The design of the PLYOS prehensor

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Abstract

Nowadays forearm prosthesis are far from optimal, factors that need to be optimized are the mass, the price and the wear temperature of the prosthesis. This can be done by choosing cardboard as constructive material. In this report the relevant control mechanisms are investigated. A body powered prosthesis voluntary closing control is chosen as the activation mechanism. This mechanism has a new feature called passive closing. This feature enables the user to grip objects with different grasp forces without exerting force with a harness. The created PLYOS prehensor can perform five prehension patterns. The voluntary closing behavior of the prosthesis can be compared with the high end available prostheses, while being at least 30% lighter than the competition. The generated pinch force of 15 N is generated with an actuation force of 35.5 N. The plyos prehensor is also tested to lift 10 kg and it is able to do 20.000 cycles of gripping (activation force 60 N) and lifting (15 N). The wet strength of the prosthesis is good, it does not jam when it is wet, while it stays strong.

1 Introduction

1.1 Relevance

When a person is born without an arm or when a person loses his arm in trauma he lacks the ability to grasp objects with this side. It is estimated that 0.5 percent of the world population could benefit of the use of an orthopedic device.[1]With the current world population this means that 34.5 million people are in this situation. Of these people, 27.5 million people live on less than 10 dollar a day. Of these people it is estimated that 2 million people have a major upper extremity amputation [2]. These people have difficulties supporting themselves, because their work abilities are impaired and they need aid. Unfortunately this aid is hard to give. The options that are available are too expensive and require too much training to aid these people. The cost of a prosthesis is therefore a high barrier to get a prosthesis.[3] Even people in developed countries without good health insurance cannot afford a prosthesis [4]. Next to the high cost of a prosthetic device there are two main problems. One of these problems is the weight of the prosthesis. The prosthesis weight is amplified because of torque compensation. This mechanism amplifies the weight of the prosthesis on the top of the stump by a factor of approximately 3 (Figure 1. The third main issue is wear temperature. Most of the time the weather in developing countries is hot and humid. This causes another problem: skin irritation because of sweat. These are the main reasons why 40-60% [5] of the upper extremity (UE) prosthetic users do not use their device for Activities of Daily Living (ADL). Also 20-40% of people with a prosthetic device do not wear it at all. Therefore a new approach is made on encountering the most important flaws in the current prosthetic designs. Therefore the Delft Institute of Prosthetics and Orthotics (DIPO) is investigating whether cardboard can be used as a constructive material in a forearm prosthesis. Cardboard is known to have a low price, which lower the cost of the prosthesis. Next to this good property, the specific strength of cardboard is also high compared to known plastics like PU. Recently a cardboard splint is developed, one of its strengths is the skin interaction [6]. Therefore cardboard can be a solution to the problems stated above.

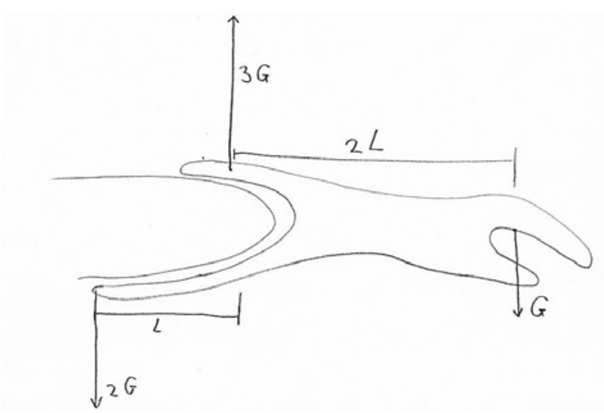

Figure 1: Weight amplification in transradial prostheses

1.2 Previous cardboard design

Prior to this research a proof of concept is given. In February 2009 a design of a paperboard hook prosthesis was made [7]. In this design the basic cosmetic demands are investigated and a basic construction is made. This is the start of this research, from this start different aspects like material choice, construction method, actuation and gripping are optimized.

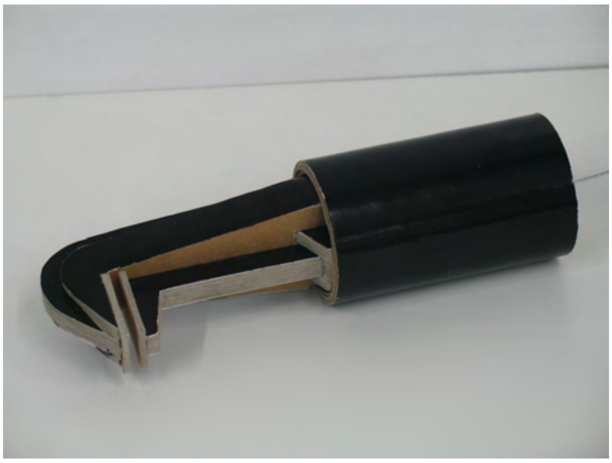

Figure 2: Previous cardboard prosthetic hook design

The first prototype of a cardboard prosthesis is shown in figure 2 . This prosthesis is a voluntary closing hook prosthesis. It is tested to be able to pull with a force of 450 N, push with a force of 490 N and lift a force of 294 N. This can be done with a prosthesis with a cost price of €4.5. Also the prosthesis weighs only 145 gram, which is a weight reduction of 10%, compared to existing prostheses.

The prosthesis has a rotating wrist to place the hook in the right position. The hook is however rather small and is not able to make a form closed grip.

1.3 Current prostheses

To understand the current approach for creating prostheses an overview of types of devices that are currently on the market is given. While doing this, it is also compared whether cardboard can function as a constructive material in these prostheses.
UE prostheses that are currently on the market can be subdivided into two main designs: passive or active prostheses. In the active prostheses there are again two subdivisions: myo-electric and body-powered devices.

1.3.1 Passive prostheses

Passive prostheses are not only used as a cosmetic device.[8] These prostheses look a lot like a natural hand, but are not capable of gripping an object. Therefore they are mostly used when no actuation of the prosthesis is needed. Examples for situations are walking, going out or carrying. Because there is no mechanism to move digits, this type of prostheses is mostly light compared to the active prostheses.
Because of the image of cardboard, it is not suitable as a cosmetic prosthesis. Traumatized persons will opt for the most realistic looking prostheses. Functionality is not their first priority, they will have to come to terms with their loss first. Therefore the target group will be people who are experienced with prostheses. They know the cons of a cosmetic passive prosthesis and therefore also want more dexterity in their prosthesis.

1.3.2 Active prostheses

Active prostheses are prostheses that can be used to grip objects. This requires a mechanism to move the digits and an activation of these mechanisms. In myo-electric devices the activation signals are provided by surface electromyography (EMG) of muscles that are left in the stump. The patient learns to activate these muscles, this signal is now collected by electrodes on the skin. EMG signals can be used to activate a motor, which moves the digits. The motor needs a battery, so the total weight of the prosthesis is relatively high.[4]
Nowadays the myo-electric hands are most likely to become the favorite. Mostly because of their natural appearance. But there are a lot of downsides to these prostheses. They do not have proprioceptive feedback while gripping an object.[9] This makes the control of the device more difficult. Because proprioceptive feedback is quicker than e.g. visual or auditive feedback. They also are very expensive [2,4], therefore people without insurance or money cannot afford these prostheses. Because of electric motors and batteries used they are also heavy and people cannot use the prosthesis throughout the whole day. On top of that,

myoelectric prostheses are very vulnerable to water and dirt.
The most positive points of cardboard are its density and its cost. These properties of cardboard are exactly the opposite of what myo-electric prosthesis are. Myo-electric prostheses aim to be high-end, while the cardboard prostheses will be created for people without a lot of money (see previous chapter). Therefore cardboard is also not suitable to use in a myo-electric prosthesis.

In a body powered prosthesis the actuation is mostly provided by muscles in the shoulder. This saves a lot of weight, because no motor or battery is needed. Therefore body powered prosthesis are still a good competitor in the upper extremity prosthesis.

When the properties of body powered prostheses are compared to the possible optimizations cardboard can provide, body powered prostheses look like the right candidate to have a cardboard basis. Most people with a body powered prosthesis don't look for a particularly good looking prosthesis, but a dexterous one. Because cardboard is cheap, the people of interest are also people with low income, so the appearance is not the most important factor. Because a body powered prosthesis is lighter than a myo-electric prosthesis the use of cardboard in this prosthesis makes this advantage extra good. A cardboard prosthesis can open up the market for developing countries because of its good price, its ease of transport and its simplicity.

Figure 3: (a) The LN-4 hand (Ellen Meadows Foundation)and (b) CZ Biomed SPT interfaces

Figure 4: V2P prehensor with I-TAL socket

1.3.3 Affordable prostheses

There are some more affordable prostheses available. Examples are the I-TAL V2P prosthesis, the LN 4 and the SPT interfaces of CZ Biomed.[2] (figure 3)

The I-TAL V2P prostheses seems the most durable one has the production costs of $250,-. The V2P has an interesting approach, it is a voluntary opening prosthesis with several positions of one point of the spring. Every position creates a different pinch force. This makes it able to hold solid heavy objects as well as soft fragile objects. It has a weight of 170 gram.[2] The LN-4 costs around $50 and it can be operated with the healthy hand. Objects can be gripped, by pushing the digits around an object with the healthy hand. The digits lock around the object and can be unlocked by pushing a lever. This hand is funded and over 7500 prostheses are given away in 56 different countries.[10]

The SPT prosthesis is a full prosthesis, which can be operated with a shoulder harness and it is voluntary opening. It costs around $595,-.[2]

Especially the socket is a problem, because it is an expensive process to create a tight fit with the residual limb. A lot of knowledge, equipment and material is needed to create the right socket. Therefore a universal socket is present in all these prosthesis. This reduces the amount of time needed to create a sufficiently tight fit.

So in the world of cheap affordable

prostheses, there is no voluntary closing prosthesis. All have a universal socket, the cheapest prosthesis is the LN-4, which is a passive prosthesis.

2 Cardboard in prostheses

Cardboard has shown to have good properties to counteract the problems stated in the introduction. It is proven that cardboard can be used as a lightweight constructive element in architecture [11]. Cardboard has also already been used to construct furniture, desks, beds, boats and even a bicycle.[12] Cardboard has some very interesting characteristics. The strengths are its recyclability, its density and its good price. But the downsides are also very well known: when cardboard is wet its strength is impaired. Also its tensile strength is lower than common used materials, such as plastics like Polyurethane and metals like Aluminum. However looking at the specific strength shows cardboard has a good ratio, because of its low density. With a higher specific strength, weight reduction is possible. So when a prosthesis is made out of cardboard, it can be made light. Because of the good price, it is also possible to create a prosthesis at low cost. This enables people with low income to get a prosthesis.

Next to these good points of cardboard, there are still some questions to be answered on how well cardboard will perform as construction material for a transradial prosthesis. In the previous design no specific material selection is made, therefore a literature study is done to provide insight in the characteristics of cardboard. In the end of the paragraph a type of cardboard is selected to use in the design of the prosthesis.

2.1 General material properties of cardboard

Cardboard is paper with a grammage of 150g/m^2 [13]. It is made out of cellulose fibers. Because of this basic ingredient it has several important features. First of all, cellulose is the most present substance on earth, it can easily be extracted from wood. So cardboard can be made anywhere on earth.

Cardboard is produced in layers, every layer consists of cellulose fibers which are aligned in the same direction, this is called the machine direction (MD). The direction perpendicular on the machine direction, but in the plane is called the cross direction (CD). The last direction is perpendicular on both the machine and cross direction and is called the transverse direction (ZD).[1]7

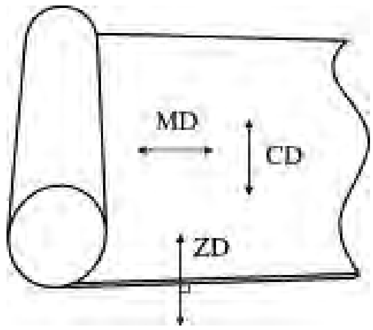

Figure 5: Directions in cardboard

By adding a lot of water in the first stage of the production, the fibers are aligned and are stacked close to each other. When the water is drained from the cardboard the cellulose fibers connect with each other through hydrogen bonds.[14] These bonds stay strong when there is no contact with water. But cardboard is hygroscopic, this means it attracts water when its near. When cardboard comes into contact with water, the hydrogen bonds between the fibers are replaced with hydrogen bonds between the fiber and water. This means cardboard loses its integrity. The humidity resistance increases with longer fibers and thicker plies. When fibers attract water they swell up. This happens mostly in the CD and ZD, so the MD is the most stable direction.

Another aspect of cellulose fibers is that it makes cardboard anisotropic. This means that the direction the fibers are aligned in is the strongest. This is an important factor in the design of the prosthesis. Cardboard is the strongest when fresh fibers are used, so recycled fibers are less strong.[15]

2.2 Material selection

From the introduction it has become clear that cardboard looks promising as an alternative constructive material for prostheses. But there are many types of cardboard structures. The structures can be subdivided in three main structures: solid, corrugated and honeycomb structured. All three types have their own pros and cons. In these structures there are also subdivisions. So a literature study has been done to select the most suitable type of cardboard. The selected cardboard has to have:

- a good specific strength
- high Young's modulus
- good humidity resistance
- good recyclability
- nice appearance
- pleasant skin interaction
- decent lifespan

From this literature study it became clear that the most suitable cardboard for a forearm prosthesis is solid cardboard. All types of cardboard can be made recycle and keep good properties, of these properties, solid cardboard gives the best results.[16] It has a high specific strength, and a good puncture resistance, which increases the lifespan of the prosthesis. Because it is solid, it is also less susceptible to humidity. Solid cardboard is also used the most in applications which require a nice appearance. These abilities favored solid cardboard above the other types of board. In this study commercially available cardboard was also investigated. Two materials looked promising, cardboard called Fix2Move which is used in splint and cardboard which is used in a birdhouse. The splint is especially selected for its good skin interaction, its good recyclability, its nice appearance and its humidity resistance. It has been proven that this material keeps enough strength to stabilise a broken bone while wet.[6] The birdhouse cardboard was claimed to be stronger than the Fix2Move cardboard and it can also withstand extreme weather conditions. These materials looked feasible for use in a prosthesis. Both materials are made without added resins, which makes them recyclable. So both materials seem to meet the demands for use in a cardboard prosthesis. But data about strength was not available. Therefore both materials had to be tested.

3 Body powered control

In the introduction it is explained that the most suitable type of actuation is body powered control (BPC). In this paragraph BPC is further explained. The methods, possibilities and limits of this type of control are described.

3.1 Actuation types

A BP prosthesis uses the human body as an actuator, for people with a trans radial arm defect there are several options to actuate the prosthesis. There are two main options, the most common used is shoulder actuation, the other is elbow actuation.[9] Shoulder actuation is performed with a shoulder harness. This harness can be worn in several ways, but the basic working principle is in every situation the same. A bowden cable is used to create a displacement. The outer sheet of this cable is connected on one shoulder, while the inner cable is placed on the other shoulder.[17] When the shoulders move away from each other a displacement and a force is exerted to the cable. With elbow control exertion of the cable is caused by extension and flexion of the elbow.

3.2 Voluntary opening or closing

Both mechanisms described above can exert a force in one direction, so a spring is needed to place the moving digit in the resting position. So there are two options to actuate a BP prosthesis, voluntary closing (VC) and voluntary opening (VO). Both mechanisms are used in current prostheses, below both types of control are discussed.

