Design of a new terminal device combining voluntary opening and voluntary closing

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by

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Preface

For the past ten months I have been working on this master thesis. Luckily, I was not alone during these months and therefore, I would like to thank some people.

First of all, my supervisor Dick Plettenburg. He took a lot of time to guide me through this project and gave useful advice when I needed it. I would also like to thank Jan van Frankenhuyzen for his help and commitment with building the prototype.

Then I like to mention my friends from the Squad, who were around at the study landscape almost everyday. I would like to thank them for the great coffee mug and the amount of cookies we consumed together everyday. For the small talk and the 'Woordgraptogram' during the breaks but most off all for the support and advice they gave me on my research and presentations.

I would like to thank my family. Leave papa en mem, tige tank foar alles in de ferline jierren. Thank you for everything you taught me about life which is probably more than I realize. And for the financial support, off course.

Lastly, I would like to thank my boyfriend Roy. For giving me all the support I needed during the largest part of my studies. Thank you for always being around, even when I was hungry.

Froukje Marije Peeters Weem
Delft, August 2019

Abstract

Upper limb amputees, using a body-powered prosthesis, generate energy with their shoulders which leads to opening or closing of the prosthesis. The preference for one of these types, voluntary opening (VO) or voluntary closing (VC), differs for individuals and for task specifics. Research is, therefore, done regarding terminal devices which provide both types. Earlier presented hybrid devices are heavy, do not provide mechanical advantage or present a difficult switching procedure. A novel VO/VC device was presented, with the promising features of easy switching and good mechanical performance. However, in user tests this device did not perform well, mainly because of its finger shape.

The goal of this study is to improve the grasping performance of the VO/VC device. Changing fingers did not create a device which could fulfil all the requirements. Instead, another idea was embodied, prototyped and tested.

This device is able switch between VO and VC, by the use of two separate pivot points. Switching between the two is done with a bi-stable mechanism, which is activated by the intact hand. Results show that the device can be used in both modes and that users are able to switch with the bi-stable mechanism, but the mechanical properties do not meet the requirements. Additionally, the device performs less than expected on the user test, due to the bad mechanical properties and misalignments in the 3D-printed prototype.

The device created is a good proof of principle for using two pivot points to shift between VO and VC. However, the bi-stable mechanism did not function as expected and a lot of friction is present leading to high forces in the cable. It is recommended to change the material, focus on using other springs which allow for larger opening widths and generate less friction and change the switching system to increase usability and safety.

Contents

1 Introduction

1.1. Upper limb amputees and prostheses

Upper limb amputees An amputee is 'a person who has had an arm or leg cut off' [1]. Limb loss is congenital or, more often, a limb is lost during life. In 2007, the Netherlands had around 1350 people with a congenital deficiency and another 2400 amputees have an acquired limb loss [2]. Limbs are lost due to trauma, neoplasia (tumour) or dysvacularity (caused by the poor vascular status of the upper limb) [3]. Besides the cause, the location of amputation differs. Fingers are most often amputated, followed by transradial (below elbow) amputation and transhumeral (above elbow) amputation [4].

Upper limb prostheses To give back some of the lost functionality, prostheses are designed. Upper limb prostheses can be split into two types: passive and active (Figure 1.1). Passive prostheses cannot be controlled. The cosmetic hand is supplied for the users appearance and the passive hand has an internal spring which can be used to hold an object when placed in the prosthesis by the intact hand. At last, the lost hand can be substituted by a tool such as knife, fork or hammer.

For active prostheses, there are two types of actuation: body-powered and external powered. A body-powered prosthesis is opened or closed with the energy generated by another body part. For upper limb prosthesis, this body part is most often the shoulder. Externally powered prostheses make use of a battery to generate energy and motors to open or close the prosthesis. The signals for opening and closing are often myoelectric signals. The EMG activity in the remaining muscles is detected and translated to an opening or closing signal.

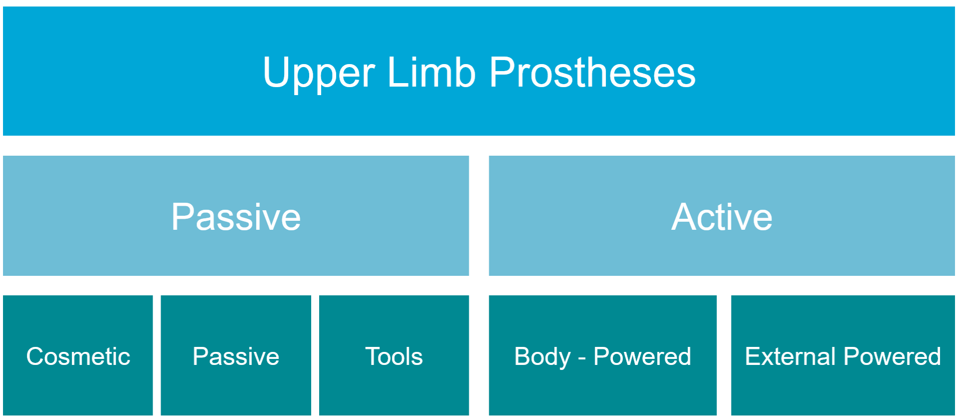


Figure 1.1: An overview of the upper limb prostheses - Adapted from [5]

Body-powered prostheses Body-powered prostheses are generally controlled by the shoulders. A shoulder harness is placed and connected to the terminal device via a Bowden cable. Moving the

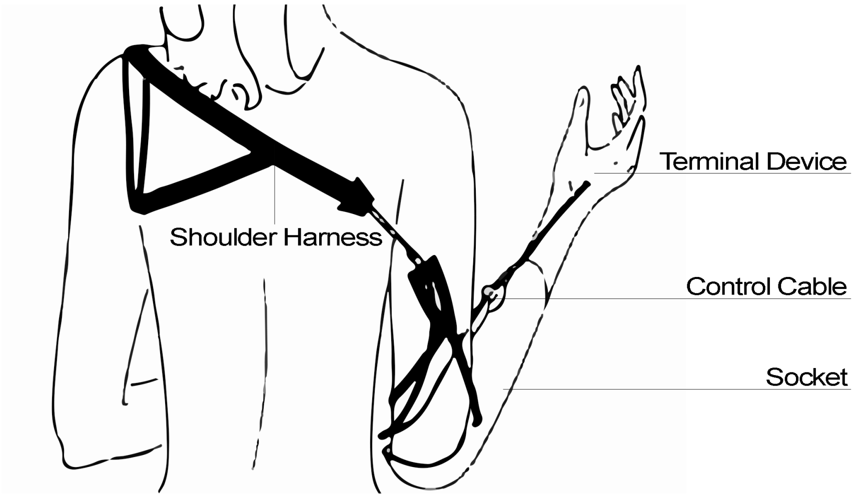


Figure 1.2: The shoulder harness connected to the terminal device via the (Bowden) cable. The socket attaches the hook to the forearm - Adapted from [5]

shoulders will pull the cable and this opens or closes the prosthesis. Figure 1.2 shows the shoulder harness, the connecting cable and the terminal device. The terminal device can be a hook or a hand. Hooks often have two fingers of which one can be moved. They are chosen because of their functionality and durability [6] [7]. Body-powered hands have at least three functional fingers (of which one is the thumb) and some additional cosmetic fingers. They are chosen in social activities, because of their appearance [6]. Besides the type of terminal device, the user has to choose between voluntary opening (VO) or voluntary closing (VC). If the device is VO, it is closed when in rest and it can be opened with the movement of the shoulders. The device is closed by a spring or elastic band. When the device VC, it is open when in rest and can be closed with the shoulders. In this case, the device is kept open by a spring.

