindrical prehension as power grasp; hook prehension falls outside both categories. (Napier, 1956, cited in Weir, 2003, 32.4.1 Anatomical design considerations)

Because of the lack of control signals, prostheses are often designed around the six grasp patterns. (Keller et al., 1947, cited in Weir, 2003) Most prostheses only have one grip pattern, e.g. Speed hand, which have a tripod power grip (palmar prehension), palmar prehension being the most common grip pattern. (Weir, 2003, 32.4.1 Anatomical design considerations) These are the most common type of non-passive prostheses, mainly because they do a good enough job while also being robust and simple. Then there are the more advanced, dexterous and complex prostheses, e.g. iLimb, which can achieve multiple grip patterns; to accommodate the lack of control signals the user must switch between the different grips using co-contraction of the muscles used to control the prosthesis through the myoelectric sensors.

3.1 Actuators

One of the main bottlenecks for prosthetic hands is the current actuator technologies which fail to provide efficient, high power density actuators small enough to fit into a hand. One solution would be to have the actuators in the arm of the prosthesis. The problem is that people are rarely amputated at the same place; therefore, a prosthesis with actuators in the arm can only fit those with a minimum amputated length. The fact that the power storages are usually placed in the arm does not help either. (Wijk, 2018) The power sources available for today’s prostheses are body-powered, electric, pneumatic and hydraulic.

The choice of actuator is crucial as it will greatly impact the design of the prosthesis; how it works, how the user interacts with it, cost of manufacture and everything in between. A big decision in prosthesis design is if it should have an external power source or be body-powered. With a body-powered prosthesis the user uses their own muscles and therefore it must be efficient and easy to use; the prosthesis should be an asset, not a burden. If the power source instead is external, the power storage should be big enough to last at least a full day of use but should be small enough to fit inside the prosthesis.

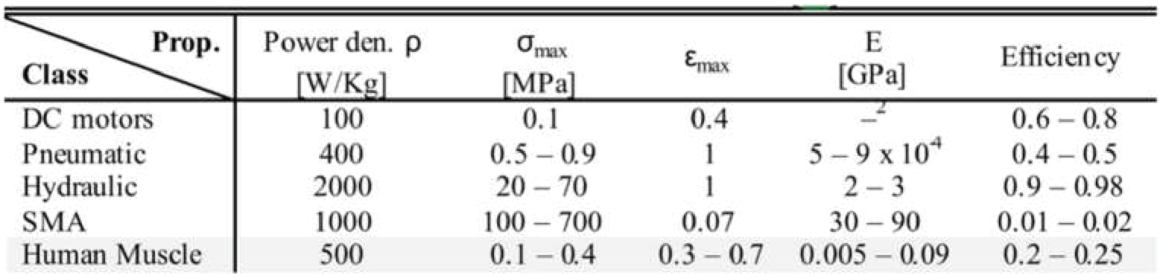
3.2 Pneumatic and hydraulic

Historically, one of the major sources of external power for prostheses. A number of prosthetic hands and arms with pneumatic power sources came about in the 1970s, but in the later years they have lost most of their popularity. The disadvantages with pneumatic power are partly the constant need for a supply of gas cylinders, often CO2. Furthermore, leakages can be a big issue as there are tubes running from the tank to the actuators. If the tubes begin to leak, not only will it drain the power source, but the pressure will also drop, weakening the actuators. There is also the problem with the size of the actuators; it is hard to find actuators that are small enough to fit more than one in a hand, if even that.

The main difference between a pneumatic and a hydraulic system is the compressibility of gas versus the incompressibility of liquid. With a compressible gas the hand will become quite compliant, which is good from a safety standpoint; it will lessen the impact when colliding with the environment. The issue with a compliant prosthesis is the lack of a strong, stable grip, which will make it hard to stop objects from slipping. With an incompressible liquid the hand will not be compliant but will have a stable grip instead. The main issues with hydraulic is the high pressure and the fact that it becomes quite messy; as there will always be small leakages. In addition, a fluid and fluid reservoir are required, adding to the total weight.

3.3 Electric power

Electrically powered prostheses are the most common type of externally powered prostheses. One major reason for the success of electrically powered prostheses is the development of batteries for the laptop and cell phone industries. Because of this, the issue of developing a reliable, portable, power dense power source has already been taken care of. The actuators used in these types of prostheses are dc motors, direct current motors. Usually the dc-motors are brushless, mainly because they are more power dense than brushed. In a dc-motor, the output torque and speed are proportional to the current and voltage drawn by the motor. This makes the actuator easy to control, and by measuring the current, voltage and speed of the motor, all of which are easy, you get the output torque. While idling, the current and torque are low, and the speed is high. The current is at its highest when the load torque is large enough to stall the motor. Because the stall current is the maximum current the motor will draw, it is therefore used to decide what current the H-bridge should be able to supply. Stall is generally something to avoid when using dc-motors as it can damage the motor. At the same time maximum torque for dc motors is achieved during stall, and the motors will stall when the prosthesis grasps an object. A brief comparison can be seen in figure 4.



Prop. Class	Power den. ρ [W/Kg]	σ_{max} [MPa]	ε_{max}	E [GPa]	Efficiency
DC motors	100	0.1	0.4	$-^2$	0.6 – 0.8
Pneumatic	400	0.5 – 0.9	1	$5-9 \times 10^4$	0.4 – 0.5
Hydraulic	2000	20 – 70	1	2 – 3	0.9 – 0.98
SMA	1000	100 – 700	0.07	30 – 90	0.01 – 0.02
Human Muscle	500	0.1 – 0.4	0.3 – 0.7	0.005 – 0.09	0.2 – 0.25

Figure 4, Brief actuator comparison (Table 1, Controzzi, 2013)

3.4 Complexity

When designing a prosthetic hand, the number of actuators to use is a quite important decision. Another important design aspect is the kinematics of the fingers. The more actuators the heavier and more complex the hand will be. The benefits of having a more complex and dexterous hand is being able to do more with it; having more than one grip pattern, generally a more stable grip, and in some cases the ability to adapt the grasp to the held object. However, there are many drawbacks with a complex prosthesis. The hand becomes less robust since complexity often comes at the expense of durability; there are more components that are liable to fail. Instead of a single, large, strong actuator, a dexterous hand uses more actuators, e.g. one per finger or, in one specific case, one per joint. Because of the restriction on space the actuators need to be smaller. This often results in a hand that have similar grip pressure as one with a single actuator, but with slower closing speed; for a comparison, se table X. When increasing the number of actuators in the hand, the net weight will also increase. Even though the actuators are smaller, the requirements for multiple gearboxes and gears will nevertheless make the hand heavier, and quite expensive.

The kinematics of the fingers also have quite an impact on the weight and complexity of the hand. The human finger contains three bones, or segments, the proximal, intermediate and distal; the more segments, the more joints. When designing the fingers there are two questions to answer, how many joints and how to control them. As the number of joints increases so does the complexity, mainly in how to control them. With more joints, the surface area of the grip will increase. The hand also becomes more anatomically correct, at least up to, and including, three joints. With only one or two DoC it is impossible to control each finger individually, even more so if each finger has two or three joints to control. Because of this, in combination with the lack of space and wanting to keep the hand light, it is not recommended to have one actuator per joint. Instead, the fingers consist of either one part or are underactuated i.e. the position of the finger joints are dependent on the MP joint.

This can be done either with linkages or with tendons. Linkages are mainly used on prostheses with few actuators, e.g. Michelangelo hand or Speed hand, both by Ottobock. Tendons on the other hand are mainly used by dexterous hands, e.g. iLimb by touch bionic and Smart hand. But the dexterous hands are moving towards using linkages instead.

There are two main advantages of using tendons. First, as a tendon is essentially just a string connecting the actuator to the finger allowing flexion, it is easily routed in whatever manner suits the design. E.g. it could be routed to an actuator in the wrist, and despite requiring it to run at an angle and, if the wrist was designed to be flexible, also cope with that, it would require nothing more than a few rollers directing it. Second, in the human hand, each joint is actuated by two tendons. In the case of the prosthetic hand though, using two actuators per joint is not done as that would be impractical; it would take up too much space and make the hand too heavy. Instead springs are used to return the finger to an original position when the tendon does not flex it. The advantage of this design is that it gives the finger a natural compliance as it is not rigidly held. This allows the fingers to bend if force is applied to the outside of the hand, e.g. if the user accidentally hits something whilst wearing the hand. If the hand was rigid this might lead to cracks and other damage, but if it is compliant it will just flex in response to the force; making the hand more durable and less annoying when it collides with the environment.

Tendons will inescapably wear as they slide over rollers and will eventually break. As this happens they will need to be replaced, which is often a rather complicated procedure. Linkages are stronger and will not wear in the same way. They are usually made from metals and have a much larger cross section area than a tendon. They are thus not as sensitive to wear and will last much longer. An additional advantage is that linkages are direct controlled, there are no springs needed to extend the fingers; this is instead done by applying force or torque directly to the finger. This means that the exact position of the finger is easier to predict; but will also make the fingers noncompliable, at least not naturally.

3.5 Method for sustained grasp

In the hand, it is desirable that the fingers should maintain their position and the power of the grasp even as the electrical power to the motors is shut off. The reason for this is threefold. First, if the hand would require constant electrical power to be supplied to the motors, the operational time between charging would be very short.

For instance, the type of motor used in the final prototype to actuate the fingers draws 1.61 A when driven into stall at 7.4 V and the type of motor used to pivot the thumb draws 1.26 A. All together they draw a current of 3*1.61+1.26 = 6.09 A. The largest capacity 7.4 V Li-ion battery pack available for purchase at Elfa has a capacity of 1400 mAh or 1.4 Ah. This gives an operating time of 1.4 Ah/6.09 A = 0.23 h = 14 min. While this is the amount of time during which active grasps can be sustained and most of the time the hand is not in active use, it is still too short a time for the hand to be practically useful.

Second, when the battery is drained no more current can be supplied to the motors. If the hand requires these to constantly maintain the grasp, the grasp will lose power as soon as the motors do. This could lead to potentially dangerous situations, e.g. if the user is carrying something heavy which might be suddenly dropped.

Third, most motors are not built to survive sustained stall. This is because the large current flowing through its windings may cause them to overheat. This in turn could lead to permanent damage to the motor.

All three of these reasons make it necessary for some mechanism which allows the grasp to be maintained without constantly supplying power to the motors to be used. This property is known as non-back drivability and such mechanisms are known as non-back drivable mechanisms, abbreviated NBDM.

Generally, worm gears, lead screws or gear pairings with a large reduction ratio is used to achieve non-back driveability. The advantages with these types of NBDM is that they are easy and cheap to design and manufacture, they can also withstand quite a lot of force. Therefore, they are the most common type of NBDM. The mayor issue with worm gears, lead screws or gear pairings is their inefficiency; to work they need to have an efficiency lower than 50 %. This is, in an application were size, and consequently motor power, is limited, quite bad.

Another option is to use roller clutches, which are unlocked when torque is applied to the input shaft but remain locked when torque is applied to the output shaft. As they are unlocked rather than using friction to achieve non-back drivability, they allow for power transmission with low losses when unlocked. Such a clutch is discussed in Miniaturized non-back-drivable mechanism for robotic applications. (Controzzi, Cipriani and Carrozza, 2010) It was developed for use with thumb joints in prosthetic hands. As a part of the project was to try approaches not previously done or deviating from the conventional solutions, the use of such a clutch was deemed interesting and it was decided to try and incorporate it into the design as the solution for non-back drivability. This was not possible however as there was no readily available clutches of this design. An equivalent clutch made by a Japanese manufacturer was suggested by Marco Controzzi.

3.6 Torque transmission

In this area there were a few alternatives. The considered options were: gears, belt transmission, chain drive, cardan shaft. The motors are placed perpendicular to the driving shaft, a shaft at the base of the finger which bends the finger. It is therefore impossible to directly transmit the torque to shaft using any method that requires parallel shafts. Thus, either bevel gears or cardan shafts would need to be utilised to align the motor torque with the driving shaft. However, cardan shafts, since they utilise universal joints, have a non-constant transmission of speed, i.e. if the input shaft rotates at constant speed the output shaft will rotate at a non-constant speed. Since a high degree of precision is needed in control of speed and position of the fingers, this makes cardan shafts unsuitable in this application. A further drawback is that the efficiency of the universal joint rapidly decreases as the joint angle goes up. As a 90° angle is required this further disqualifies the cardan shaft for use here.

What then remains are bevel gears which will give a constant ratio between the speed and torque on the input and output shaft of the gear, provided that gears with an involute profile are used. These are used to align the torque so that it acts on an axis which is parallel to the axis that coincides with the driving shaft.

When the torque is properly aligned, it must be transmitted all the way from the shaft driven by the motor to the driving shaft. For parallel shafts either belt transmission, chain drive or gear trains can be utilised. After looking at the available of the shelf parts for each of these methods, it was concluded that both chain drive and belt transmission were unsuitable due to the size of available parts.