3.2.1 Voluntary closing

This displacement and force create the actuation of the digit in the terminal device. In this way a human can provide a force of maximal 40 N [18] and a displacement of 53 +/- 10 mm [19]. It is also examined that the maximal required pinch force is 34 N [20]. With these boundaries in mind DIPO has tested five commercially available voluntary closing

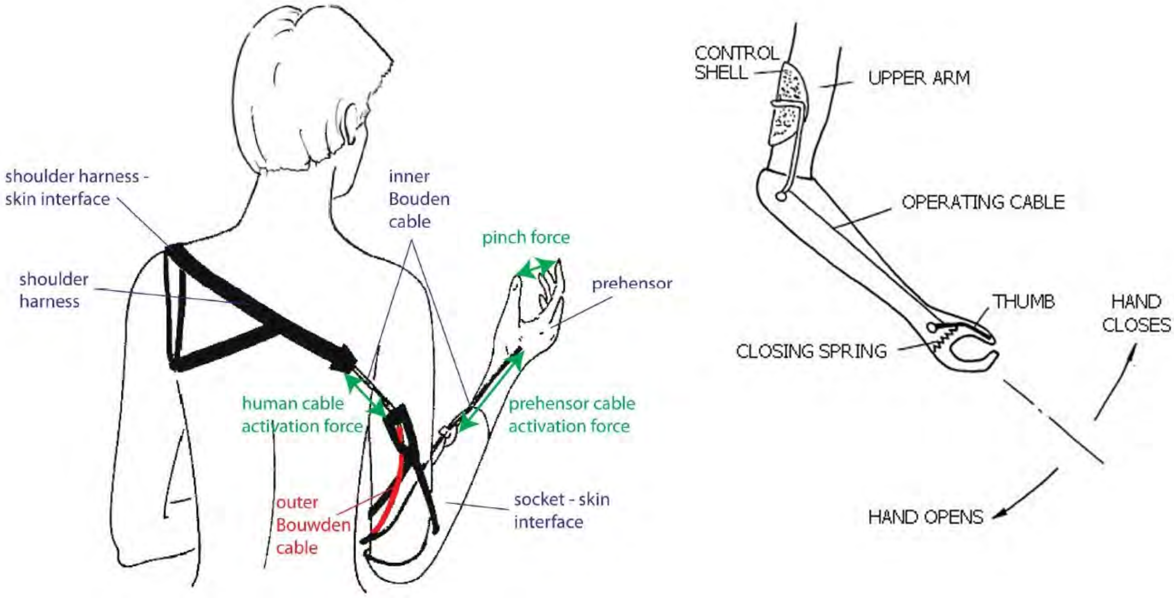

Figure 6: Shoulder actuation (left) and elbow control(right)

prostheses.[21] This research showed that only one prosthesis approaches the demands for usability. This device is the TRS hook, it needs a cable force of approximately 65 N to provide this force. The efficiency of the bowden cable causes another 20-40% increase of force at the shoulder muscles. Most people cannot reach this force, so this is a major flaw in the design of voluntary closing prostheses.

Figure 7: TRS prehensor

Exerting high forces decreases the comfort of wearing the prosthesis. So current VO prostheses are not comfortable. Another aspect of comfortability is the time a force needs to be exerted. When an object is gripped with a VC prostheses, an actuation force is needed to hold the object. When an object is held for a long time fatigue of the shoulders occurs. This is another downside of VC prostheses. To account for this problem lock mechanisms are introduced. Lock mechanisms are used to hold an object without exerting force or to keep the hand closed while not being used. This provides some advantages for donning and doffing, appearance (looks natural in resting position) and fatigue. Unfortunately current prosthesis lose on average 9.45 N of pinch force during the transition of active gripping to gripping by the lock mechanism.[2]1 This might cause an object to fall due to too little grip force. The TRS hook is a simple hook without a locking mechanism. A locking pin is available to keep the prehensor closed.

On top of the discomfort of too high actuation forces or the lack of a good working locking mechanism current VC prostheses are heavy. The average weight of the investigated prostheses is 340.4 g (min 248 g, max 423 g).[2]1 This is relatively high compared to the light V2P prehensor of 170 g.

3.2.2 Voluntary opening

As explained in the previous paragraph VC prosthesis require high actuation forces and cause fatigue while holding an object. Also their hand is open in the resting position, which does not look good. To counteract these problems VO prostheses are used. These prostheses do not require an actuation force to grip objects. Therefore holding an object is easier to do, no actuation force is required,

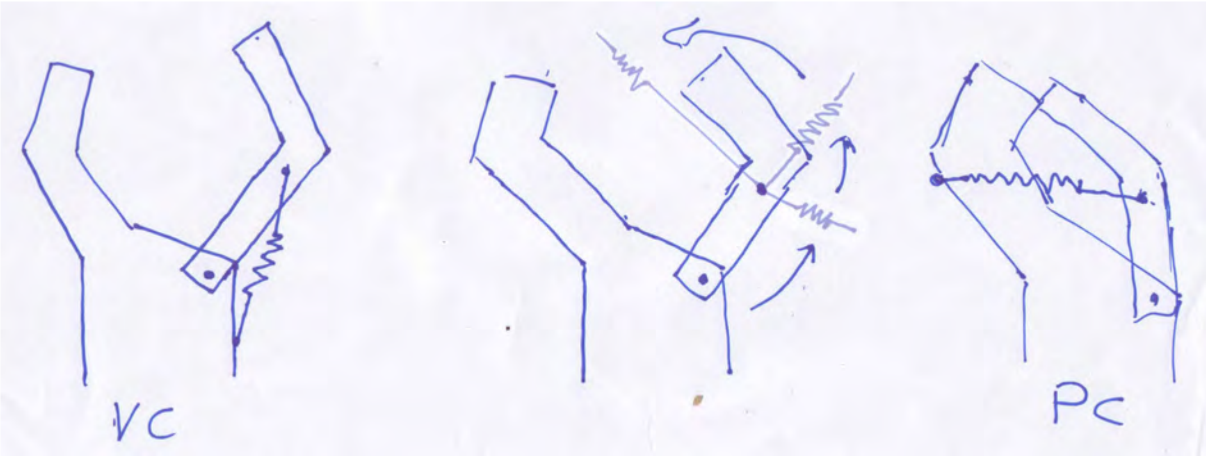

Figure 8: Concept of passive closing
left: Voluntary closing mode, the spring opens the hand. Actuation of the cable causes closing of the hand.
right:Passive closing mode, the spring closes the hand. The hand cannot be actuated with the cable.

so fatigue does not cause discomfort. Also the hand is closed in rest, which creates a more appealing look. These benefits come at a cost: Most voluntary opening prostheses have only one available pinch force. This is inconvenient for holding different types of objects. Heavy solid objects need a high grip force, while fragile or soft objects need a low grip force. So the hand is closed with a high force and the user provides an actuation force to loosen the grip. So with an increasing actuation force, the gripping force decreases. This makes this mechanism physiologically incorrect.[9] An example to counteract this inconvenience is the V2P prehensor. This device can exert pinch force from 8-78 N. This creates the possibility to provide a strong grip, while also be able to hold fragile objects. This device weighs only 170 g, which is significantly less than the lightest VC prosthesis.

3.3 Actuation type of choice

So we have two difficulties: discomfort due to actuation forces in VC prostheses and ease of control in VO prostheses. Although current VC prostheses are hard to use, the basic concept of this actuation type provides to lowest mental load due to the physiologically correct actuation. When picking up light objects is all a user does, this actuation type is sufficient for his/her activities. When heavy objects are used for a long time VO prostheses are the best option. No actuation is needed when an object is gripped, so no mental load is required in holding these objects. The prosthesis is basically used passively. Therefore a new type of gripping is introduced in this design: Passive gripping.

Passive gripping is achieved by replacing the return spring in such a way that the direction of spring force is changed (Figure 8).

Passive gripping can only be achieved with a voluntary closing prosthesis. For simple tasks the voluntary closing movements are used. But when an objects needs to be gripped for a long time, holding a broom for example, the springs of the prosthesis can be transferred to another position. This position needs to create a closing movement of the gripper. In this way holding an object for a long time does not fatigue the user, because no force needs to be exerted.

Passive gripping is the solution, it gives the benefits of controlling the grip intuitively. It also provides the possibility to grip objects for a long time, without fatiguing the user. The common complaint that the hand is open in the resting position has also no ground anymore. When the hand is planned to not be used for a while, the passive gripping can also be used. This creates a natural look in the resting position. It also provides the ability to easily don and doff, while wearing the prosthesis.

Table 1: List of demands

Cosmetics	dimensions should be natural Dimensions of hand (l x w x h): < 163 [mm] x 71 [mm] x 54 [mm]* Length thumb part = length to opposite thumb [mm]* Printed in different skin tones
Comfort	weight should be < 145g Good skin interaction at the socket Smooth design to avoid dirt Wear on clothes should be minimized Use of biocompatible materials: non toxic or allergic triggering parts*
Control	ease of picking up objects Line of sight: as large as possible* Body-powered: cable actuated* Hook activation → voluntary closing Grip diameter: 8 [mm] - 70 [mm]* High friction in hand/hook*
Cost	< €50,- production time should be low production should be easy and intuitive Man hour for production: < 2 hours Transportation costs should be low locally available material must be used
Strength	able to do ADL Mass object to lift > 250 [N]* Should perform ADL for at least three months - Fatigue wet-strength/coated

*: Retrieved from prior research of I. van der Veld.

4 Approach

4.1 List of demands

With the information gathered from literature as a starting point the design can be made. In this section the problems are summarized and the goal of this research is given. The goal is then separated in specific demands in the list of demands.

4.2 Problem definition and design goal

several problems can be noticed. Current body powered prostheses do not perform sufficiently, either they require too much activation force or are controlled counter intuitively. They weigh too much and the socket sweats too much. This can be combined in the following problem definition:

Current active upper extremity prosthesis are too heavy, too expensive and sweat too much.

In the introduction also an alternative is presented. An UE prosthesis made out of cardboard. The prove of concept is given in research.[ivan] This design is not dynamically tested. To know whether a cardboard prosthesis can perform Activities of Daily Living (ADL) research has to be done. Therefore the goal of this research is:

Design an affordable Body Powered (BP) Upper Extremity (UE) cardboard prosthesis, which is able to perform Activities of Daily Living (ADL) for at least 3-6 months.

The goal can be made more specific when different aspects of the design are separated in a list of demands (Table1). This list of demands will be the guideline in prototyping the prosthesis. Every aspect of the prosthesis will be compared with this list. When the solution meets the demands it is approved. In this way a reliable product which will be good can be realized.

The first three parts of the list of the demands are part of the vision of DIPO namely the three C's: Cosmetics, Comfort and Control. The requirements for cost and strength complete the list. The argumentation for these demands is given in appendix A.

5 Material Selection

In the literature study two interesting types of cardboard were selected. They are claimed to be strong, but no hard data is available on these two boards. So tensile tests are needed to give more insight in the strength properties of these types of board.

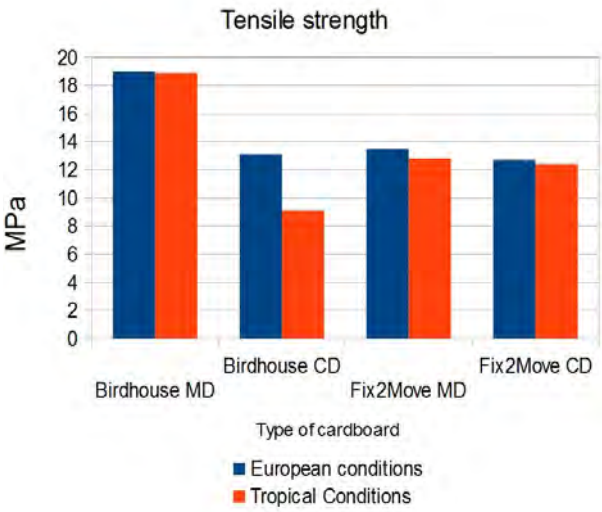

Figure 9: Tensile strength in the given conditions

5.1 Testing of cardboard

Tensile testing of cardboard is specified in ISO-norms and is different from testing metal. A full description of the tensile tests can be found in appendix B. Because cardboard is a fibrous material strength needs to be tested in different directions of the plane. With a standard tensile test only the in-plane directions (MD and CD) can be tested.

The shape of the specimen is also different, it has no strain gauge such as metal specimens.

Because cardboard is sensitive to water, the environmental conditions for testing are very important. For a tensile test the temperature and the relative humidity have to be conditioned into regulated conditions. The two tested conditions are european conditions and tropical conditions. Which are respectively 23 ^{0}C - 50% relative humidity and 27 ^{0} C - 65% relative humidity. These conditions are chosen because the prosthesis should be able to last in tropical conditions to be useful throughout the world.

Both materials are tested conform the norms. First the samples are cut into the right shape, next they are put into a moisture oven to create the right conditions. When these conditions were reached, the samples were tested in both the MD as the CD. The results of the tensile tests is given in figure 9

The birdhouse cardboard is stronger, especially in the MD. But its strength in the CD direction also decreases rapidly when it is wet. The Fix2Move cardboard has a high wet-strength, but its dry strength is less.

The density of the materials is also tested, this is not done conform the given norm ISO 536, because the moisture oven was too small to condition the specimen. Therefore this is done at room temperature with plates of a different size.

The thickness of the board is $2.9mm$ for birdhouse cardboard and $3.0mm$ for the fix2move cardboard.

The density of both boards is calculated with these values and is: $368.91kg/m^3$ for birdhouse cardboard, which gives a maximal specific strength of $51.5kNm/kg$. The density of Fix2Move cardboard is $401.06kg/m^3$, which gives a maximal specific strength of $33.7kNm/kg$. The specific strength of the common used plastic polyurethane is ca. $33kNm/kg$.[22] So birdhouse cardboard has a very good specific strength compared to this plastic. This makes it possible to create a light prosthesis.

The demand for performance in ADL can be met by the birdhouse cardboard. When a force of 250 N is pressing on the tip of one digit of $100mm$. With a digit that is 7 layers thick and $20mm$ the stress at the outside of the digit is the highest. When the digit is assumed to be an uniform beam with half of the thickness c the maximum stress at the base of the beam can be calculated with the following equations:

$$250N \cdot 100mm = 25000Nmm$$

$$I = \frac{bh^3}{12} = \frac{20mm \cdot 20.3^3mm}{12} = 13.942,378mm^4$$

$$\sigma_{max} = \frac{Mc}{I}, c = \frac{20.3}{2} = 10.15$$

$$\sigma_{max} = \frac{25000 \cdot 10.15}{13.942,378} = 18.20MPa$$

From these equations can be concluded that the birdhouse cardboard is the only board that can lift $25kg$. Also the fatigue properties of a material with a higher tensile strength are better. So the birdhouse cardboard will have a longer lifetime. The wet/strength of the Fix2Move board is better in the CD, but for the MD birdhouse cardboard is superior. Therefore the birdhouse cardboard is also stronger on this point. Another important feature of the material is the skin interaction. The Fix2Move cardboard is currently used as a replacement of cast. It is claimed to have a very pleasant skin interaction, for the birdhouse board this is not tested. Most probably the Fix2Move board will have a better skin interaction, since it is made to interact with skin.

The last point of the list of demands which will be discussed is the weight of the prosthesis. Birdhouse cardboard has the lowest density and the highest tensile strength. So its specific strength is the highest. This creates the possibility to make a light prosthesis.

From these points the best cardboard to use in a prosthetic hand is birdhouse cardboard. For the socket Fix2Move cardboard seems promising since the loads are lower in this part and it is proven to have a good skin interaction.

6 Concepts

In the following paragraphs concepts of the three subdivisions will be given. At the end of the chapter the concept of choice for these subdivisions will be given.

6.1 Basic principle

The basic construction should be done in such a way it is intuitive and easy to construct the prosthesis. Therefore the production method should be simple and cheap. As explained in the list of demands, creating a prosthesis out of plates fulfills these demands. Transportation will be cheap and the tool required to create the shapes is inexpensive. The prosthesis can be delivered as a kit, which is easy to put together. Cardboard kits can be put together in basically two ways, gluing and a slot mechanism. Both mechanisms will shortly be discussed.

6.1.1 Glue

When glue is selected to connect parts with each other, the right type of glue has to be chosen for this. There are several options for this glue, in this section those options will be discussed and the final type of glue is chosen. Because cardboard is cellulose based the first wood glue is the best type for gluing. There are several types of this glue. Glue has classifications for durability which are specified in NEN-EN 204:2001. This norm classifies thermoplastic resin based wood adhesives for non-structural applications into durability classes D1 to D4. The most standard wood glue has a D2 classification, therefore this type is not chosen for this prosthesis. There is also a more durable glue, an example is construction glue of Bison, this has a D4 classification. This glue is specifically intended to be used in constructions with wood and metals. It is durable and because the cardboard is used intensively, it needs to be strong. With this glue all materials are proved to stay strong when wet. The shapes have to form three parts, the terminal device, the basic construction with spring placement and the arm portion. All three subdivisions have to be build with one of these constructions.

6.1.2 Slot mechanisms

The second method is a slot mechanism, this concept is widely used in cardboard models. This method is very easy to assemble and requires no glue. Therefore the construction time of parts with a slot mechanism will be very low. In the picture it is seen that the cardboard is concedntrated at the centre of the construction. This does not create the best strength for the total assembly.