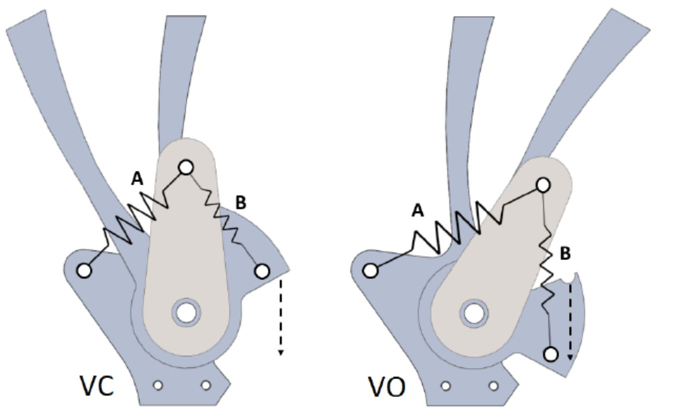
1.2. Novel hybrid hook

A hook which combines both VO and VC is called a hybrid device or VO/VC device. A literature study [8] on VO, VC and VO/VC devices identifies the advantages and disadvantages of both output types and gathers earlier designed VO/VC devices. Based on these results, a new hybrid device was designed [8]. Results of the literature study and the newly designed prosthesis are shown in this section.

A VO device has the benefit that it can hold objects when the cable is relaxed. Additionally, the hook is closed when in rest, which is more appealing and makes it easier to put the hook in a pocket. Disadvantages mentioned for VO devices are the amount of pinch force which cannot be varied and that for each movement the spring force should be overcome to open the prostheses. In contrast to that, VC devices are chosen because the grasping force can be controlled and there is more motion feedback. Moreover, the input force from the shoulder is proportional to the grip force. However, this device is open when in rest, leading to getting caught behind objects and when holding an object, force should always be exerted by the shoulders which often leads to fatigue. All together, benefits in one mode are seen as a problem in the other mode. The position in rest for example or the choice over grasping force. A combination of the two types, with all the benefits and without the weaknesses, seems like a best-of-both-worlds solution.

That a combination would be beneficial for the user is found as a result in a study regarding the functioning of both VO and VC body-powered prostheses during activities of daily living [9]. Tasks with heavy objects were preferred with the VC device, where tasks which involve simultaneous movement (key turning for example), were preferred with the VO device. Additionally, the subjects in this study expressed their desire for a terminal device that could switch between these modes.

Eight hybrid terminal devices were found [8], but none of them made it to the market yet. Mainly because of heavy and bulky mechanisms, high internal forces and unfavourable mechanical advantage. Focus points for these hooks were: low mass, simplicity of the mechanism and favourable mechanical advantage. With the focus points and found pitfalls in early hybrid hooks, a new hybrid prehensor was designed [8]. The design consists of two passive tongs and an active one, which can slide through the passive ones. Two springs are used to create enough pinch force in VO and not to much force which should be overcome in VC. Figure 1.3 shows the use of the device in two drawings and shows a picture of the final device.



(a) Drawing of the two modes used in the novel device. Spring B is elongated in VC mode and spring A is elongated in VO mode.

(b) Picture of the novel device

Figure 1.3: Drawing and picture of the hybrid hook designed by Coehoorn [8]

Evaluation of the new hybrid terminal device was done by mechanical and user tests. Comparison to VO hooks [10], shows that the novel design has an acceptable weight, small opening width and does not perform well in the open and close tests. However, the pinch force is sufficient compared to other hooks, but not when compared to the set requirement. Comparison to VC hooks [11] shows that the weight is good, opening width still small, work and hysteresis are good and required pinch force sufficient. The Southampton Hand Assessment Procedure (SHAP), used to evaluate hand or prosthesis performance, had a weak outcome. Only 20 of the 26 tasks could be performed, probably because of the shape given to the fingers. This led to a functionality score lower than all other SHAP prosthesis outcomes [9] [12].

The novel hook provides the use of both a VO and VC hook, without the need for another hand to switch between the modes. As the weak performance in the SHAP test was due to the finger shape, future research should be regarding finger design. Other recommendations are lowering the amount of work and hysteresis through increasing mechanical advantage and reconsidering the amount of necessary pinch force.

1.3. Finger shape

The novel hybrid hook had a weak performance in the SHAP test, due to the shape of the fingers. To improve the functioning of the novel hybrid device, the finger shape should change. As a preparation for this thesis project, a literature study into finger shape was performed [13]. The goal of this literature study was to find the best finger design for a prosthetic hook. The study was split into three sections: the requirements for a hook, an inventory of existing hooks in design papers and patents and the third section included studies in which hooks were compared to each other on function and/or appearance.

It was found that a hook prosthesis is useful at work/school and less used during personal tasks like eating and recreation. It was furthermore identified that a non-prehensile movement, where a grasp is not involved, is more often performed than grasping of an object. An example of a non-prehensile movement is pressing a paper against a table. But, it was also identified that the often-used power grasp, was lacking in most hooks. The following requirements were identified for a good grasp: the maximum opening width should be 100mm without losing the ability to grasp smaller items and a pinching force of 67N should be available to grasp all types of objects.

The split-hook designed by David W. Dorrance in 1912 is seen as the first prosthetic split-hook. Design papers and patents were gathered, to identify the improvements and in which areas these improvements were made. The hooks tried to improve grasping very large objects with for example adding an extra finger or adding several radii to the fingers. Other areas of improvement were the inner surface of the hook and the aesthetics.

Since lots of these devices did not make it to the market, they were not evaluated. For that reason, it is impossible to say if these features improved hook functioning. All studies in which hooks are evaluated and compared to each other were gathered. Studies and outcomes differ much, which again led to no conclusion. However, these studies show that the Model 5X fingers perform well in almost all studies.

This study will be used to set up the requirements for a new prosthetic hook. No clear conclusion could be given why the Model 5X performed best, so no specific features could be extracted from this design. However, areas of importance were found in this study and should be taken into account when designing new hook fingers.

1.4. Research goal

The literature study [8] regarding VO and VC hooks shows that combining the two types is beneficial for the user. Furthermore, it demonstrates the possibility to switch without using the intact hand. However, this prosthesis was not able to perform well in the SHAP-test, mainly because of its finger shape. A new literature study [13] shows how important finger shape is and which requirements apply to the finger design.

The goal of this thesis is to create a terminal device which combines both voluntary opening and voluntary closing. The first step in this process was to improve the earlier designed VO/VC device by changing the finger shape and by improving the mechanical advantage. Nevertheless, when studying the limitations of the mechanism it was found that the requirements of sufficient opening width and enough pinch force with only changing the finger shape, could not be met. This study is available in appendix B.

To create a device that can meet all the requirements, it was decided to focus on another concept, earlier presented [8]. This concept gives more freedom in designing or choosing fingers. It was rejected because of force limitations, but since the force requirements have changed (see appendix A) it will be possible to use this concept. As second step to reach the set goal, the new VO/VC concept was designed, fabricated and evaluated.

1.5. Readers guide

This document consists of three parts: the introduction, the scientific paper and the appendices. The first part introduced the topic and showed the goal of this thesis. The scientific paper presents the study done regarding the second research goal and includes a description of the design, the evaluation methods and the results. The appendices explain the design requirements, go in to detail on the design and its evaluation and the study regarding fingers shape is presented in appendix B. For a full overview of this thesis project, it is important to read all the parts of this report.

2

Scientific Paper

Design of a prosthetic terminal device with the ability to shift between voluntary opening and voluntary closing.

