The WILMER Appealing Voluntary Closing Prehensor

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ABSTRACT

The voluntary opening prostheses have a limited pinch force, limiting the performance of the users in their daily activities. The proprioceptive feedback provided by these prostheses is inverse and very counterintuitive. This is caused by the voluntary opening operating principle of these prostheses.
In order to improve the functional performance of the WILMER appealing prehensor for toddlers, the Delft Institute of Prosthetics and Orthotics suggested to transform the operating principle of this split-hook from voluntary opening to voluntary closing. Conform this suggestion a new mechanism is designed and prototyped.
Three concepts are proposed and the best among them is further elaborated into a prototype. This prototype is tested using an existing test bench. The energy dissipation is lowered with a factor of 2.5 in comparison with the best performing commercially available voluntary closing prosthesis, which shows the higher efficiency of the proposed design as compared to the currently available prostheses. The force transmission ratio of the prototype is 0.5, representing the ratio between activation force and pinch force. This is comparable with the best available voluntary closing prosthesis. Whereas the new design has no protruding mechanical parts out of the frame compared to the other voluntary closing prostheses, reducing damage to the clothing considerably.
Conform the benefits of this new prosthetic device, it is a better performing voluntary closing prosthesis than the commercially available ones. Its performance together with its appearance makes it a promising alternative for the commercially available VC prostheses for the unilateral below-elbow amputees.

Keywords: prosthetic design, upper limb prostheses, body-powered prostheses, split-hook prostheses, voluntary closing, testing of prostheses

Introduction

The human hand is one of the most complex and challenging structures of the human anatomy to restore or replace. The hand is a complicated sensory mechanism, with incomparable proprioceptive and sensory feedback capacities. Mimicking the human hand is a very complex challenge. It takes a great effort to replace even a few functions of the hand. The two types of prosthetic actuation generally known today are the Body-Powered (BP) and the Externally-Powered (EP).[1]

Externally-Powered (Electric) prostheses

The EP prostheses are commonly controlled using the surface electromyography (EMG). These prostheses provide the user only with visual feedback and some incidental feedback (noise, vibration).[2] The visual monitoring requires high mental load for the control of the EP prostheses[3], as they are not controlled subconsciously.[4]
The EP prostheses do not provide the amputee with any proprioceptive feedback. Absence of this feedback decreases the speed and accuracy of the fine[5] and gross[6] motor skills. Proprioceptive feedback from a natural hand provides the brain with information including the grasping force and opening

width of the hand. The lack of this information will result in a too strong or a too weak grasp. This may result in either breaking or dropping the grasped object. The absence of proprioceptive feedback reduces the ease of use[7, 8], which may be experienced as uncomfortable and unreliable. These are the general reasons for rejection of the prosthesis.[9, 10]

Body-Powered prostheses

The BP prostheses are powered by the muscle effort of the amputee. They are most commonly controlled by a Bowden cable anchored to a shoulder harness. This alignment is seen in Figure 1. The amputee utilizes the relative motion between the parts of the human body to control the prosthetic device. This occurs through the harness and the cable system. Most of the existing BP prostheses require too high activation forces. This leads to muscle fatigue, discomfort, irritation and at last to rejection of the prostheses.[9, 11-13]

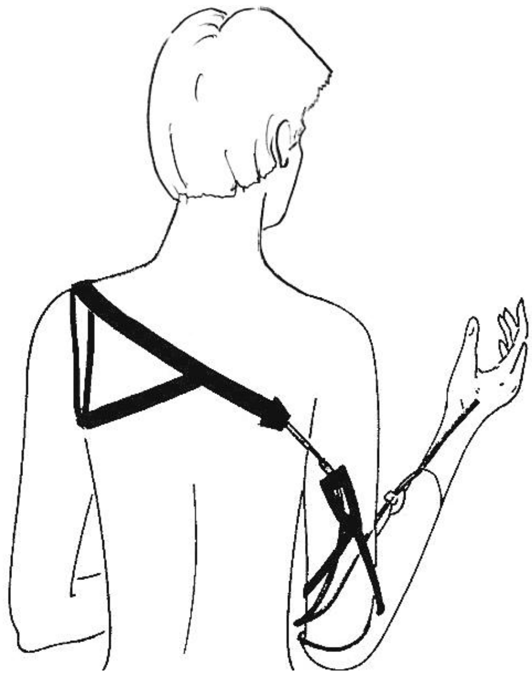

Figure 1 Bowden Cable in anchored to the shoulder harness to control the prosthesis.

The advantage of the BP prostheses is that they provide the amputee with proprioceptive feedback.[14] This feedback is considered to be necessary for good control of the prosthetic device.[15] The displacements of the Bowden cable and the resulting forces on the skin provide the user of the prosthesis with proprioceptive feedback, regarding the opening width and the applied pinch force.[14]

The documented types of BP prostheses are the voluntary opening (VO) and the voluntary closing (VC) prostheses. They are distinguished by the difference in their operating principles.

The operating principle of VO system is presented in Figure 2.a. The VO system opens the fingers of a mechanical terminal device by overcoming the spring force that closes the prosthesis. The spring force will perform the grasping action, when the cable tension created by the amputee to open the fingers is released. This spring has a high stiffness as it is responsible for the pinch force. The VO control type requires a high activation force to overcome the spring force every time the prosthesis is used, resulting in muscle fatigue. The provided force feedback by the VO prostheses is inverse and very counterintuitive, due to their operating principle.[16]

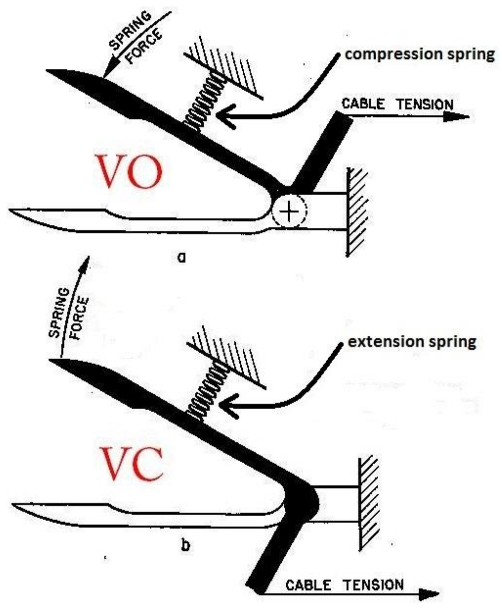

Figure 2 a. VO operation principle, b. VC operation principle (Klopsteg & Wilson; 1968).

Carlson measured and compared the efficiency of these two prosthetic control types.[17] The results show that the VO prostheses require several times more mechanical energy than the VC prostheses to operate. As the spring in the VO prostheses provides the pinch force, holding an object for a longer period of time it is not tiresome.

The operating principle of VC system is presented in Figure 2.b. The VC system closes the fingers of the prosthetic device by overcoming an opening biased force (spring force). As this spring is intended to only guarantee the open rest position of the prosthesis, it has a much lower stiffness compared to the spring required in VO prosthesis.

An activated VC prosthesis performs immediately a grasping action, as the activation force of the prosthesis is proportional to the pinch force. The pinch force is determined by the amputee's muscle force. The VC operation principle provides the amputee with direct force feedback. The delivered pinch force is mostly limited by the strength of the user. In the VC operation principle the user needs to maintain the tension in the control cable to maintain the grasp. For this reason holding an object for a longer period of time can be fatiguing. Therefore a locking mechanism is provided with most of the VC prostheses.[16]

In contrast with this thought, Radocy stated that maintaining the pinch force represents the metabolic work by the muscles. The required continues control of the prosthesis supports the amputee to improve the muscle tone and increase the muscle sensitivity.[18] It is clear that there are disagreements concerning the required continuous control for the VC prostheses. Another disadvantage of the VC system is the open rest position, as it might be less cosmetic.

A preliminary literature survey is carried, where the BP prosthetic operation principles are compared.[19] This survey showed that the poor performance characteristics, reliability factors and inappropriate design criteria of the available VC prostheses are responsible for the dominance of the VO and the EP prostheses. The same conclusion is also accomplished by Bob Radocy.[18]

The VC operation principle is the better choice for the below-elbow amputees, conform the benefits and possibilities of this type of control. New VC prosthetic designs and improvements are required to develop these possibilities.

Background

Hook prostheses have performed in general, functionally better than hand prostheses[13]. They are rejected and eventually discarded, due to their deterring outward appearance. This rejection is seen specially among the children and their parents.[20] The cause for this rejection is the discrepancy between the expectations of the patients with an arm defect and the reality. The user wants and expects a prosthesis that looks naturally beautiful, is comfortable to wear and is easy to use.[21, 22] Therefore cosmesis, comfort and control are the three major design requirements.[23] These three are the aspects in which improvements could be realized for hand and hook prostheses.

Delft Institute of Prosthetics and Orthotics (DIPO), a research group at the department of BioMechanical Engineering at the Technical University of Delft, developed a prosthetic prehensor for children 4-9 years. It is designed with the objective of preserving the functionality of the standard split-hook prosthesis, while improving its outward appearance.[24] The traditional split-hook prosthesis is cosmetically very deterrent.

The WILMER appealing prehensor (Tweezer) shown in Figure 3, is a mechanical operated VO device. All mechanical parts are within the frame and covered by a polyurethane cosmetic cover that can be made in almost any desired color. The prosthesis is clinically tested by the children. The test had a total time of use of more than 200 months. The mechanism revealed to be very robust and reliable. The colorful cover is highly appreciated by the children. Damage to the clothing is considerably reduced, due to the smooth outline of the prehensor and the integration of the control cable.[20]

Figure 3 Tweezer developed by DIPO (Delftprosthetics.nl).

Points of improvement

In order to improve the functionality of the Tweezer, DIPO suggested to transform the operating principle of this split-hook from voluntary opening into voluntary closing. The new VC prosthesis will offer the amputee active control over the amount of pinch force exerted. It will accommodate the amputee with the functional action of the kind found in the natural hand.

A possible drawback is the open rest position, typical for a VC terminal device. Another issue may occur in the transmission of the activation force into a pinch force. As a result of the geometry of the Tweezer the transmission ratio may be limited, resulting in an unsatisfactory low pinch force. The challenge is to keep all the mechanical parts within the frame, realizing a sufficient force transmission ratio. This ratio is the division of activation force and its corresponding pinch force. These are quantified in the design criteria.

Problem definition

The problem definition of this project is to transform the operating principle of the Tweezer from the VO to the VC, considering the geometrical limitations and the design criteria.

The goal

The goal of this project is to redesign the controlling principle of the VO Tweezer, resulting in a prototyped VC version of the Tweezer.