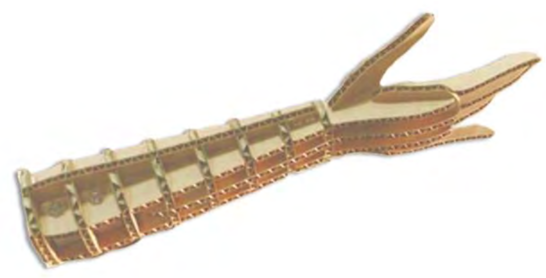

Figure 10: Arm created with a slot mechanism

6.1.3 Construction mechanisms per subdivision

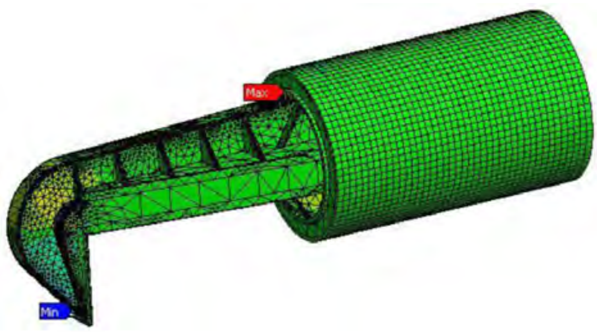

Figure 11: Stresses in the hook

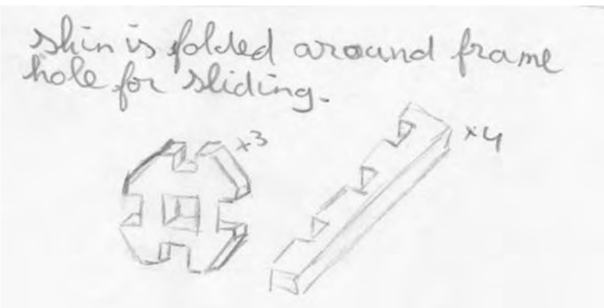

Figure 12: Slot mechanism for the socket

Considering the aspects of the construction mechanisms described above the choice of basic construction principle is chosen to be a glued construction for every subdivision of the prosthetic hand. The socket will be created with a slot mechanism, because from earlier research it is clear that the highest stresses do not occur in the socket (figure 11). When the cardboard is placed on the outside of the basic parts like in figure 12 a light and hollow structure is created. The outside layer can be folded around the structure like the Fix2Move immobilizer. The ribs can be connected with the octagons through a slot mechanism, this creates an easy constructible and glueless connection. In the previous paragraph the socket is chosen to look like the Fix2Move humerus immobilizer. This is conform the common used sockets which are used in third world countries (LN-4, I-TAL). To keep the prosthesis connected to the stump an extra connection can be made just above the elbow. This will create the ability to carry objects with the arm hanging. When this extra feature does not exist, the prosthesis will fall off. The socket will not be further investigated in this research.

6.2 terminal device

6.2.1 Digits

The terminal device is an important factor in the prosthesis. It provides the interaction of the prosthesis with the environment. Therefore it has to withstand harsh conditions. Wear, humid, large forces and many other influences should not harm this part of the prosthesis. While this is the most vulnerable part of the prosthesis, it is also the most dynamic part. For a better acceptance this part should also should look as natural as possible. These requirements make it hard to find a suitable concept of the terminal device.

The digits of the hand need to be able to grasp different objects. This should be as intuitive and dexterous as possible. Healthy humans are able to intuitively grasp an object in a stable way. So the digits should be able to mimic a healthy hand. A human hand can perform several grips or prehension patterns, these patterns are classified in seven patterns.[1]9 It is impossible to recreate all these pattern into one solution. So the patterns that are used extensively in healthy gripping should be copied into the. In Figure 13 all basic patterns are displayed, together with a mechanical equivalent of this pattern.

Different patterns are investigated in use and from research it is clear that palmar (a,b) and lateral (d) patterns are used intensively in gripping and holding the object.[23]

So this gives some basic requirements for the digits. It should be able to perform at least the palmar and the lateral prehension pattern

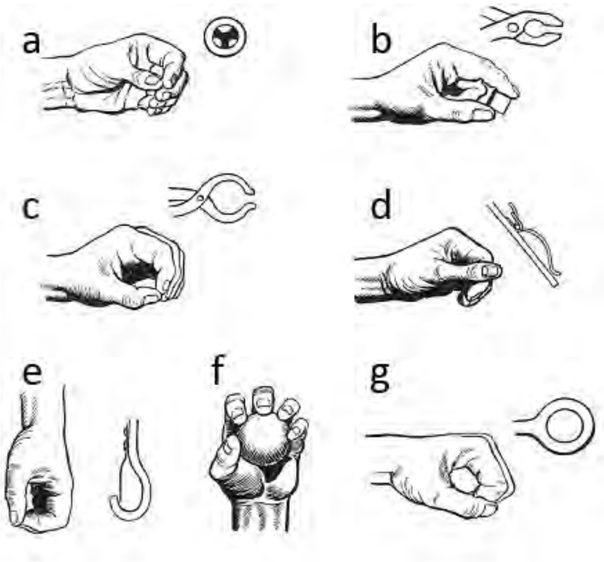

Figure 13: Hand prehension patterns. a, palmar prehension b, palmar prehension. c, tip prehension. d, lateral prehension. e, hook prehension. f, spherical prehension. g, grasp prehension

while looking natural compared to a healthy arm in the resting position.

From the previous chapter another requirement of the prosthesis is to create passive gripping. The direction of the spring force should be able to change in a simple procedure.

To create these grips the terminal device has to be able to move. Moving the gripper can be done in basically two ways: a linear and a rotary motion. Both might bring a solution so a comparative assessment has to be made.

The assumption for this part is that a human can perform a displacement of the cable of 40mm.[1]9 Previous research shows that a grip to be functional should be able to open at least 60-80mm. So with a linear mechanism a grip opening of only 40 mm can be reached. Therefore the linear motion needs a gear to perform the right grip. A rotary motion also has difficulties with the pinch force. Because no durable gear can be created with cardboard, a direct transfer on the hinge should cause an closing movement of 60-80mm of the tip of the finger. To perform this motion the radius of the tip of the digit should be twice the size of the radius of the actuation. This also means that the pinch force at the tip will be twice as low.

The market for below elbow prostheses is small, so every person without a hand should be able to wear the prosthesis. This means that the hand dimensions, given in the list of demands should not be exceeded. When the mechanism is larger than the hand itself, not every patient is able to fit the hand. This reduces the market even further.

These designs can be compared with each other with help of the list of demands. For the cosmesis demands the lifelikeliness is important, this is not the most important factor, so this demand will be weighted with 1. The compactness or amount of material which is needed can be connected to weight. When weight is saved, the prosthesis will be more comfortable and it will be able to fit on every amputee. This demand will have a weight factor of 1. The control demands for the terminal device are the most decisive. The prehension patterns that are possible is the most critical demand and will be weighted 2 per possible prehension pattern. When passive gripping is possible the prosthesis will provide the user to grasp objects without exerting force. This decreases the fatigue and therefore increases the comfort and ease of control of the prosthesis. This is a very important aspect and will be weighted with a factor 2. To suppress the cost price the construction has to be easy and intuitive, therefore the demand for creation with flat plates is also included. This factor is weighed with 1. The strength of the prosthesis increases the durability, this is an important point and therefore it will be weighted with a factor 2. The pinch force that will be available at the tip of the digits needs to be high to lower the activation force. This will decrease the fatigue and therefore increase the control and comfort. This is an important feature, since this is a major flaw in current designs[2]1. Another aspect of increased control is the opening of the digits. With a wide opening the prosthesis is able to lift a large variety of objects. This increases the ease of control and it therefore will be weighted with a factor two. These demands are combined and weighted for the created concepts. With this list the most promising design is the hinge prehensor without a lateral grip. Passive closing is easily implemented, while the hand looks the most natural.

6.2.2 Concepts

With these requirements in mind several concepts are made:

All concepts have a groove in the middle of one digit. This will create three contact points like the palmar prehension pattern 'a' in figure 13

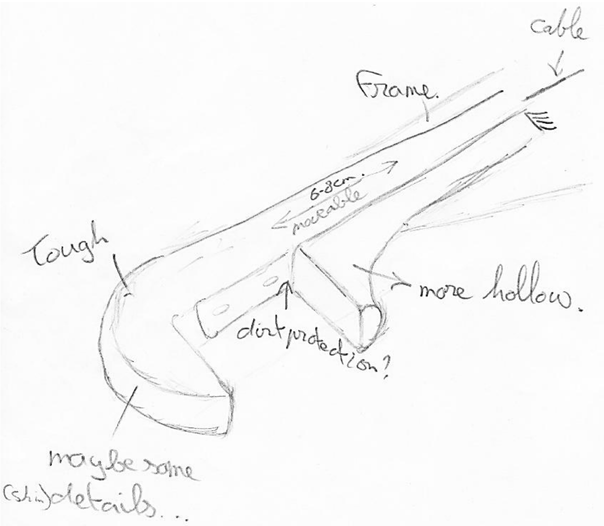

Figure 14: Slide with drawer slide

Sliding mechanism (basic earlier design Figure 2):

This design is basically the design which is the starting point of this research, it is proven to withstand the basic forces is might face. Therefore it might be a good candidate to improve in this research. The basic design however lacks some usefulness. The gripping patterns that can be reached are 'a','b','c' and 'e' can be used, while the shape does not look lifelike. The space needed for the mechanism is also large, because of the linear motion the amount of grip opening should also be present at the base of the prosthesis. This enlarges the size of the prosthesis, which causes that some user cannot wear the prosthesis. The prosthesis will then be too long to look good and use properly. To summarize a list of pros and cons is given.

Pros:

- strength
- Easy to create voluntary closing unit with flat plates
- Only cardboard is used
- Usable pinch force is high
- Already investigated

Cons:

- Not compact
- A lot of area interaction (wear)
- Compression spring needed, spring not interchangeable
- No passive closing possible
- More material needed (weight)
- More change of jamming
- not lifelike
- not enough opening possible

Figure 15: Telescopic drawer slide

Because an opening width of 60-80mm is needed to grab a variety of objects the opening capabilities of the prosthesis should be doubled. This is possible with a telescopic drawer slide (Figure 15). So in this concept a gear should be made, this will decrease the pinch force, but increase the opening width. The wear of the dynamic part will be lower, as is the friction. Introducing such a part will however increase the cost price and decrease the possibilities of producing the prosthesis locally. It also will increase the weight of the prosthesis significantly. This is summarized in the following list.

PROS:

- Extra strength because of metal part
- Solid firm connection part
- solid attachment of spring and actuation cable
- enough opening possible

CONS:

- Other material needed
- Extra weight though metal
- Maximum pinch force decreases

Figure 16: Two digits prehensor without lateral grip

With this in mind, several other options are considered, unlike the hook of earlier design, the hinge model will be a prehensor. A prehensor is a terminal device which is not a hook, but also is not a hand.[1]8 For the hinge two types of grippers also looked promising, a hinge with and without lateral grip. First the hinge without lateral grip is considered.(Figure 16

A hinge will create a more compact mechanism, which does not need a lot of space in the arm area. This increases the usefulness of the prosthesis. A hinge will also create a motion that is more lifelike. It can perform the basic prehension patterns ’a’,’b’,’c’ and with passive closing also ’g’. The spring can be placed outside, which makes it easy to replace. With the right dimensions also a good opening width of the digits is possible. The use of cardboard with a hinge is however untested and it is not sure whether this will meet the fatigue demand. The pros and cons are summarized below.

PROS:

- Compact
- Looks more lifelike
- Possibility of passive closing possible
- Easy placement of spring on the outside
- enough opening is possible

CONS:

- Wear on one point
- Hinge needed, not investigated yet
- Loss of pinch force due to torque arm ratio

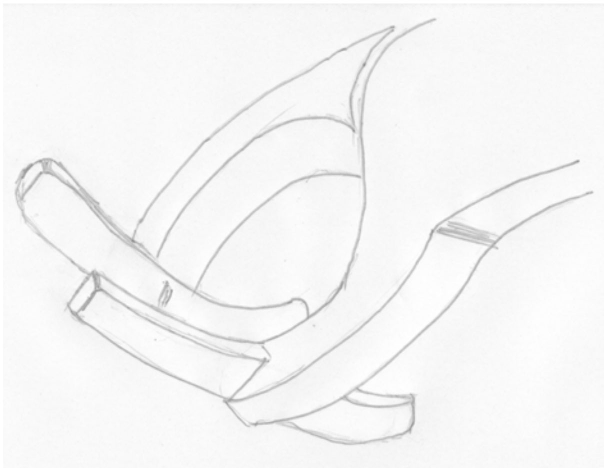

Figure 17: Two digits lateral grip

A lateral grip (Figure 17) is considered to be used the most[2]1, so this design is also considered. It has the basic properties of the hinge without a lateral grip, but because of the lateral grip the hook prehension ’e’ and the lateral prehension ’d’ can be performed. This increases its gripping abilities. Because of the lateral grip the prehension pattern ’g’ is not possible. The spring cannot fold around an object, because the lateral grip is in the way. This also seriously reduces the usefulness of the passive gripping possibilities. The

Table 2: Selection of terminal device shape

	lifelike	prehension patterns possible	passive gripping possible	easy to create with flat plates	strength	compact-ness	High pinch force possible	enough opening possible	Total points
weight factor	1	2	2	1	2	1	2	2	
hook without gear	-	4	-	+	+	- -	+	- -	4
hook with telescope drawer slide	-	4	-	+/-	++	-	-	+	8
hinge with lateral grip	+/-	5	-	+	-	+	+/-	+	10
hinge without lateral grip	+	4	+	+	+	+	+/-	+	17

lateral grip will be harder to create, since this includes a change of direction (3d shape) in the digits. The increase of weight at the tip of the prosthesis will decrease the comfort, while it has more change to break. The pros and cons are summarized below. PROS:

- Tighter grip with flat objects
- More prehension patterns possible

CONS:

- No passive closing possible
- Does not looks lifelike
- The construction needs to be 3D less strong, harder to create

6.2.3 Choice of terminal device shape

All design demands given at the start of this chapter are combined and graded in table 2. This gives a clear sign that a hinge prehensor without a lateral grip is the best choice for a basic shape of the terminal device. It is compact, versatile and easy to create with limited resources.

6.2.4 spring mechanism

The springs that are used in the prosthesis have to be widely available and durable enough to be reliable. Because the springs are located in the hand, the weight of the springs should be as low as possible. Also the durability and the energy efficiency should be considered. Last but not least is the initial length and the spring constant. Because springs have proven to be unreliable and will need changing on failure, the springs should be placed on simple to reach position. This means the spring will also be able to withstand UV-light.

So there are some major points of interest: Low hysteresis, availability, price, flexibility, durability and weight.

There are several options for a spring in a prosthesis. Currently wilmer prostheses use a PU o-ring.O-rings are widely available in rubber, so these will be tested. PU o-rings are claimed to have a better UV resistance and will therefore be more durable. O-rings with a diameter up to 50mm are reasonably available. In this research o-rings with a diameter of 45 and 50 mm are tested. Another widely available material is the inner tube of bicycle or car tires. The advantage of these materials is that the size of the spring can be chosen. The tube can be cut at a different angle, which results in a spring with a longer initial length and a smaller spring constant. Products which are also elastic and widely available are hair elastics. So these will also be tested. Of course a common metal spring will also be included in this research.

To get an idea of how the springs perform a

Table 3: Selection of spring

	Hysteresis	Availabiliy	Price	Flexibility	Durability	Total points
Weight factor	2	1	1	1	2	7
Rubber o-rings ø50 mm	-	++	++	+	- -	-1
Metal spring	++	- -	- -	-	++	3
Hairband	+	++	++	++	+/-	8
Inner tube	- -	++	++	++	- -	-2

spring characteristic graph is made. Testing is done in a machine which is described in appendix C. The spring is spanned in the machine in a way the load cell measures 0 N. From this point the spring is elongated.

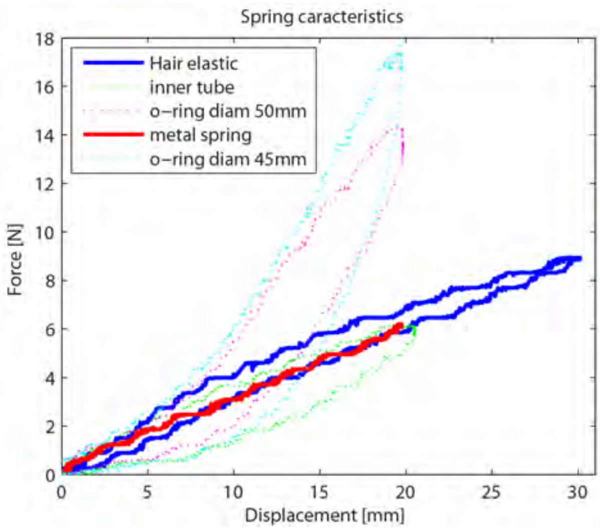

Figure 18: elongation (x) vs. spring force(y)

When the spring cannot be elongated anymore the tension is slowly released. In this way a spring characteristic can be made. This is done for every spring mentioned above. The results of this test are given in figure 18.

From the picture can be seen that rubber does have one downside, it has a high hysteresis. With a high hysteresis the user has to pull hard to close the hand, while a smaller force is available to open the hand. This causes unnecessary actuation forces or lower pinch forces. Because the pinch force already an issue in current VC prostheses[2]1, this is an undesirable property. From the viewpoint of hysteresis a metal spring has huge advantages, it nearly has no hysteresis. The hysteresis of an inner tube and the o-rings is very large, therefore those are discarded as a possibility to use. Hair elastics score better and are considered as a serious option. Apart from the small hysteresis of the hair elastic the characteristics of both the hair elastic and the metal spring are approximately the same.