Once again, what remains are gears. Here a large assortment was available and with-it enough flexibility in gear size and shaft distance to realise the full transmission.

The conclusion of all this is that the entire transmission from motor to finger is made up of gears and shafts. This makes it possible to realign the torque with a necessary angle, using bevel gears, transmit it radially, using straight gears, and transmit it axially, using shafts.

3.7 Motor control

Control of the motors is of course essential to make the hand work properly. It must be possible to switch the polarity of the voltage over the motors to switch the direction of rotation and thus allow for both flexion and extension of the fingers and thumb as well as adduction and abduction of the thumb.

Furthermore, as the gearboxes can take a maximum input torque of 400mNm and a maximum input rotational speed of 8000 rpm both rotational speed and torque from the motors must be controlled. The speed is measured with an encoder fitted to the motor. Torque is indirectly measured through measuring the current and the rotational speed. This is because the torque is directly proportional to the current and the rotational speed, as expressed by the following equation, in the source given as:

$$T = \frac{V\omega k}{R} k$$ (Collins, 2018)

In the following calculation the following denominations are used:

$$M = T = torque$$

$$V = U = voltage$$

$$\omega = rotational\ speed$$

$$R = electrical\ resistance$$

$$I = electrical\ current$$

$$k = constant$$

$$c = constant$$

$$k \neq c$$

Using European denomination:

$$T = \frac{V\omega k}{R} k = M = \frac{U\omega k}{R} k$$

Ohm’s law states:

$$U = RI <=> I = \frac{U}{R}$$

This leads to:

$$M = \frac{U\omega k}{R} k = I\omega kk = I\omega k^2$$

As k is a constant, k^2 is thus also a constant and can be denoted as c

Thus:

$$M = I\omega c$$

To have full control of the motor, rotational speed and current through the motor will be measured as stated above. Both will then be controlled by controlling the voltage to the motors, as both are dependent on the voltage. Lower voltage gives a lower rotational speed and a lower current and thus lower torque.

The control can be realised as shown by the chart below.

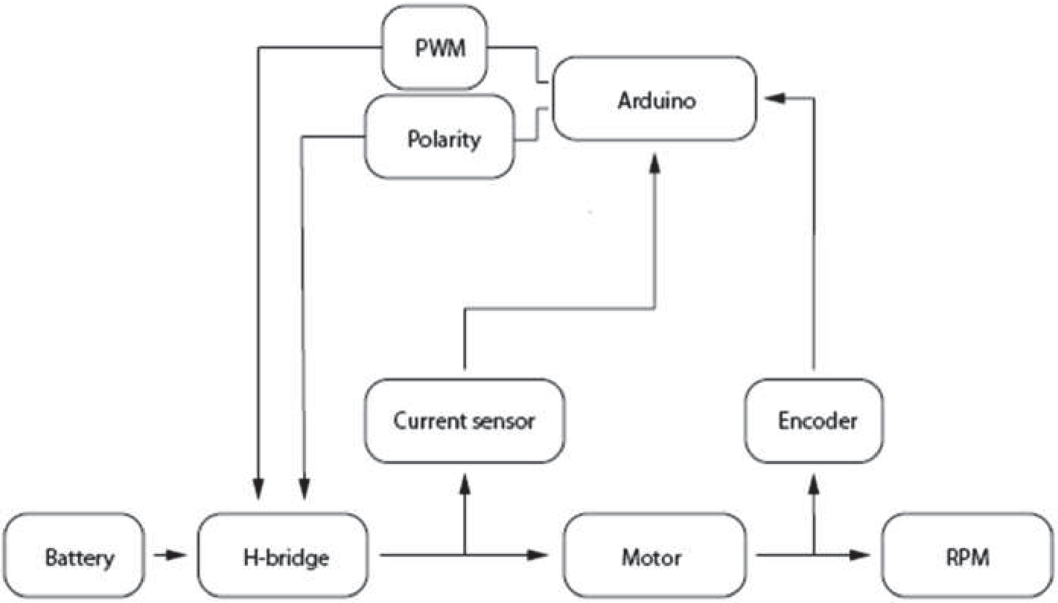


Figure 5, Motor control chart

The Arduino will receive the signals from the current sensor and the encoder. Based on this, it will set a voltage by way of a PWM-signal. This PWM signal is sent to the h-bridge, which drives the motor. In addition, the Arduino also send a signal deciding the polarity of the voltage that the h-bridge supplies. Which polarity is set depends on whether the hand is supposed to flex or extend, as the polarity of the voltage decides the direction of the rotation of the motor.

4 Interview and user needs

4.1 Ulrika Wijk, researcher

An interview was held with Ulrika Wijk, who is a researcher at Lund university, doing research at the hand surgeon in Malmö. From this interview it was gathered that the most important with the prosthesis was that if was robust and functional. Normally people either use Otto Bocks Myo VariPlus Speed, or similar, or just a cosmetic hand. Dexterous hands are not used very often because they are expensive, weak and takes time to learn. The user learns how to use a specific prosthesis and it takes time to learn a new one, especially a dexterous prosthesis with multiple grips. A benefit of dexterous prostheses is the usability of multiple grips, e.g. for a computer mouse, and the conformability of the grip. The interview in its entirety is presented in appendix A.

4.2 Users

Two people who use prosthetic hands were also interviewed. The first user had only had the prosthesis for less than a year. He used a body-powered hook because of his work as a farmer; the prosthesis will quickly get dirty and it needs to be reliable even in a rough environment. The contact surface of the hook was knurled metal. This meant that softer material, e.g. wood, plastic, etc. was no problem to lift, but harder material, e.g. metal, was much harder.

The other user had a myoelectric prosthesis and had had the prosthesis for 30+ years. He uses the prosthesis daily and compares the prosthesis to a pair of socks; something you put on in the morning and take of in the evening, but otherwise don’t think about. He has good control of the prosthesis and thinks the feedback is quite good and compares it to lifting with a plier. The things that are the most important for him is that the prosthesis should be robust. It needs to function and the less of a hassle it is, the better. It also needs to look like a hand. It can make surrounding people or the situation a bit uncomfortable if it does not; the less noticeable the prosthesis is, the better.

4.3 Needs

From the interview with Ulrika and the users it was gathered that it is less about specific features and more about the general feel of the prosthesis. The hand should feel and move naturally, it should not require much, if any, thought to operate. It should not move or really do anything at all on its own accord; it should be fully controlled by the user. The prosthesis should be robust enough to endure, not only a normal day, but essentially any environment; it would be a bit too ambitious to expect to bathe with it, but durability should not be a limitation. Lastly it is important that the prosthesis is discrete and preferably look and move exactly like a human hand. According to one of the users, appearance is probably more important than people first think; it is only after using a prosthesis that one realises just how important it is.

4.4 Functions

Nether the users or Ulrika had any specific functionalities directly related to the mechanics of the prosthesis. Instead they gave a broader picture for how the prosthesis should handle and feel. This made it hard to translate their wishes into any new feature. Instead it gave us characteristics that are desirable by users, mainly durability and preferably dexterity. Since the cosmetics of the hand are mainly realised with an outer shell and silicone glove, it will not be a focus in this prosthesis.

5 Design of the CB-hand

The hand is called the CB-hand, which is an abbreviation of the Compatible Bending Hand.

When designing the CB-hand some rules of thumb produced by Belter, (Belter et al., 2013) where used as a guideline. This together with the interview became the core instruments when deciding which concept to keep, which to reject and how to improve the concepts.

The rules of thumb when designing a prosthetic hand by Belter:

- The total weight of the prosthesis (including mechanism, glove, electronics, etc.) should be below 500 g. The human hand weights about 400g.
- A lighter prosthetic hand is particularly better for people with high-level amputation because of power and weight constraints of the entire prosthetic arm.
- Simple and robust finger kinematic designs are preferred at this time over anatomically correct finger designs.
- Powered adduction of the thumb is highly desirable since it allows for active posture control such as switching from lateral prehension to palmar prehension.
- The use of brushless motors instead of brushed motors is preferred because of performance versus weight considerations.
- A maximum pinch force at the fingertip of 65 N during palmar prehension is recommended.
- 230 °/s should be achieved by a high-performing prosthesis, while 115 °/s is a minimal acceptable speed.
- Compliance in the mechanical design of a prosthetic hand can be achieved in various ways (conforming fingertip/palmar pads, compliant actuators designs, collapsible linkage systems, compliant joints, etc.) and is highly recommended by the authors.

- Highly functional grasping hands should be designed with a low number of actuators with transmissions that allow for all functional grasping postures.

5.1 The size of the hand

As the hand is supposed to be small enough to fit a woman or child, the smallest measurements that could be found were used to determine what size hand should be. This data was a study of body measurements of Koreans “Anthropometric Classification of Human Hand Shapes in Korean Population”. (Jee et al., 2016)
To determine the proportion between finger length and finger bone length, Proportions of Hand Segments (Buryanov and Kotiuk, 2010) was used.

5.2 Finger design

5.2.1 Finger concepts

In the first stage two concepts were developed. The first concept was made to be cut from MDF boards, or similar. When the proximal joint (grey disc) rotates, so will the intermediate and consequently the distal joint, making the finger bend.

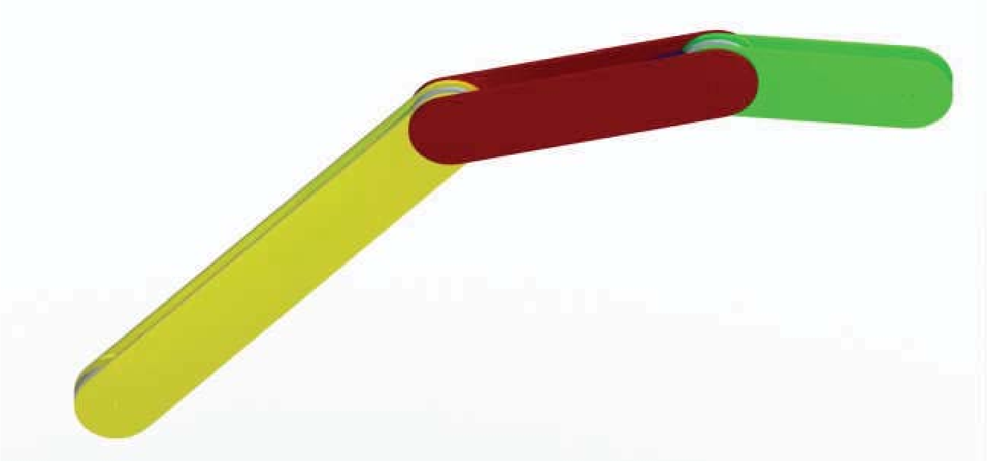


Figure 6, Design of the first concept

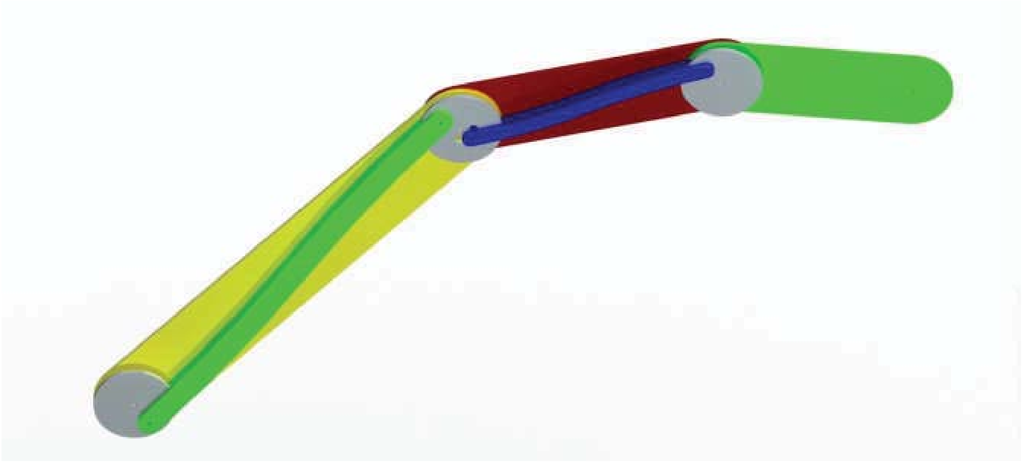


Figure 7, Design of the first concept

The second concept is essentially the design developed by Dechev, Cleghorn, Naumann. It was derived from the illustration of the design in their report "Multiple finger, passive adaptive grasp prosthetic hand". (Dechev, Cleghorn and Naumann, 2001) It was created with the intention of having a starting point for the design of the fingers.