Design criteria

To establish a list of design criteria it is very important to listen to the wishes and demands of prosthetic users. The amputees have three major demands as earlier stated in the introduction. These are cosmesis, comfort and control. The three major demands are divided in sub-demands by Radocy.[18] Most of the sub-demands stated by him are quantified and applied in this design project. As this prosthetic split-hook is meant for children between 4-7 years, this quantification is specifically tuned to this target. For this group is a limited amount of data available from the literature. The available datasets for adults are used to estimate a required dataset for children. Based on the ratio of the length of children 4-7 years to adults, the available data for adults is scaled with a factor 0.5.

Pinch force

The studies concerning the pinch force and the strength of children 4-7 years are not widely done. There are no generalized statements for this group, considering the required pinch force.

Shaperman[25] did a literature survey, focused on the strength of the children 2-4 years. The goal was to estimate the required pinch force for the activities of the daily living (ADL) of children. This data was aimed for the future prosthetic development. Shaperman stated from the report of Gottlieb[26] a minimum pinch force of 9 to 18 N respectively for children 2-4 years as a design criterion for the development of BP prostheses.

Van Lunteren[27] reported a continuous pinch force of 10 N to be sufficient enough to perform most of the tasks from the ADL of children. Commonly, a continuous pinch force of 10 N is used as a design criterion. For this study, 10 N is set as the minimum required pinch force.

Opening width

Johan Nieuwendijk[28] assembled a list of objects encountered in the daily life of adults. He measured the relevant sizes of objects to determine the required grip size. The results suggested a required opening width of 70 to 80 mm for adults. To translate these values for a child size hand of 4 years, these values are scaled with a factor 0.5. The resulting required opening width for the children of 4 years is 35 to 40 mm. The field research of Van Lunteren[29] resulted in a list of actions, observed in the most of young children with a unilateral amputation. He reported that an opening width of 35 mm is sufficient enough for the ADL of children. The findings of Van Lunteren are in the same order of magnitude with those suggested by Nieuwendijk.

One of the requirements in this project is to maintain the frame and the cosmetic cover of the Tweezer. The fame of the Tweezer limits the opening width to a maximum of 50 mm. As the final design is meant for children of 4-7 years, a wider range of opening width is required than those proposed by Van Lunteren and Nieuwendijk. The original opening width of 50 mm of the Tweezer is set as the minimum required opening width.

Activation force

Field research by Taylor[14] on 50 adult subjects resulted in a list of maximum forces and displacements. He stated a maximum control force of 280 ± 24 N from the arm flexion. The quarter of this force is the resulting maximum activation force for children of 4-7 years, as the relation of force with length is quadratic. The resulting 70 ± 6 N could be the maximum generated cable force by a child.

Shaperman[30] measured the strength of 14 unilateral congenital below-elbow limb amputees of 3-6 years. The measurements are performed for the shoulder (humeral) flexion, shoulder (humeral) abduction, shoulder girdle elevation and shoulder girdle protraction (abduction). The maximum measured force is 62 N of shoulder girdle elevation. This force is in line with the scaled force of 70 ± 6 N minus the standard deviation. The 62 N is set to be the maximum generated cable force by a child of 4-7 years.

According to Monod[31] 18 % of this maximum generated cable force is acceptable for the continuous use, preventing the muscle fatigue. This force is also called the critical force. For the intermittent contractions of 0.5 work-to-rest ratio, Monod reported 38 % of the generated cable force as the critical force. For these intermittent contractions an activation force of maximum 23.5 N is set to be the demand. Moreover a comfortable continuous activation force of 11 N is set as a wish for this design.

Cable excursion

Taylor[14] measured the maximum cable excursion by the shoulder control for adults. The maximum cable excursion is scaled down from 53 ± 10 for adults to 26.5 ± 5 mm for children using the same ratio of 0.5 as introduced before. There is no optimum displacement of the Bowden cable reported in the literature related to the optimum proprioceptive feedback.

Geometrical criteria

The frame and eventually the cosmetic cover of the Tweezer are kept in their original state. A wide study is performed to acquire the appearance of this prehensor and to obtain the satisfactory of its users[20]. For the cosmetic design of this split-hook, many aspects are taken into account. A very important aspect is the length of the mechanism proximal of the wrist. This length should be as short as possible, as it will limit the use for the amputees with long stumps. Moreover the size of the prosthesis should be in the same magnitude as the natural hand, from the cosmetic point of view. To still fulfill these demands all the mechanical parts should be kept within the frame of Tweezer.

The anthropometry data by Chandler reports the mean weight of the hand of six adults.[32] A mean of 387 ± 76.5 g from left and right hand is calculated from this data. The Dined anthropometric database[33] reports for children 5-6 years and adults 20-60 years the hand lengths of 187 and 127 mm respectively. A weight of 121,2 ± 24 g ($387 \pm 76.5\,\mathrm{g} \cdot \left(\frac{127}{187}\right)^3$) for the target group is calculated using the ratio of these hand lengths to the power of three, as the volume ratio is considered for the calculation of weight. This is in line with the weight of 125 g of Tweezer. Wearing a prosthesis is a completely different experience compared to the natural hand as a part of body. The aspiration is to make the prosthesis as light as possible. A weight of 120 g is set as the maximum weight.

Practical considerations

Reliability is one of the most important factors in the use of any prostheses. An unreliable prosthesis will be abandoned by the amputee.[10] There are many factors involved within the reliability of a prosthetic device. Withstanding perspiration, splash, dust and sand are some of those factors.

The external loads applied to the prosthesis in the ADL of children are taken into account. The construction of the prosthesis should

withstand the weight of the amputee, in the case of hanging with the prosthesis.
The VC prostheses have an open rest position. This is often mentioned as a drawback, considering the cosmetic point of view. For this reason most of the VC prostheses are provided with a locking mechanism. Smit[13] recommended from his measurements that the existing locking mechanisms used in the available VC prostheses, should either be improved or abandoned. It seems that the existing locking mechanisms when activated, are causing a high pinch force drop. This results to an insufficient grip to maintain the grasp. If implementing of a locking mechanism in the new design will influence the reliability of the prosthesis, the preserving of reliability will count heavily.

Summary of the design criteria

A summary of the design criteria is given as follows:

- Minimum 10 Newton of pinch force;
- Minimum opening width of 50 mm;
- Maximum 23.5 N of activation force;
- The cable excursion for a child should be less than 26.5 ± 5 mm;
- All the mechanical parts should be kept within the frame of the Tweezer, ensuring that the cosmetic cover of the Tweezer will fit the frame;
- The total weight of the prosthesis should not exceed the 120 g.
- Use of a locking mechanism should be considered.

Methods

Constraints

The interior of Tweezer is shown in Figure 4. Any new mechanism is limited to the interior dimensions of this prosthetic hook. The maximum interior diameter of the frame of this split-hook is 30 mm. The maximum height of this cylindrical interior is 37 mm.
To apply a momentum around the hinge of the finger, the force has to seize on the available area of the thumb sole. The position of the hinge of the finger is preserved, as any change to this position requires new design of the fingers. Also the fixed hinge of the mechanism is preserved, as the frame is made massive there to carry its axle.

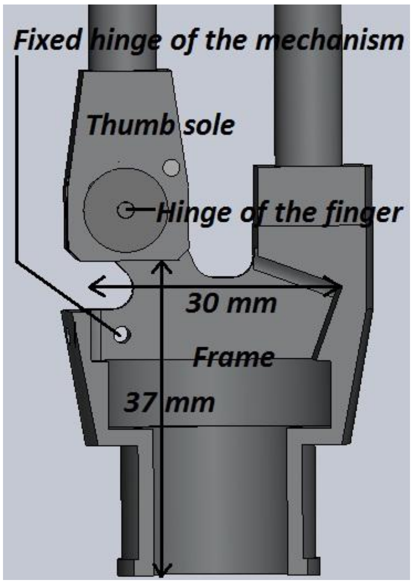

Figure 4 The frame and thumb sole of Tweezer are the dimensional constraints.

As the use of the frame of Tweezer is preserved, one finger is fixated and the other finger is performing the pinch. The simplicity in design and the ability to withstand the side forces when holding an object are the major reasons for this fixation, as it will secure the grasping action.
These are the constraints for the conceptual design and optimization of the prototype.

Conceptual design

Three concepts are proposed, considering the design criteria discussed before. The concepts are either based on simplicity, low cost or high mechanical efficiency. This is done to realize a wide range of mechanical solutions.
A locking mechanism is not included in these concepts, as it is a design challenge itself. The existing locking mechanisms are avoided[13], where the reason is explained in the design criteria.
The available room inside the frame of Tweezer is limiting the size of the mechanism and any significant translation or rotation. Therefore some of the mechanical solutions like the hydraulics and the pneumatics are abandoned in early stages of the conceptual design. The reliability issues, high overall cost and the required maintenance cycle contributed to this decision.

The force transmission ratio was central in the thoughts in this conceptual design as a design challenge. It is important to state that this is the first time in the design of a voluntary closing split-hook that all the mechanical parts are inside the frame. This is limiting the space for ability to amplify the mechanical effort.

Concept 1

The first concept utilizes a variable mechanical advantage mechanism with a holding assist. The great advantage of this mechanism is its efficiency. This mechanism operates in two stages. The first stage is closing the finger until the object is met, using a minimum activation force. In the second stage a pinch force is generated, using a minimum amount of cable displacement. This results theoretically in zero mechanical work. Therefore is the energy dissipation of the mechanism theoretically zero. The relation of cable excursion and activation force of such a mechanism is presented in Figure 5.

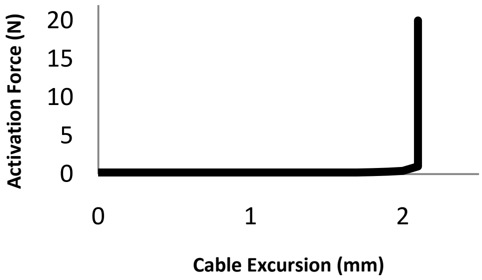

Figure 5 The relation of 'cable excursion vs. activation force' for a variable mechanical advantage mechanism.

The schematic representation of this operation principle is shown in Figure 6. The extension spring ensures an open rest position of the rotatable finger, as this is required in a VC prosthesis. When a force is applied to the hinge as indicated with an arrow, the angle between the first and the second rod increases. This results in the rotation of the finger toward the object using a minimum amount of energy. Until this stage the compression spring performs as a part of the second rod. Therefore the stiffness of the spring is adapted to the minimum effort required to close the finger. When the finger meets the object the second phase of the variable mechanical advantage starts.