The information gathered is summarized in table 3

From this table is clear that the best choice for the spring is a hair elastic. Therefore the spring to use in the prosthesis will be a elastic band.

7 Modeling

Now the basic concept is chosen, the in depth modeling is started. This is done in several steps. The first step is the determination of the actuation part. The pinch force and the opening behavior of the prehensor should be known before the final design can be made. When this is done, the shape of the prehensor is modeled. In every subsystem the MD is chosen to be in the length direction, in line with the stump. This is because stress will build up when the torque is high.

7.1 Actuation

7.1.1 Movement and pinch force

To keep everything low tech, no gearing was used. Therefore the radius of the pulling circle is fixed for a given angle change. This creates several problems:

To get a reasonably strong pinch force, the radius has to be big, to create a higher torque on the digits. But with a big radius, the angle change of the digit is getting smaller. Given the constraint that the wrist size should be reasonable[24] this limits the possibilities. When both digits are moved, there is no space for both arms to move. Therefore a zigzag test specimen was made. This was still too big in the wrist and proved to be too weak. It collapsed with a pulling force of around 30 N. Therefore a new approach was made. Use only one moving digit. This improves the stiffness of the system and also improves the size of the wrist. Because now there is only one hinge. The stiffness of the system has to be considered. 5-layers proved to be almost sufficient. So the next step will be optimizing the digit design.

7.1.2 Hinge

The hinge is an important part of the prosthesis, it is loaded the most so when this subsystem holds, the rest of the prosthesis can also be constructed in such a way it will last. There are several options to create the hinge. In this thesis three types of hinges are considered, in order off simplicity they are: cardboard-metal, metal-metal and ball-bearing. To minimize the cost the easiest way to make a hinge is simply a hole in the cardboard layers and a aluminum hinge. Because the behavior of cardboard in dynamic interaction with metal in a hinge is unknown, this behavior should be tested. When the results of these tests do not meet the demands, a step in complexity is taken. When the demands are met with the simplest possible solution this solution is chosen.

To do so several tests to check whether a hinge can last in different situations is done. The first test is the opening and closing behavior of the hinge (figure 19). In this situation there is no force on the hinge in one direction. Only the pulling force and the spring force are present. The hinge is also pressured when objects are lifted, these forces are in another plane. So basically two situations have to be tested. The dynamic opening and closing situation and the static grip situation.

Both tests can be performed with a simple pneumatic setup. For the first situation the digit can be loosely connected to the pneumatic cylinder. The linear motion of the cylinder can now be translated in a rotary motion around the hinge. In this way the hinge is tested. To test whether this setup would last, a simple test, without any spring- or actuation force was

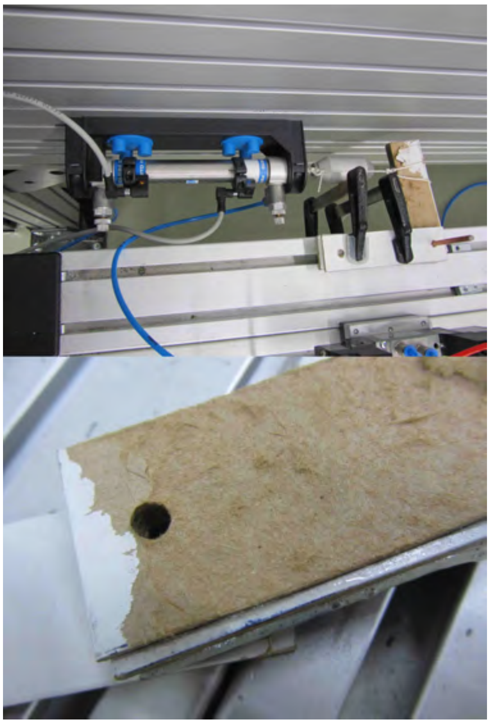

Figure 19: Testing of hinge, top: opening closing test. Bottom: cardboard after 35.000 cycles of opening/closing and pushing

done. This test gave some first clues of the cardboard construction. With 35.000 cycles the hinge kept its form. This is a good sign for further testing, but inspection from this testing model gave some insight in the behavior of cardboard. To test the basic hinge only the digit of seven layers was glued. The other sides of the hinge, two layers thick were not glued. This setup was not stiff enough. Therefore some adjustments are made. The digit will be seven layers thick, but at the place of the hinge it will be five layer thick. The other side of the hinge will now be four layers thick. This brings the total amount of layers around the hinge to thirteen in stead of the original eleven from the model. The four layers on the outer sides of the hinge are glued together to create extra stiffness.

The holes for the hinge are created with an industrial drill, this gives excellent straight holes with a diameter of 5mm. However, with drilling it is always the case that the edges are not clean. These imperfections can be an easy starting point for fatigue failure. Therefore another option is considered, this option is punching. Machines that originally punch metal plates create perfect holes with smooth edges in the cardboard. But this option creates another problem, the alignment of the holes is now more difficult. With a mold this problem might be solved. When we look further in the future the second option looks the best, because it creates clean holes and every piece of the prosthesis is punched out of a plate. For the tests the drilling option is chosen, because a straight hole is more important than a clean edge. This is because of the friction a misalignment creates. With more friction the performance of the prosthesis is decreased. Therefore this option is chosen above the most intuitive option in this thesis. With a good construction plan, the punching option is the best.

The hinge is a simple cut-off nail which is put trough a hole in the cardboard. This hinge is reinforced with a ring, this is to prevent the cardboard from wear. It is not proven that this ring is necessary.

7.1.3 Actuation cable

The string that was used in the first setup proved to fray very fast. Therefore no non-metal strings are used. A RVS cable is used to provide the durability needed in this prosthesis.

7.2 prehensor

In the previous chapter the hinge is chosen as the type of actuation. This is mainly to provide the ability of most of the prehension pattens, the ability to easily implement passive closing and the natural look in the resting position. These patterns need to be met by the final design. In the hinge paragraph the thickness of the digits is set to be seven layers. To provide the prehension patterns and the looks several important points are needed in the final design:

- Grooves in one digit → palmar grip ’a’
- Flat points at the tips → palmar grip ’b’, lateral grip ’d’
- Pinch points → Tip prehension ’c’
- curves in the digits → natural look, grip patterns ’f’ and ’g’
- provide a good connection for the spring

With the conclusions of the hinge test a basic model in solidworks is made. This was done to see where some modifications in the model could be made. Also to provide insight in how the subsystems should be connected with each other.

Figure 20: Basic model hand

The result is shown in figure 20. When a groove is filed in the center of one digit, the palmar prehension ’a’ is possible. A small groove in the middle leaves straight parts to provide prehension patterns ’b’, ’c’ and a simulation of the lateral prehension ’d’. The hand looks natural when closed. The shape of the digits also provides to hold bottles. The shape of the digits is thought to be sufficient. It can create the most important grips that are also used with a healthy hand. Only the hook function is not covered with this design, a solution has to be found for this flaw in the design.

7.3 Placement of the spring

The spring in a prosthesis is proven to be unreliable. Therefore the place of the spring has to be easily reachable. Next to this demand, the prosthesis should also be able to change the mode from voluntary closing to passive closing. Therefore the possible places of the spring decreases even further. Also it needs to fit in a rigid place of the prosthesis. These demands limit the placement of the spring. To provide a stable solution either one spring at the center of the hand or two springs symmetrically should be used. From the tests it is shown that one hairband cannot provide enough force to open the hand. Therefore two springs are chosen to operate the opening motion.

Therefore the placement of the spring is chosen to be on the outside of the prosthesis according to figure 20. This basic position is chosen as a starting point for the precise placement of the spring. The connection points for the springs are a RVS rod which is longer than the prosthesis. So only one rod is needed to provide a solid connection point for both springs. There is one connection on the moving digit, and one on the base of the prehensor. So when the prehensor closes, the spring is elongated and the moment arm decreases. This should provide a nearly constant torque.

From simulation is seen that the arm of the spring in the given setting decreases linearly (figure 21, while the elongation of the length increases non-linearly (figure 22). So to create a constant torque this non-linear behavior has to be counteracted since T=u*a. From the first test hair bands proved to be the best choice and these do have a non-linear spring characteristic.

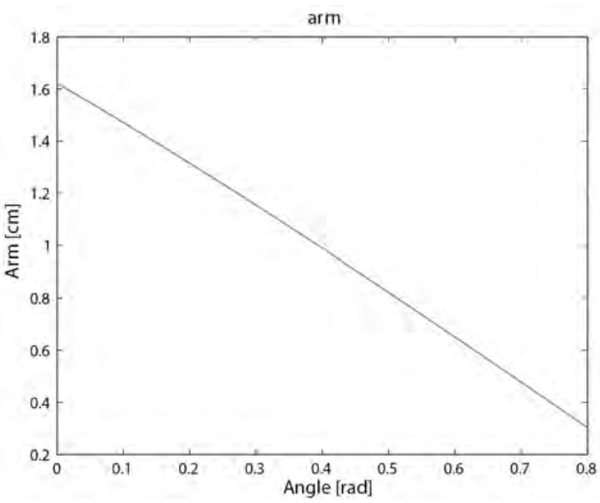

Figure 21: linear decrease of arm of torque

However, the torque still behaves in a form like figure 23. The arm of the torque created by the spring decreases too fast. This can be counteracted by guiding the hair elastics in such a way that the torque will be almost constant. To do this an oval shape is added in the simulation. The torque will now be more

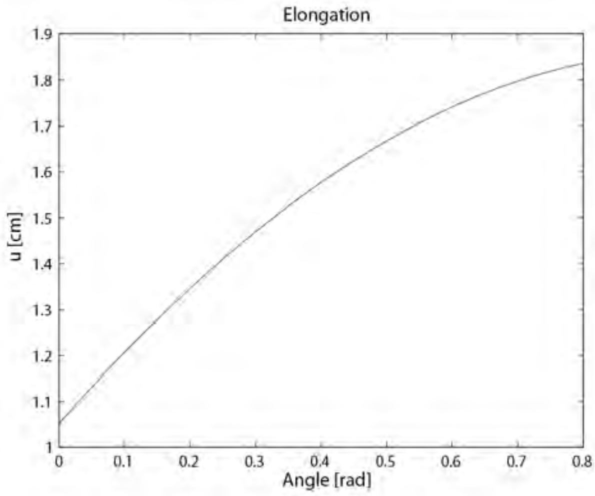

Figure 22: non-linear increase of elongation

constant and looks like...

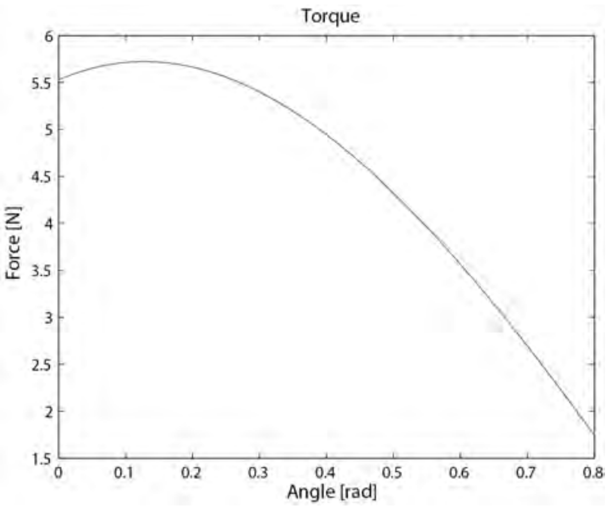

Figure 23: Calculated torque without arm compensation

In matlab the spring characteristics generated with the spring test were used to find the optimal placement of the spring. Because of the decrease of the moment arm, the arm becomes negative. This means the spring is not able to open the hand anymore, but it provides a pinch force. This cannot happen when the prosthesis is in use, so this should be fixed. This problem is resolved in the design by creating an oval shape in line with the springs. Now the arm of the force can be guided in such a way the torque is about the same. In this way the torque is in every situation nearly the same. This provides a even feel (feedback loop) over the whole spectrum. This is beneficial for controlling the prosthesis [9].

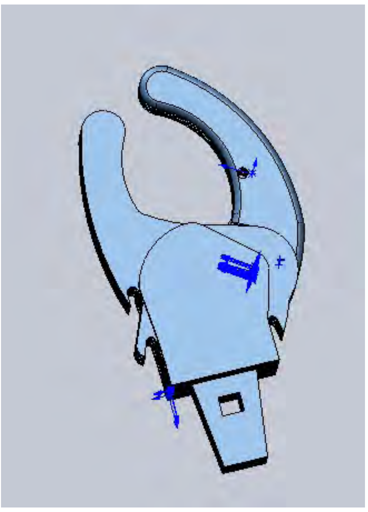

Figure 24: Hand with guide for hairbands and connection points for passive closing

To provide the ability to change the spring force from opening the hand to closing the hand, the connection point at the base of the prehensor is made in the shape of a hook. Also the rod which is used as a supporting point is elongated, so it can be grasped with the healthy hand easily. Now the spring can be folded around the prehensor to the other place. This type of gripping simulates prehension pattern 'g'. At this spot several hooks are present to attach the spring to. This provides different grip forces with different objects. The hooks to place the spring connection in can also be used to hang plastic bags on. This provides another passive use of the prehensor. An updated design is shown in figure 24.

7.4 Connection prehensor to the socket

This connection has to be easy to connect, while also being sturdy. The operating string/cable has to be aligned properly and the digits need to be placed at the right angle.

To keep the prosthesis light, this connection point should also be made out of cardboard.

For the connection of the hand with the arm portion an octagon of three layers thick with a hole in it is chosen. This hole is five layers of cardboard thick and is three centimeters wide. The hand has an extension with a tapered shape. The base of this shape is also three centimeters. In this extension also a hole in the middle, for the locking pin and a hole in the side for the string is constructed. Now the hand can be locked, while the string moves through the middle of the hand. This creates an easy to mount connection. The connector between the hand and the arm portion has an octagonal shape, this is based on the Fix2Move humeral immobilizer. The cardboard plate can be folded around this shape and be connected to the stump with several leather straps.

8 testing results

After the hinge testing was done and the final model was created, a real life test was done. The efficiency, the durability, the strength and the fatigue of the plyos prehensor were tested. In this section the results of these tests are given.

8.1 Comparative tests

In earlier research currently available prostheses are compared with each other to see what the useful performances were.[2]1 This is a good measure for comparing VC prostheses with each other. Therefore the plyos prehensor will undergo the same tests. The test bench which is used is described in appendix C.

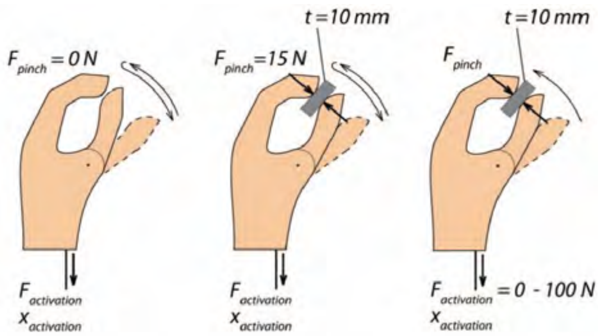

Figure 25: Left: Closing test, middle: Pinch test, right: Pull test

The prototype was subjected to the three different tests, which are described in previous research (figure 25).

Closing test - The cable was pulled until the prosthesis was closed. When the prosthesis was

closed it was immediately opened again. In this process the hysteresis of the prosthesis could be measured. Also the actuation force could be measured.
Pinch test - The pinch force sensor (thickness = 10 mm) was placed in between the fully opened fingers. The cable was pulled until a pinch force of 15 N was reached. When this force was reached, the hand was reopened again. In this process the activation force for reaching a pinch force of 15 N was measured. Also the work needed to pinch 15 N was calculated.
Pull test - The pinch force sensor (thickness = 10 mm) was placed in between the fully opened fingers. The cable was pulled until an activation force of 100 N was reached.

To get an average value, the first two tests were repeated three times. The pinch test was performed one time. All data is imported in MATLAB, where the data is processed into clear plots.