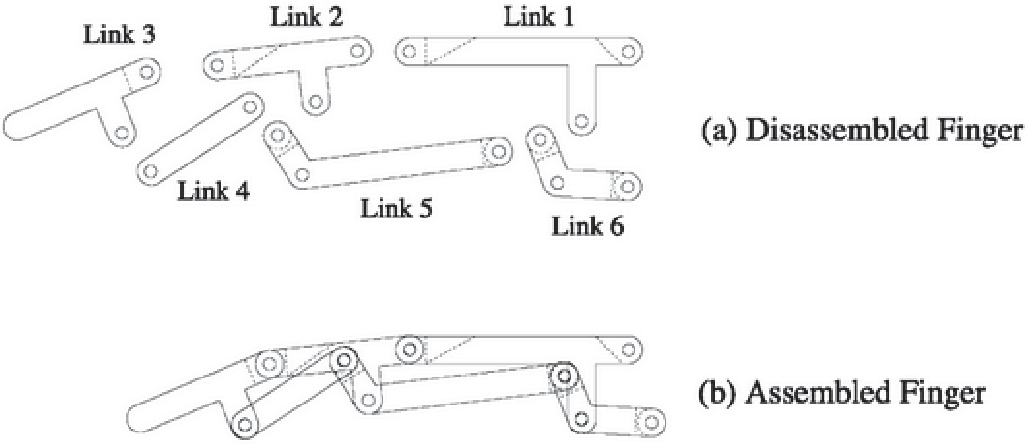


Figure 8, The design of the finger and the individual links (Figure 1, Dechev, Cleghorn and Naumann, 2001)

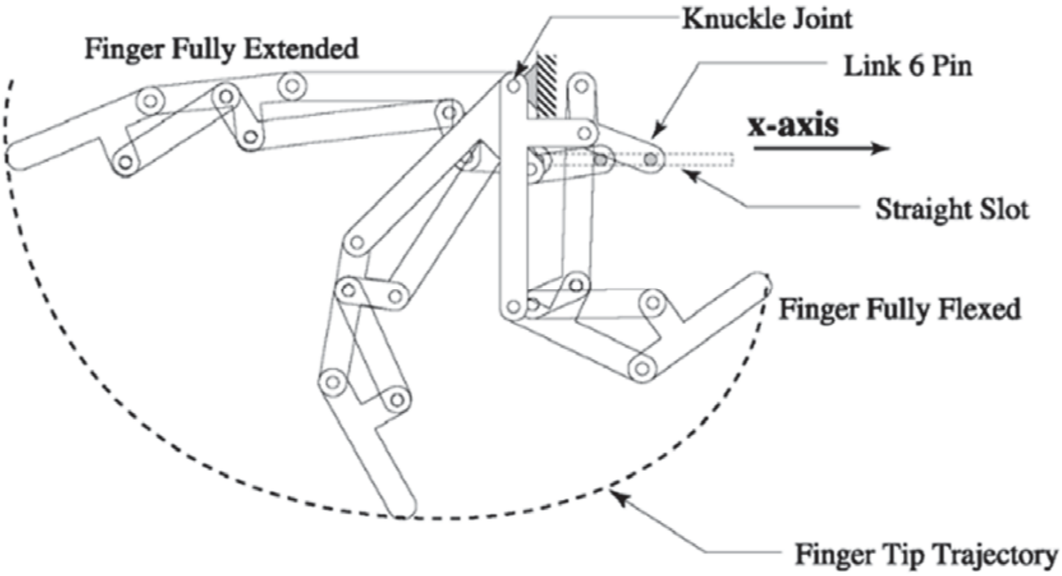


Figure 9 The bending of the finger (Figure 2, Dechev, Cleghorn and Naumann, 2001)

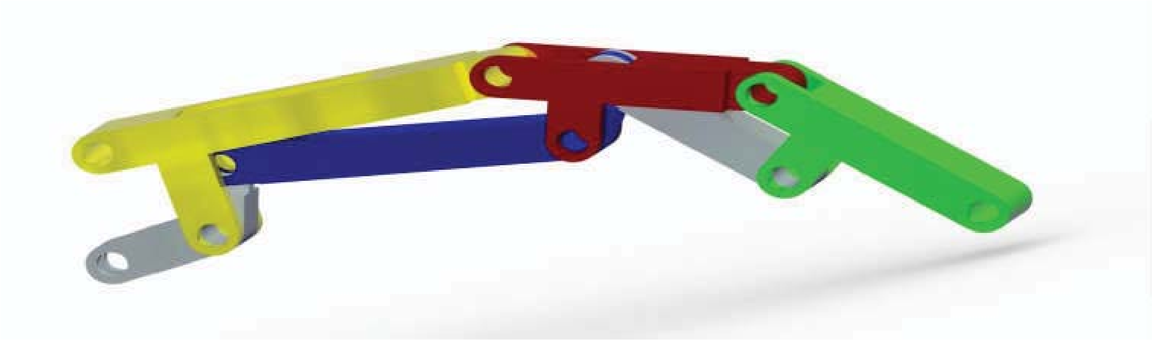


Figure 10, The second finger design as it was derived, here rendered by Creo.

Figure 11, The second finger design as it was derived, here 3D printed and assembled.

When evaluating the concepts, the second one was chosen for 3D printing. Mainly because the design made it much easier to print, and to get some idea of how it worked. The first concept on the other hand was only drawn in Creo. From this it was decided to continue and improve with the second concept. The reasoning was due to robustness, and complexity. The first concept contains a lot of small parts making it liable to failure, while the second one had fewer, less complicated components. The second concept, which became the first prototype, was also more intuitive to improve.

Criticism

The linkages collide with each other so that the finger cannot bend in the way it is supposed to. The finger moves by a linear movement of the proximal link resulting in the bending of the finger. This requires a linear motion, which can be hard to achieve if a rotating motor is used. The advantage of using linear motion is that it makes position control much easier. It can also make it possible to make the fingers complaint, e.g. Bebionic.

Improvements

The linkages will require some redesigning so that the finger may bend correctly. If a rotational motor is to be used the bending of the intermediate and distal part needs to be dependent on the position of the MP joint; similar to the first concept. Rotational movement is easier to design. There is no need to find a motor with linear movement, and such mechanisms often have high friction.

5.2.2 Second prototype

After the first prototype, the finger went through several iterations ere a second prototype was printed. Firstly, the prototype was improved with some ideas from the first concept, mainly how to bend the intermediate and distal parts; Bebionic hand v2 by RSL Steeper was also used as inspiration. This resulted in the concept seen in figure 12. The free end of the red link will be fastened on the hand frame; similar to Bebionic hand v2.

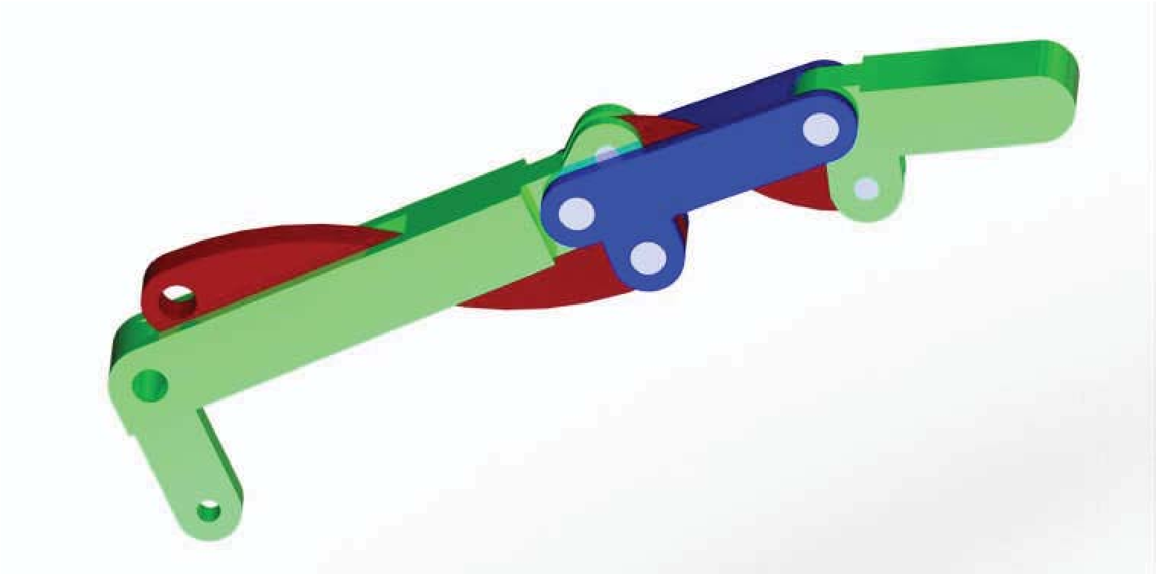


Figure 12, Combination of the first prototype and concept No. 1

A similar concept, but with a slightly different structure, can be seen figure 14 and figure 15. This was developed to see if the force in the finger could be increased by changing the position of the links. When a force is applied to the tip of the finger, the resulting torque on the drive shaft varies with the lever arm, see figure 13. Because the motors will apply a constant torque, the grip force will vary as the hand closes.

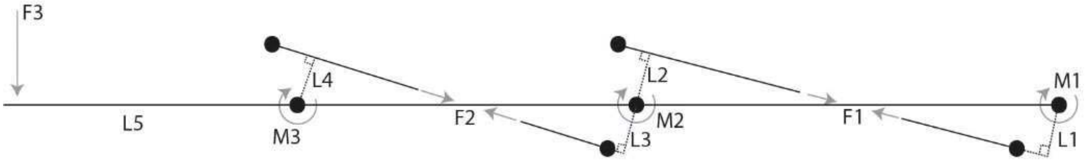


Figure 13, M1, M2 and M3 are the torque of the joints. F1 and F2 are the forces in the bending linkages (red linkages in figure 12). F3 is an external force at the tip of the finger. L1, L2, L3, L4 and L5 are the lever arms to the joints.

$$M1 = F1 * L1$$

$$M2 = F2 * L3 - F1 * L2$$

$$M3 = F2 * L4 - F3 * L5$$

The result was that the force did increase, but only when the finger was somewhat straight. As the finger flexed, the force decreased to below that in the original structure. The force is most critical with a flexed finger, or closed grip. For this reason, the concept was scrapped.

Figure 14, Similar concept as figure 12, but with a different structure.

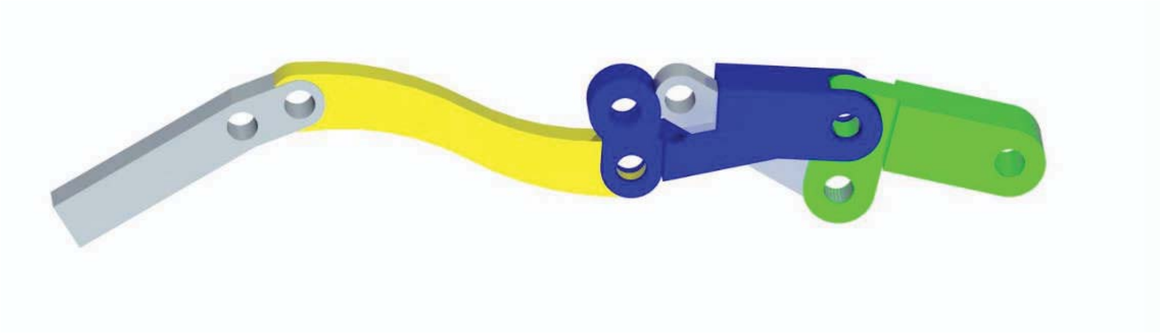


Figure 15, same as figure 14, but with the proximal part hidden.

A big challenge of the second prototype was to see if it is possible to make the distal part adaptable by attaching a spring to the distal link. The 3D print of the prototype can be seen in figure 16 through 19.

Figure 16, Second prototype. Side view, flexed finger

Figure 17, Second prototype. Side view, extended finger

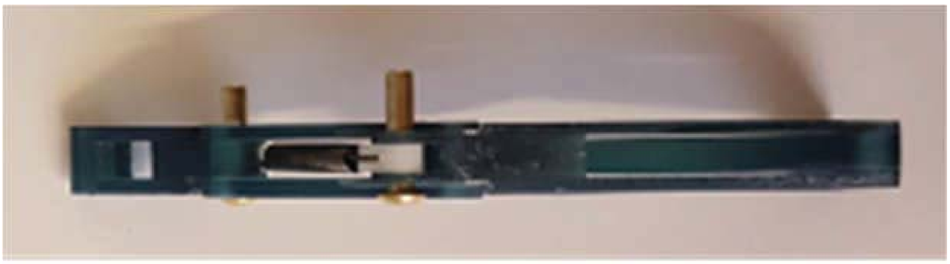


Figure 18, Second prototype. Back view

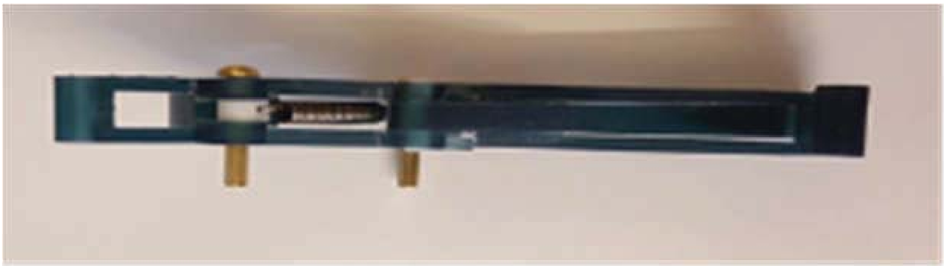


Figure 19, Second prototype. Front view

Criticism

The link and bending of the finger work well with the new design. The spring idea seems to work. There is a problem when straightening the finger and some limitation of the bending caused be the spring. The full functionality and bending of the finger are hard to test without a thumb to test the grip.