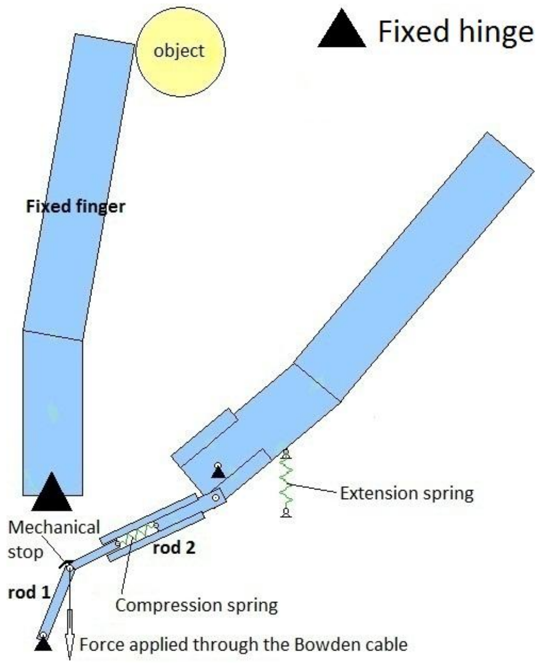

Figure 6 Concept 1.

In this stage a small translation of the Bowden cable is required to align rod 1 and 2. A pinch force is generated. Presence of a mechanical stop prevents the hinge to nod away toward the other side. When the first and the second rod are aligned, the compression spring has storage the energy. The compression spring is assisting the user in maintaining the pinch force. There is a much lower force required to maintain the grip force than without the holding assist. The force required to maintain the pinch force is a force sufficient enough to keep the rods aligned.

The disadvantage of this concept is that the pinch force varies properly with the different size of objects. The pinch force increases with increasing size of objects, where the storage energy of the compression spring increases with the size of objects. This could disturb the proprioceptive feedback.

Concept 2

Second concept is a simple conversion of the VO operating mechanism of Tweezer to a VC operating mechanism, applying minimum amount of changes. This concept is a low cost directed solution.

A lever is added to turn the applied force direction, making it a VC mechanism. This concept is presented in Figure 7. The mechanism uses three levers to amplify the activation force into a pinch force. Here is also

a spring added to guarantee the open rest position. Applying a force as indicated with an arrow turns the force direction by the first lever towards the second lever. From this stage everything is the same as the mechanism found in the Tweezer. As the second lever is fixed with a joint to the world and is L shaped, its circulation around the fixed joint will push the small rod between this lever and the finger in the direction of the edge of the finger. This will result in a momentum counterclockwise in the hinge of the finger. Eventually the fingers enclose the object.
The disadvantage of this concept is the usage of many hinges, resulting in high hysteresis of the mechanism.

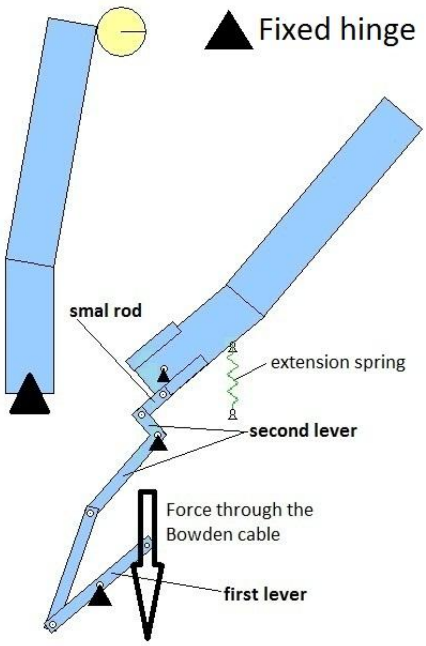

Figure 7 Concept 2.

Concept 3

Concept 3 is schematically presented in Figure 8. This concept uses two levers, amplifying the exerted force twice to generate a pinch force. The concept is based on simplicity using minimal number of hinges, resulting in low hysteresis.
The extension spring guarantees the open rest position. The lever enables the generation of a momentum around the fixed hinge of the finger. As the shaft seize on the lever, the rotation of the lever results in translation of the shaft. The reaction force generated along the shaft is amplified one more time, as the shaft seize on the finger with a distance to the hinge of the finger.

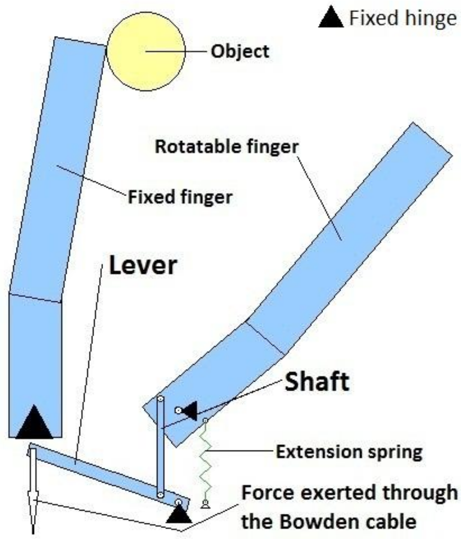

Figure 8 Concept 3.

This concept has the disadvantage of high reaction forces, where the bearings and axles are exposed to.

Conceptual rating

The three concepts are compared and rated based on efficiency and reliability of the mechanism. The efficiency and reliability is divided in below parameters:

1. Force transmission ratio is a measure for the (in)efficiency. This ratio is from zero to one, where one is the best transmission ratio. This ratio is obtained from the contact force of the tip of the fingers to an activation force of 15 N. Here is the influence of friction in the mechanism neglected.
2. Hysteresis is influenced by friction in the hinges. The energy dissipation in every hinge is considerable. As the number of hinges increases, the energy dissipation increases. A mechanism is more efficient, as lower its energy dissipation. The number of hinges used in the mechanism is a measure for the (in)efficiency.
3. The number of parts is a measure for reliability. Increasing number of parts requires a higher interaction mutually. Higher interaction increases the chance of failure.

4. Dirt sensitivity of the mechanism is also a measure for reliability. When dirt enters the room where mechanism is located, it can cause failure. Parts including cavity are more sensitive for failure.

Also the named advantages and disadvantages of the concepts are taken into account for the choice of final concept.

Dimensional design, materials and optimization

The lever and the shaft are dimensioned as the two general parts. Considering the expected functionality of this prosthesis, any excursion of the Bowden cable should transform into a pinch force. Deformations of the mechanical parts are strongly prohibited. Any deformation in the mechanism leads to energy dissipation. For this reason dimensioning of the parts of the designed mechanism are based on the stiffness calculations. The parts are dimensioned assuming the maximum activation force stated in the criterion.

The materials are chosen using the occurring stresses in the parts of the mechanism, resulted from the maximum activation force. The materials are chosen observing their mechanical and chemical properties. The chemical properties are important, as the materials used in prosthesis should not be or become toxic due to any chemical reaction.

To optimize the final concept, it is simulated in Working Model.[34] The locations of the hinges are determined by optimizing them separately, considering the constraints. There is one extra constraint involved in this optimization and that is the maximum cable excursion as set in the design criteria. The optimization is applied for a fully open prosthesis, as this open rest position determines the constraints. The optimization is based on the outcome of force transmission ratio, where the prosthesis is fully closed. The change of this ratio in relation with the position of hinges is considered as linear.

The try and error method is used as the optimization method. A grid is chosen inside the determined optimization area. The change of the force transmission ratio is calculated for every chosen position on the grid, until the optimum is found.

Prototype evaluation

In order to quantify the performance of the built prototype, it is evaluated measuring the below parameters:

- Opening width in resting position;
- Maximum displacement of the Bowden cable;

  The work is calculated with equation 1. It is the integration of the amount of required activation force over the range of cable displacement.

  $$\boldsymbol{W = \int_0^l F(x) \cdot dx} \qquad \textbf{(1)}$$

  Where $\boldsymbol{F}\ (\boldsymbol{N})$ is the force exerted along the path with length $\boldsymbol{l}\ (\boldsymbol{mm})$.
- Work required to close the prosthesis;

  Hysteresis is a measure for the (in)efficiency of the prosthesis. The prosthesis is more efficient, as lower the energy dissipation is. The amount of hysteresis is calculated with equation 2.

  $$\boldsymbol{Hysteresis = W\ closing - W\ opening} \qquad \textbf{(2)}$$

  Where $\boldsymbol{W}$ is the work applied in $\boldsymbol{MPa}$.
- Energy dissipation by closing and reopening the split-hook;
- Required activation force to generate a pinch force of 15 N;
- Input/output force relation.

These are some of the parameters also measured by Smit[13]. He made an objective comparison of the performance of several commercially available VC upper-limb prostheses. Similarity in the choice of parameters is deliberately, as it makes the comparison of the results possible. Firstly the results are used to verify the design criteria.

The measurements are performed using a custom-build test bench by Smit[13], shown in Figure 9. This manually controlled bench is used to measure the activation force using a force sensor and the Bowden cable displacement using a linear displacement sensor. To measure the pinch force a custom-build pinch sensor is included. The bench is extensively specified by Smit. The test bench is connected to a computer. The included data acquisition interface makes it possible to record the data.

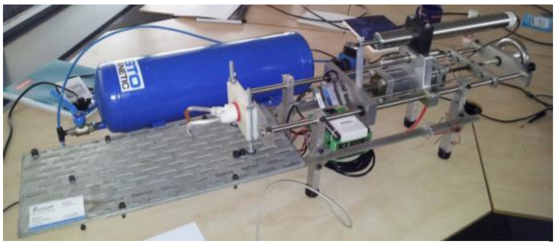

Figure 9 **Test bench build by Smit to measure the Bowden cable displacement and the corresponding activation forces and pinch forces.**

Test description

Two tests are performed using the bench. The named parameters are either measured, calculated or plotted from the outcome of these tests. The obtained data is processed in Matlab[35]. These two tests are described below:

Closing test: The cable is pulled manually, using the bench until the split-hook is fully closed. Immediately after the split-hook is closed, it is fully reopened again.

Pinch test: The split-hook is closed until the pinch force sensor (10 mm thick) is sized and pinched by a force of 15 N. When this force is reached the split-hook is fully reopened again. The both tests are repeated for four times.

Results

Choice of the final concept

Basic requirement are fulfilled in all of the concepts. The concepts are rated using the below factors as explained in the conceptual rating:

1. Force transmission ratio:
   Force transmission ratio of concept 1 is better than the other two concepts, as it uses a variable mechanical advantage mechanism. Force transmission ratio for concept 2 and 3 are obtained from simulations in Working Model[34] and additional calculations. Concept 3 shows a force transmission ratio of 0.84, where concept 2 has a force transmission ratio of 0.48.
2. The number of hinges:
   The spring mechanism of concept 1 is assumed to have the same amount of hysteresis as a hinge. Therefore concept 1 has 4 hinges. Concept 3 uses three hinges. Concept 2 uses 6 hinges, resulting in the most energy dissipation comparing the three concepts.
3. The number of parts:
   Concept 3 counts the least number of parts. Concept 1 with 5 parts is most sensitive for failure, compared with the other two concepts.
4. Dirt sensitivity:
   Concept 1 requires a part using a spring mechanism. This has a negative contribution on the clearance of the mechanism, compared to the other two concepts.