Froukje Peeters Weem

Abstract—**Upper limb amputees with a body-powered prosthesis have to choose between a voluntary opening (VO) or a voluntary closing (VC) terminal device. Both types have their strengths and weaknesses and preference for one differs for individuals and tasks. Research shows that combining both types in one device would be beneficial for the user. Attempts for such a device were made but do not meet the requirements yet. In this study, a new VO/VC concept is embodied, built and evaluated.**

This concept introduces a new mechanism with two pivot points, which allows for easy switching between both VO and VC. Two separate springs are used, providing a low closing force in VC and a higher pinch force in VO. The prototype is evaluated in a mechanical test and with the Southampton Hand Assessment Procedure.

The results show that using both modes leads to higher scores compared to using one mode. However, switching between modes is not that easy since the remaining forces on the axes are high. In addition, cable forces are increased due to energy losses in the system. The scores were low compared to other devices, due to the mechanical properties and misalignments in the prototype.

The design and prototype leave room for improvement on usability, mechanical advantage, pinch force and opening width. Recommended is to focus future research on switching methods and the material used for the device. Concluded is that a hybrid prosthesis is beneficial for the user and providing such a device with two pivot points is a possible method.

I. Introduction

Body-powered prostheses are often used to substitute the hand when an upper limb is lost. These prostheses make use of the movement and energy provided by other body parts. The terminal device is connected to a shoulder harness via a Bowden cable and with the movements of the shoulders, the user is able to open or close the body-powered prosthesis. Users can choose between a hand or a hook as a terminal device. The hand is chosen for its appearance, often during social events [1], where the hook is chosen because of its ruggedness, durability [1] [2] and good sight on the grasped objects [1] [3]. Another advantage is that the hook is lightweight [4].

A prosthetic hook comes in two different types: Voluntary Closing (VC) and Voluntary Opening (VO). A VC hook is opened in rest and with the excursion of the Bowden cable, the hook will close. The force created in the tip of the hook is directly related to the force exerted by the shoulders. A VO hook is closed when in rest and opens with pulling the Bowden cable. The force in the tip is determined by the strength of the spring in the device. Several advantages and disadvantages for both types of output were identified [5].

The main advantage for a VC device is the good force and motion feedback [6]. Furthermore, the pinch force exerted by the prosthesis can be controlled and varied for different types of objects to be grasped [7]. The main disadvantage for VC devices is that gripping an object for a longer time is fatiguing since the force should be constantly applied by the shoulders [6]. Another regularly mentioned weakness is that the hook is open in rest which leads to getting caught behind objects or clothes [6]. Both problems can be prevented by a locking mechanism but they are often mechanically inefficient [8]. A third disadvantage for VC is that, for picking up a small object, the prosthesis is further away from the body because of the large cable travel. This limits the area in which the prosthesis can be used [9].

The main benefit for VO is that an object is held within the fingers as long as the cable is relaxed which leads to lots of freedom and does not cause exhaustion [10]. Another strength is the closed resting position of the hook when no object is grasped, which makes putting on clothes easier [10]. The main disadvantage of VO is the constant force between the fingers which cannot be varied for different kind of objects [7]. An additional problem with only one (generally relative high) force is that the shoulders need to overcome this force every time the prosthesis should be opened [7]. Another weakness for VO is that the area in which the prosthesis is used for grasping a small object, is close to the body [9].

For both types, strengths and weaknesses were found. Besides these differences, the different types influence the way a task can be executed. Berning et al. [11] showed that the VO hook was preferred in tasks which involve simultaneous movement and that VC was preferred in tasks with heavy objects. Participants in this study agreed that a device that can change between VO and VC would be beneficial. The idea for such a hybrid device is not new. Coehoorn [5] identified eight different hybrid devices which are able to switch between VO and VC. None of these devices made it to the commercial market yet. Often due to bulky and heavy mechanisms which made the device uncomfortable to wear. Other devices failed because of high internal forces, inefficient gears or unfavourable mechanical advantage. Some devices had a favourable mechanical advantage and others were priced for their appearance or low weight. However, these strengths were overruled by their weaknesses. The only device without large weaknesses and with a lightweight, compact mechanism is the design made by Sensinger et al. [12]. The appearance of this hook is similar to the standard Model 5X hook but this design has an extra switch which can be moved by the intact hand. This switch guides the device in its two positions: VO

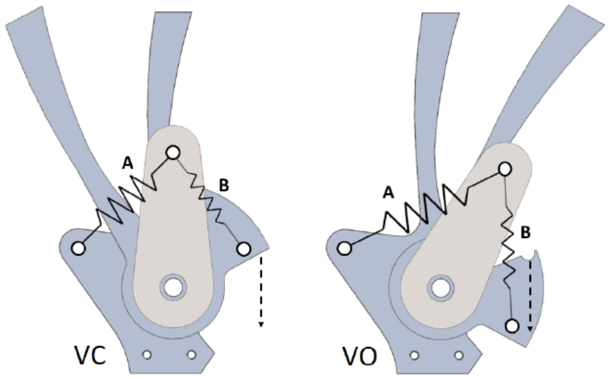


Fig. 1: Drawing of the novel device, in the two modes. Spring B is elongated in VC mode and spring A is elongated in VO mode. [5]

or VC. The results show that using the preferred mode leads to a higher functionality score than only using VO or VC for all the tasks. This result is in line with the earlier referred study [11] and confirms the need for a VO/VC device.

The device presented by Sensinger et al. [12] is not available to the user yet and has one drawback: to switch between the modes an intact hand is needed. This hand should be present and the need for this hand limits the freedom to hold another object simultaneous. Coehoorn made a novel design [5], which is able to switch between the modes without the use of the intact hand. This novel VO/VC hook is accommodated with one movable finger, which can slide through two stationary fingers. When the cable is relaxed, the movable finger is on one side and the system is VC (Figure 1, left). When the cable is pulled and no item is grasped, the movable finger moves through the stationary fingers and the system becomes VO (Figure 1, right). Because two separate springs are used, the closing force needed in VC is low where the pinch force provided in VO is high. This, together with the easy mode switching, presents a device with promising design features. Nonetheless, the device did perform not as expected in the user test, mainly due to the bad gripping characteristics of the fingers. An approach was made to improve the shape of the fingers. However, since the mechanism limited the opening angle of the fingers and increasing the length of the fingers led to unrealistic cable forces, changing the fingers was not enough to meet the requirements for a novel VO/VC device.

A new VO/VC device is presented in this paper. The main idea was contrived earlier [5], but it was not elaborated or built. This concept allows larger opening widths since cable excursion is no longer shared over both modes and leaves more freedom for finger design. The device is evaluated in a mechanical and in a user test. The results of these tests allow for comparison to the described VO/VC devices [5] [12].

II. Methods

A. Terminal Device Design

Requirements: The main objective of this new VO/VC design is to switch between the two modes, without the use of the intact hand. The other requirements were based on the three main requirements for upper limb prostheses: comfort, cosmesis and control [13].

Comfort:

Mass: The weight of the APRL hook was classified by over 95% as satisfactory [14]. This weight is 248g [8] and this is, therefore, the maximum weight.

Cosmesis:

Dimensions: Acceptable dimensions are the dimensions of a normal hand minus one SD: length 170mm and width 76mm [15].

Control:

Pinch force VO: A reasonable pinch force in VO is 14N, because it is too low for some tasks but too high for others [11].

Activation force: Men can provide a force of 66N with their shoulders fatigue-free and women a force of 38N [16]. So, the maximum activation force should be 38N.

Cable excursion: Cable excursion should not exceed 80mm [17] but based on shoulder measures, the cable excursion should be 53mm [18]. Since increasing the cable excursion helps to create a desired pinch force [17], it was decided to set a maximum cable excursion of 70mm.