Improvements

Change the spring link so that the straightening of the finger works as intended; hopefully also make the finger a bit sturdier. Build a hand with a thumb and more fingers to test the grip.

5.2.3 Third Prototype

The third prototype was a half-completed hand, with the thumb, index and middle finger. The goal was primarily in designing the thumb. The thumb was placed in the bottom of the hand with the abduction adduction centre in between index and middle finger similarly to Bebionic and iLimb. The thumb was also divided into three segments, not counting the module that enables abduction and adduction. Another purpose was also to get an idea how to design the grip of the hand, primarily palmar prehension.

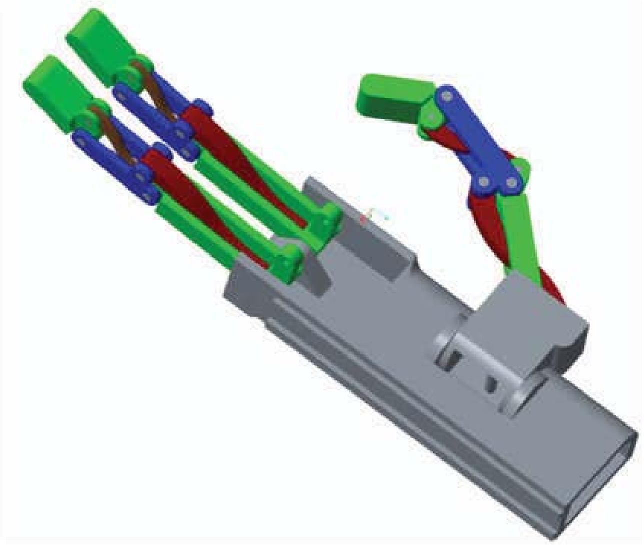


Figure 20, Third Prototype

Criticism

The thumb has the wrong proportions, to have three segments is probably not necessary; It only makes the thumb unnecessarily complex without much benefit. The grip was quite good, but felt a bit wrong, mainly a result of the length and position of the thumb.

The fingers need to be redesigned. Because of the spring link the finger cannot be bent to the full extent. Making the finger into three parts also makes the prosthesis needlessly complex; It does not add to the stability of the grip in any significant way. Making the hand adaptable with springs might be a solid idea but is almost impossible to incorporate in its current design.

Improvements

Remove the third part on the thumb and probably change its position. Remove the link between the intermediate and distal part of the finger; if the finger still needs to be adaptable a new implementation is needed.

6 Result

6.1 Torque transmission system

The torque transmission system consists of bevel gears, spur gears and shafts supported by the frame of the hand and ball bearings. In the fingers, the system gives a reduction of 4 between the motor and driving shaft. In the thumb, it gives a reduction of 5.33. This gives a further step of reduction after the gearbox. In addition to making the hand stronger, and slower, it also serves to reduce the torque that might be applied backwards on the output shaft of the motor package. This reduces the strain on the NBDM which must lock the output shaft from rotating due to torque applied in this direction and thus helping in ensuring that the grip is sustained after power to the motors are shut off.

All of the gears are bought from Lemo Solar and are made from tool steel. A selection of the gears used is shown in figure 21.

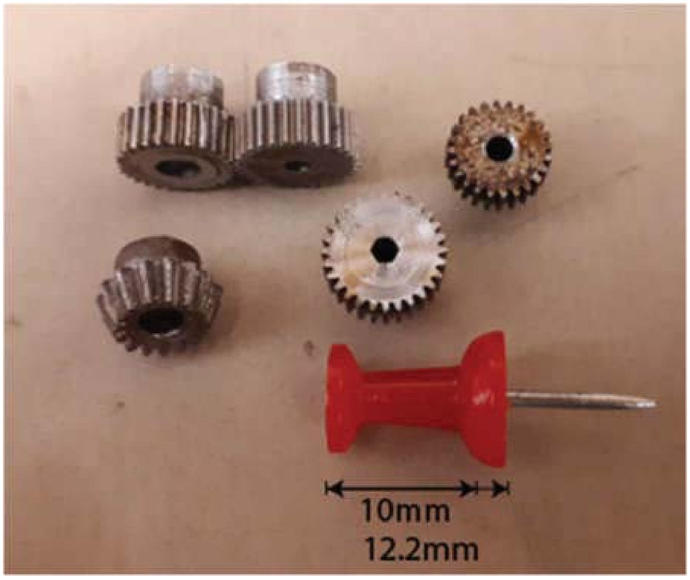


Figure 21, A selection of the gears

The shafts are made from silver steel of the Sandvik 20AP quality. In a few places, it was necessary to have a shaft with a diameter of 4 mm in one end and 2 mm in the other end as bevel gears and spur gears with respective diameter had to be fitted to the same shaft. In these cases, the shafts are connected by shaft couplers.

Drawings of the torque transmission from motor to driving shaft is shown in appendix B1 and appendix B2.

The specification of the gears with relevant data and Lemo Solar product numbers as well as gear numbering by proximity to the motors are found in appendix C.

A drawing of the shaft coupler can be found in appendix D.

6.2 Type of actuator

The chosen actuators are brushed dc motors. The reason for choosing electrical motors is their high-power density and the relatively convenient power supply provided by Li-ion batteries. The reason for choosing brushed motors are that they are cheaper and easier to control, as no special control circuit is necessary.

The motors were chosen from those that fit the NBDM, made by Adamant Namiki. They are fitted to NBDM and gearbox in a single package. First 12V motors were considered, but in order not to have to use a voltage regulator between the batteries and the motors, 7.4V motors were instead chosen. For the flexion and extension of fingers and thumb, 12x30 mm motors are used which gives a stall torque of 8.55 mNm. As it was considered less important to have high power for the ab/adduction of the thumb, a smaller 12x15 mm motor is used. This motor gives a stall torque of 3.40 mNm.

6.3 NBDM

The NBDM used in the hand was suggested by Marco Controzzi as a response to the request for using the clutch designed by Federico Montagnani, Marco Controzzi & Christian Cipriani. It is developed by Adamant Namiki in Japan and is a system fitted to a motor in combination with a planetary gearbox. This provided the most efficient and convenient solution to both the non-back drivable and reduction problem that could be found.

6.4 Gearbox

The gearboxes used are made by Adamant Namiki and are made to fit the motors and NBDM. They are planetary gearboxes and give a reduction of 58.

6.5 Hand frame and thumb attachment module

The purpose of the thumb attachment module is the enable motor-driven adduction/abduction of the thumb. It also houses the main transmission for flexion/extension of the thumb. The size of the thumb module is partly a result of trying to find bevel gears to support the angle of 50 degrees. But it is also a result of changing the angle of the torque, which requires either bevel gears or worm gears. Because of the low efficiency of worm gears, bevel gears were used instead. To fit the bevel gears inside the thumb module it needed to be larger than intended.

The hand frame is made from Nylon using Selective Laser Sintering at the 3D printing laboratory at IKDC. Thereafter holes that could not be printed is drilled and sanded in necessary places to ensure smooth gliding at contact surfaces. The thumb attachment module is made from Rigid Resin from Formlabs. (Support.formlabs.com, 2018)

Drawings of the frame can be found in appendix E.

Drawings of the thumb attachment module can be found in appendix F.

6.6 Fingers

The final design of the fingers is a rework on the third prototype. The link that underactuated the DIP joint is gone. Instead the distal part is free to bend from 0 to 45 degrees with a spring that rests at approximately 35 degrees. This way the bending of the distal joint is not dependent on the rest of the finger; the hope is that it will adapt to the grabbed object and therefore give a better grip. The proximal and intermediate part is essentially identical to the third prototype.

The thumb is positioned at a 50-degree angle and consist of a proximal and a distal part. The IP joint is underactuated and connected to the MP joint by two linkages. In commercial prosthetic hands the thumb is usually placed at the bottom right corner of the hand and is not placed at an angle, e.g. iLimb. This enable the designer to fit one motor inside the thumb and save space inside the hand. Since this prosthesis has a shorter thumb placed at an angle to the rest of the hand, the motor cannot fit in it. This design was inspired from Azzurra hand. (Controzzi, 2013)

The fingers and thumb, except for the linkages, are 3D printed just as the hand frame and thumb attachment module. At first the thought was to mill the linkages from a 1.5mm steel sheet. To save work the linkages was instead 3D printed to test the concept with a backup plan to laser stamp them if they brake to easily.

From FEM analysis the stress in the linkages will exceed 120 MP. Nylon has an ultimate strength of about 120 MPa. (Materialguide Amidplast, 2008) The result is that nylon linkages may be durable enough for demonstration but will break during heavier load.
The little, ring and middle fingers are connected to the same motor. This way the hand can be controlled with four motors, instead of six. According to Montagnani, Controzzi and Cipriani (Montagnani, Controzzi and Cipriani, 2016), when an opposite thumb is present, independent fingers only give an advantage with precision grips. For this reason, the index finger will be independent, as this is the one used in precision grips.

Drawings of the fingers can be found in appendix G.

6.7 Assembly

The final prototype can be seen in figure 22 through 26.

The majority of the components that needs to stick to each other, e.g. gears to shaft, fingers to driving shaft, are glued with Loctite 420. Originally these were meant to be fixed by way of an interference fit. However, the diameter of the hole in the gears is slightly larger than the diameter of the steel rods from which the shafts are crafted. Where Loctite could not be used the shaft was deformed so that an interference fit could be achieved.

After the fingers and gears were assembled it was found that some of the gears, mainly the small ones, and the ring finger slipped on the shafts. One reason for the slipping was the friction in the system; a result of the fact that the axis of the ring finger not being properly aligned with the rest of the transmission system. Another reason was probably the Loctite not getting in between the shaft and the gear; the larger the area of bonding, the stronger it gets. In case it was a problem with the specific glue, universal power epoxy was also used, but the result was the same.

Another issue was to attach the thumb attachment module. The problem the bevel gears that was supposed to form a 40-degree angle; instead it was closer to 50-degree. As a result, when the module was in place, the gears interfered too much with each other and they could not rotate.

From the result, the concept seems to work, but the construction shows that the manufacturing technique does not. Firstly, the accuracy of the 3D printer was worse than expected, adding about 0.1 – 0.2 mm in all dimensions. As a result, there was quite a lot of post processing and the transmission did not fit well enough; the gears have way too much backlash and does not run smoothly.

Another result of the bad accuracy was the point- and index finger not being able to bend more than half the intended way. This because the linkages controlling the PIP joint was to think to fit between the proximal part and the gear of the MP joint.