From these results the concepts are rated for efficiency and reliability. Also for the rating the advantages and disadvantages of the concepts is taken into account. The ratings are shown in Table 1. The indicated numbers in the table match the numbers form the conceptual rating.

Table 1 **The comparison and the rating of the three concepts, where + is better, +/- is neutral and - is worse relatively. The numbers correspond with the numbers used for the named factors.**

	Concept 1	Concept 2	Concept 3
1	+	-	+/-
2	+/-	-	+
3	-	+/-	+
4	-	+/-	+/-

Based on these ratings, concept number 3 is chosen as the final concept.

Resulting dimensions and materials

The lever and the shaft and their corresponding axles and bearings are dimensioned. The materials for the named parts are chosen using the calculated stresses occurring in them. The results are presented in ***Appendix A***.

The lever's length is depending on the defined constraints and obstacles along the travel of the lever. The lever is chosen to have the maximum permissible length to generate the maximum possible momentum around the fixed hinge of the lever. By preventing the large displacement of the line where force is exerted along as shown in Figure 10, the variation of the force transmission ratio for different size of objects is minimized. Therefore the rest angle of the lever is set to be 5 degrees, considering also the constraints.

Optimization results

Two parameters are optimized considering the constraints. These two parameters are the locations of the hinges of the shaft, as indicated in Figure 10. To locate the optimum position of hinge 1 it is moved along the indicated path. The force transmission ratio is observed. The optimum location for this hinge is founded as close as possible to the fixed hinge of the lever. Hinge 2 is optimized, while hinge 1 is located at its optimum. The indicated area is the search grid. Placing hinge 2 outside this area makes the mechanism unstable. The optimum place for this hinge is the top right of the area, considering the changing force transmission ratio. The resulting optimization determines also the required length of the shaft.

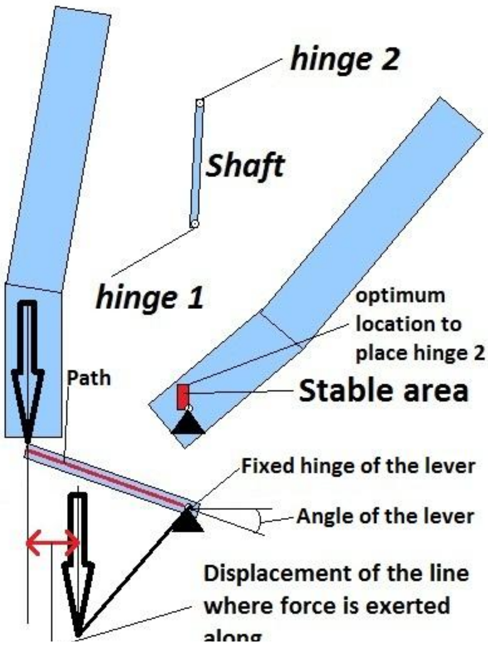

Figure 10 The optimization path and area for the location of hinges of the shaft.

The final concept is elaborated into a prototype. The resulted prototype is shown in Figure 11. See ***Appendix C*** for the technical drawings of the new prosthesis.

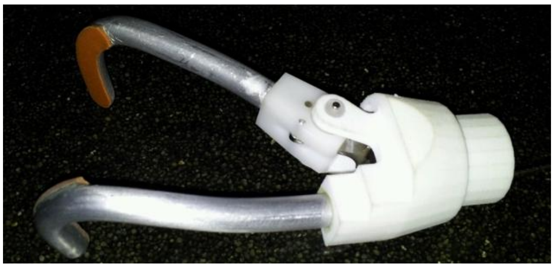

Figure 11 The prototype of the WILMER appealing VC Prehensor (VC Tweezer).

Prototype evaluation results

The overview of geometrical properties and the test results of the prototype are presented in Table 2. The measured results by Smit for TRS GRIP 2S are also given in this table for comparison. It is important to state that TRS GRIP 2S is intended for 11-adults, where information like mass and opening width cannot be compared with VC Tweezer.

A maximum distance of 50 mm is measured between the fingers at rest.

A total weight of 120 g including the cosmetic cover is estimated from the assembled model in SolidWorks.

The maximum cable excursion is 18.1 ± 0.1 mm form the obtained data at the closing test. This can be seen in Figure 12.

Figure 12 shows the hysteresis of one cycle obtained from the closing test. The disturbances in this figure are caused by the sliding mechanism of the test bench, where the sliding occurs with some hitch. The area under the graph of 'cable excursion vs. activation force' of the closing phase of closing test minus the same area for the opening phase corresponds with the hysteresis of the mechanism. The data processing to calculate the hysteresis of one cycle is performed in Matlab (***Appendix B***). It is applied to the data obtained from the four test repetitions of the closing test. The average of the hysteresis and the standard deviation of these four repetitions is 18 ± 2 Nmm.

Table 2 Overview of the geometrical properties and the test results.

Prostheses	Mass (gr)	Opening width (mm)	Maximum cable excursion (mm), n=4	Work closing (Nmm), n=4	Cycle hysteresis (Nmm), n=4	Required cable force for a 15 N pinch (N), n=4
TRS Hook, Grip 2S	318	72	49 ± 0.1	284 ± 3	52 ± 1	33 ± 0.2
VC Tweezer	120	50	18.1 ± 0.1	30 ± 2	18 ± 2	32 ± 0.2

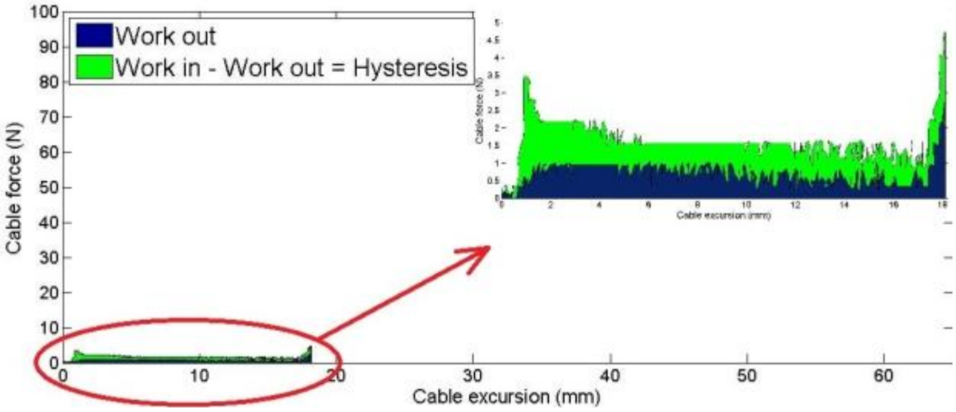

Figure 12 The hysteresis or energy dissipation of one cycle, where the prosthesis is closed and reopened.

An activation force of 32 ± 0.2 N, required to pinch the force sensor with 15 N, is averaged from the four repetitions of the pinch test. As the relation between the activation force and the pinch force is linear the force transmission ratio is considered to be constant. This is presented in Figure 13. This ratio is approximately 0.5.

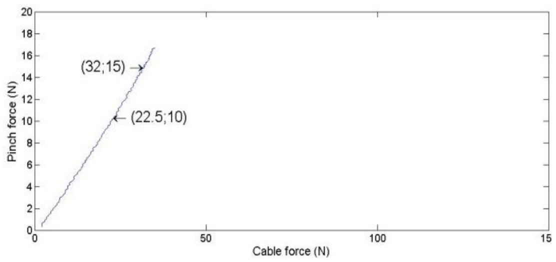

Figure 13 The linear relation of activation force and pinching force for the VC Tweezer.

Test limitations

The spring provided for this prototype is not the original spring as chosen. This spring comes close to the originally chosen spring, according its specifications. The initial tension of the used spring is higher than required. This will affect the hysteresis of the mechanism negatively.

The used material for the bearings has low surface pressure strength. This limits the maximum exerted activation force to 35 N when testing the prototype.

Some parts of the prototype are manufactured with rapid prototyping techniques. The rapid prototyped material is very friable. This limits the maximum exerted activation force when testing the prototype.

Discussion

A new VC prosthesis is designed and prototyped to enhance the performance of the Tweezer. The new VC prosthesis is tested showing the expected performances. The result of every parameter concerned this prosthesis is discussed below.

Opening width

The measured minimum opening width corresponds with the opening width determined as the design criterion. The measured maximum cable displacement of 18.1 ± 0.1 mm is less than the maximum cable excursion of 26.5 ± 5 as stated in the design criterion.

Geometry

From the geometric point of view, the outer dimensions are unchanged compared to the Tweezer. This ensures that the original cosmetic cover will fit the new design as intended. It is very hard to estimate the weight of the new prosthesis due to the use of different material for the rapid prototyping. A total weight of 120 g including the cosmetic cover is estimated from the assembled model in SolidWorks.

Activation force

The corresponding activation force for the minimum required pinch force of 10 N is 22.5 N (Figure 13). This is within the asked 23.5 N maximum activation force, where intermittent contractions of 0.5 work-to-rest ratio are assumed. The measured activation force of 22.5 N is higher than the critical force for the continuous use. The activation force required to pinch the pinch sensor of 10 mm thick for the prostheses from the study of Smit together with the VC Tweezer is shown in Figure 14.

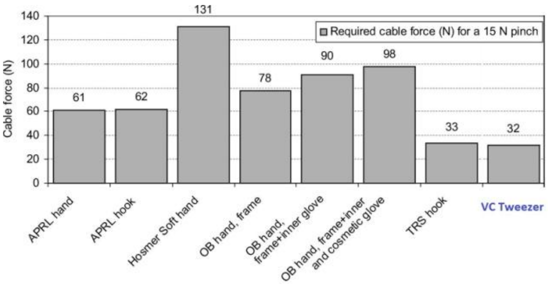

Figure 14 The activation force required to pinch the pinch sensor of 10 mm thick. (Smit, 2010)

Force transmission ratio

The calculated force transmission ratio of approximately 0.5 is nearly equal to the best performing VC prosthesis (TRS GRIP 2S) from the study of Smit.[13] The relation of activation force and pinch force for TRS GRIP 2S is shown in Figure 15. Comparing this figure with Figure 13 shows that the relation of 'activation force vs. pinch force' for TRS GRIP 2S and VC Tweezer is nearly equal.