Opening width: To grasp as many items as possible, the opening width should at least be 83mm [19] [20].

Prehension type: In an ideal situation, the prosthesis includes the most popular types: tip, palmer and lateral [19]. Since tip and palmer are most often used, they are required in this design.

Using two pivot points: To enable the terminal device to use both VO and VC, this new device is equipped with two separate pivot points. Each pivot point is related to one of the two modes. When the pivot point on the right is activated (see Figure 2), the system is voluntary closing. Excursion of the cable will then lead to the closing of the prosthesis. When the pivot point on the left is activated, the terminal device is voluntary opening. Excursion of the cable will lead to the opening of the prosthesis. These modes result in two different movements, as illustrated in Figure 2. To generate these movements, two compression springs were used to open the prosthesis in VC and close the prosthesis in VO. The Bowden cable, connected between the two pivot points, can be used to compress the springs. These springs are indicated in Figure 2 by their guiding cylinders.

Switch between pivot points: To provide fast and efficient switching between the two pivot points, a bi-stable mechanism was chosen. This mechanism was created by placing a tension spring between the lever which connects the axis and the stationary part of the prosthesis, as illustrated in Figure 3. With switching the pin at the back of the prosthesis (see Figure 2 D & H), the spring will be elongated in the first half of the movement and will pull back at the second half, adding force to this movement. With this movement of the pin, one axis will be pushed up where the other axis will lose its uplifted position. Switching between the modes can only be done when the prosthesis is in the closed position. For switching from VO

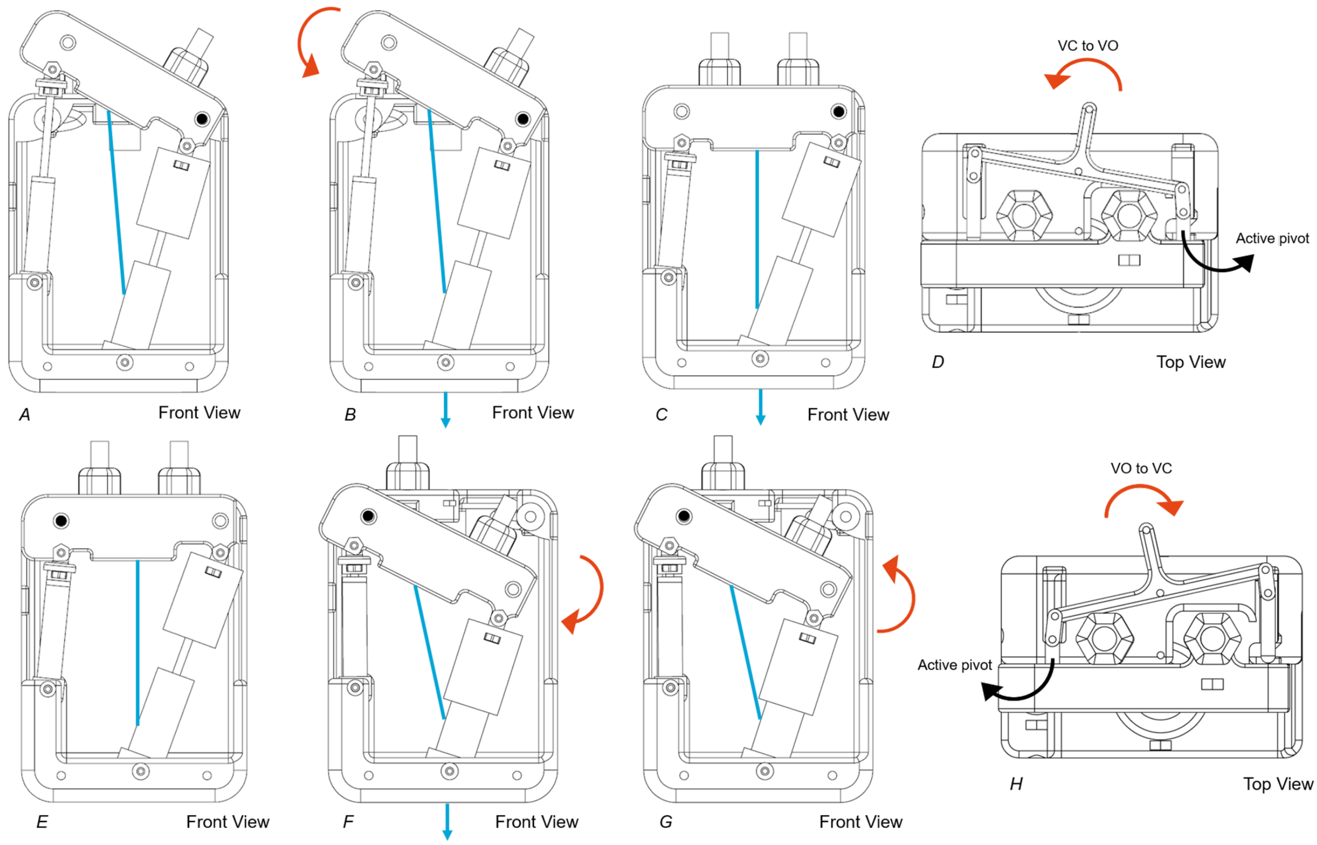


Fig. 2: Movements of the terminal device. The connections to the fingers are shown on top of the device, with two nuts and the active pivot is indicated by a black dot. On the top row, the VC movement is shown. When the cable (shown in blue) is pulled, the device starts rotating (B). When it is fully closed (C), the activated pivot (indicated by the black dot) can be switched to VO (D). When the cable is pulled in VO, the device opens (F). When the cable is relaxed, the prosthesis closes (G). When fully closed, the pivot can be switched again.

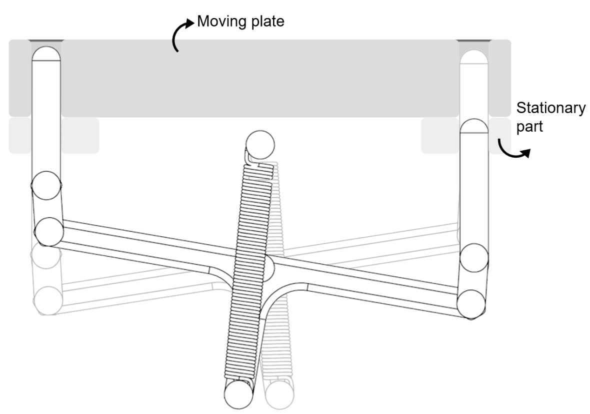


Fig. 3: The bi-stable mechanism, added in the device to create an easy and safe switch. The spring is connected at the top to the stationary part and at the bottom to the lever which is connected to the axes. The two stable positions are shown.

to VC, the cable should be relaxed and when switching from VC to VO, the cable should be pulled just enough to fully close the prosthesis. The current prototype was tested using a switch on the back, operated by the intact hand, to evaluate the use of two pivot points and the bi-stable mechanism. In future designs, the switch could be incorporated in the device and operated by the moving finger.

Parameters compression springs: Two compression springs are used, one for VO and one for VC. The VO spring should allow the prosthesis to close with a pinch force of 14N while respecting the cable force and opening width requirements. Although the VC spring should push the prosthesis fully open, this force has to be overcome when closing the prosthesis and creating a certain pinch force in the fingertips. Therefore, the force created by the VC spring should be as low as possible. Additionally, the distance over which the spring can be compressed, influences the opening width of the device. So, the maximum and compressed length were taken into account. The springs used were the best options available off-the-shelve. The resulting pinch and cable forces, expected after Matlab [21] calculation, are shown in Figures 4 - 6. The modelled opening widths are 67mm (VO) and 65mm (VC).