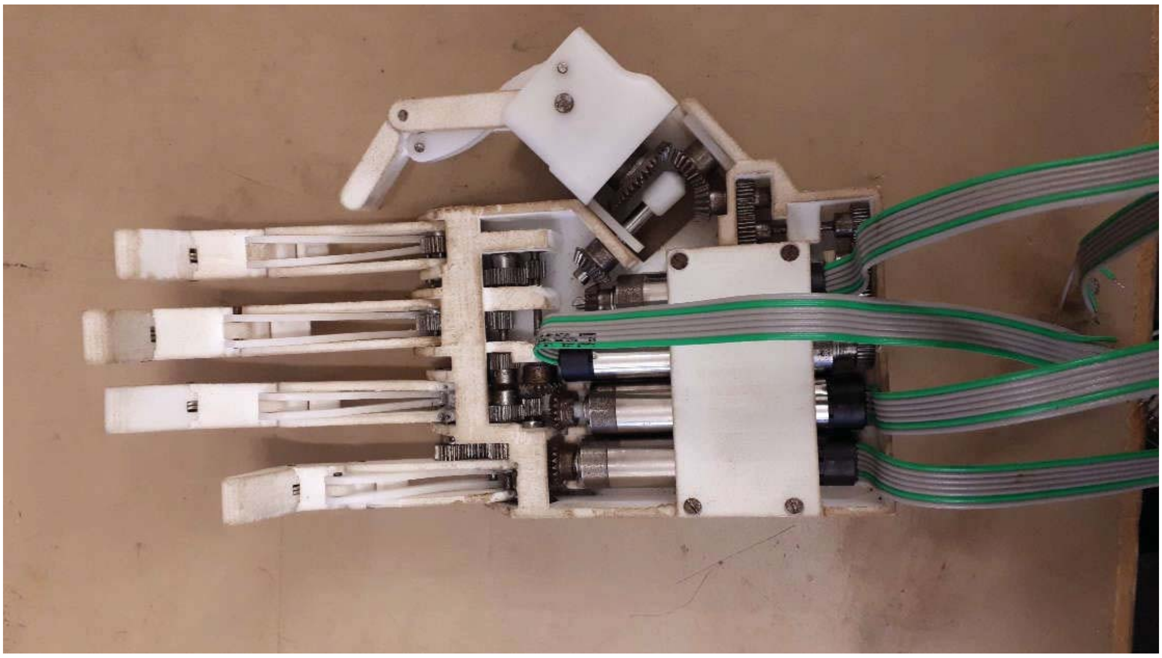


Figure 22, The final prototype. Front view

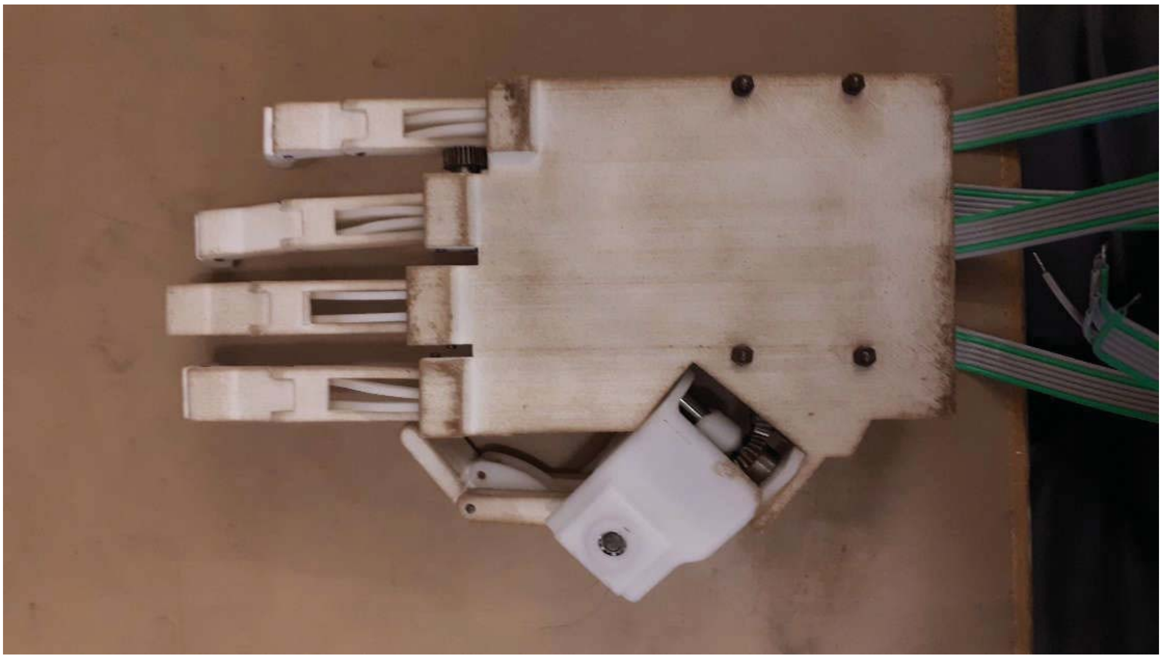


Figure 23, The final prototype. Back view

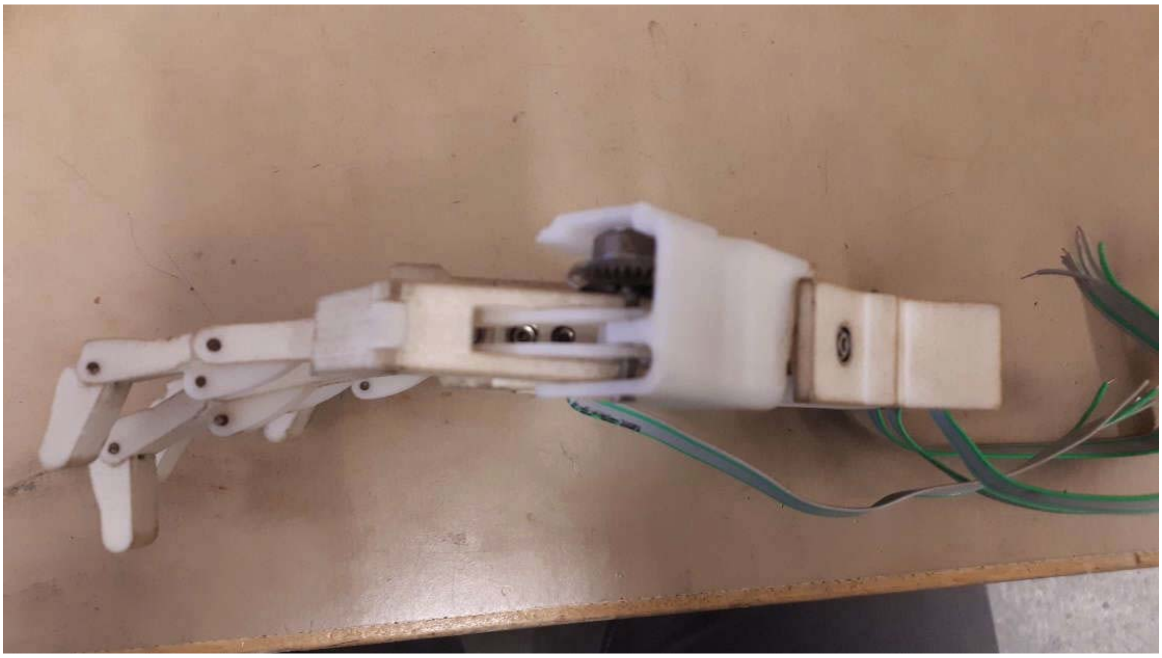


Figure 24, The final prototype. Side view

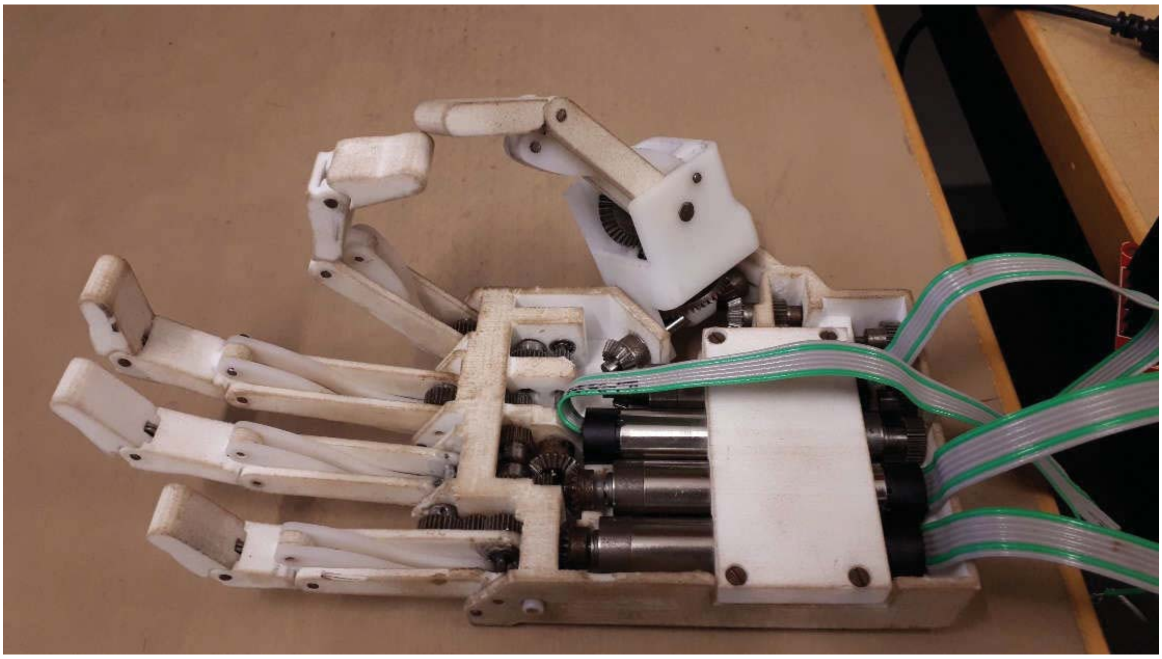


Figure 25, The final prototype. Palmar prehension, two fingers

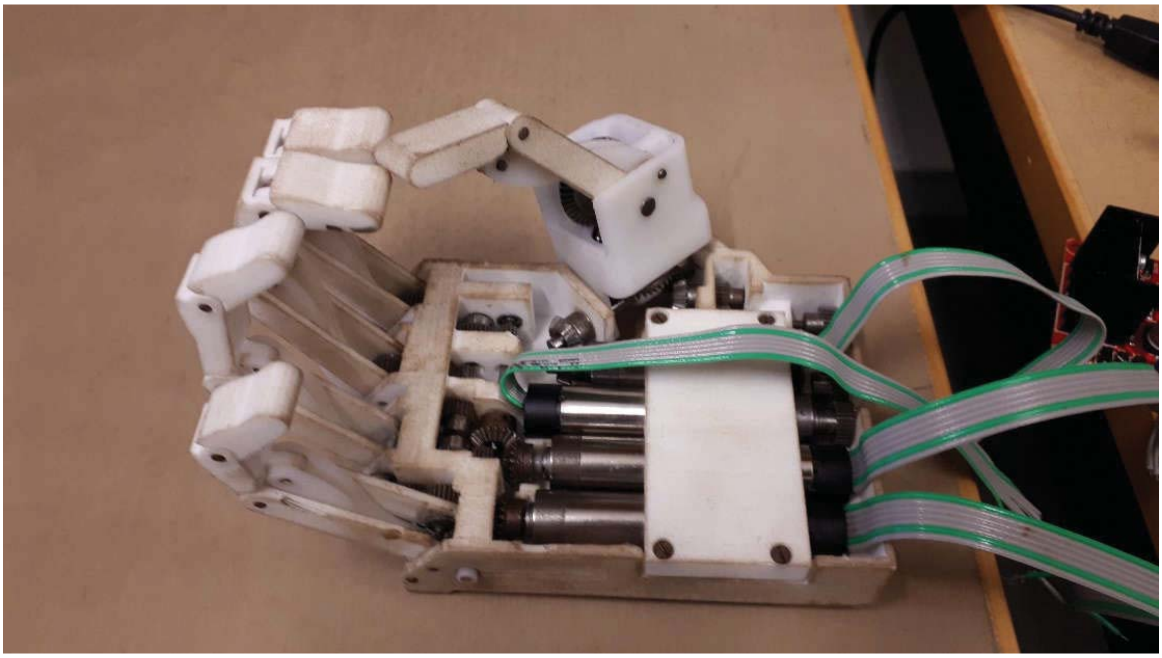


Figure 26, The final prototype. Palmar prehension, three fingers

7 Discussion

7.1 The size of the hand

A large issue when designing the hand was the limitation in size. As the hand is supposed to match the size of an average Korean woman, it is quite small. This limitation forced a rather complex system of gears for torque transmission with gears to be packed quite tight. It also required the gears to have a very small module, 0.3, which reduces robustness as the individual teeth are very small and the shaft distances are very short which requires a high degree of precision in the placement of the shafts. As this was not achieved to a satisfactory degree, there is a lot of added friction in the torque transmission system. This caused problems such as gears not staying fixed to the shafts and fingers getting stuck.

The size of the hand also required very small and compact motors which is by far the largest cost of the hand. But even though very small motors where used, together with the fitted gearbox and NBDM, they took up the largest portion of space in the hand. Using even smaller motors could be a solution, but that would also lead to a loss of power, making the hand weaker or slower or both. Even if shorter motors where used, as the transmission is in its current form, it will not make the hand shorter. To shorten the hand, the transmission needs to be rearranged. This is especially true for the transmission to the thumb, both for flexion/extension and abduction/adduction; it is the main reason for the added length of the hand.

In the end, the target size of the hand was not quite achieved. The hand is slightly longer, about one centimetre. This issue is exacerbated by the fact that in an actual prosthesis the hand would be even longer, as the length would have to accommodate an arm sleeve fixture as well as the internal components of the mechanism driving the hand. This could possibly be counted as being a part of the wrist rather than the hand, but it is not guaranteed that it would not change the length of the hand. The biggest issue is the thumb attachment module, which seems unproportionally large in contrast to the rest of the hand. This is so, as it must accommodate a large gear, a smaller substitute for which was not found. A such smaller gear could reasonably be found, which would alleviate this problem.