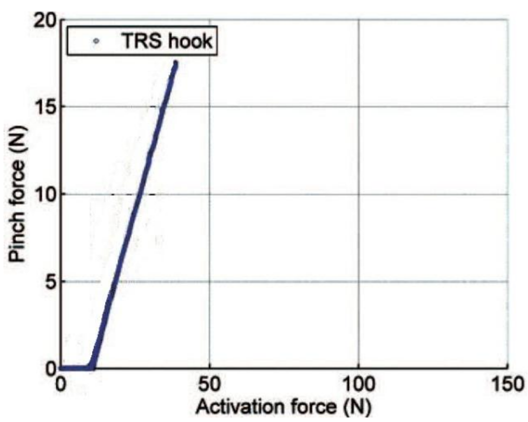

Figure 15 The relation of activation force and pinch force for TRS GRIP 2S GRIP 2S. (Smit, 2010)

Work closing

Work required to close the prosthesis is more than 9 times lower than the TRS GRIP 2S. A complete overview of closing work and hysteresis of all the prostheses from measurements of Smit together with the VC Tweezer is presented in Figure 16.

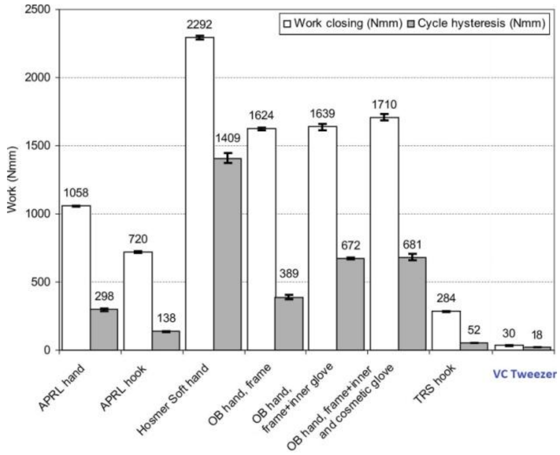

Figure 16 The work required to close the prosthesis and the hysteresis of one cycle. (Smit, 2010)

Hysteresis

The energy dissipation of 18 ± 2 Nmm is a factor 2.5 lower than the measured hysteresis of 52 ± 1 Nmm for TRS GRIP 2S. Figure 17 shows the hysteresis of one cycle for TRS GRIP 2S. Comparing this figure with Figure 12 proves this statement. The hysteresis for the new prosthesis is even lower if the original spring is used. The effect of the high initial tension of the used spring could be seen from the peak in the beginning of the graph of work input in Figure 12, as it was already predicted.

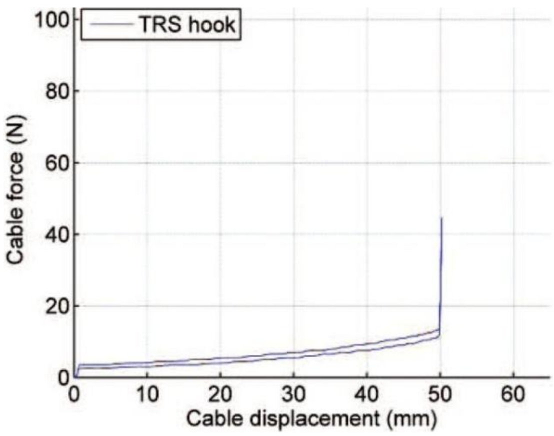

Figure 17 The hysteresis of one cycle for TRS GRIP 2S. (Smit, 2010)

Required force to reopen the prosthesis

The measured activation forces when the finger is reopened are very low. This low force will not be sufficient enough to overcome the friction in the Bowden cable to guarantee the reopening of the split-hook. Also the inefficiency of the Bowden cable transmission will have a major contribution to this issue. The solution might be the use of a stiffer spring with a higher preload. This option will result in a higher hysteresis of the mechanism. Another solution is an additional spring apart from the device, in line with the Bowden cable. A possible configuration is presented in Figure 18. This will guarantee the reopening of the split-hook without any side effect for the efficiency of the prosthesis. The graph of 'cable excursion vs. activation force' will slightly shift upwards, due to this solution.

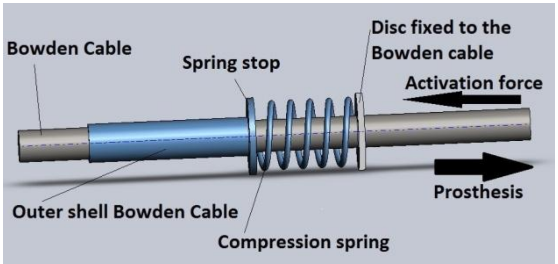

Figure 18 A mechanical solution to guarantee the reopening of the prosthesis.

Required activation force to close the prosthesis

The minimal activation force required to close the finger and to start generating a pinch force of 2 N is estimated from the data obtained from the closing test. This amount of activation force required to close the finger is very low compared to the other VC prostheses from the research of Smit[13]. From this study the lowest required activation force to close the device and generate a pinch force is from the TRS GRIP 2S hook with 11 N. This shows that the new prosthesis requires less activation force to close the finger.

Conclusions

All the design criteria are met and the corresponding conclusions are specified below:

- A minimum opening width of 50 mm is realized, ensuring the ability to handle the objects from the ADL of a child.
- The measured activation force of 22.5 N corresponding with the required minimum pinch force of 10 N is less than the maximum of 23.5 N activation force stated as the design criterion. The new VC prosthesis can be used with the intermittent contractions, at a work-to-rest ratio of 0.5, without muscle fatigue.
- The measured cable excursion of 18.1 ± 0.1 mm is less than the maximum cable excursion of 26.5 ± 5 mm stated as the design criterion.
- The functional performance of VO Tweezer is improved.
- The new VC prosthesis has with a factor 2.5, a lower hysteresis than the TRS GRIP 2S. This proves that it is more efficient than the TRS GRIP 2S.
- The new prosthesis requires less activation force to close the finger than the TRS GRIP 2S.
- All the mechanical parts are kept within the frame of the Tweezer ensuring that the cosmetic cover of the Tweezer is fitting the frame.
- The total weight of the prosthesis is equal to the maximum determined weight of 120 g.
- The calculated force transmission ratio of approximately 0.5 including the other named benefits of this VC prosthesis, makes it a promising alternative for the commercially available VC prostheses for the unilateral below-elbow amputees.

Recommendations

The following recommendations are given to further enhance the efficiency of the VC Tweezer:

- To realize the continuous activation without muscle fatigue, the activation force should be even more lowered and is brought within the critical force range.
- To guarantee the reopening of the prosthesis, an additional spring is required in the path of the Bowden cable. As the

spring is added, the relation of 'cable excursion vs. activation force' should be compared with the results from this evaluation.

- Build the prototype from the designated materials and repeat the test at the higher activation forces to verify these results.
- Pinch force is not only depending on the activation force, but it also varies using the different size of objects. It is recommended to measure the relation of 'activation force vs. pinch force' for the other size of objects. The results should be compared with the results from this evaluation to obtain the range of variation of the force transmission ratio.
- To lower the total weight, research is recommended concerning the alternative materials for the different parts including the cosmetic cover, as the weight of the cover includes more than 29% of the total weight.
- Life cycle of the new prostheses should be tested.
- The new prosthesis should be clinically tested, where feedback experience by the user is analyzed.
- This concept should also be optimized for the other age groups.

Acknowledgements

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Appendix A: Realization of the final concept

This section is dedicated to the dimensioning of the parts. Beside this the materials are chosen from the stress calculations. The calculations are done assuming a maximum exerted force of 65 N on the Bowden cable. This is rounding up of the supposed maximum generated cable force of 62 N from the activation force criterion. The 65 N is used as the maximum external load for the calculations and eventually for the dimensioning of the loaded parts. Almost all the visible parts, concerning the dimensions, from the Tweezer are preserved. Any change to these parts is minimum, limited to changing the place of a hole or adding a groove to a part. This is done to make sure that the cosmetic cover of the Tweezer will still fit the new design. The focus is on the operating mechanism inside the frame. Figure 19 is used as the reference to refer to the different parts of the mechanism.

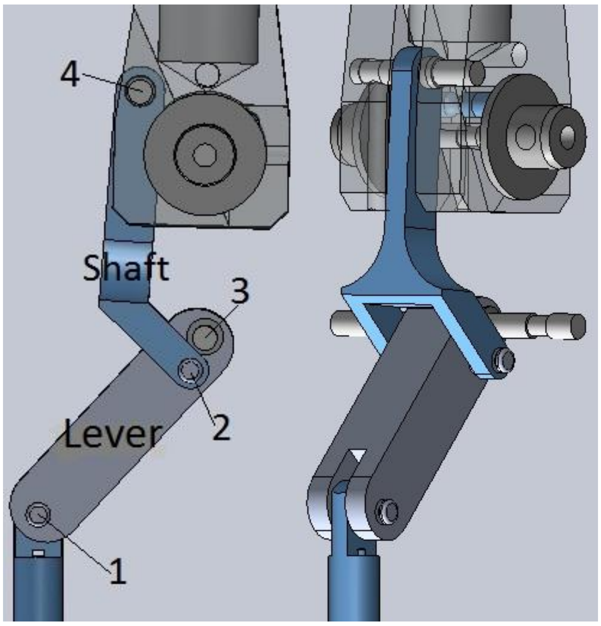


Figure 19 The parts of the controlling mechanism.

Lever

There are two general parts which are dimensioned. These are the lever and the shaft.
The RVS 304 is hard and durable. Considering the material properties and the relatively lower price of RVS 304, the lever is made from the RVS 304. The lever's length is depending on the obstacles inside the frame, along the travel of the lever. Based on this travel the length of the lever is set to be 24 mm.
Before any failure is occurred in the mechanism, the bearings are already affected. Surface pressure at the most loaded bearing is normative for the cross-section area of the lever, as this will succumb first.

Bearings

Two different materials are used for the bearings applied to the Tweezer. First was the PCTFE Eriflon (Figure 22) the standard material used for the bearings. Due to the noise production after a while and the durability issues, the more expensive VESPEL SP-211 (Figure 23) is applied in some locations. For this prototype the PCTFE Eriflon is considered sufficient enough, as some of the part are rapid prototyped and the prototype is not tested at the maximum load. Calculations are made for both of the bearing materials.
There are three holes required in the lever (Figure 19). The biggest surface pressure on the bearings does not take place at the hinge where the external load is applied. Based on the calculations of the reaction forces on the lever (Figure 20), hinge 2 used to connect the shaft to the finger will face the highest reaction force. Any succumb due to the surface pressure will take place at that hinge. Using the surface pressure equation (equation 3), the minimum required cross-section area for the lever is calculated.

$$\sigma_{max} = \frac{P_{max}}{A} \qquad (3)$$

Where σ_{max} is the compress strength of the material, P_{max} is the maximum surface pressure and A is the projection of the area (Figure 21) where the maximum surface pressure is applied to.