The amount of work and the hysteresis is calculated with the following equations:

$$W = \int_0^l F(x) \cdot dx$$

$$\Delta W[Nm] = W_{closing}[Nm] - W_{opening}[Nm]$$

8.1.1 Closing test results

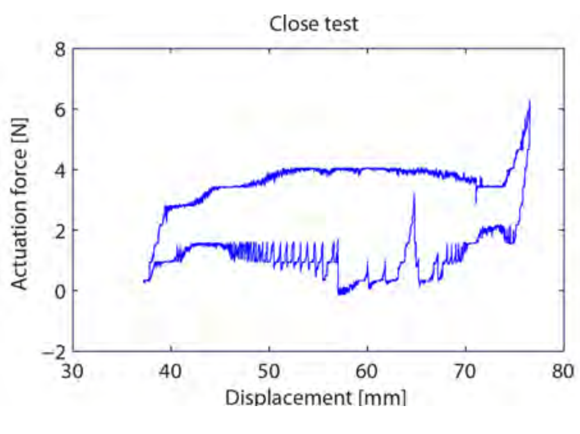

Figure 26: The displacement of the actuation cable plotted against the actuation force

A plot of a closing test is given in figure 26 It can be seen that the actuation force is constant while the hand is closing. This means that the hand will give the same feedback in every position. This is designed, so it is a good result. Also can be noticed that the cable force is very low when the hand is opening (1.5N). This force is most probably too low to overcome the friction caused by the bowden cable. The total amount of work which is needed to close the hand is 213 Nmm For the whole cycle the hysteresis is 122 Nmm.

8.1.2 Pinch test results

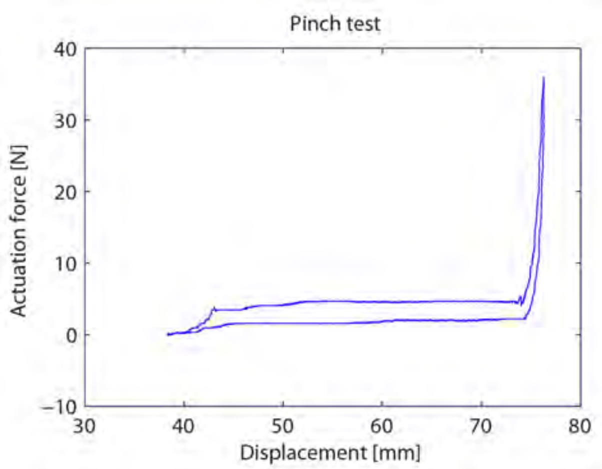

Figure 27: Pinch test

A measure of the efficiency of the hand is the pinch force compared with the pulling force on the cable. There is energy loss due to friction in the system. Also a spring is needed to pull the moving digit back in the resting position. Both cause a loss of pinch force with a given actuation force in the operation cable. While doing this test, the efficiency of the prosthesis is also measured with the amount of work needed to close the prosthesis and pinch 15N. A plot of the actuation force against the pinch force is given in figure 27 The total amount of work which is needed can be calculated from this data and is 310 Nmm

8.1.3 Pull test results

The pinch forces are measured, while also the position and the actuation force is measured. The hand is again spanned in the machine described in appendix B. The actuation force is slowly raised and the pinch force is measured. The cable force is now increased to 100 N(figure 28). This force will probably never be reached by a user. Since research shows that a user can produce repeatable forces of 40 N. When we consider the hand as a frictionless

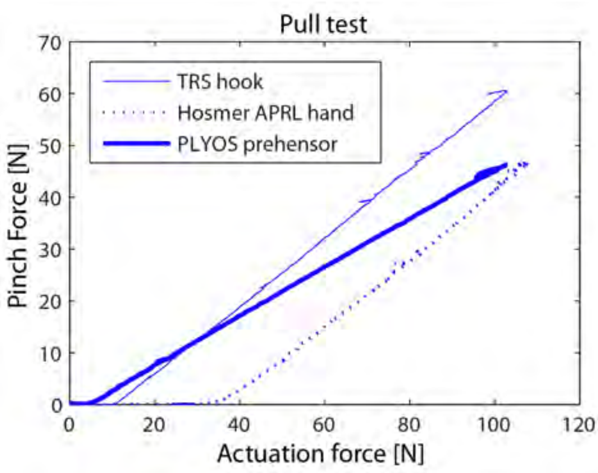

Figure 28: Plot of the pinch force generated at a given actuation force during the pull test

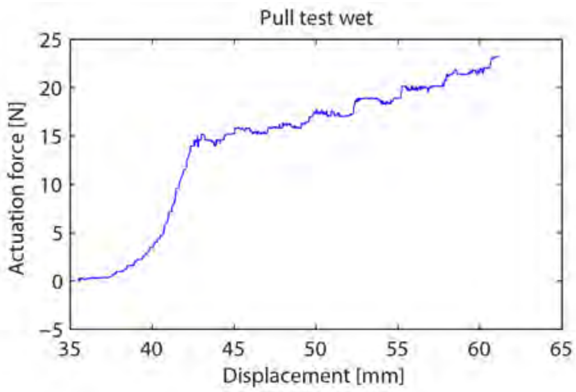

Figure 29: The wet pull test

and springless system, the pinch force is 19.57 N with an actuation force of 40 N. In reality this force is 15.15 N. This is an efficiency of 77.43%

In the spectrum which can be used by an average person (0-40N) the prosthesis performs in the top of the spectrum. Because of a low activation force, the prosthesis can grip with an actuation force as low as 7N. This is the best of all current prostheses. The increase of pinch force is lower than the TRS hook and the Hosmer APRL Hand, this causes a second place at an actuation force of 30N. 100 N will most probably never be reached by a user, so in efficiency the plyos hand ends 1st/2nd.

The same setup is used to perform tests with a wet prosthesis. To create a wet situation the hand is put under a water tap for 90 seconds. Then the prosthesis is tested again. The results of this test is displayed in figure 29.

This result is a lot less, this is because the prosthesis jams. Also this test is done after the fatigue test, which caused the moment arm to decraese (next chapter). The prosthesis functions, but functions less good when it is wet.

8.1.4 Comparison with existing VC prostheses

With the results given in the previous paragraphs a comparison table can be created:

In comparison with current VC prosthesis, the plyos scores well. These are the best results, the prosthesis will most probably perform less when a higher spring force is used to reopen the prehensor again. Also when the prosthesis is wet, the results will be worse.

8.2 Specific plyos tests

8.2.1 Passive closing tests

Figure 30: Left: Passive grip mode 1, form closed grip. Right: Passive grip mode 4, open grip

The results given in the previous paragraph compare the plyos prehensor with VC behavior. The plyos prehensor also has a feature that does not exist in current voluntary prostheses. This is called passive closing, this is explained in previous chapters. The passive gripping in this prototype can be placed on four positions. The pinch forces that can be reached with these positions are between the 6-8 N. Of course these forces increase when the hand is in a more open position. This is the case when a

Table 4: Overview of the geometrical properties and the test results of the tested prostheses.

Prosthesis	Mass(gr)	Opening Width (mm)	Maximum cable excursion (mm), n=3	Work closing (Nmm), n=3	Cycle hysteresis (Nmm), n=3	Work closing and pinching 15 N (Nmm), n=3	Required cable force for a 15 N pinch (N), n=3	Pinch force at a cable force of 100 N (N)
Hosmer APRL hand,52541 (L) size 8	347	44 (70*)	37 ± 0.1	1058 ± 4	298 ± 8	831 ± 1	61 ± 0.6	41
TRS hook, Grip 2S	318	72	49 ± 0.1	284 ± 3	52 ± 1	243 ± 3	33 ± 0.2	58
PLYOS prehensor	122	71	37.91 ±	213 ± 18	122 ± 6.8	310 ± 55	35.5 ± 0.1	45.3

*Thumb positioned in wide position.

bottle of water is held in the prehensor. When the passive grip is set at the first position while the bottle is gripped, the prehensor provides enough force to hold this bottle steady. The bottle can also be gripped when the prehensor is set into passive mode four. In this way a normal non-form closed grip is created. This also creates a tight grip with a bottle of water (figure 30).

8.2.2 Fatigue tests

The testing of the hinge in the previous chapter is also done with the prototype. This time both tests are combined in one test. The prosthesis is first closed with a force of 60 N, when the hand is closed its tips are pressed with a force of 10 N. This represents picking a pack of sugar.

This procedure is repeated for 20.000 times, a photo of the prosthesis is given in figure 31. From the photo it is clear that the prosthesis is able to last for 20.000 cycles.

8.2.3 Strength test

The strength of the prototype is also tested. Several important load cases are tested. It is able to lift objects of 10 kg when the hand is in the horizontal position.

Figure 31: The hinge after 20.000 cycles of gripping and picking up

9 Commercial aspects

9.1 Explanation of the name PLYOS

The name plyos is chosen for several reasons: Firstly the prosthesis is made out of plies, this creates a significant difference in comparison with other prosthesis. Even the cardboard hook had round parts, which cost more space and cost more energy to create. Therefore the first part of the product name is 'ply'. With this in mind the name is extended to plyos, plyos is short for plyometrics.[25] Plyometrics is a type of exercise training designed to produce fast, powerful movements, and improve the functions of the nervous system. This is exactly what is intended with the plyos prehensor. It is designed to create powerful grips, more powerful than the competition. With the passive gripping the fatigue of the user is decreased, while keeping a powerful grip.

9.2 Implementation in the commercial world

Because of the low rate of UE amputees in the world it is hard to get a competitive position in this world. Especially since the developed countries are more interested in more advanced prostheses. This means the products has to be commercialized as a product that is intentionally for developing countries or people without proper health insurance. There are several competitors in this field, which are mentioned in this report.

To implement this prosthesis in existing programs it is wise to find a local producer of cardboard. This helps to improve the local economy to the fullest. Another wise aspect of the introduction to the market is to create more prosthetic and orthotic devices of the same material. A prosthetic leg is more common, so it can suppress the cost price of the base material. Also an agreement with innova medical can be made. In this way the prosthesis can lift with the upcoming interest in this splint. To improve the implementation and decrease production times it is also wise to improve on aids for gluing the parts together. With molds the gluing of the prosthesis can be performed easier. In this way the production times will be lower and the expertise of the producer can be less. In the most perfect situation the aid is so much, the amputee can construct its own prosthesis. This will delete the production costs totally. Also the device will be more part of the owner. A device that is created by the user feels more like your own.

So for a summary, the material has to be made locally. Once the production has started, other products with the same material have to be developed. The final construction has to be automized or aided so the production times decreases.

10 Discussion & conclusion

The design created in this thesis started with the list of demands, in this chapter these demands are compared with the final design of the Plyos prehensor.

10.1 Cosmetics

10.1.1 Dimensions should be natural

Figure 32: Healthy hand and Plyos hand in resting position

From this figure it is seen that the prehensor looks a lot like a healthy hand in the resting position from the top. Because it has only two digits the side view of the prehensor look unnatural. This is done to reduce the weight of the prosthesis and therefore be more comfortable.

10.1.2 Dimensions of hand (l x w x h): < 163 [mm] x 71 [mm] x 54 [mm]

the dimensions of the hand are: 140 x 90 x 22. This is in the order of the size of a human hand.

10.1.3 Length thumb part = length to opposite thumb [mm]

The basic design of the hand is created by copying a healthy right hand. So the length of the thumb is the size of a healthy thumb.

10.1.4 Printed in different skin tones

The cardboard which is used also exists in a printed form. In this research no printing is done. Only a few parts of the prehensor need printing for cosmetic reasons. Other parts might be printed with instructions, this will further increase the ease of construction.

10.2 Comfort

10.2.1 Weight should be < 150g

The demand for weight is met with a good buffer. The prosthesis is weighed to be 122

g. This is well below the demand given at the start of this research. This is 72% of the weight of the V2P prehensor, the most advanced competitor on cheap prostheses. This will be the main selling point of the prosthesis.

In the tests is also shown that te prosthesis cannot lift an object of 15 kg, this is less than other prostheses. Therefore the strength on impact is not good. To improve this ability maybe more material is needed at the weak spots. This will increase the weight of the prosthesis, but with an increase of 50% of its weight the Plyos prehensor will still be lighter than every competitor.

A decrease of the weight is also possible when a reliable model can be made. For this reliable model extra software and data on the specific cardboard are needed. The testing of cardboard can be done according to the norms, which are extensive. With data on short span compression, puncture resistance and impact strength a reliable model can be created. When this model is complete a FEM analasys can be made, this creates reliable models.

10.2.2 Harness

All calculations which require the actuation force as an input are assumed to have BP actuation with a shoulder harness. This is done because the shoulder harness is the most intensively used method for actuating aBP prostheses.

10.2.3 Soft inside

The designed arm portion is not tested, but the mechanism is clear. It has basically no soft inside, but a bandage provides the soft skin interaction. This is common with other prostheses that are currently used.

10.2.4 Smooth design to avoid dirt

The end design has three openings to the inside mechanism. The openings are as small as possible. But because of the swelling of cardboard when it is wet openings are necessary to prevent jamming when the prosthesis is wet. In the first design a large opening was present at the inside of the prehensor. This gap was closed, which also improved the strength of the prosthesis. In the water test it was clear that water could enter the mechanism quite easily. This caused swelling of the internal mechanism, which caused jamming and serious pinch force reduction.

10.2.5 Wear temperature and Use of biocompatible materials: non toxic or allergic triggering parts

This aspect is not tested, but for the arm portion the Fix2Move cardboard is implemented in the design. This cardboard is created to feel good when it is in contact with the skin. Therefore the expectations are that this cardboard will improve the wear temperature of the prosthesis. The same holds for the skin interaction in the light of toxicity and allergic reactions. The cardboard that is in contact with the stump is already used in the same situation, so this won't be a problem.

10.2.6 Wear on clothes

This aspect is also not tested, but BP prosthesis have the reputation to wear clothes easily with the bowden cable. To reduce the wear an angle in the connection point is created, but this only has a small effect.

10.3 Control

A good looking comfortable prosthesis should be easy to control, because this is the initial goal of the prosthesis. Therefore this is one of the most important parts of the prosthesis.

10.3.1 ease of picking up objects

In the design the different types of gripping are considered. Six out of seven prehension patterns are simulated in the end design. With active control four different prehension patterns can be generated. When passive gripping is used six prehension patterns can be used. This creates a versatile gripping situations, which create endless possibilities to pick objects.

10.3.2 Line of sight: large as possible

The lack of proprioception creates the need of increased visual feedback. To make it easier to see, the design is basically 2D. When the top of the prosthesis is seen, it is easy to extrapolate this position. Therefore it is easy to see where the prosthesis is in space.

10.3.3 Body-powered: cable actuated voluntary closing

This design is met, it is shown that the prosthesis can compete with current VC prostheses. The pinch force is a competitor for the first place, in new conditions

10.3.4 Grip diameter: 8 [mm] - 70 [mm]

This design is met, the maximal opening of the prosthesis is 72 *mm*. This is enough to hold a bottle of water or wine. Both types of gripping can generate enough gripping force to hold these objects. This opening diameter is the largest of all VC prostheses, so it can pick larger objects and is thus more versatile. When those objects are gripped they also are stable because of the straight sides of the digits. This creates enough area to provide enough friction force to hold the objects.

10.4 Costs

10.4.1 < €50,-

The prosthesis is made out of cardboard, which is cheap. The humerus immobilizer is available for €13,- so the price of the cardboard in this prehensor will probably lie in this range. For the hinge and the connection points a RVS rod with a diameter of 5 *mm* is used, which is currently available for the price of €5,60/m. Hair elastics cost €2,99 per ten pieces. The actuation cable will cost €1,60/m, approximately 500 *mm* is needed. High performance glue (D4-norm) costs €14,05/750 g.

The prosthesis will probably cost something in the range of:

Table 5: Estimated material costs

Cardboard	€10,-
RVS rod 150 mm of ø $5mm$	€0,84
Two hair elastics	€0,60
RVS cable $0.5m$	€0,80
Glue (D4-norm)	€1,-
Total	€13,24

10.4.2 production time should be low and production should be easy and intuitive

Glueing plates on top of each other is by far the most simple way to make this design. A simple press with the mold is the only thing that is needed to create the right pieces. No difficult corners or extra modifications have to be made. The education for creating this prosthesis is easy to do, because the instruction can be printed on the pieces itself. Therefore the production time will be low, when the pieces are pinched out only glueing needs to be done. Glueing will take about ten minutes, this must be done in at least two steps. After each step the glue needs to dry for four hours. So the prosthesis is ready within a day, with only half an hour of men hour.

10.4.3 Transportation costs should be low

Because no round shapes are used, but only flat plies, the plyos prosthesis can be transported compactly. Instructions can be printed on the plates, which also negates the need of a manual.

10.4.4 locally available material must be used

The creation of cardboard is an energy consuming process, therefore it cannot be made locally. A factory in Africa might be used to produce the cardboard. There are cardboard factories in Africa.[26]

10.5 Strength

10.5.1 able to do ADL

The first thing that is looked into is the pinch force the plyos prehensor can generate. This is very good compared to the competitors. The introduction of passive gripping even further improves the abilities of the user to create firm grips with a reliable gripping. The use of passive gripping decreases the fatigue, so it increases the wearing time. Overall this prosthesis will be able to do ADL. The prosthesis can create a pinch force of 34 N with an actuation force of 75 N This is still too high, but the extreme cases can be performed with passive gripping.