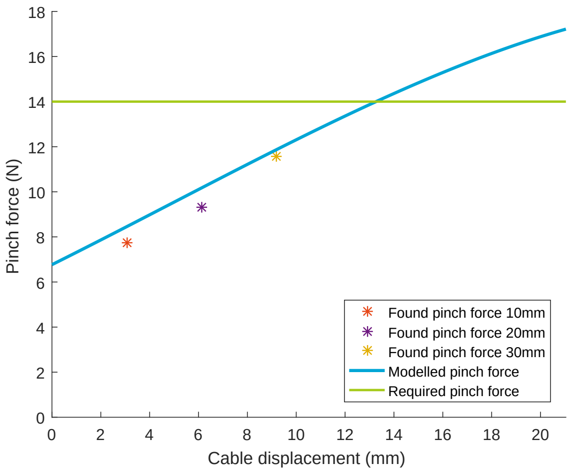


Fig. 4: Expected pinch forces in VO and found pinch forces during the pinch test. The requirement for pinch force is not met for all the opening angles, but the found pinch force is in line with the in Matlab modelled pinch force.

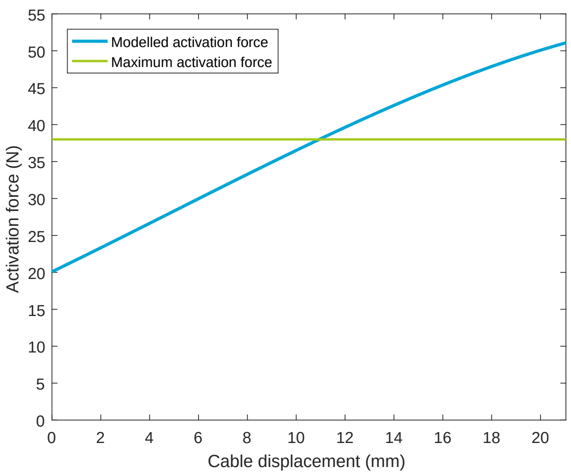


Fig. 5: Expected activation force in VO. For grasping small objects, which do not need a large opening of the prostheses, the requirement for activation force is met in the model.

B. Terminal Device Testing

Mechanical testing: Mechanical testing of the prototype is done to evaluate the mechanical performance of the device and to compare the prototype to other existing devices. The mechanical tests were equal to the ones done by Smit & Plettenburg for VC devices [8] and by Smit et al. [22] for VO devices. The custom-built test bench as described in [22] was used. Since the properties differ much between hands and hooks, the outcome of this test is only compared to the assessed hooks. The VC hooks which were tested are the Hosmer APRL VC and the TRS Grip 2S. The evaluated VO hooks are the Hosmer model 5XA, the Hosmer Sierra 2 Load VO hook, the RLS Steeper Carbon Gripper and the Otto Bock model 10A60 hook.

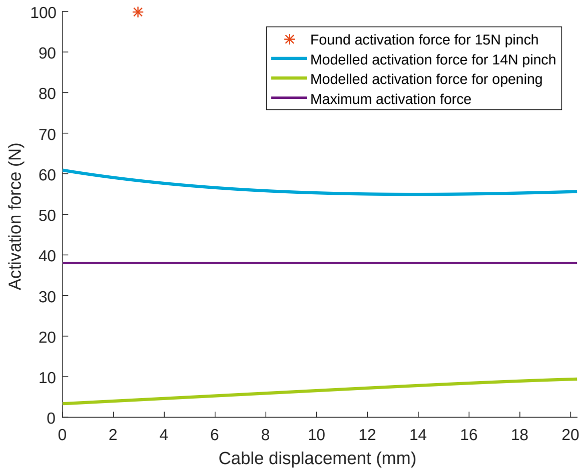


Fig. 6: Expected activation forces in VC and found activation force in the pinch test. The requirement for activation force is met for closing the prosthesis but not for pinching 14N. The found activation force is much higher than modelled, since the measured pinch force is 15N but mostly due to friction in the device.

VC tests: To evaluate the important mechanical properties of the prototype the following three tests were performed in VC-mode:

1) **Closing test**. The fully opened fingers were closed by pulling the cable until the prosthesis was closed. The prosthesis was reopened by releasing the cable. The displacement of the cable and the cable activation force were measured.
2) **Pinch test**. A force sensor (thickness = 10mm) was placed between the open fingers and the cable was pulled until a pinch force of 15N was reached. The prosthesis was reopened by releasing the cable. The displacement of the cable and the cable activation force were measured.
3) **Pull test**. A force sensor (thickness = 10mm) was placed between the open fingers and the cable was pulled until an cable force of 100N was reached. The displacement of the cable and the pinch force in the tip were measured.

Test 1 and 2 were performed four times each, to obtain an average value. The pull test was performed once. Besides the results of these tests, the mass and the maximum opening width were measured.

VO tests: Since VC and VO have different properties, other tests were performed with the prototype in VO-mode:

1) **Open and close test (full opening)** The cable was pulled until the prosthesis is fully opened. Then the prosthesis was closed again by releasing the cable with the same speed. Cable force and displacement were measured during this test.
2) **Pinch force test** Three different pinch force sensors (thickness of 10, 20 and 30mm) were placed, one by one, between the fingertips and the pinch force was measured.

Test 1 was performed four times to obtain an average value. The pinch force test was performed once. The maximum opening width was measured again since this differs in VO and VC mode.

User functionality testing: Besides testing the mechanical functioning of the prosthesis, the use of the prosthesis was evaluated. This done with the Southampton Hand Assessment Procedure (SHAP) which allows for evaluating prosthetic functioning in a research setting [23] [24]. Furthermore, since other prostheses have been evaluated with this test, a comparison is possible. SHAP consists of 26 tasks. Six objects tasks were done with a light and a heavy object. These tasks relate to the six possible hand prehension patterns. In addition to that, fourteen Activities of Daily Living were performed. All tasks will be timed by the participants themselves and an Index of Functionality (IOF) is calculated by the SHAP-website. The participants got to try the prosthesis in both VC and VO mode previous to the test. During this time the participant could grasp some objects until the prosthesis felt familiar. Each task was performed three times: first time in VO or VC mode, the second time in the other mode (VO/VC) and the third time in the preferred mode for that specific task. The order for VO/VC in the first and second round was randomized. Before each task, the user could practice the specific task (in the specific mode), as recommended in the SHAP-protocol. Before performing the task in preferred mode, the participant could not practice.

Data processing: With the obtained IOF-scores, a one-tail paired Student t-test was performed to find the paired differences between using the VO mode compared to the preferred mode and between using the VC mode compared to the preferred mode. Averaged IOF-scores per mode were compared to results of other terminal devices. Additionally, the preferred mode for each task was collected and an overview of the preferred distribution is given.

III. Results

A. Prototype

The prototype is built as described in section II-A. Two pictures of the prototype are presented in Figure 7 and demonstrate the prototype in its VC and VO mode when the cable is relaxed. This prototype was made to evaluate the functionality of the concept. The device is a good proof of principle because it can switch and enables the device to be used in both VC and VO mode. Nevertheless, the device has its shortcomings. Because of the 3D printed parts, axes are tilted easily which makes switching difficult. Additionally, the direction in which the cable is pulled has a negative effect on the cable force. Furthermore, due to some misalignments, the terminal device is not able to fully close in VC. This same misalignment is present in VO, where the device is still able to close but should be aligned with the intact hand or by pulling the cable when switching modes.