As the VESPEL has more than two times the compression strength of the Eriflon, it also requires less surface area to withstand the maximum load. Calculated cross-section areas for the VESPEL and the Eriflon are respectively 11.5 mm^2 (8) and 4.3 mm^2 (9). Limited available area and the fact that the hinge 2 is located as close as possible to hinge 3, pleads for the use of axles having a diameter of 2 mm. To withstand the maximum surface pressure at hinge 2, the Eriflon requires an almost three times bigger cross-section area than the VESPEL. This results in a thicker lever and eventually a heavier prosthesis. Based on these calculations for the final design, the use of the bearings made from the VESPEL material is unavoidable. The hinges 3 and 4 are also facing a high reaction force, requiring the use of the VESPEL as the bearing material.

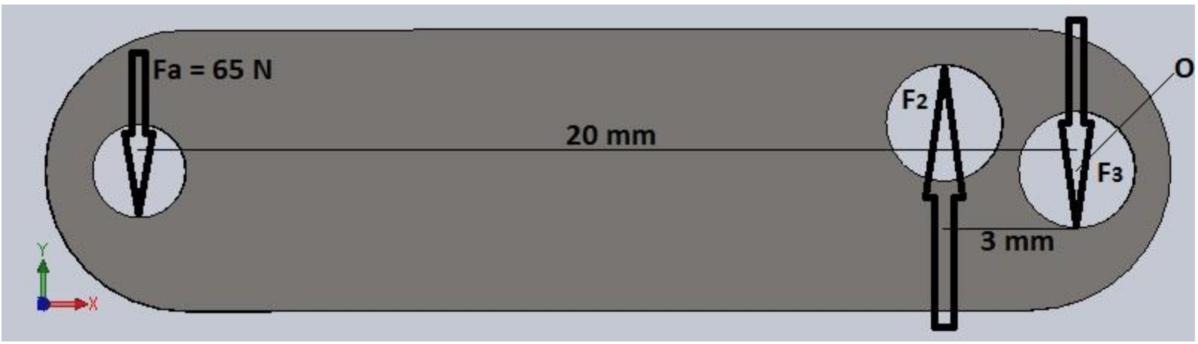


Figure 20 The FBD of the lever.

$F_a = 65\ N\ maximum\ activation\ force$

$$\sum M_o = 0$$

$65 \cdot 20 - F_2 \cdot 3\ = 0, \quad F_2 = 434\ N$ (4)

$\sum F_y = 0\,, F_3 = 369\ N$ (5)

$\sum F_x = 0$

For the FBD of the lever see Figure 20.

Bearing 2:

$\sigma_{max} = \frac{P_{max}}{A}, \quad P_{max} = F_2$

Given surface pressure strength (σ_{max}):

PCTFE Eriflon: $\sigma_{max} = 38\ N/mm^2$ (6)

VESPEL SP-211: $\sigma_{max} = 102\ N/mm^2$ (7)

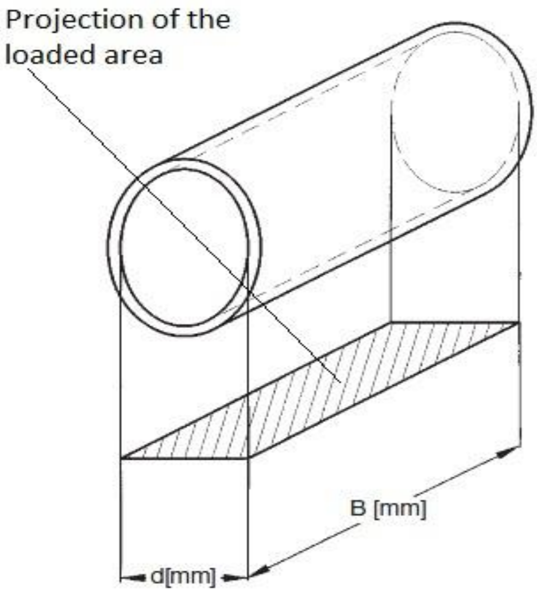


Figure 21 Projection of the loaded surface.

Given $d = 2\ mm$

Required area (Figure 21) to withstand maximum surface pressure:

PCTFE Eriflon: $A = 11.5\ mm$ (8)

VESPEL SP-211: $A = 4.3\ mm$ (9)

The same values apply for bearing 4 used in the shaft (Figure 19).

ERIKS

Solutions in Plastics

PCTFE - Datasheet

ASTM or UL test	Properties	PCTFE
	PHYSICAL	
D792	Density (lb/in³) (g/cm³)	0.077 2.13
D570	Water Absorption, 24 hrs (%)	< 0.01
	MECHANICAL	
D638	Tensile Strength (psi)	5,300
D638	Tensile Modulus (psi)	207,000
D638	Tensile Elongation at Break (%)	150
D790	Flexural Strength (psi)	8,500
D790	Flexural Modulus (psi)	180,000
D695	Compressive Strength (psi)	5,500
D695	Compressive Modulus (psi)	180,000
D785	Hardness, Shore D	D90
D256	IZOD Notched Impact (ft-lb/in)	5

__Figure 22__ **Properties of PCTFE Eriflon (ERIK's datasheet).**

HIGH PERFOMANCE PLASTICS

VESPEL® SP-1/SP-21/SP-22/SP-211/SP-3

Polyimide

** VESPEL® is the registered trademark of

DUPONT

Vespel® is one of the highest performing engineering plastics currently available. Vespel® will not melt and can operate continuously from cryogenic temperatures to 550°F (288°C), with excursions to 900°F (482°C). Vespel® parts consistenly exhibit superior performance in a variety of applications requiring low wear and long life in severe environments

ADVANTAGES:

Excellent Temperature Resistance · High Wear Resistance (Especially SP-21) · Dimensionally Stable · Resistant To Radiation

APPLICATIONS INCLUDE:

Rotary Seal Rings · Thrust Washers And Discs · Bushings · Flanged bearings · Plungers · Printer Wire Guides · Spline Couplings· Wear Strips · Valve Seats · Thermal And Electrical Insulators · Wafer Clamping, Polishing And Grinding Rings · Wafer Guides and Carriers · Vacuum Pads · Die Pickup Collets

GENERAL PROPERTIES	ASTM or UL Test	SP-1 Typical Values	SP-21 Typical Values	SP-22 Typical Values	SP-211 Typical Values	SP-3 Typical Values
Filler Material	-	Unfilled	15% Graphite	40% Graphite	10% PTFE, 15% Graphite	15% Moly
PHYSICAL						
Density (g/cm³)	D792	1.43	1.51	1.65	1.55	1.6
Water Absorption, 24 hrs @ 73°F (%)	D570	0.24	0.19	0.14	0.21	0.23
MECHANICAL @ 73°F						
Tensile Strength (psi x 10^3)	D1708	12.5	9.5	7.5	6.5	8.2
Tensile Modulus (psi)	D1708	–	–	–	–	–
Tensile Elongation (%)	D1708	7.5	4.5	3	3.5	4
Flexural Strength (psi x 10^6)	D790	0.16	0.16	0.13	0.1	0.11
Flexural Modulus (psi x 10^5)	D790	4.5	5.5	7	4.5	4.75
Compressive Strength,10% strain (psi x 10^3)	D695	19.3	19.3	16.3	14.8	18.5
Compressive Modulus (psi x 10^5)	D695	3.5	4.2	4.75	3	3.5
Hardness, Rockwell	D785	E45-60	E25-45	E5-25	E1-20	E40-55
IZOD Notched Impact (ft-lb/in)	D256	0.8	0.8	–	–	0.4

__Figure 23__ **Properties of Vespel SP-211 (www.pactumax.com).**

Shaft

The form of the shaft (Figure 24) is enforced by the available room. In the resting position the three hinges are in one line (Figure 24), resulting in a curved shaft. To locate the shaft as close as possible to hinge 3, the other end of the shaft is constructed as a fork (Figure 24). This fork is enveloping the lever.

Stiffness is very important for the shaft, preventing it from deformation. This is why it is chosen to make the shaft also from RVS 304. The same maximum reaction force working on the lever is also loading the bearing of the shaft. Therefore the same dimensions calculated for the bearing of the lever, are also obtained for the bearing of the shaft.

The shaft is dimensioned on the basis of the required area for the bearing and the available room.

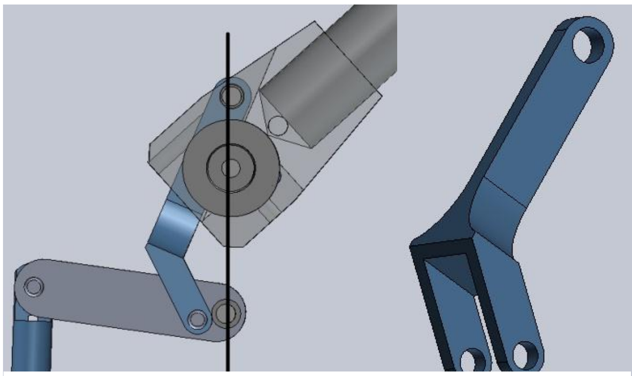


Figure 24 The shaft is curved due to the geometric limitations and it is constructed as a fork to be able to position it near to the fixed joint of the lever.

Axles

Axles of the Tweezer are made from RVS 303. The RVS 303 has a good machinability and a high oxidation resistance, which is ideal for the use in the prostheses. But it has a low yield stress. This concept is involved with higher bending stresses, where at some of the axles higher than the yield stress of RVS 303. For this reason the RVS 303 is not a suitable material to apply as the axle material in those hinges.

Some of the axles are introduced before, concerned there diameter. Eventually all of the axles are chosen to have a diameter of 2 mm. This choice is linked to the limited area imposing this dimension. The shear stresses occurring in all axles are below the yield stress of RVS 303 (12).

The maximum bending stress deserves more attention in this concept. The material applied for the axles used in the hinges 2, 3 and 4, is very important. High reaction forces at those axles are causing high bending stresses. As these axles have a diameter of 2 mm, this dimension has a negative contribution to the bending stresses arising in these axles. The longest axle from these three axles is used in hinge 3. Calculating the bending stress in this axle has helped to choose a material for the axles used at the hinges 2, 3 and 4. As the RVS 303 is sufficient for the rest of the axles, it is applied to those.