10.5.2 Mass object to lift > 250 [N]

This demand cannot be met. The prosthesis broke with a weight of 15 kg. It failed near the hinge, where the construction is only two layers thick. At this place the area is small, so a lot of stress is present at this place. Another weak point of this point is the instant transition from two to five layers. This creates a stress concentration at the point of failure. Possible changes are increasing the amount of layers, or increasing the area by making the prosthesis wider at this point.

10.5.3 Should perform ADL for at least three months

The fatigue of the prosthesis is tested at room temperature, 20.000 cycles are performed with an actuation force of 60 N. With the assumption of 150 gripping movements a day, this stands for 4.5 months. The prosthesis was still working properly after these cycles, but one part weared off a lot. This is the part where the actuation cable makes a sharp corner. After 20.000 cycles approximately 10 mm was worn off. This decreased the arm of the actuation torque, which resulted in a moment of $3.5 \cdot 40 = 140Nmm$, which is $40Nmm$ less. However, the fatigue test was done with three actuations of $60N$ every second. This creates a lot of impact on this specific spot, therefore it is unlikely the prosthesis will be worn down as much as in the test at this point. Wear on the hinge could not be detected with the naked eye, so this part will hold for the demanded time. This test was done in only dry conditions, because the assumption is made that the inside of the prosthesis does not get as wet as the outside of the prosthesis. Wetting of the prosthesis also causes delamination. The delamination properties of cardboard are not tested. The wear of the digits in intensive use is also not tested, since this is hard to do in a machine. Therefore it is advised to test this prosthesis in real life.

10.5.4 wet-strength/coated

The wet strength test did not give good results, a not must be given that the wet test was done after the fatigue test. So the arm of the actuation torque was already decreased. This should have lowered the aquired pinch force with a approximately $4N$, but the drop was $10N$. This was caused by jamming of the prosthesis. The water was also sprayed inside the holes of the prosthesis, so the inside mechanism was sodden. This caused swelling of the cardboard, which caused jamming of the hinge. When it rains, the inside mechanism will most probably not be wetted like this. So in ADL the prosthesis will not suffer as much from this mechanism. In the final design the space between the moving parts is designed to be 0.5 layer. This is 1.45mm, which prevents the mechanism from jamming.

11 Recommendations

From the discussion and conclusion it is clear that the prototype of the plyos prosthetic prehensor shows enormous results. There are however some points which can be improved. The pinch force which is needed in ADL can still not be reached with an activation force of 40 N. This might be solved with an increase of the arm of the torque. This increase causes a wider model of the prehensor, which increases the area of the point of failure. This feature will increase the strength of the prehensor and the gripping abilities.

The real life test are not done yet. This is mainly because no connection to existing socket is made. This type of connection can easily be installed in stead of the cardboard connection. By doing this, the product can also be sold without a socket and a wrist rotation is easily implemented. With real life tests the wear of the digits can be investigated. The passive gripping is only tested on objects, the use of passive gripping is not tested, so the user friendliness is unknown.

The fire resistance of the plyos prosthetic hand is not tested, because glue can be lit, this might be dangerous. The glue is just normal glue, maybe with more contact with the suppliers better glue is possible.

Last, but not least, more material tests should be done to understand the behavior of this type of cardboard better. With extra data and extra software a reliable model can be constructed. With this model weak spots can be recognized and weight optimization is possible.

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Appendix A:Arguments for list of demands

September 22, 2011

Appendix A:Arguments for list of demands

Cosmetics

The life likelyness of current VC prosthesis is low, in the design priorities given by research it is shown to be one of the most important factors [4]. Therefore the hand should look as natural as possible. van der Veld has gathered basic information about the average dimensions of hands and arms [7]. From this research the given demands are extracted.

Comfort

Weight < 145g

A major cause of discomfort is the weight of the prosthesis [4,21]. The lightest prehensor or hook that is found is the V2P prehensor which is 170g. This is a good competitor and therefore the plyos prehensor should have a lower mass.

Harness

The prehensor is assumed to be operated with a shoulder harness. This is because good data about the possibilities with this harness is available. Also the harness is the most common used actuation principle.

Skin interaction

This includes the demands for wear temperature and comfort of socket. Because cardboard shows a solution in this type of socket design a socket should be create with good skin interaction abilities.

Smooth design to avoid dirt

Dirt is the nemesis of a prosthesis. It makes the prosthesis look ugly and it wreckes the mechanism. Therefore the outside of the design should be smooth, while leaving no openings to the mechanism. When the mechanism is shielded from the outside world, it will last longer.

Control

Ease of picking up objects

The prosthesis should be made in such a way that a large variety of objects can be grasped. This influences the shape of the digits of the prehensor.

Line of sight: as large as possible

Because users lack an amount of proprioceptive feedback, the vision of the user has an important role in feedback. Therefore the line of sight should be as large as possible.

Body Powered: cable actuated

This is the same as in the comfort part

Cost

material costs < €50,-

The prosthesis should meet the demands for cost, or else it won't be interesting to use. The LN-4 prosthesis costs this much and is appreciated very much. To give competition the price should be at least lower.

production time should be low, production should be easy and intuitive. Man hour for production: < 2 hours

Because the material costs will be low, production costs will contribute for a substantial part in the costs. Therefore the construction should be easy and intuitive. Preferably a amputee should be able to construct the prosthesis by itself. This will cut out the production costs almost entirely.

Transportation costs should be low

The first products will probably not be constructed in developing countries, because the cardboard will most probably first be created in the Netherlands. To be able to keep the transport costs low the space it should take to keep an unconstructed prosthesis should be as low as possible.

locally available material must be used

When the prosthesis is used in developing countries and a part of the prosthesis breaks, it should be easy to repair it. Therefore every part of the prosthesis should be made out of material which is widely available. This will reduce repair costs and reduce the time to get the parts. In developing countries prostheses are used less because of the lack of money of the users.[3]

Strength

able to do ADL,Mass object to lift $>$ 250 [N]*

Cardboard is known to be a vulnerable material, therefore the strength properties of the final design should be tested. The user of the prosthesis should be able to perform ADL tasks. A maximum pinch force of 34N is needed to perform ADL tasks. This pinch force should not cause damage to the digits. Also objects should be lifted. In previous research the demand is set to 250 N, this is the maximum a person is allowed to lift at work. This demand is extreme. But when the prosthesis is able to lift 250 N it will also suffer less from fatigue or impacts.

Should perform ADL for at least three months - Fatigue

Cardboard is most of the time used in static situations. Therefore the fatigue behavior of cardboard is unknown. The fatigue strength of parts that are dynamically loaded should be tested. Simulations of lifting and grabbing for at least three months should be met.

wet-strength/coated

Cardboard is known to have strength reduction when it is wet. The prosthesis should be able to function while it is wet.

Appendix B: Testing of cardboard

September 22, 2011

Appendix B: Testing of cardboard

To give a basic understanding of the properties of the cardboards which are used this appendix is created. Every specimen needs to be conditioned before it is tested. After the specimen has the right condition it can undergo its test. In this research a tensile test is done. Both processes will be explained in separate paragraphs.

Conditioning of cardboard

Conditioning of cardboard is regulated in ISO 187 [reference book]. The climates the cardboard should be conditioned in are specified as:

- European conditions $\rightarrow$ temperature: (23 $\pm$ 1) $\circ$C relative humidity: (50 $\pm$ 2)%

- Tropical conditions $\rightarrow$ temperature: (27 $\pm$ 1) $\circ$C relative humidity: (65 $\pm$ 2)%

Figure 1: Conditioning the speciments in the moisture oven

To reach these conditions the cardboard samples (specific information about size in next chapter) are put into a moisture oven (figure ??). The samples are ready when in an hour difference the mass of the specimens is less than 0.25%. Because uniform conditions are reached when this happens the samples are not dried before conditioning.

Figure 2: Tensile device with specimen

Tensile tests

Tensile testing is regulated by ISO 1924-2:2007. In this norm several headlines are described, these will be explained in this paragraph.

Specimen

For a cardboard tensile test a specimen without a strain gauge is used. The specimens are cut to the length of (230 $\pm 2)mm$ and a width of (15 $\pm 0.1)mm$. This is done with a paper cutter to provide straight lines. The specimens are conditioned in the oven and need to be conditioned during the test. Because the tensile device did not had environmental control, the specimens are packed into aluminum foil to keep the right conditions.

Testing parameters

Tensile testing is done in a zchweck This device device which is used is shown in figure ??. The span width of the specimen is (180 $\pm 1)mm$. According to the norm the specimen should be clamped with a gripper which has one round gripper. This is to avoid failing of the specimen near the grip area. This gripper was not available, but a test is a pass when failure of the specimen occurs at at least $15mm$ from the gripper. With the flat gripper most of the specimens failed within this range, so a flat gripper is used. When the specimen is spanned into the device, the device pull at the specimen at a speed of $20mm/s$. Tests are performed in the MD and CD in both conditions. When 10 specimens are tested a consistent result is gathered. Detailed documentation of the test are shown in the next pages.

Zwick / Roell

Test report

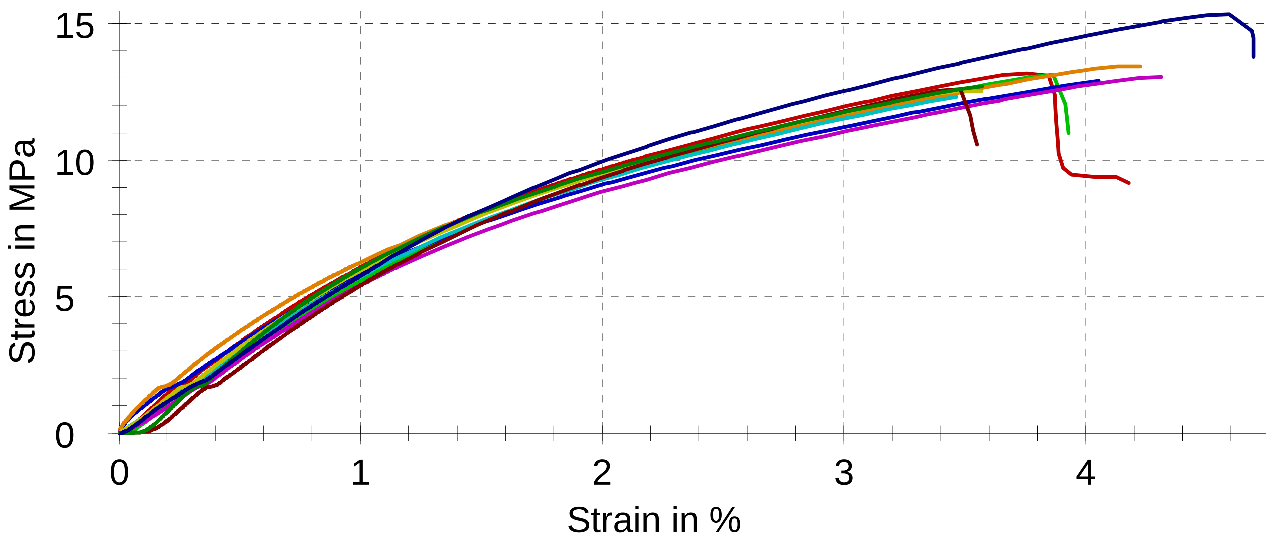
Customer	:	Specimen type	:
Job no.	:	Pre-treatment	:
Test standard	:	Tester	:
Type and designation of	:	Notes...	:
Material	:	Machine data	:
Specimen removal	:		

Speed E-Modulus : 20 mm/min
Test speed : 20 mm/min

Test results:

Legends	Specimen no.	Text	E_{mod} GPa	yield stress (Rp 0.2%) MPa	Tensile strength MPa	dL at break %
	1	CW - 100% , HEAT - NO	0,430	10,3	13,2	4,2
	2	CW - 100% , HEAT - NO	0,556	8,43	13,1	3,9
	3	CW - 100% , HEAT - NO	0,529	7,96	12,9	4,1
	4	CW - 100% , HEAT - NO	0,570	7,94	13,4	4,2
	5	CW - 100% , HEAT - NO	0,543	7,80	13,0	4,3
	6	CW - 100% , HEAT - NO	0,565	8,15	12,3	3,5
	7	CW - 100% , HEAT - NO	0,591	8,16	12,5	3,6
	8	CW - 100% , HEAT - NO	0,597	8,40	12,6	3,6
	9	CW - 100% , HEAT - NO	0,652	8,01	12,7	3,6
	10	CW - 100% , HEAT - NO	0,597	9,11	15,3	4,7

Series graph:



Statistics:

Series n = 10	Begin of E-Modulus determination MPa	Specimen no.	E_{mod} GPa	yield stress (Rp 0.2%) MPa	F_{x1} MPa	F_{x2} N
$\bar{x}$	2	6	0,563	8,43	12,8	374
s	0,000	3	0,0581	0,768	2,88	12,2
ν	0,00	55,05	10,32	9,11	22,45	3,28

Series n = 10	Tensile strength MPa	dL(plast.) at F_{max} mm	F (0mm) N	dL at F_{max} %	F_{Break} N	dL at break %	a_0 mm	b_0 mm	S_0 mm²
$\bar{x}$	13,1	2,8	0,08	3,9	483	4,0	2,65	15	39,75
s	0,849	0,6	1,97	0,4	57,7	0,4	0,000	0,000	0,00
ν	6,47	21,21	-	10,34	11,96	10,35	0,00	0,00	0,00

Zwick / Roell

Test report

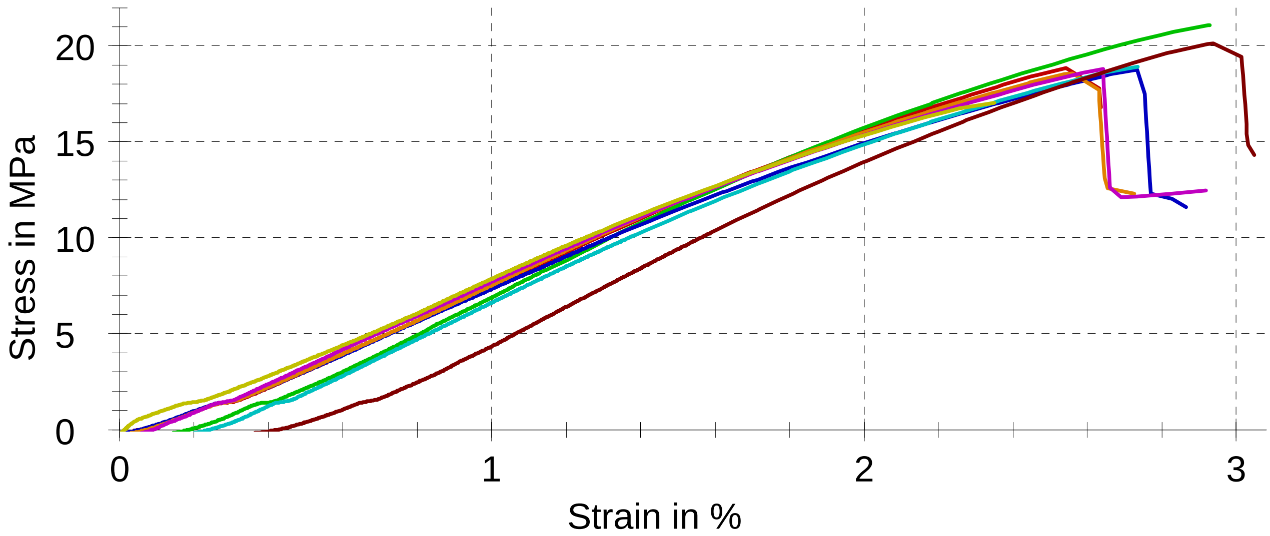
Customer	:		Specimen type	:
Job no.	:		Pre-treatment	:
Test standard	:		Tester	:
Type and designation of	:		Notes...	:
Material	:		Machine data	:
Specimen removal	:			

Speed E-Modulus : 20 mm/min
Test speed : 20 mm/min

Test results:

Legends	Specimen no.	Text	E_{mod} GPa	yield stress (Rp 0.2%) MPa	Tensile strength MPa	dL at break %
	1	CW - 100% , HEAT - NO	0,893	18,0	18,8	2,6
	2	CW - 100% , HEAT - NO	0,964	18,3	21,1	2,9
	3	CW - 100% , HEAT - NO	0,855	16,6	18,7	2,9
	4	CW - 100% , HEAT - NO	0,894	17,2	18,6	2,7
	5	CW - 100% , HEAT - NO	0,883	16,7	18,8	2,9
	6	CW - 100% , HEAT - NO	0,944	16,4	18,9	2,7
	7	CW - 100% , HEAT - NO	0,848	16,7	17,0	2,3
	8	CW - 100% , HEAT - NO	0,998	18,3	20,1	3,0