B. Mechanical Test

Table I shows how the prototype complies with the requirements. Figures 4 - 6 show the expected and the found

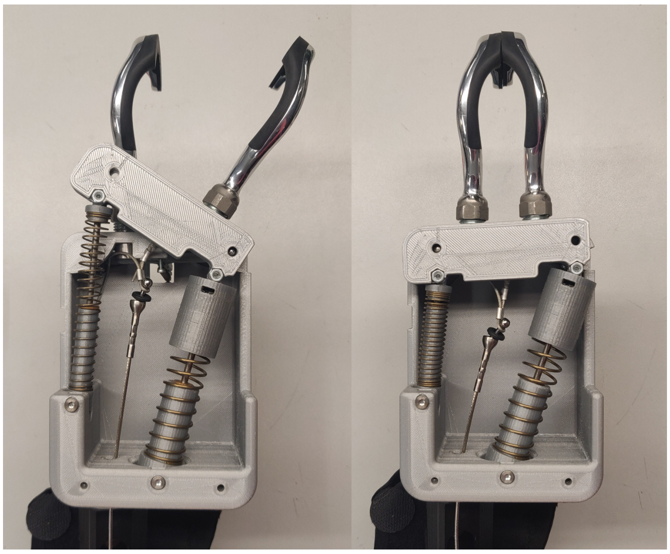


Fig. 7: Pictures of the prototype, without the protecting cap. The device is in VC mode on the left and in VO mode on the right.

activation and pinch forces. Figure 8 was obtained during the open and close test in VO and Figure 9 during the closing test in VC. Figure 10 presents the graphs obtained in the VC pinch test. The results shown in Table I are compared to other terminal devices in appendix A. The open and close test with an opening of 50mm, mentioned in the appendix, was not performed because the device could not open to 50mm. Furthermore, the closing of the prosthesis in VC mode was not indicated with a 1mm thick steel plate, which is done in [8], since the fingers could not fully close. Closing of the prosthesis was indicated by observing the pull force; a strong increase in force, indicates a closed prosthesis. The results show that the pinch force in VO is as expected. However, the cable forces are higher for both VO and VC. This is in line with the large amount of hysteresis found, indicating that a lot of energy is lost in the system. The device has bad mechanical properties compared to existing devices. The amount of work and hysteresis are similar to other devices, as the cable excursion for this device is short.

C. User Functionality Test

Because a large pull force was found in the mechanical tests, opening the prosthesis during the user test would be too heavy. The VO spring was shortened before the user tests, which decreases the initial spring force. The new pinch force for a 10mm thickness changed to 5.4N and the cable activation force to fully open the device is $\sim$ 77N. The prototype was evaluated by 9 participants with two intact hands (age 25 $\pm$ 1 yr; 5 males, 4 females; 7 right-hand dominants) in the SHAP-test. Only 23 of the 26 tasks were performed. 'Simulated Food Cutting' was not done because of the low pinch force. 'Lifting a Heavy Object' and 'Lifting a Light Object' were not possible because of the small opening width of the prosthesis. Most participants could switch themselves, others needed some help,

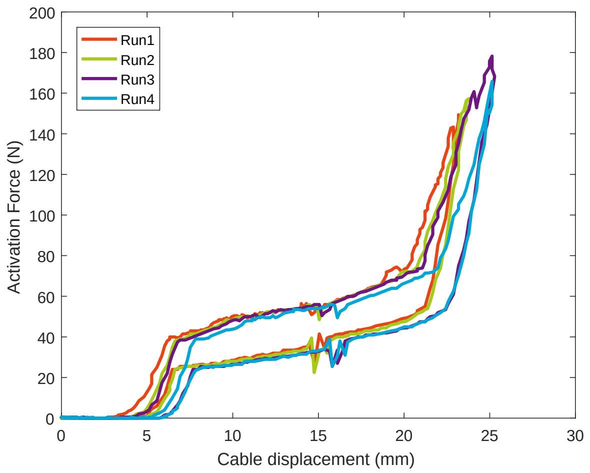


Fig. 8: Force displacement graph for each run for fully opening the prosthesis in VO.

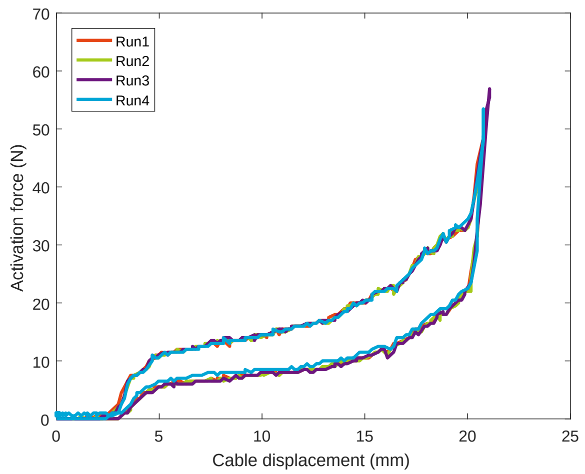


Fig. 9: Force displacement graph for each for fully closing the prosthesis in VC.

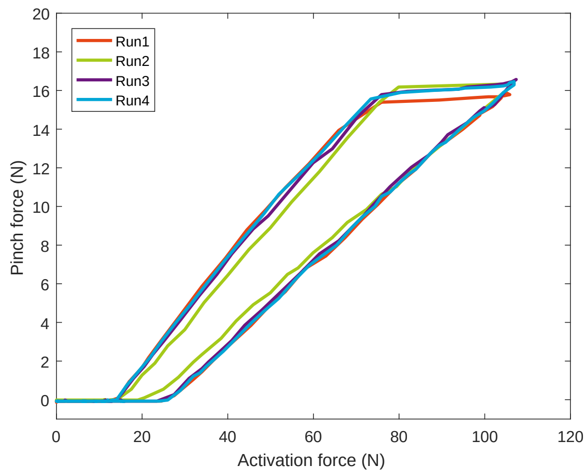


Fig. 10: The pinch force plotted against the activation force measured in the pull cable in VC mode

TABLE I: Requirements and parameters for the new device. *closed/open, †object thickness 10mm, ‡VO/VC

Parameters	**Requirement**	**Parameters new design**
Comfort		
Mass	max. 248g	332g
Cosmesis		
Dimensions	length: max. 170mm, width: max 76mm	length: 206mm width: 85/106mm*
Control		
Pinch force VO	min. 14N	7.7N†
Cable force VO	max. 38N	162.6 ± 12.39N
Cable force VC (pinch 15N)	max. 38N	99.9N
Cable excursion	max. 80mm	20.81 ± 0.83mm /20.84 ± 0.15mm ‡
Opening width	min. 83mm	49/56mm ‡
Prehension type	palmer and tip	lateral and extension

but all participants could perform the tasks in the two different modes. The resulting IOF-scores are presented in Table II and compared to earlier assessed prostheses [5] [11] [12] in Table III. The available prehension patterns are shown in Table I. The prehension patterns were compared after normalization [25]. Lateral, extension and spherical have a normalized score above 1 and are, therefore, more functional than the other types. The contribution of spherical (palmer prehension) will be discussed.

The p-values presented in Table II indicate a significant difference between preferred mode and VO and between preferred mode and VC. This proofs that using a hybrid device leads to a higher score then only using VO or VC. This result is equal to the results presented in similar studies [5] [12]. Table III shows that the tested device performs worst of all compared to VC-devices and is second worst compared to other VO-devices. In the hybrid mode (preferred mode), the device performs better than the device presented in [5] and worse compared to the one presented in [12].