If the size cannot be reduced when gears are used, then it could possibly be done if tendons were used instead. For this to work the thumb and the transmission to the thumb must be redesigned. There might also be a need to change the motor that drives extension/flexion, specifically the gearbox; the reduction might not be suitable for a tendon. Any of these solutions may help reducing the size of the thumb attachment module. Compacting the hand to reach the targeted size could also be possible. However, these will have to be tasks for potential successors.

7.2 Problems with fitting the gears and fingers to shaft

When building the prototype, one of the biggest issues was attaching the gears and fingers to the shafts. There are a couple of alternatives, but only a few were viable in this situation. The main obstacle was the cramped space and the layout, meaning the gears needed to be attached when already in place. One alternative is to use an adhesive, in this case Loctite 420, which works well in that it was easy to place the gears and to make sure everything is in place. The problem was that it sometimes did not attach properly. In some cases, the gears or fingers came loose even during light loads. Another alternative is to use interference fit, this was achieved by a small deformation of the shaft. The issue was making sure the gears did not get stuck in the wrong position, and it left little room for errors. This is also in some places very difficult to achieve as the gears must be fitted to the shafts in place in the hand frame. Welding was not an alternative as the plastic would melt, it would deform the shaft and the precision required was to minute.

Having a way of allowing the gears and bearings to be fitted to the shafts before they are placed in the hand frame would probably make assembly much easier and give a better result. If this was achieved, all gears and bearings could be placed using interference fit, which would make a much stronger bond than the adhesive bond mainly used in the prototype. An example of a solution that would allow this can be found in appendix H.

7.3 Manufacturing of the parts

Most of the parts were 3D-printed in Nylon using Selective Laser Sintering at the 3D printing laboratory at IKDC. This technique had some issues with poor accuracy, even if it is better than most 3D-printers. The problem was that, because every part is so small, the accuracy needed to be much better than could be achieved. The consequence of this is that the dimensions of the manufactured parts deviated from the ideal measurement. For holes the diameter was too small, and outside measurements were too large. As a result, the holes had to be drilled by hand after printing which made their position and diameter somewhat arbitrary. This made the transmission system imperfect with unnecessary friction as a result. Better accuracy should go a long way to rectify this. It is believed that this degree of accuracy could be achieved if the frame of the hand was milled in a multi-axis machine rather than 3D-printed. Having a transmission system that fits together better would also lessen the torques that would have to be carried from shaft to gear and reverse. Thus, better accuracy in the manufacturing of the hand frame could make it easier to fit the gears to the shafts, as the bond would need to withstand lower torques.

7.4 The gears

In the prototype, steel gears are used for the torque transmission system. This is because the forces on the gear teeth could not be ascertained and thus the strongest available material was used. The steel gears that were used have sharp teeth, which makes meshing more difficult. Gears made from a softer material might have more rounded teeth, which would make them less sensitive to imperfections in the torque transmission system. To investigate whether it is possible to use another material, an analysis of the forces would have to be done. This was not done during the thesis as it is quite a difficult task and would have taken up too much time. However, gears made from another material, e.g. POM, could have been tested at first, instead of steel gears. This experimental approach would have been the easiest and would have given a clear result. With the current design of the hand it is however difficult to disassemble the torque transmission system once it is assembled. Thus, if the gears failed it might be necessary to rebuild the entire hand.

The module of the gears is very small, 0.3, which makes the shaft distance very short. This makes it more sensitive to differences in shaft distances, as the relative difference is larger. If a larger module, e.g. 0.5, could be used, it would be easier to assemble the torque transmission system. With a more forgiving assembly procedure, the internal friction in the system might be reduced and thus improving efficiency and reducing the forces on the gears.

7.5 Teething the driving link

Because of the problem with fitting the fingers on the shaft, one solution could be to have gear teeth directly on the fingers. Instead of trying to fix a gear or shaft to the driving link, it could itself be teethed. This would remove the issue of fitting the gear or shaft to the link altogether, which would be beneficial. This would of course put higher requirements on the material and manufacture technique of the fingers. It would also make the drawing of them in CAD a bit more difficult; the teeth must be quite exact to fit with the other gears.

If achieved the result would likely be better than in the current prototype. It would be easier to assemble. It would also be less sensitive to shafts that are not perfectly aligned. The design of the torque transmission system would also be easier as it would eliminate a few gears.

7.6 Tougher material

Since the hand will be exposed to impacts and a strenuous environment, it is important that the material is tough. If plastic is used, it would preferably need to be glass fibre reinforced; the problem with fibre reinforced plastic is to find an acceptable manufacture technique. Some of the material, namely the Rigid Resin was far to brittle, breaking by just being dropped from a table. Another alternative is to use aluminium, in which case durability would not be a problem; but weight and manufacturing probably will.

7.7 Using springs for a passive adaptive grip

In the hand, springs are used in the DIP joint to allow for passive adaptability to a gripped object. This was realised with a high degree of success and indeed the tips of the fingers will now bend in response to force applied to them, whilst pushing back against the object applying the force and resetting their position once the force is removed. As far as can be asserted, it seems that this solution could be beneficial, and it does not seem to weaken the finger. However, the impact this has on the grip of the hand has not been evaluated to any significant degree. The reason being that the prototype has such problems with build quality that it is not very functional. It should however be included and tested should a second prototype be made.

7.8 Finger robustness

Because of the problems with assembling the hand it is hard to say if the design of the fingers achieves the intended goals. The fingers are less sturdy than intended, but that is mainly a result of the bad fit between shaft, fingers and hand. The spring at the DIP joint could also make the hand less sturdy, but it is hard to tell without fully testing the hand; potentially the spring is a bit weaker that intended. Considering the circumstances, the design of the fingers is probably robust enough to handle most situations, if properly produced.

Another problem is evaluating the link that controls the PIP joint, the bending link. From the analysis made with Ansys, only the bending link needs to be made of metal for the purpose of lifting and gripping. But since it was made of plastic, no conclusion can be made whether plastic for the rest of the fingers is enough. Even if it would have been made from metal, the grip could still not be fully tested because of the problems with the prototype. Another problem with the grip is that the bending link is not thin enough, resulting in the finger only bending about half the way.

This could be solved by either making the fingers wider or make the bending link thinner. The problem with making the bending link thinner, is that it could then break more easily during heavier loads. As a result, the best solution is to make the fingers, specifically the middle and index finger, a bit wider.

8 Conclusion

This thesis investigated the functionality, and lack of functionality, in modern prosthetic hands and what further functionality people that use prosthetic hands would like to see in them. This was used as a starting point for developing and building a prosthetic hand. It can be said that for existing functionality, the main line is drawn between dexterity, i.e. the ability to move fingers independently and form different grips, and robustness and strength. One of the most common prosthetic hands is Otto Bock's VariPlus Speed. This hand only offers the tripod grip, a palmar prehension grip, but is on the other hand robust enough to use while, for example, riding a mountain bike. On the other hand, there are some research hands that have a higher degree of dexterity but are too weak for anything but lighter everyday use. What the user wants is essentially a robust hand that looks like a real hand, at least at a passing glance. It could also be dexterous, but this is a second concern as most users utilise their remaining natural hand for complicated task, e.g. writing.

From this, it was decided to attempt to design a hand that is more dexterous in the respect that it can move the index finger independently of the rest of the fingers and adduct and abduct the thumb whilst still being robust. A second concern that came up was that many hands are designed with the hand of a man in mind. Thus, they are often too big for women and children. Therefore, it was also decided to try to design the hand with the hand size of a Korean woman as a reference, as this was data for small hands that was found. The point being that it is much easier to enlarge a small hand than it is to reduce the size of a large hand.

The result of the development and consequent construction of the hand was not great, there were many problems with the prototype. However, these are viewed as being mostly due to an imperfect construction of the prototype. Given better manufacturing of the parts and better techniques during assembly, the design should work. This being said, there are design choices that should be reviewed, these are listed as future work. The current prototype is a first step. It shows that developing a fairly dexterous prosthetic hand that is small enough to be a better fit women and children better, with the potential to be robust, is possible. It could be worked on further to create a second prototype that, with better build quality, would be more robust.

9 Future work on prototype

The focus for future work is firstly to make a fully functional prosthesis. This way the design can be properly evaluated, making it possible to correct and improve the design.

What follows is several areas which either needs to be improved.

- **Machined hand frame**
  A machined hand frame could, as previously stated, heighten the accuracy of the hand frame and reduce friction in the torque transmission system.

- **Analysis of gear forces to establish necessary material**
  As the exact forces on the gears were not known, the strongest available material, steel, was used for the gears. It might be cheaper and easier to get a correct fit if it could be established that another material could be used, such as brass or POM.

- **Make sure the fingers can bend all the way without the links interfering with the gears**
  As it is now, the links that make the PIP joint bend as the MP joint bends collide with the gear that is driving the finger at a certain point. This prevents the finger from flexing fully. This is a problem for the index and long finger. Having a larger slot into which these links should fit next to the gear would be necessary to allow full flexion.

- **Attach the gears and fingers to the shaft in a way that enables them to be removed while also not slipping**
  Because of the problems with fixing the gears and fingers to the shafts another method is needed. The best way would probably be to fix them with a pin or a wedge. This way the gears can be placed in the right position before being fixed. There is also room for errors since the wedge or pin can be removed if needed. It would also make sure that the gears would not slip even during heavy loads.

- **Size of the hand and thumb module**
  The hand is currently a little longer in comparison to the data that was used to determine what size it should be. This was necessary to fit the motors into the hand. However, to be as lifelike as possible the hand should be shortened. The thumb attachment module should also be made smaller, primarily in width and height, but also in length.

- **Size of gears**
  The module and size of the gears should be looked over. It is possible that a larger module could be used.

- **Test teethed driving links**
  Try out making the driving links teethed to allow them to directly couple to the torque transmission system.

- **Tougher material**
  A prototype in a tougher material should be made as the plastic was too weak in some places.

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Appendix A: Interview on the use of prosthetic hands, Ulrika Wijk

What is the most common type of prosthesis people want, and why?
Ottobock Myo VariPlus Speed with a three-point grip or similar, or just a cosmetic motionless prosthesis. Advanced models are too weak; they are not robust enough to take every day wear. They are also expensive and takes a lot of practice to use.

How important are looks, is it better with a more aesthetically correct hand with low functionality or a less aesthetically correct hand with higher functionality?
Appearance is important and usually more important than people first let on. People born without one hand do not have as large an issue with a less lifelike hand. For children, it is more important that is fun, since it is not a hand it does not have to look like one either.

What do people usually feel is missing in available prostheses, and what complaint are there?
The weight is centred too far to the front. The sleeve gets warm and sweaty. The grip is too small. Advanced prostheses are too weak but give a good grip.

What improvements do you think would most important to make in prostheses?
A better grip and a better distribution of the weight.

Where are people usually amputated?
People born without a hand usually retain about one third of the forearm. For others the position of the amputation is random.

How long should a prosthesis last?
A few years. It is usually declining battery time that causes the prosthesis to be replaced.

Is there a benefit to placing the motors in the wrist?
Would give a better weight distribution. There would still be a fair number of people that could use it.

Is an electrically adjustable thumb a good idea?
It might be good; however, all delay is bad (writers remark: electrical adjustments entail delays, due to signal travel time and motor speed etc.). It is very important that the hand is fast, delays can quickly become wearisome.

What is most lacking in the grip?
Conformability of the grip. The Myo VariPlus Speed only has a small three-point grip. At the same time, it must be strong enough.