Series graph:



Statistics:

Series n = 8	Begin of E-Modulus determination MPa	Specimen no.	E_{mod} GPa	yield stress (Rp 0.2%) MPa	F_{x1} MPa	F_{x2} N
$\bar{x}$	2	5	0,910	17,3	-	602
s	0,000	2	0,0534	0,813	-	22,7
ν	0,00	54,43	5,87	4,71	-	3,77

Series n = 8	Tensile strength MPa	dL(plast.) at F_{max} mm	F (0mm) N	dL at F_{max} %	F_{Break} N	dL at break %	a_0 mm	b_0 mm	S_0 mm²
$\bar{x}$	19,0	0,7	-13,79	2,7	618	2,8	2,65	15	39,75
s	1,19	0,1	0,89	0,2	137	0,2	0,000	0,000	0,00
ν	6,25	19,18	-6,46	7,45	22,14	7,85	0,00	0,00	0,00

Test report

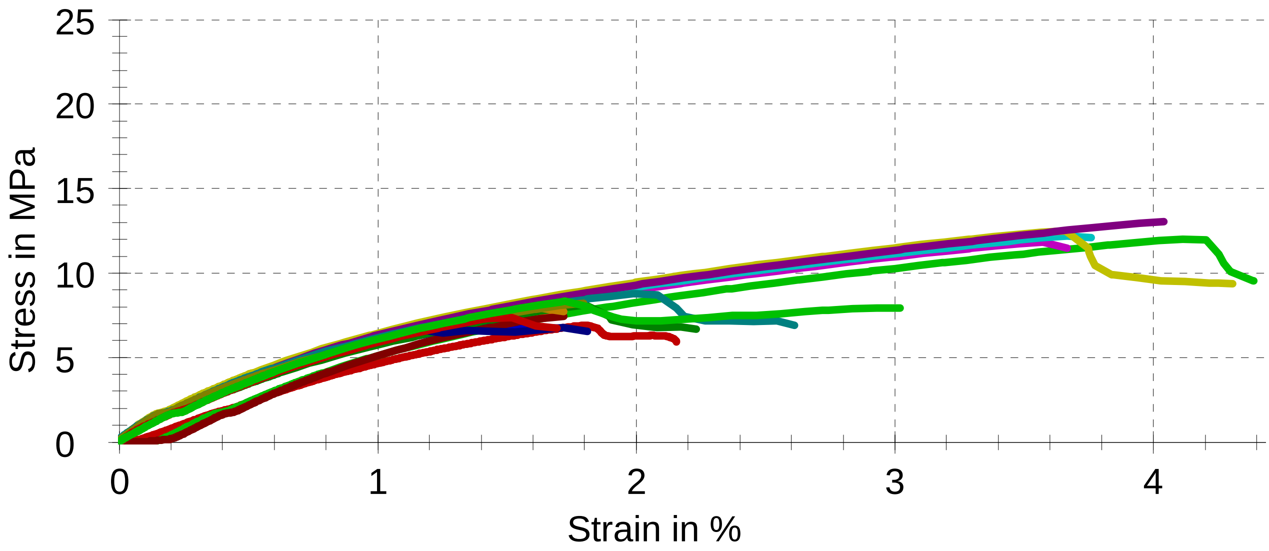
Customer	:		Specimen type	:	
Job no.	:		Pre-treatment	:	
Test standard	:		Tester	:	
Type and designation of	:		Notes...	:	
Material	:		Machine data	:	
Specimen removal	:				

Speed E-Modulus : 20 mm/min
Test speed : 20 mm/min

Test results:

Legends	Specimen no.	Text	E_{mod} GPa	yield stress (Rp 0.2%) MPa	Tensile strength MPa	dL at break %
	1	CW - 100% , HEAT - NO	0,502	-	6,90	2,2
	2	CW - 100% , HEAT - NO	0,603	6,61	12,0	4,4
	3	CW - 100% , HEAT - NO	0,651	5,92	6,89	1,7
	4	CW - 100% , HEAT - NO	0,652	6,77	7,79	1,7
	5	CW - 100% , HEAT - NO	0,664	6,64	11,8	3,7
	6	CW - 100% , HEAT - NO	0,670	6,79	12,2	3,8
	7	CW - 100% , HEAT - NO	0,686	6,88	12,5	4,3
	8	CW - 100% , HEAT - NO	0,638	6,69	7,46	1,7
	9	CW - 100% , HEAT - NO	0,594	6,50	8,11	2,2
	10	CW - 100% , HEAT - NO	0,663	6,53	6,77	1,8
	11	CW - 100% , HEAT - NO	0,664	6,73	7,94	1,7
	12	CW - 100% , HEAT - NO	0,699	6,84	13,0	4,0
	13	CW - 100% , HEAT - NO	0,657	6,56	8,78	2,6
	14	CW - 100% , HEAT - NO	0,632	6,44	8,19	1,8
	15	CW - 100% , HEAT - NO	0,620	6,70	7,34	1,7
	16	CW - 100% , HEAT - NO	0,652	6,87	8,35	3,0

Series graph:



Statistics:

Series n = 16	Begin of E-Modulus determination MPa	Specimen no.	E_{mod} GPa	yield stress (Rp 0.2%) MPa	F_{x1} MPa	F_{x2} N
$\bar{x}$	1	9	0,640	6,63	12,1	322
s	0,000	5	0,0461	0,239	0,421	45,8
ν	0,00	56,01	7,19	3,61	3,48	14,24

Series n = 16	Tensile strength MPa	dL(plast.) at F_{max} mm	F (0mm) N	dL at F_{max} %	F_{Break} N	dL at break %	a_0 mm	b_0 mm	S_0 mm²
$\bar{x}$	9,13	1,8	0,86	2,4	327	2,6	2,6	15	39,00
s	2,30	1,3	3,59	1,0	83,9	1,0	0,000	0,000	0,00
ν	25,17	71,73	-	43,66	25,69	39,49	0,00	0,00	0,00

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Test report

Customer	:		Specimen type	:
Job no.	:		Pre-treatment	:
Test standard	:		Tester	:
Type and designation of	:		Notes...	:
Material	:		Machine data	:
Specimen removal	:			

Speed E-Modulus : 20 mm/min
Test speed : 20 mm/min

Test results:

Legends	Specimen no.	Text	E_{mod} GPa	yield stress (Rp 0.2%) MPa	Tensile strength MPa	dL at break %
	1	CW - 100% , HEAT - NO	1,05	14,0	18,7	2,7
	2	CW - 100% , HEAT - NO	1,01	14,3	19,2	2,8
	3	CW - 100% , HEAT - NO	0,992	14,6	18,8	2,7
	4	CW - 100% , HEAT - NO	1,02	14,5	18,9	2,8
	5	CW - 100% , HEAT - NO	1,08	14,6	19,7	2,6
	6	CW - 100% , HEAT - NO	0,913	15,3	19,2	2,8
	7	CW - 100% , HEAT - NO	1,02	14,9	18,4	2,4
	8	CW - 100% , HEAT - NO	0,942	13,7	17,3	2,7
	9	CW - 100% , HEAT - NO	0,981	14,1	18,2	2,5
	10	CW - 100% , HEAT - NO	1,06	13,8	18,0	2,8
	11	CW - 100% , HEAT - NO	1,05	14,2	19,1	2,5
	12	CW - 100% , HEAT - NO	1,07	13,8	19,3	2,6
	13	CW - 100% , HEAT - NO	1,10	15,4	20,1	2,8
	14	CW - 100% , HEAT - NO	1,04	14,0	19,6	2,8

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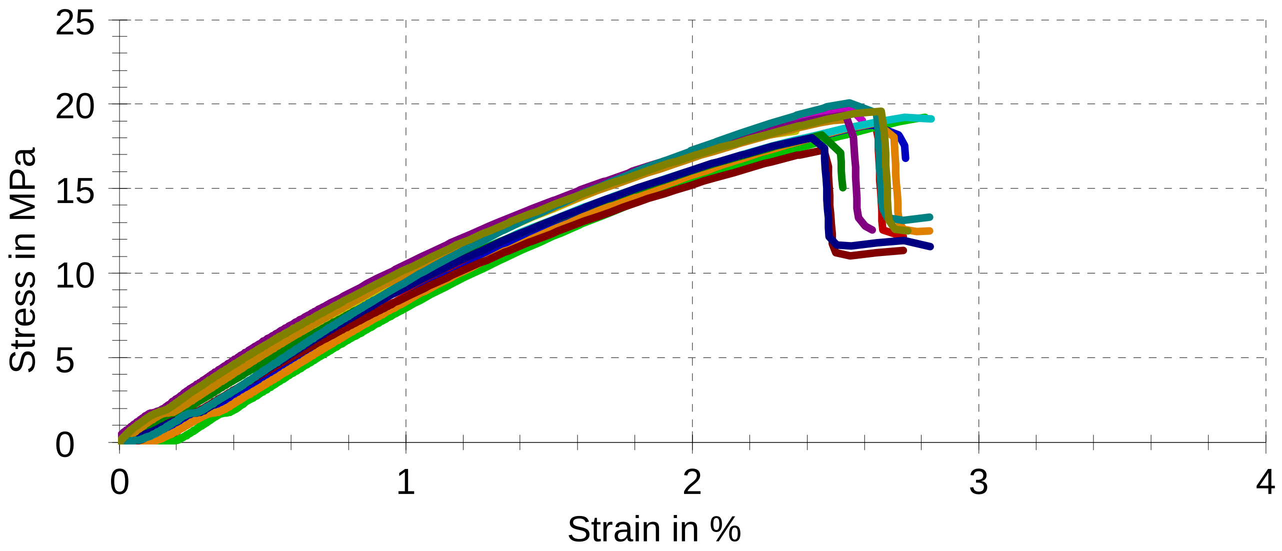
Series graph:



Statistics:

Series n = 14	Begin of E-Modulus determination MPa	Specimen no.	E_{mod} GPa	yield stress (Rp 0.2%) MPa	F_{x1} MPa	F_{x2} N
$\bar{x}$	2	8	1,02	14,4	-	637
s	0,000	4	0,0542	0,544	-	26,6
ν	0,00	55,78	5,29	3,79	-	4,18

Series n = 14	Tensile strength MPa	dL(plast.) at F_{max} mm	F (0mm) N	dL at F_{max} %	F_{Break} N	dL at break %	a_0 mm	b_0 mm	S_0 mm^2
$\bar{x}$	18,9	1,2	-1,70	2,6	592	2,7	2,6	15	39,00
s	0,744	0,1	5,99	0,1	127	0,1	0,000	0,000	0,00
ν	3,94	12,33	-	4,84	21,39	5,39	0,00	0,00	0,00

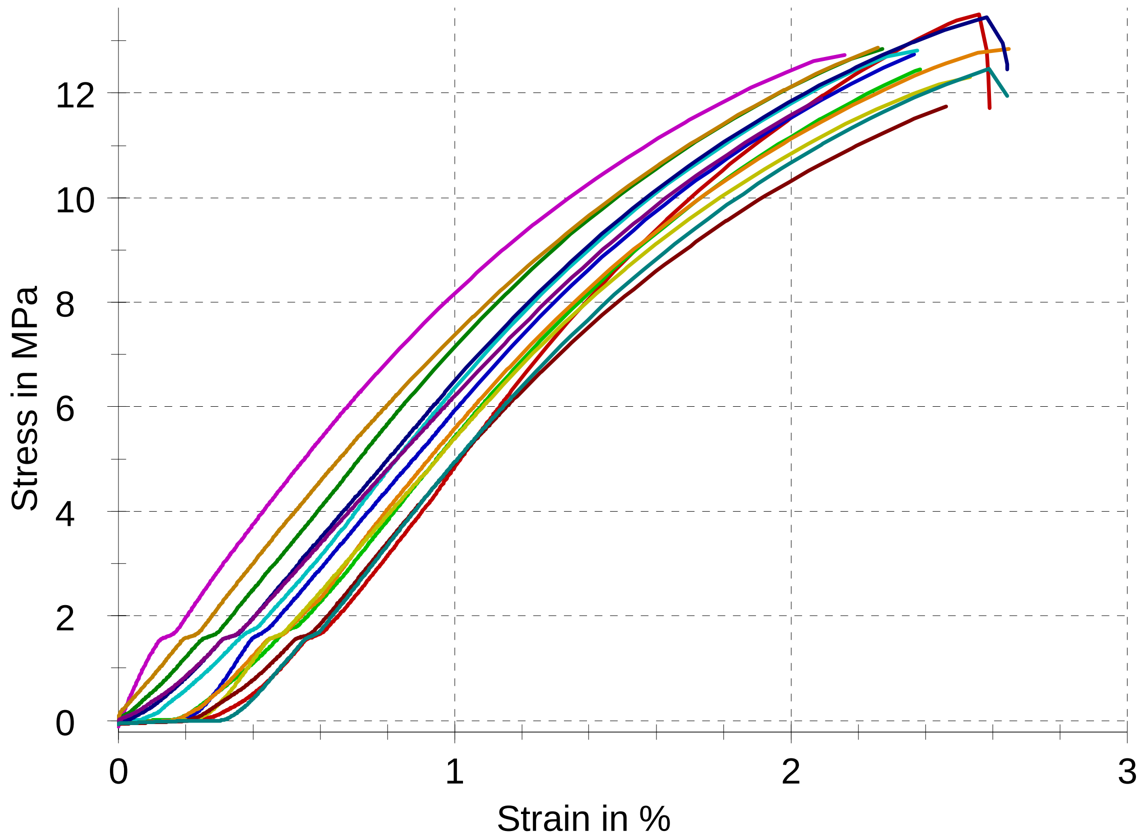
Test report

Customer	:	Specimen type	:
Job no.	:	Pre-treatment	:
Test standard	:	Tester	:
Type and designation of	:	Notes...	:
Material	:	Machine data	:
Specimen removal	:		

Speed E-Modulus : 20 mm/min
Test speed : 20 mm/min

Test results:

Legends	Specimen no.	Text	E_{mod} GPa	yield stress (Rp 0.2%) MPa	Tensile strength MPa	dL at break %
	1	CW - 100% , HEAT - NO	0,843	11,5	13,5	2,6
	2	CW - 100% , HEAT - NO	0,791	10,5	12,5	2,4
	3	CW - 100% , HEAT - NO	0,755	11,0	12,7	2,4
	4	CW - 100% , HEAT - NO	0,803	10,2	12,8	2,6
	5	CW - 100% , HEAT - NO	0,836	10,1	12,7	2,2
	6	CW - 100% , HEAT - NO	0,799	10,8	12,8	2,4
	7	CW - 100% , HEAT - NO	0,734	10,4	12,3	2,5
	8	CW - 100% , HEAT - NO	0,758	9,62	11,8	2,5
	9	CW - 100% , HEAT - NO	0,793	10,7	12,8	2,3
	10	CW - 100% , HEAT - NO	0,754	11,1	13,5	2,6
	11	CW - 100% , HEAT - NO	0,774	10,4	12,9	2,3
	12	CW - 100% , HEAT - NO	0,712	11,2	11,9	2,1
	13	CW - 100% , HEAT - NO	0,794	9,98	12,5	2,6



Series graph:

Statistics:

Series n = 13	Begin of E-Modulus determination MPa	Specimen no.	E_{mod} GPa	yield stress (Rp 0.2%) MPa	F_{x1} MPa	F_{x2} N
$\bar{x}$	2	7	0,780	10,6	-	482
s	0,000	4	0,0378	0,536	-	26,1
ν	0,00	55,63	4,84	5,06	-	5,41

Series n = 13	Tensile strength MPa	dL(plast.) at F_{max} mm	F (0mm) N	dL at F_{max} %	F_{Break} N	dL at break %	a_0 mm	b_0 mm	S_0 mm^2
$\bar{x}$	12,7	1,0	-2,50	2,4	521	2,4	2,8	15	42,00
s	0,509	0,2	2,13	0,2	18,7	0,2	0,000	0,000	0,00
ν	4,02	19,85	-	7,28	3,59	7,78	0,00	0,00	0,00