The preference for a specific mode can be found in Figure 11. A full overview of the choices is shown in appendix B. Participants had different preferences for several tasks. All participants agreed on using VC for the 'Heavy Power' and on using VO for 'Open/Close Zip' and 'Rotate a Screw'. A small overall preference for VO was found.

IV. Discussion

A new VO/VC device was designed, built and evaluated. The study demonstrates that using two pivot points is a viable method when integrating both VO and VC in one device. The prototype shows that switching with the intact hand is possible and that using a tension spring in a bi-stable mechanism enhances switching.

Evaluating the device was done by both mechanical and user testing. The mechanical tests showed that high cable forces were present when closing or opening the prosthesis and that large energy losses occur during use of the device. The IOF-scores obtained during the user test are poor compared to other existing devices. However, the results proof that using both VO

TABLE II: Index of Functionality (IOF) scores for 9 subjects

IOF scores	P1	P2	P3	P4	P5	P6	P7	P8	P9	Mean ± SD	p-Value
VO	42	33	46	49	40	45	36	40	40	41 ± 5.0	
VC	35	36	42	56	33	28	35	34	38	37 ± 7.9	
Preferred mode	47	46	49	58	44	48	34	48	43	46 ± 6.3	
Preferred mode - VO	5	13	3	9	4	3	-2	8	3	5.1 ± 4.3	0.0077
Preferred mode - VC	12	10	7	2	11	20	-1	14	5	8.9 ± 6.4	0.0032

TABLE III: IOF scores for different terminal devices

Prehensor Type	Source	IOF: Mean ± SD
VO	[11] Berning et al.	53.6 ± 10.9
	[12] Sensinger et al.	50.2 ± 7.3
	[5] Coehoorn	37.7 ± 6.0
	New Design	41.2 ± 5.0
VC	[11] Berning et al.	55.4 ± 11.5
	[12] Sensinger et al.	53.8 ± 11.0
	[5] Coehoorn	40.3 ± 6.8
	New Design	37.4 ± 7.9
Hybrid	[12] Sensinger et al.	57.4 ± 6.2
	[5] Coehoorn	42.1 ± 6.2
	New Design	46.3 ± 6.3

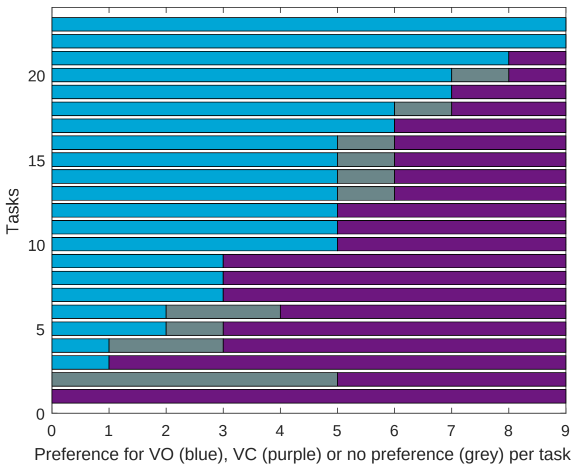


Fig. 11: The user preference over 23 SHAP tasks. The tasks are ranked based on the amount of subject choosing VO. A small overall preference for VO is indicated since their is slightly more blue (VO) than purple (VC).

and VC in one device is favourable over only using one of the types.

The embodiment of the prototype influenced the results in both mechanical and user testing. The device is longer, wider and heavier and does, therefore, not fulfil the requirements. This is due to the use of 3D printing. Using this type of manufacturing saved time and costs, but the drawbacks influenced the functioning of the prototype. Besides the unfavourable sizes and weight, misalignment was found in the fingertips. This might be due to the higher tolerances found in 3D printing compared to for example machining or due to a mistake when constructing the parts.

The bi-stable mechanism, present in the device to enhance switching and preventing a moment without an axis active, did not function properly. Most participants were able to switch between modes themselves and alignment of the parts was done by the intact hand or with pulling the cable. The mechanism did enhance switching but since the axes tilted and the holes were not perfectly aligned, the spring was not strong enough to finish the switching movement. Thus, the switch should be guided during the full motion by the intact hand which made it possible to pause the movement halfway. This creates the situation where the device can fall apart, which happened once during the user test. This did not influence the results but decreased the safety and usability of the device.

The opening width is relatively small compared to other devices for both VO and VC. This was already expected based on the opening width modelled. The opening angle of the device was limited by the maximum compression of the guidance systems of the springs, which were added to prevent buckling. Because they had to be 3D printed, the parts were kept simple, and thus no telescope mechanism was included. This reduced the maximum compression to half the total length, resulting in a relative small opening width. The opening width during VO was further reduced by the design of the fingers, which was unclear during the design phase. The thickness and curvature of the fingers were not estimated precisely, which led to errors in the prototype. One of these fingers hitting the wall limited the opening angle, as shown in Figure 2-F. Furthermore, the opening width in the tip is smaller for both VC and VO than modelled, because the model did not take into account the curvature to the tip. Measuring the opening width at the most extreme point of the fingers gives an opening width of 65mm in VC, which is equal to the modelled opening width.

High cable forces were found when using the device. A reason for this is the direction of the cable. The location of the cable was changed compared to the original design as shown in Figure 2, to the configuration as shown in Figure 7.

This direction reduces the moment arm of the cable force around the pivot. In addition, the cable is pulled along a wall, leading to friction and therefore higher cable forces. Other sources of friction were found around the axis and in the two spring-guiding systems. For finding the main source of the energy losses, a small comparison test was done with pushing the moving finger instead of pulling the cable. Measuring the hysteresis during a full movement with pushing gives 78% of the total hysteresis. This indicates that the main reason for high cable forces is the friction in the device.

The found cable excursion is in line with the modelled one, which is strange because the opening angle for VO is smaller. It is unclear why this is the case, but it might be due to elongation in the cable or due to movements in other directions.

Several issues are present which could explain the low IOF-score. First of all, cable forces were relative high compared to other devices which made the tasks in the SHAP-test more exhausting. Secondly, the device could not open as far as other devices, which made some tasks more challenging and others even impossible. Third, the pinch force in the device for VO was relatively low and the cable force for pinching in VC relatively high, which made it difficult to hold an object firmly. Finally, the skew opening of the device might have influenced the performance. The pivot points are located on the side of the prosthesis which creates a different opening compared to a hook which has one pivot point in the middle.

This skew opening might have influenced VC more than VO, since VO had an higher IOF-score than VC, which is not in line with other study results. Another reason for the difference between the VO and VC mode is that the device could not close in VC where it could in VO. Since both the overall IOF-score and the difference between VO and VC could be explained by several reasons, it is hard to conclude if the skew opening influenced grasping.

Subjects in the user test had to choose their preferred mode. Since the opening width in VC was larger compared to VO and because the fingers could not fully close in VC, the participants' choice was influenced by the functioning of the prototype. Subjects might prefer VC when large objects need to be grasped and pick VO when flat products like papers are involved. This hypothesis cannot be proven since data on task choices in previous studies is not available.

Each task in the SHAP-test is based on a single prehension type of the human hand, or a combination of multiple. The participants in this study did not necessarily use the prescribed prehension pattern to fulfil the tasks. This influences the IOF-scores of the individual prehension types. An example is the spherical task; the ball could not be grasped and thus it was 'scooped' over the small wall. This task and others related to the spherical grasp, were performed with a movement which is not representative for a spherical grasp. Although the normalized score for the spherical grasp above 1, it was concluded that this grasp is less functional in the device.

The SHAP protocol is unclear about using prostheses and this might evoke differences in results. One aspect which might influence the results was the small range of motion which the participants had because the prosthesis was placed in front of their intact hand. For this reason, small participants had to get of their chair to finish their task and participants in general could not sit in front of the tray when grasping an object but had to move to the side. Additionally, users were placed on an office chair which was used to move during several tasks.