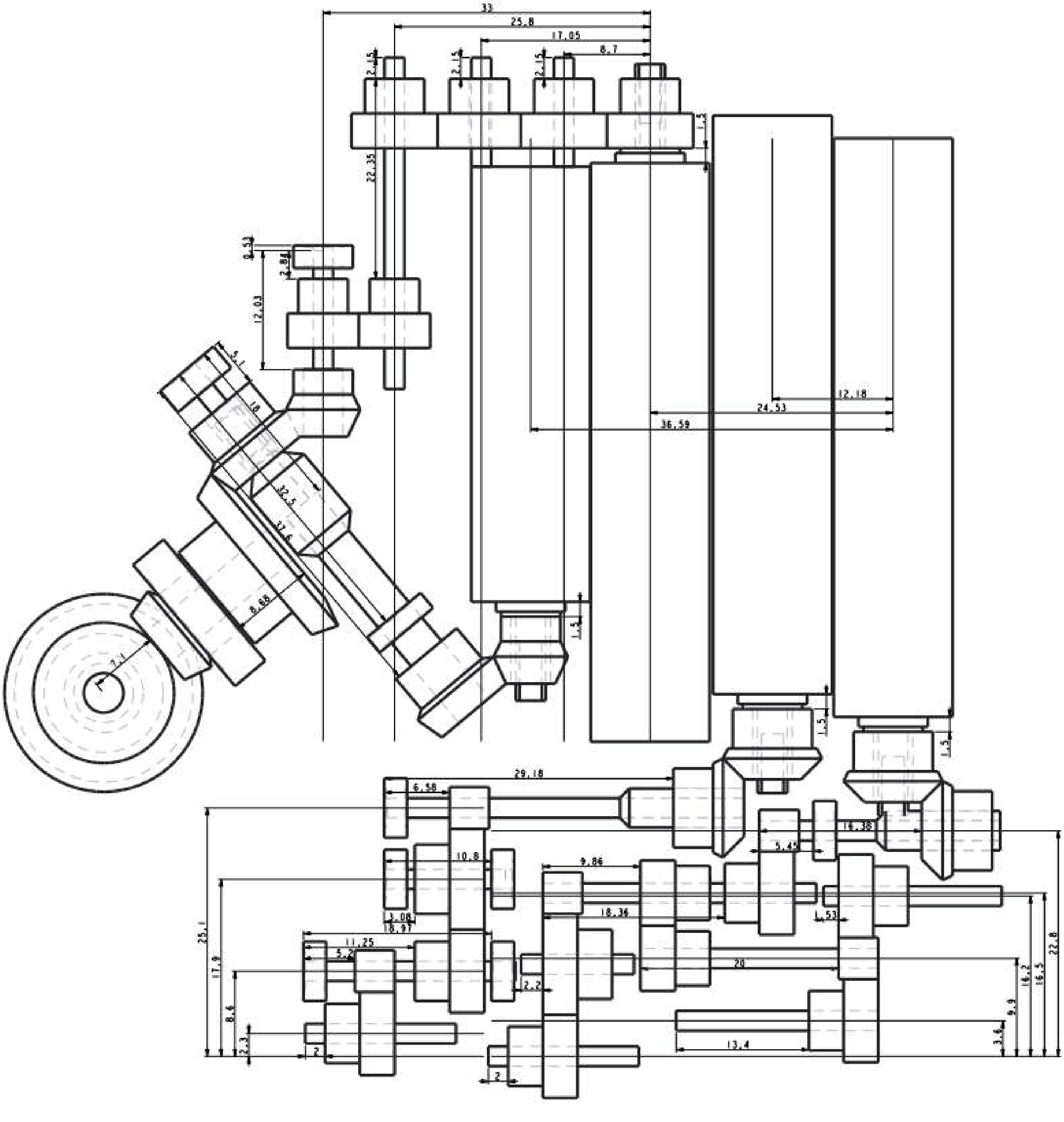
Other remarks
With large objects, contact area is not a large issue. The problem is rather when trying to get a grip on a small object.

The prosthesis is usually used as a supportive hand; it is not used for complex tasks when one biological hand remains.

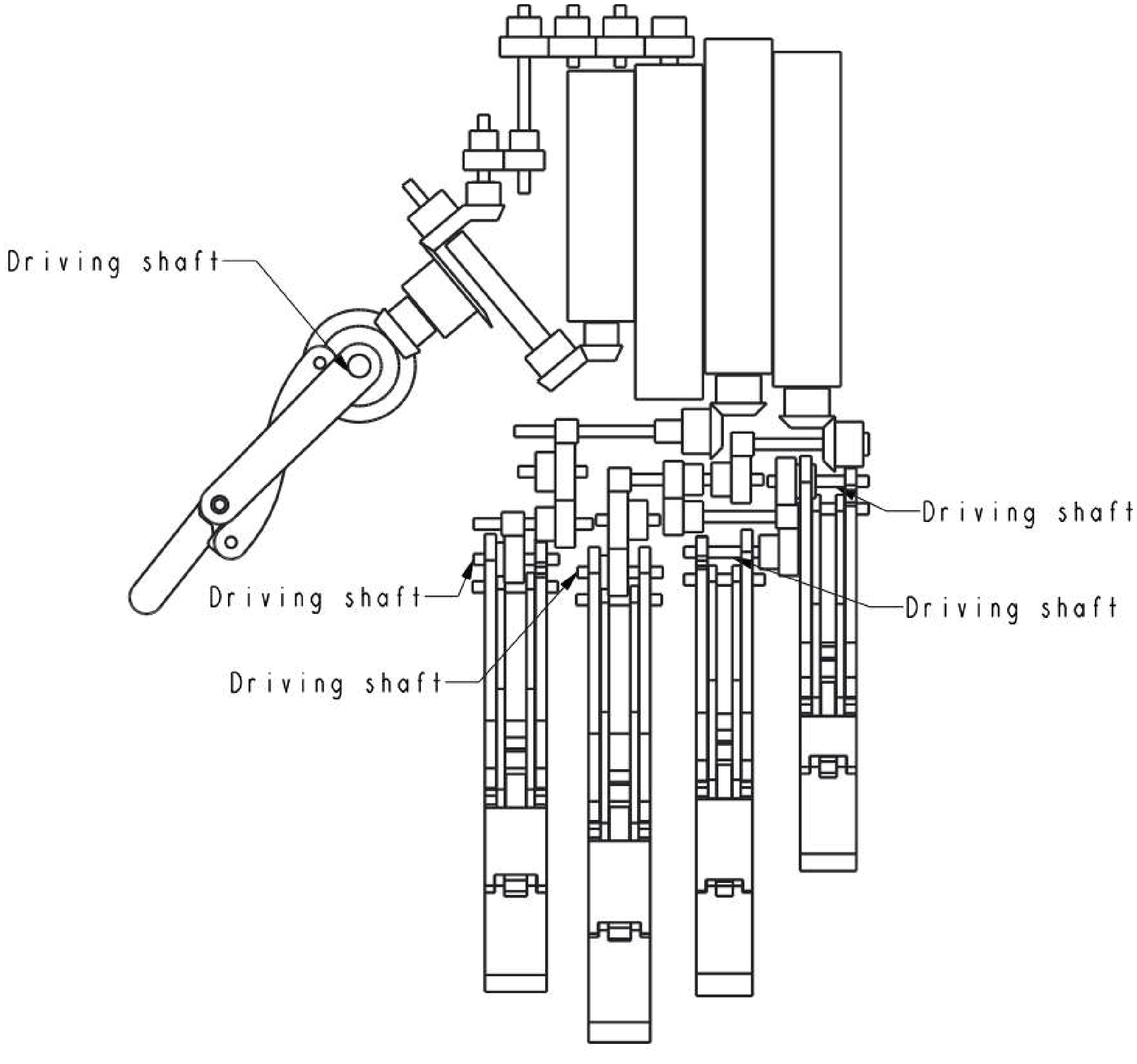
The grip is initiated in the fingertips

Stability is more important than dexterity.

Appendix B1: Drawing of torque transmission system



Appendix B2: Drawing of torque transmission system



Appendix C: List of the gears in the torque transmission system

Thumb								
Pair	1	2	3	4	5	6	7	Total ratio
Gear	1-2	2-3	3-4	5-6	7-8	8-9	10-11	
Ratio	1	0.96551724	1.03571429	1	1.3333	2	2	5.3333333
Gear	No. Teeth	Art.No	Gear type No.					
1	29	RBSS0329	1					
2	29	RBSS0329	1					
3	28	SRS0328	2					
4	29	RBSS0329	1					
5	24	SRS0324	3					
6	24	SRS0324	3					
7	15	360276	4					
8	20	360260	5					
9	40	360261	6					
10	20	360260	5					
11	40	360261	6					

Index					
Pair	1	2	3	4	Total ratio
Gear	1-2	3-4	4-5	2	
Ratio	1	2.42857143	0.82352941	2	4
Gear	No. Teeth	Art.No.	Gear type No.		
1	20	360211	7		
2	20	360211	7		
3	14	RS20314	8		
4	34	SRS0334	9		
5	28	SRS0328	2		
6	14	RS20314	8		
7	28	SRS0328	2		

Long ring little joint shaft			
Pair	1	2	Total ratio
Gear	1-2	3-4	
Ratio	1	2	2
Gear	No. Teeth	Art.No	Gear type No.
1	20	360211	7
2	20	360211	7
3	14	RS20314	8
4	28	SRS0328	2

Ring little joint shaft				
Ring				
Pair	1	2		Total ratio
Gear	1-2	3-4		
Ratio	1	2		2
Little				
Pair	1	2		Total ratio
Gear	1-2	3-5		
Ratio	1	2		2
Gear	No. Teeth	Art.No	Gear type No.	
1	22	SRS0322	10	
2	22	SRS0322	10	
3	14	RS20314	8	
4	28	SRS0328	2	
5	28	SRS0328	2	

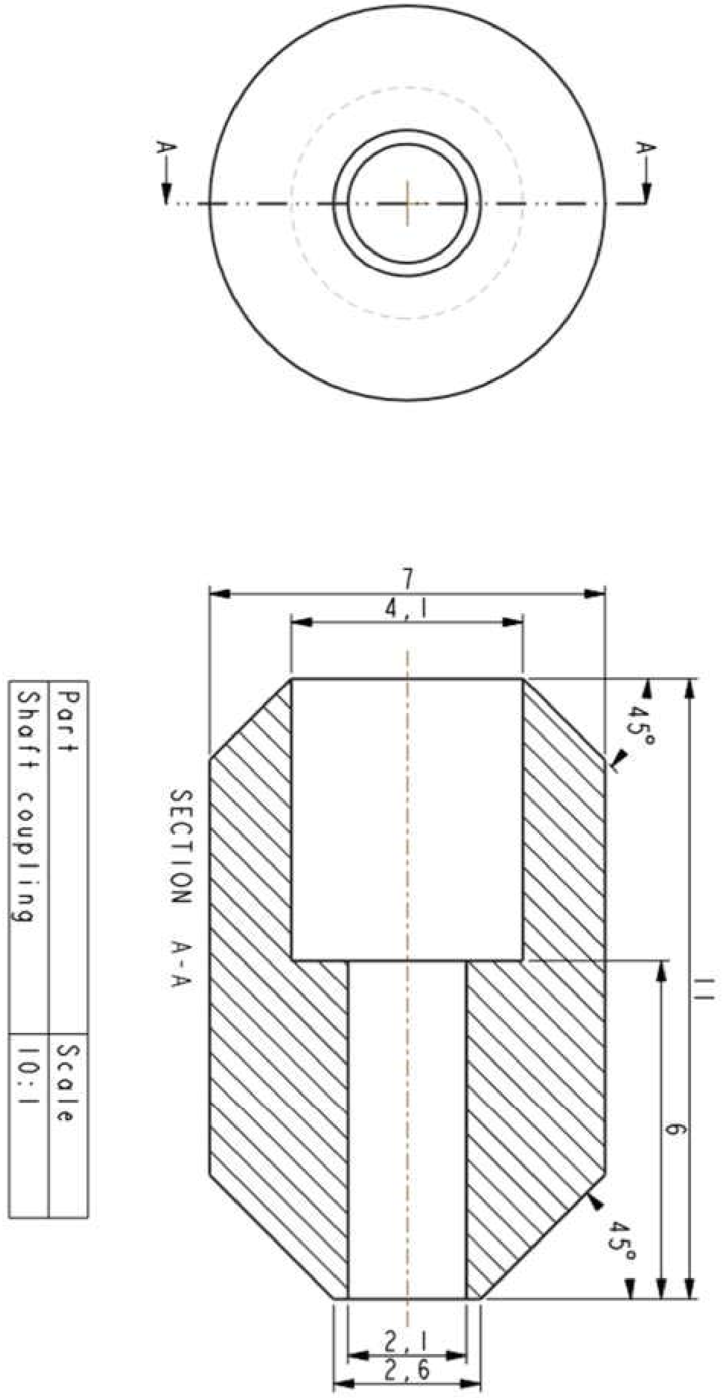
Long				
Pair	1	2		Total ratio
Gear	1-2	2-3		
Ratio	2.4285714	0.82352941		2
Gear	No. Teeth	Art.No.	Gear type No.	
1	14	RS20314	8	
2	34	SRS0334	9	
3	28	SRS0328	2	

Thumb add/abduction				
Pair	1			Total ratio
Gear	1-2			
Ratio	1.3333333			1.3333333
Gear	No. Teeth	Art.No.	Gear type No.	
1	15	360276	4	
2	20	300260	5	