Occurring shear stress (Figure 25) is the highest in axle 4. The shear stress is calculated for this axle. If the calculated shear stress is lower than the yield stress of RVS 303, the other axles are definitely satisfying the mechanical demands concerning the shear stress.

$$\tau_{max} = \frac{P_{max}}{A} \qquad (10)$$

$$A = \pi \cdot r^2 = 3.14\ mm^2 \qquad (11)$$

$$\tau_{max} = \frac{217}{3.14} = 69\ MPa < 207\ Mpa \qquad (12)$$

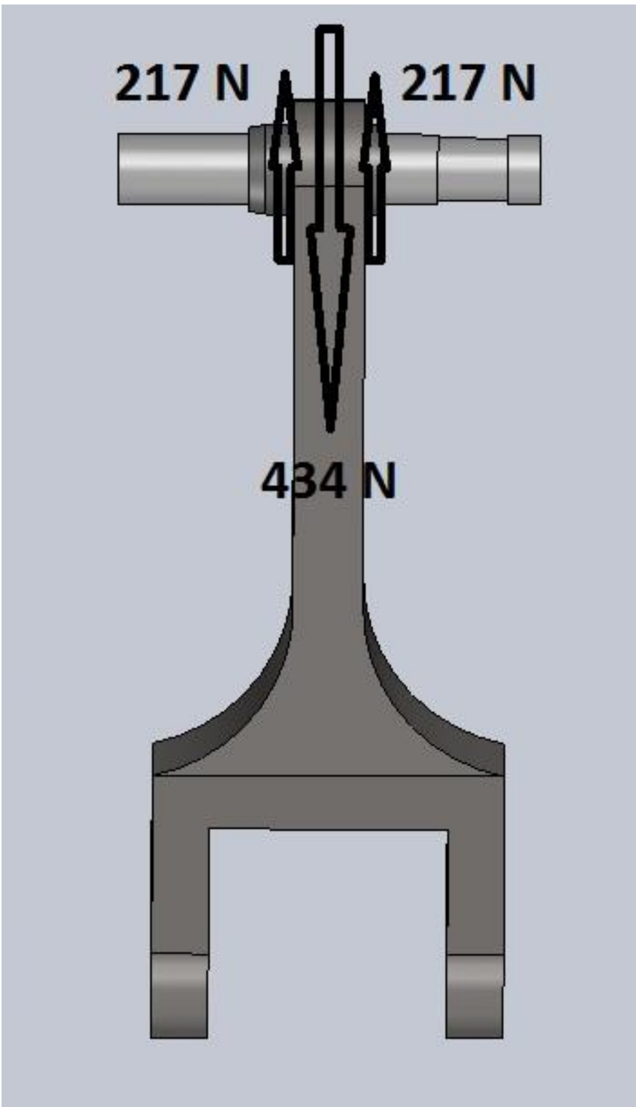


Figure 25 Occurred shear stress in axle 4.

Axle of the fixed hinge

Assuming the lever in the horizontal position while the maximum load is applied (Figure 26), is describing the scenario of the highest bending moment occurred on axle 3. Due to the assumption of an object of a certain size between the fingers, this hinge is assumed being fixed. From the snapshot of the sum of the forces working on the lever (Figure 20), a force of 369 N (5) is loading axle 3 (Figure 28). This load results in a maximum bending stress of 788 MPa (14). To verify these analytical analyses also numerical analysis are applied in Ansys. This numerical analysis shows a maximum bending stress of 743 Mpa (Figure 27). This verifies the analytical outcome.

An often used material in the prostheses is titanium. The Ti-6Al-4V (Grade 5) has the required mechanical properties (Figure 30) to be used as the axle material in the indicated high loaded hinges. This type of Titanium has a minimum yield stress of 828 MPa. The calculated maximum bending stress of 788 MPa is lower than the yield stress and thus tolerable. This material is applied to the axles 2, 3 and 4.

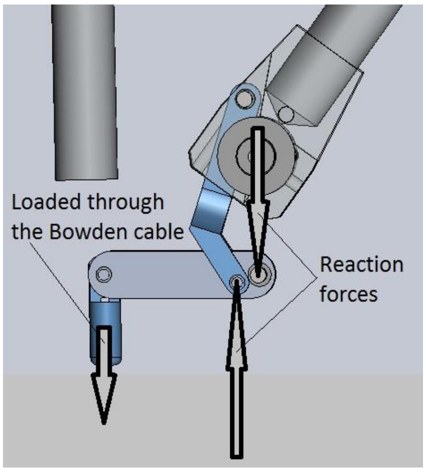


Figure 26 Lever in the horizontal position, resulting in the maximum reaction forces.

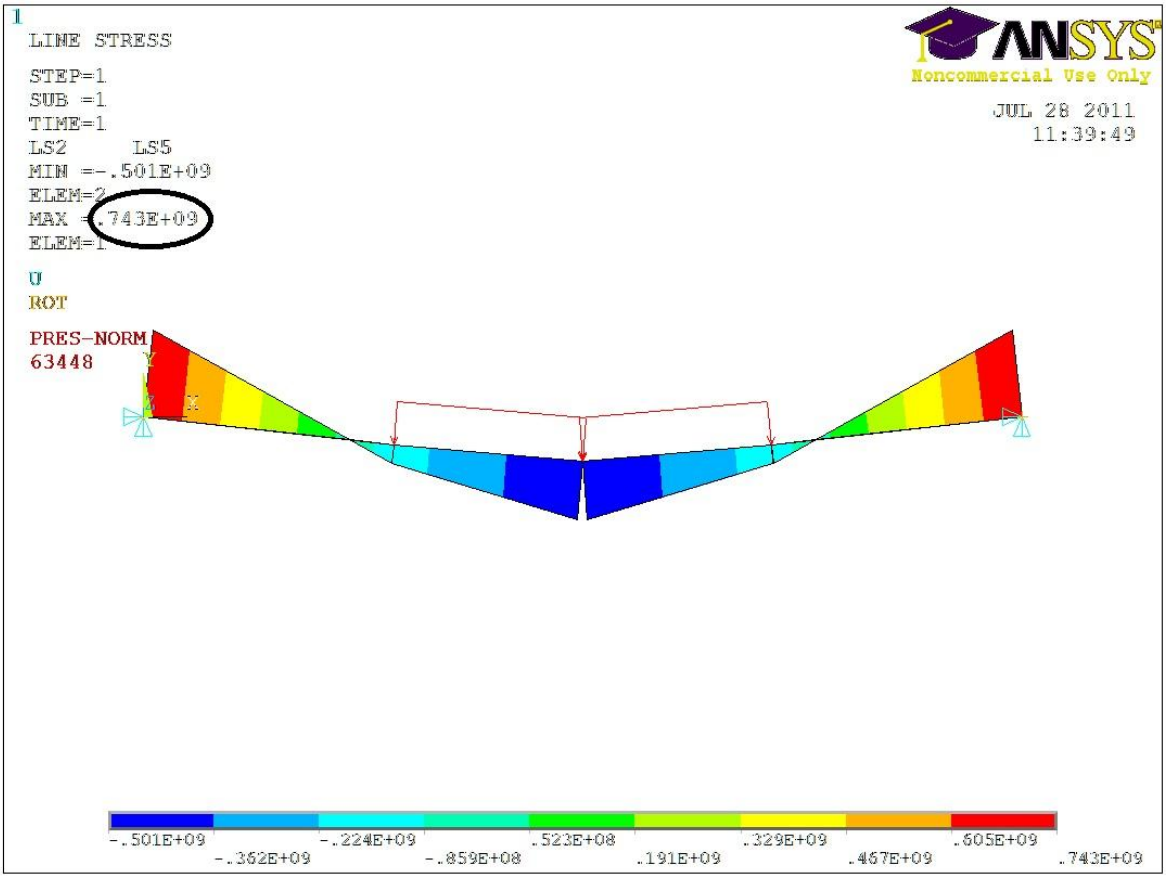


Figure 27 Numerical analyses of the bending stress in axle 3.

Maximum moment:

Bending angle is zero in the middle of axle 3 (Figure 28):

$$\frac{P \cdot L^2}{2 \cdot EI} = \frac{M_o \cdot L}{EI}, L = \frac{L}{2}$$

$$M_o = \frac{P \cdot L}{4} = \frac{369 \cdot 13.5}{4} = 1245\ Nmm \qquad (13)$$

The bending moment line is shown in Figure 29.

Maximum bending stress:

$$\sigma = \frac{M \cdot y}{I} = \frac{622.5 \cdot 1}{0.79} = 788\ N/mm^2 \qquad (14)$$

Where:

$$I = \frac{1}{4} \cdot \pi \cdot r^4, y = r$$

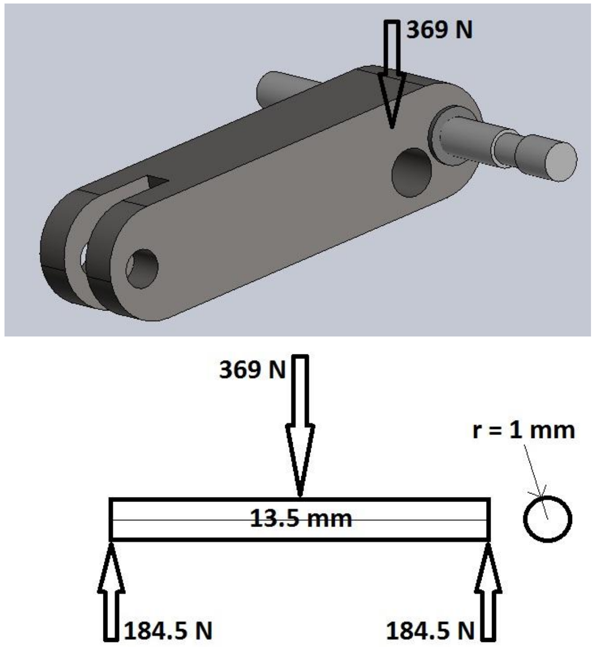


Figure 28 The FBD of axle 3.

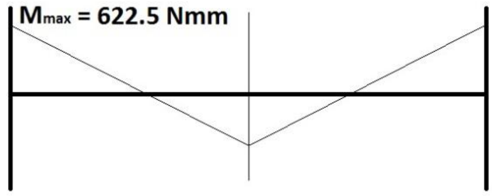


Figure 29 The bending moment line.

Ti-6Al-4V (Grade 5)

High Strength Titanium Alloy

DATA SHEET

ENGINEERING RAW MATERIALS

TYPICAL APPLICATIONS

Aero-engine components, Airframe components, Marine equipment, Offshore oil & gas equipment, Power generation industry, Autosport components, Medical equipment.

PRODUCT DESCRIPTION

Ti-6Al-4V (Grade 5), classed as an alpha-beta alloy, is the most widely used of the high strength titanium alloys. The alloy combines its good mechanical strength and low density (4.42 kg/dm^3) with excellent corrosion resistance in many media. Grade 5 titanium is fully heat treatable (solution heat treatment plus aging) in sections up to 25mm and can be employed up to around 400°C.

Ti-6Al-4V ELI (Grade 23) has a reduced oxygen content (0.13% max.) compared with Grade 5. This confers improved ductility and fracture toughness with some reduction in mechanical strength. Uses include fracture critical airframe structures and for offshore tubulars.