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Test report

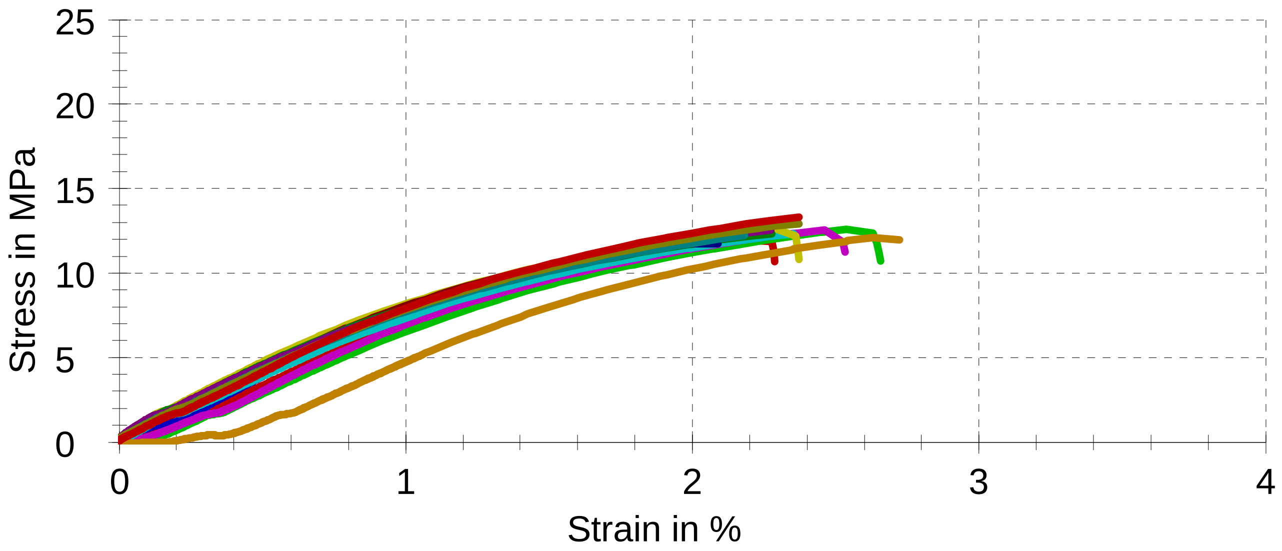
Customer	:	Specimen type	:
Job no.	:	Pre-treatment	:
Test standard	:	Tester	:
Type and designation of	:	Notes...	:
Material	:	Machine data	:
Specimen removal	:		

Speed E-Modulus : 20 mm/min
Test speed : 20 mm/min

Test results:

Legends	Specimen no.	Text	E_{mod} GPa	yield stress (Rp 0.2%) MPa	Tensile strength MPa	dL at break %
	1	CW - 100% , HEAT - NO	0,765	9,62	11,9	2,3
	2	CW - 100% , HEAT - NO	0,776	9,59	12,6	2,7
	3	CW - 100% , HEAT - NO	0,887	9,05	11,8	2,1
	4	CW - 100% , HEAT - NO	0,864	8,83	12,0	2,2
	5	CW - 100% , HEAT - NO	0,877	9,18	12,6	2,5
	6	CW - 100% , HEAT - NO	0,778	9,47	12,3	2,4
	7	CW - 100% , HEAT - NO	0,857	9,39	12,7	2,4
	8	CW - 100% , HEAT - NO	0,863	9,64	13,0	2,4
	9	CW - 100% , HEAT - NO	0,834	9,06	12,3	2,3
	10	CW - 100% , HEAT - NO	0,805	9,40	11,8	2,1
	11	CW - 100% , HEAT - NO	0,769	9,53	12,1	2,7
	12	CW - 100% , HEAT - NO	0,806	9,46	12,6	2,3
	13	CW - 100% , HEAT - NO	0,814	9,37	12,2	2,2
	14	CW - 100% , HEAT - NO	0,802	9,89	12,9	2,4
	15	CW - 100% , HEAT - NO	0,851	10,1	13,3	2,4

Series graph:



Statistics:

Series n = 15	Begin of E-Modulus determination MPa	Specimen no.	E_{mod} GPa	yield stress (Rp 0.2%) MPa	F_{x1} MPa	F_{x2} N
$\bar{x}$	2	8	0,823	9,44	-	472
s	0,000	4	0,0413	0,320	-	20,5
ν	0,00	55,90	5,02	3,39	-	4,34

Series n = 15	Tensile strength MPa	dL(plast.) at F_{max} mm	F (0mm) N	dL at F_{max} %	F_{Break} N	dL at break %	a_0 mm	b_0 mm	S_0 mm²
$\bar{x}$	12,4	1,4	1,91	2,3	485	2,3	2,7	15	40,50
s	0,460	0,2	4,82	0,2	33,6	0,2	0,000	0,000	0,00
ν	3,71	11,98	-	7,15	6,92	7,83	0,00	0,00	0,00

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Test report

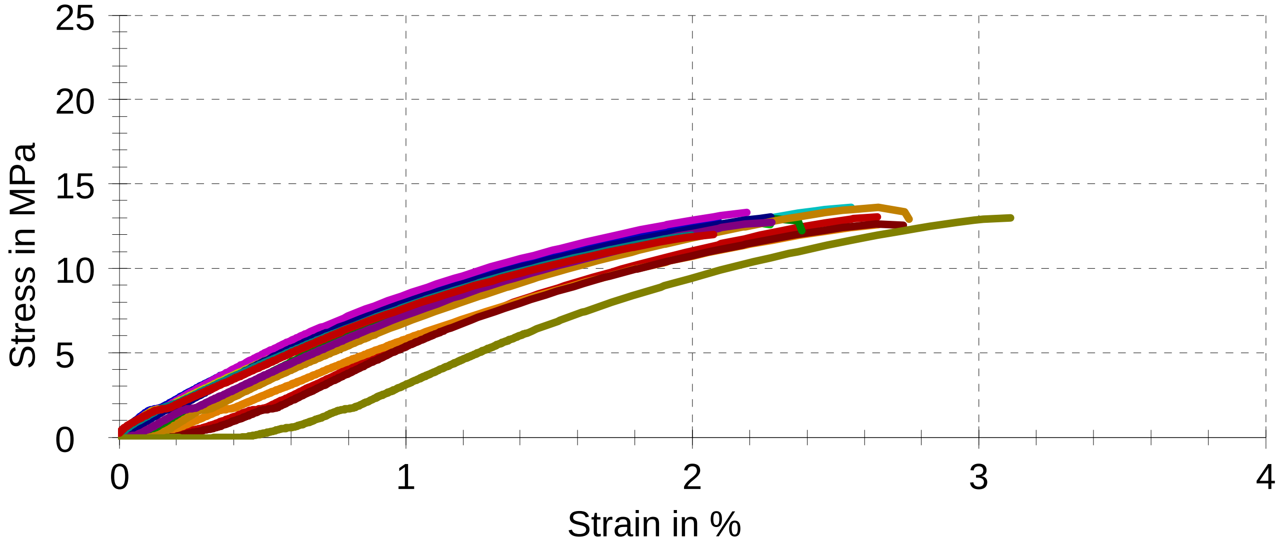
Customer	:	Specimen type	:
Job no.	:	Pre-treatment	:
Test standard	:	Tester	:
Type and designation of	:	Notes...	:
Material	:	Machine data	:
Specimen removal	:		

Speed E-Modulus : 20 mm/min
Test speed : 20 mm/min

Test results:

Legends	Specimen no.	Text	E_{mod} GPa	yield stress (Rp 0.2%) MPa	Tensile strength MPa	dL at break %
	1	CW - 100% , HEAT - NO	0,760	10,3	13,0	2,6
	2	CW - 100% , HEAT - NO	0,824	9,67	12,8	2,3
	3	CW - 100% , HEAT - NO	0,817	9,93	12,8	2,1
	4	CW - 100% , HEAT - NO	0,678	10,0	12,6	2,6
	5	CW - 100% , HEAT - NO	0,883	9,96	13,3	2,2
	6	CW - 100% , HEAT - NO	0,870	9,75	13,6	2,6
	7	CW - 100% , HEAT - NO	0,770	10,2	12,4	2,1
	8	CW - 100% , HEAT - NO	0,797	9,66	12,6	2,7
	9	CW - 100% , HEAT - NO	0,862	9,97	13,0	2,4
	10	CW - 100% , HEAT - NO	0,857	9,65	13,0	2,3
	11	CW - 100% , HEAT - NO	0,758	10,3	13,6	2,8
	12	CW - 100% , HEAT - NO	0,775	10,4	12,7	2,3
	13	CW - 100% , HEAT - NO	0,757	10,1	11,9	2,0
	14	CW - 100% , HEAT - NO	0,740	10,1	13,0	3,1
	15	CW - 100% , HEAT - NO	0,758	9,95	12,0	2,1

Series graph:



Statistics:

Series n = 15	Begin of E-Modulus determination MPa	Specimen no.	E_{mod} GPa	yield stress (Rp 0.2%) MPa	F_{x1} MPa	F_{x2} N
$\overline{x}$	2	8	0,794	10,0	-	475
s	0,000	4	0,0576	0,241	-	37,5
ν	0,00	55,90	7,25	2,41	-	7,88

Series n = 15	Tensile strength MPa	dL(plast.) at F_{max} mm	F (0mm) N	dL at F_{max} %	F_{Break} N	dL at break %	a_0 mm	b_0 mm	S_0 mm²
$\overline{x}$	12,8	1,2	0,19	2,4	515	2,4	2,7	15	40,50
s	0,489	0,2	5,09	0,3	18,6	0,3	0,000	0,000	0,00
ν	3,81	15,44	-	13,11	3,62	13,33	0,00	0,00	0,00

Test report

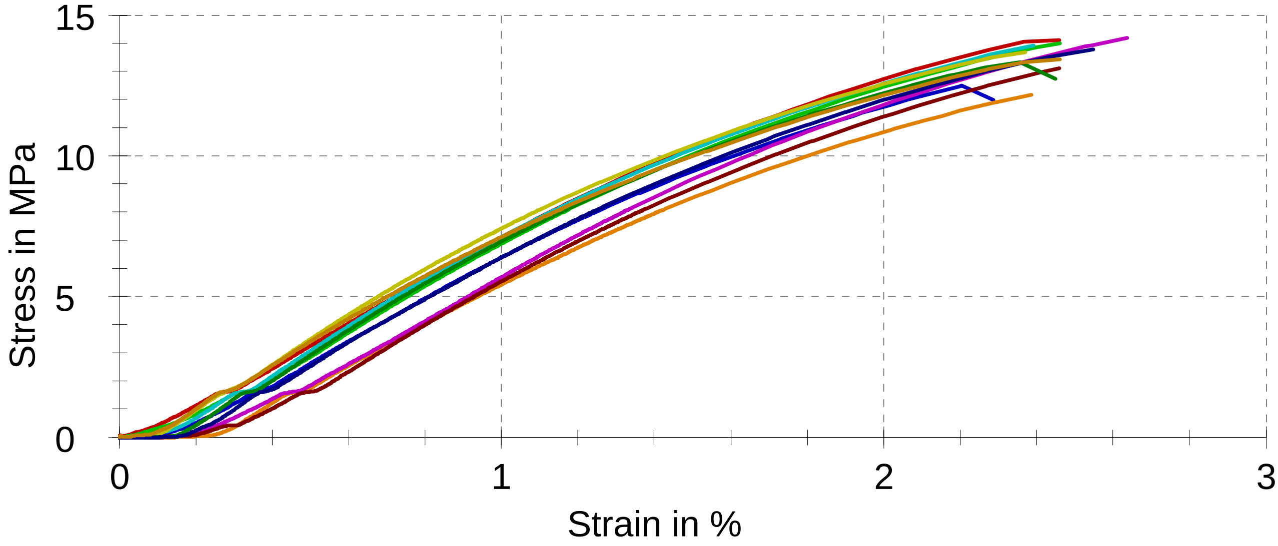
Customer	:		Specimen type	:
Job no.	:		Pre-treatment	:
Test standard	:		Tester	:
Type and designation of	:		Notes...	:
Material	:		Machine data	:
Specimen removal	:			

Speed E-Modulus : 20 mm/min
Test speed : 20 mm/min

Test results:

Legends	Specimen no.	Text	E_{mod} GPa	yield stress (Rp 0.2%) MPa	Tensile strength MPa	dL at break %
	1	CW - 100% , HEAT - NO	0,792	11,6	14,1	2,5
	2	CW - 100% , HEAT - NO	0,792	11,5	14,0	2,5
	3	CW - 100% , HEAT - NO	0,735	11,1	12,5	2,3
	4	CW - 100% , HEAT - NO	0,683	10,9	12,2	2,4
	5	CW - 100% , HEAT - NO	0,762	11,9	14,2	2,6
	6	CW - 100% , HEAT - NO	0,805	11,4	13,9	2,4
	7	CW - 100% , HEAT - NO	0,803	11,1	13,7	2,4
	8	CW - 100% , HEAT - NO	0,755	11,2	13,1	2,5
	9	CW - 100% , HEAT - NO	0,797	11,0	13,3	2,4
	10	CW - 100% , HEAT - NO	0,749	11,5	13,8	2,5
	11	CW - 100% , HEAT - NO	0,748	11,0	13,4	2,5

Series graph:



Statistics:

Series n = 11	Begin of E-Modulus determination MPa	Specimen no.	E_{mod} GPa	yield stress (Rp 0.2%) MPa	F_{x1} MPa	F_{x2} N
$\bar{x}$	2	6	0,765	11,3	-	506
s	0,000	3	0,0371	0,317	-	23,8
ν	0,00	55,28	4,85	2,81	-	4,70

Series n = 11	Tensile strength MPa	dL(plast.) at F_{max} mm	F (0mm) N	dL at F_{max} %	F_{Break} N	dL at break %	a_0 mm	b_0 mm	S_0 mm²
$\bar{x}$	13,5	0,9	-2,34	2,4	561	2,4	2,8	15	42,00
s	0,659	0,2	2,21	0,1	32,4	0,1	0,000	0,000	0,00
ν	4,89	16,16	-	4,58	5,78	3,77	0,00	0,00	0,00

Appendix C: Performance test setup and test descriptions

September 22, 2011

Appendix C: Performance test setup and test descriptions

Basic setup

Apparatus and procedure. A custom-build test bench was used to measure the tensile force and the displacement of the activation cable of the prosthesis. The bench was manually operated. The pinch force applied by the prosthesis was measured using a custom-build pinch force sensor. The sensors were connected to a laptop by a data acquisition interface. All components used are listed in Table I. The bench was used to measure the cable force and the cable excursion together with the pinch force produced by the terminal device.

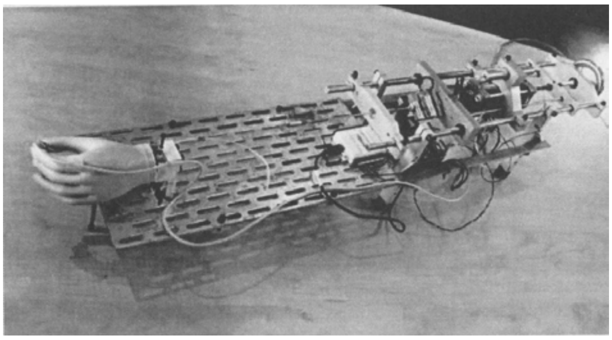


Figure 1: Test setup

All tests considering activation force, elongation and pinch force are done with the setup showed in figure 1

A detailed schematic setup is shown in figure 2

Table 1: Components used in the test bench

Component Disctiption	
Force sensor	Zemic: FLB3G-C3-50kg-6B
Amplifier	Scaime: CPJ
Linear displacement sensor (LVDT)	Schaevitz: LCIT 2000
Power supply	EA: EA-PS 3065-05 B
Computer interface	National Instruments: NI USB-6008
Pinch force sensor	Double leave spring with strain gauges

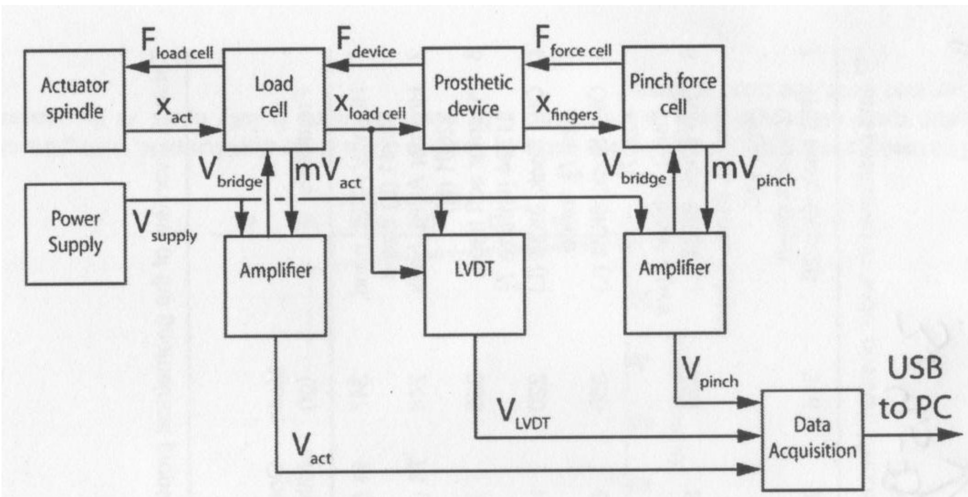


Figure 2: Schematic test setup