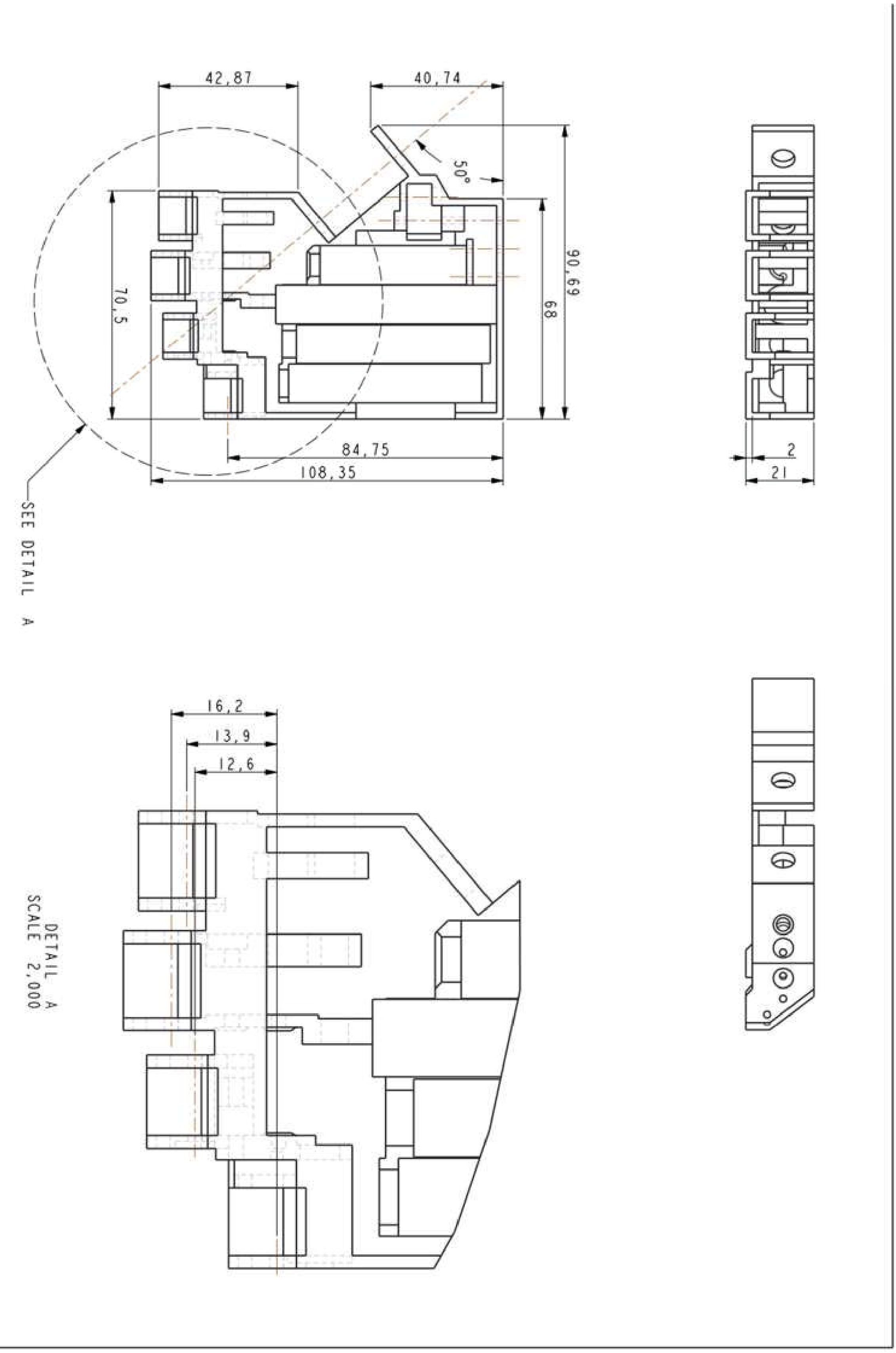
Gear type No.	Art.No	Amount	No. Teeth	Pitch diameter	Pitch radius	Outer diameter	Width
1	RBS0329	3	29	8.7	4.35	9.3	7
2	SRS0328	7	28	8.4	4.2	9	7
3	SRS0324	2	24	7.2	3.6	7.8	7
4	360276	2	15	7.5	3.75	8.8	7
5	360260	3	20	10	5	11.2	7.5
6	360261	2	40	20	10	20.3	8.4
7	360211	4	20	10	5	10.7	7
8	RS20314	5	14	4.2	2.1	4.8	4
9	SRS0334	2	34	10.2	5.1	10.8	7
10	SRS0322	2	22	6.6	3.3	7.2	7
	No. Gears	32					

Gear type No.	Teeth width	Base diameter	Hole diameter	Module	Angle	Cad angle	Price (€)	Total price (€)
1	3.5	6	2	0.3	N/A	N/A	2.9	8.7
2	3.5	6	2	0.3	N/A	N/A	2.9	20.3
3	3.5	5	2	0.3	N/A	N/A	2.9	5.8
4	3	6	4	0.5	25	65	12.2	24.4
5	3	8	4	0.5	15	75	11.9	35.7
6	3	12	4	0.5	75	15	12.1	24.2
7	3	8	4	0.5	45	45	10.9	43.6
8	4	N/A	2	0.3	N/A	N/A	3	15
9	3.5	7	2	0.3	N/A	N/A	3	6
10	3.5	5.5	2	0.3	N/A	N/A	2.9	5.8
								189.5

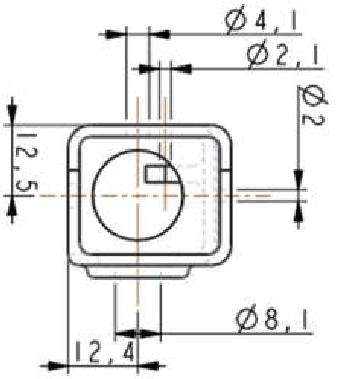
Appendix D: Drawing of the shaft coupling

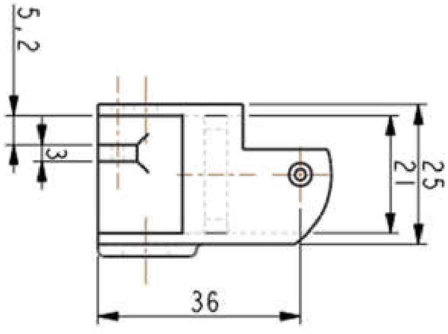


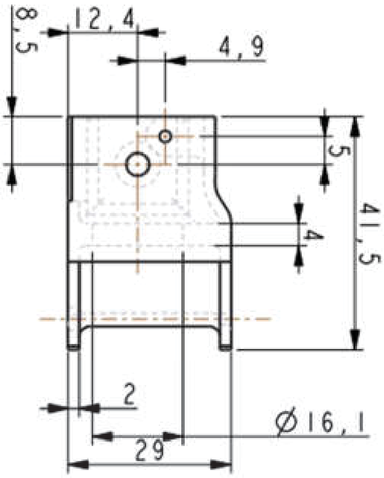
Appendix E: Drawing of the hand frame



Appendix F: Drawing of the thumb attachment module

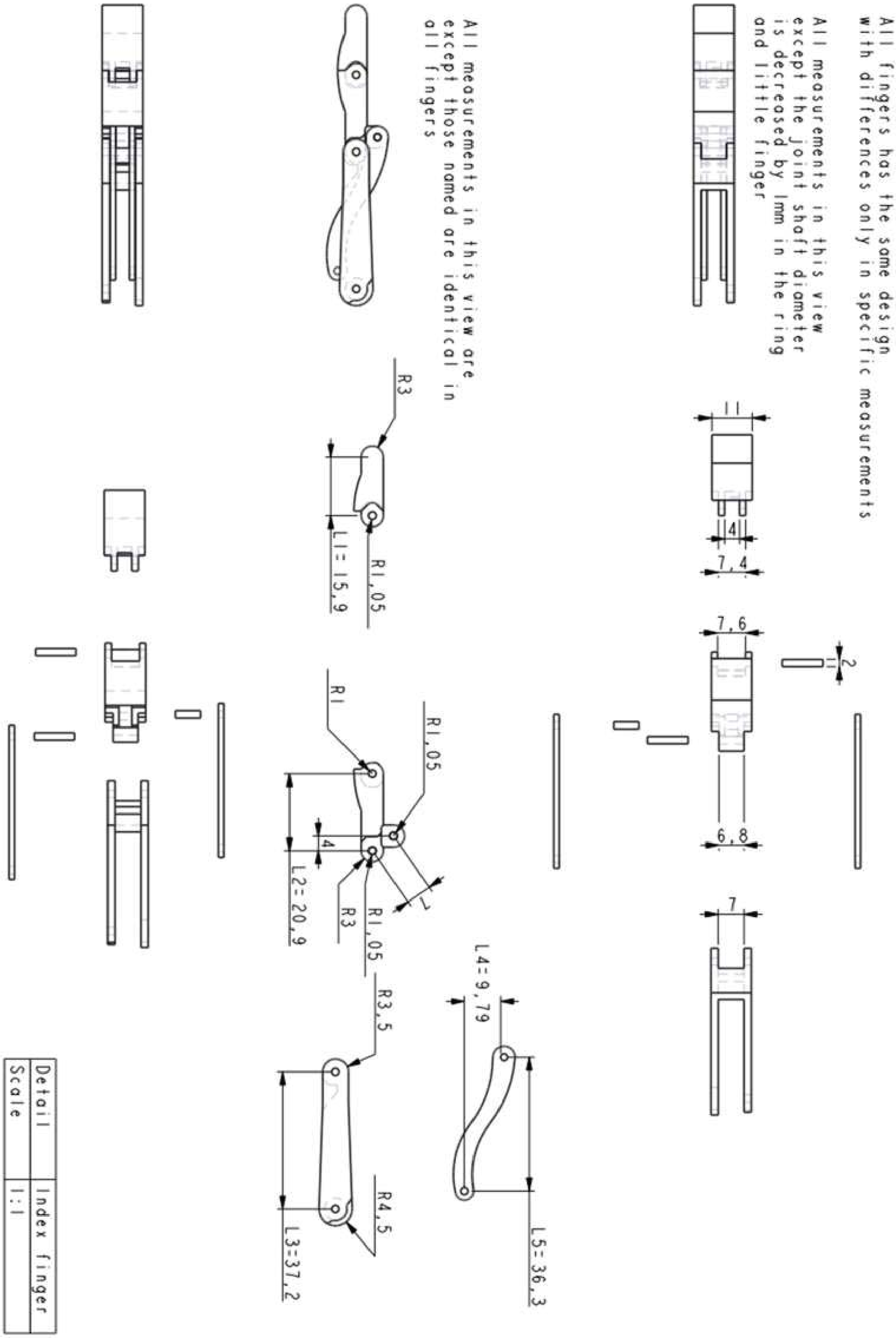






SCALE	PART
1:1	THUMB ATTACHMENT MODULE

Appendix G: Drawing of the index finger



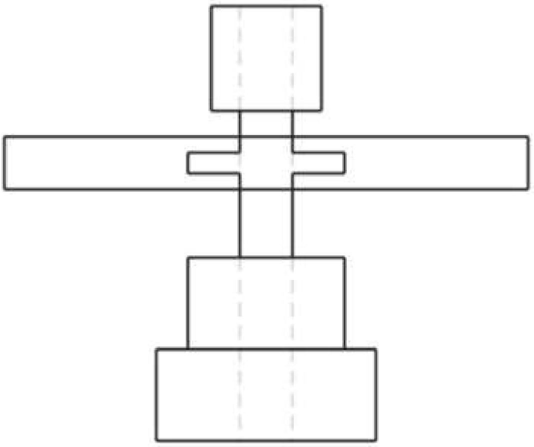
All measurements in this view are except those named are identical in all fingers

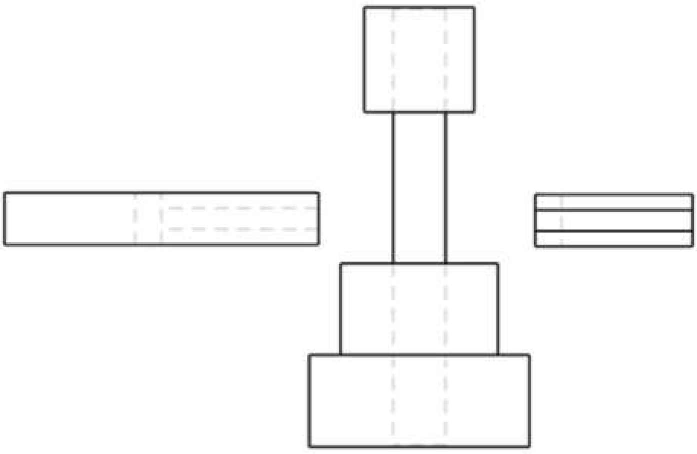
All fingers has the same design with differences only in specific measurements

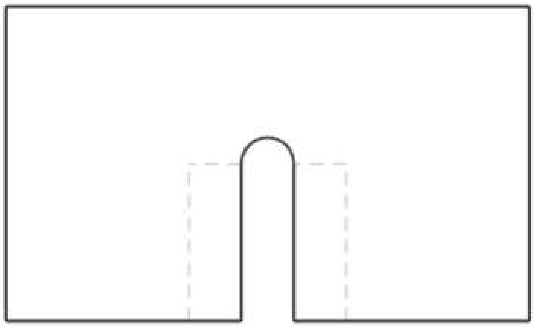
All measurements in this view except the joint shaft diameter is decreased by 1mm in the ring and little finger

Detail	Index finger
Scale	1:1

Appendix H: Solution removable shaft placement







Example for placeing shaft in the hole after fitting the gears using a slit with a closing piece to allow the placement in the hand frame