CORROSION RESISTANCE

Grade 5 titanium offers excellent resistance to many marine and offshore oil & gas environments. Titanium and its alloys resist a wide range of acid conditions being highly resistant to oxidising acids, possessing useful resistance to reducing acids and offering good resistance to most organic acids at lower concentrations and temperatures. Titanium should not be used with red fuming nitric acid and is rapidly attacked by hydrofluoric acid. The addition of 0.05% palladium (grade 24), 0.1% ruthenium (grade 29) and 0.05% palladium and 0.5% nickel (grade 25) significantly increases corrosion resistance in reducing acid chloride and sour environments, raising the threshold temperature to well over 200°C.

MATERIAL SPECIFICATIONS

- UNS R56400
- ASTM B348 Grade 5
- BS 2TA11
- AMS 4911
- AMS 4928
- MIL-STD-2154

FABRICATION

Weldability – fair

Specified bend radius for <0.070 in. x thickness - 4.5

Specified bend radius for >0.070 in. x thickness - 5.0

(typical values)

AVAILABILITY

Bar, wire, sheet, plate, extrusions, forgings, seamless pipe/tube.

CHEMICAL COMPOSITION

(Bar to ASTM B348 Grade 5)

%	N	C	H	Fe	O	Al	V
Min.						5.5	3.5
Max.	0.05	0.08	0.015	0.40	0.20	6.75	4.5

MECHANICAL PROPERTIES (Bar to ASTM B348 Grade 5)

	Minimum	Typical
UTS, MPa	895	1,000
0.2% PS, MPa	828	910
Elongation, % in 4D	10	18
Reduction of area, %	25	-
Elastic modulus, GPa	-	114
Hardness, HRC	-	36
Charpy V-notch impact, J	-	24

Smiths High Performance
Unit O
Stratton Business Park
London Road
Biggleswade
Beds
SG18 8QB

Tel: 01767 604 708
Fax: 01767 312 885
Email: info@smithshp.com

For more information about our company and the rest of our product range please visit our website at: www.SmithsHP.com

Figure 30 Properties of Ti-6Al-4V (www.smithshp.com).

Spring

The spring is assuring that the finger is in an open position at the rest. The position of the spring is chosen at the end of the design process, considering the left space. Due to the chosen position, the spring is an extension spring. A compression spring can loosen from its position during the operation of the prosthesis. This is why an extension spring is preferred. The required length of the spring at rest and closed position of the prosthesis are set to be respectively 10 mm and 15 mm. The minimum required force to keep the prosthesis open is a measure for the spring force. This is measured from the Tweezer. After applying a safety factor of 2 it is set to be 0.2 N. Due to the limited room the diameter of the spring is also considered.

From the catalogues of Tevema (Figure 31), a supplier of the springs, a suitable spring fulfilling the named requirements is chosen. The spring with the product number T40640 is manufactured from stainless steel. It has a resting length of 10 mm, a maximum extension length of 29.31 mm and a diameter of 4.32 mm. It has a low initial tension of 0.2 N, which has to be overcome to activate the spring. From the provided information by the manufacturer, the load at the extended length of 15 mm is 0.95 N, influencing the efficiency of the prosthesis minimally.

Trekveren — *Extension Springs*

Ressorts de traction — ***Zugfedern***

1 KG=9,80665 NEWTON 1 N=0,10197 KG

				Verenstaal DIN 17223-1.1200 EN10270-1						Roestvast DIN 17224-1.4310 EN10270-3					
d	Dm	Lk	Lo	Fo	C N/mm	Sn	Fn	Nummer	Prijs-groep	Fo	C N/mm	Sn	Fn	Nummer	Prijs-groep
0,32	1,88	1,89	4,70	0,96	3,27	2,12	7,91	T30620	C	0,8	2,81	2,07	6,62	T40620	F
	1,88	3,19	6,00	0,96	1,79	3,88	7,91	T30620A	C	0,8	1,54	3,78	6,62	T40620A	F
	1,88	5,09	7,90	0,96	1,08	6,45	7,91	T30620B	C	0,8	0,93	6,29	6,62	T40620B	F
	1,88	7,99	10,80	0,96	0,67	10,37	7,91	T30620C	C	0,8	0,58	10,11	6,62	T40620C	F
	1,88	12,79	15,60	0,96	0,41	16,85	7,91	T30620D	C	0,8	0,35	16,43	6,62	T40620D	F
	1,88	19,19	22,00	0,96	0,27	25,50	7,91	T30620E	C	0,8	0,23	24,86	6,62	T40620E	F
	2,50	3,68	7,60	0,62	0,65	8,16	5,94	T30630	C	0,5	0,56	7,95	4,97	T40630	F
	2,50	7,88	11,80	0,62	0,29	18,37	5,94	T30630A	C	0,5	0,25	17,91	4,97	T40630A	F
	2,50	12,68	16,60	0,62	0,18	30,04	5,94	T30630B	C	0,5	0,15	29,28	4,97	T40630B	F
	2,50	14,98	18,90	0,62	0,15	35,63	5,94	T30630C	C	0,5	0,13	34,73	4,97	T40630C	F
	2,50	17,18	21,10	0,62	0,13	40,98	5,94	T30630D	C	0,5	0,11	39,95	4,97	T40630D	F
	2,50	19,78	23,70	0,62	0,11	47,30	5,94	T30630E	C	0,5	0,10	46,11	4,97	T40630E	F
	2,50	22,28	26,20	0,62	0,10	53,38	5,94	T30630F	C	0,5	0,09	52,03	4,97	T40630F	F
	2,50	24,88	28,80	0,62	0,09	59,70	5,94	T30630G	C	0,5	0,08	58,20	4,97	T40630G	F
	3,20	3,52	8,70	0,40	0,33	12,98	4,63	T30635	C	0,3	0,28	12,65	3,88	T40635	F
	3,20	7,72	12,90	0,40	0,14	30,03	4,63	T30635A	C	0,3	0,12	29,27	3,88	T40635A	F
	3,20	12,52	17,70	0,40	0,09	49,52	4,63	T30635B	C	0,3	0,07	48,27	3,88	T40635B	F
	3,20	14,82	20,00	0,40	0,07	58,86	4,63	T30635C	C	0,3	0,06	57,37	3,88	T40635C	F
	3,20	16,72	21,90	0,40	0,06	66,58	4,63	T30635D	C	0,3	0,05	64,90	3,88	T40635D	F
	3,20	19,62	24,80	0,40	0,05	78,35	4,63	T30635E	C	0,3	0,05	76,37	3,88	T40635E	F
	3,20	22,12	27,30	0,40	0,05	88,50	4,63	T30635F	C	0,3	0,04	86,27	3,88	T40635F	F
	3,20	24,72	29,90	0,40	0,04	99,06	4,63	T30635G	C	0,3	0,04	96,56	3,88	T40635G	F
	4,00	3,38	10,00	0,24	0,18	19,81	3,70	T30640	C	0,2	0,15	19,31	3,10	T40640	F
	4,00	7,58	14,20	0,24	0,07	47,04	3,70	T30640A	C	0,2	[illegible]	[illegible]	3,10	T40640A	F
	4,00	12,38	19,00	0,24	0,04	78,16	3,70	T30640B	C	0,2	0,04	76,17	3,10	T40640B	F
	4,00	16,88	23,50	0,24	0,03	107,33	3,70	T30640C	C	0,2	0,03	104,61	3,10	T40640C	F
	5,18	4,45	13,20	0,09	0,06	46,33	2,85	T30650	C	0,1	0,05	45,15	2,39	T40650	F
	5,18	7,35	16,10	0,09	0,04	78,85	2,85	T30650A	C	0,1	0,03	76,84	2,39	T40650A	F
	5,18	12,15	20,90	0,09	0,02	132,68	2,85	T30650B	C	0,1	0,02	129,30	2,39	T40650B	F
	5,18	18,55	27,30	0,09	0,01	204,44	2,85	T30650C	C	0,1	0,01	199,23	2,39	T40650C	F

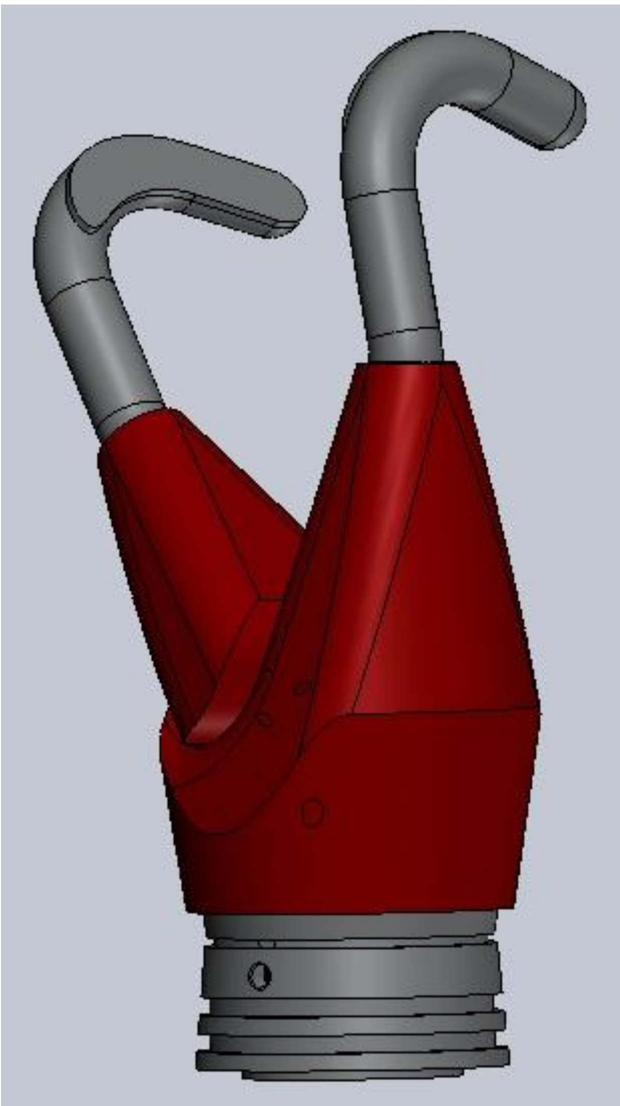
Figure 31 Part of the catalogues of Tevema (extension springs).

Appendix B: Matlab function to calculate hysteresis

Matlab function provided by Smit.

```
function [data_out]=integration(test)

% Create variables
x=test(:,1);
y=test(:,2);

% Prepare an emty vector
A=zeros(length(test),1);

for n=2:length(test);

    % Work done per sample step
    A(n,1)=(x(n)-x(n-1)).*((y(n)+y(n-1))/2);

end

% Create a vector with summed values of A
B=sum(A);
data_out=B;
```

Appendix C: Technical drawings



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