V. Study Limitations

The switching mechanism without the use of the intact hand was left out, as explained was in section II-A. Incorporating this idea in plastic was not possible and due to time limitations, it was chosen to exclude this part in the prototype. Including a switch without the use of an intact hand will increase the functionality of the device, because the spare hand can simultaneously be used for other activities.

The springs used in the device are off-the-shelf springs. Using standard springs in VO limits the range of pinch forces. A custom spring could be designed with a lowered spring constant but a high initial force. This creates a more constant force over the several opening widths.

The user test was performed with 9 participants, all with two intact hands. Since the device is designed for upper limb amputees, the subjects were not representative. With only 3750 upper limb amputees in the Netherlands [26], selecting a representative subject group was beyond the scope of this study.

VI. Recommendations

Since the device does not function according to the requirements, more research is needed. The switching mechanism should be improved with respect to safety, ease of use and switching without the use of the intact hand. It is furthermore recommended to pay attention to the material used to improve the strength and durability of the device. Finally, it is recommended to optimize the springs. By designing own springs, pinch and cable forces should be improved. Choosing for longer springs and changing the embodiment of the device will allow for larger opening widths as well.

VII. Conclusion

A hybrid terminal device was embodied, prototyped and evaluated. Concluded is that two pivot points can be used for switching between VO and VC. However, the evaluation shows that the presented prototype does not meet the requirements. Recommendations are given for future work in order to fulfil the need for a device which provides both VO and VC.

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APPENDIX A
CHARACTERISTICS OF EXISTING PROSTHETIC HOOKS

TABLE IV: Characteristics of existing VO prosthetic hooks, from [22]

Characteristics		**Hosmer Model 5X**			**Hosmer Sierra 2 Load VO Hook**		**RSL Steeper Carbon Gripper**		**Otto Bock Model 10A60**		**Coehoorn [5] VO**	**New Device VO**
		1 band	2 bands	3 bands	Setting 1	Setting 2	Setting 1	Setting 2	Setting 1	Setting 2		
Mass (gr)		87	90	92	242	242	171	171	223	223	213	332
Max. Open (mm)		88	88	88	66	66	97	97	67	67	65	49
Max. Cable Excursion (mean $\pm$ SD, n = 4)	Test 1: Full (mm)	45 $\pm$ 0.2	46 $\pm$ 0.1	46 $\pm$ 0.1	34 $\pm$ 0.1	35 $\pm$ 0.0	43 $\pm$ 0.2	43 $\pm$ 0.1	35 $\pm$ 0.1	35 $\pm$ 0.1	21 $\pm$ 0.0	20.8 $\pm$ 0.8
	Test 2: 50mm (mm)	24 $\pm$ 0.1	25 $\pm$ 0.1	25 $\pm$ 0.0	26 $\pm$ 0.0	26 $\pm$ 0.0	28 $\pm$ 0.1	28 $\pm$ 0.1	27 $\pm$ 0.0	27 $\pm$ 0.2	19 $\pm$ 0.1	-
Max. Cable Force (mean $\pm$ SD, n = 4)	Test 1: Full (N)	48 $\pm$ 12.0	72 $\pm$ 3.5	95 $\pm$ 4.2	67 $\pm$ 7.9	117 $\pm$ 6.4	70 $\pm$ 0.4	75 $\pm$ 0.2	36 $\pm$ 0.0	101 $\pm$ 0.5	128 $\pm$ 2.3	162.64 $\pm$ 12
	Test 2: 50mm (N)	25 $\pm$ 0.3	50 $\pm$ 0.2	71 $\pm$ 0.2	40 $\pm$ 0.3	82 $\pm$ 0.1	43 $\pm$ 0.3	48 $\pm$ 0.1	32 $\pm$ 0.5	94 $\pm$ 0.3	124 $\pm$ 1.5	-
Open and Close: Full (mean $\pm$ SD, n = 4)	Work (Nmm)	1,128 $\pm$ 14	2,248 $\pm$ 10	3,206 $\pm$ 18	1,243 $\pm$ 11	2,642 $\pm$ 14	1,619 $\pm$ 2	1,848 $\pm$ 7	1,002 $\pm$ 3	2,752 $\pm$ 6	1,827 $\pm$ 69	1207 $\pm$ 109
	Hysteresis (Nmm)	290 $\pm$ 3	394 $\pm$ 6	458 $\pm$ 4	379 $\pm$ 1	571 $\pm$ 2	487 $\pm$ 4	510 $\pm$ 2	482 $\pm$ 5	555 $\pm$ 15	767 $\pm$ 18	425 $\pm$ 78
Open and Close: 50 (mean $\pm$ SD, n = 4)	Work (Nmm)	574 $\pm$ 3	1,173 $\pm$ 6	1,684 $\pm$ 4	868 $\pm$ 1	1820 $\pm$ 2	846 $\pm$ 4	992 $\pm$ 2	775 $\pm$ 5	2,033 $\pm$ 15	1,624 $\pm$ 20	-
	Hysteresis (Nmm)	120 $\pm$ 4	154 $\pm$ 3	186 $\pm$ 4	245 $\pm$ 3	337 $\pm$ 2	267 $\pm$ 4	272 $\pm$ 6	353 $\pm$ 6	421 $\pm$ 16	698 $\pm$ 9	-
Pinch Force Test 3	10mm (N)	9	14	24	9	24	11	14	11	24	20	8
	20mm (N)	9	19	29	11	27	11	13	11	31	24	9
	30mm (N)	9	20	33	11	29	11	14	11	37	27	12

TABLE V: Characteristics of existing VC prosthetic hooks, from [8]

Characteristics	**Hosmer APRL hook**	**TRS hook**	**Coehoorn [5] VC**	**New Device VC**
Mass (gr)	248	318	213	332
Opening width (mm)	73	72	65	56
Maximum cable excursion (mm) (mean $\pm$ SD, n = 4)	38 $\pm$ 0.1	49 $\pm$ 0.1	20 $\pm$ 0.4	20.8 $\pm$ 0.15
Work closing (Nmm) (mean $\pm$ SD, n = 4)	720 $\pm$ 6	284 $\pm$ 3	41 $\pm$ 0.3	353 $\pm$ 1.6
Cycle hysteresis (Nmm) (mean $\pm$ SD, n = 4)	138 $\pm$ 3	52 $\pm$ 1	11 $\pm$ 0.3	142 $\pm$ 12
Work closing and pinching 15N (Nmm) (mean $\pm$ SD, n = 4)	687 $\pm$ 2	234 $\pm$ 3	65 $\pm$ 0.8	452 $\pm$ 10
Required cable force for a 15N pinch (N) (mean $\pm$ SD, n = 4)	62 $\pm$ 0	33 $\pm$ 0.2	51 $\pm$ 1.6	100 $\pm$ 0.7
Pinch force at a cable force of 100N (N) (mean $\pm$ SD, n = 4)	30	58	31	15
Pinch force drop at a 15N pinch (N)	10 $\pm$ 1.5	-	-	-

Appendix B
Preferred modes for the SHAP tasks

TABLE VI: Preferred mode for each task for each participant

Tasks	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**
Spherical - Light	VC	No	No	No	VC	No	No	VC	VC
Tripod - Light	VC	VC	VC	VC	VO	VO	VC	VO	VC
Power - Light	VC	VO	VC	VC	VC	VC	VC	VC	VC
Lateral - Light	VO	VO	VO	VO	VO	VO	VC	VC	VO
Tip - Light	VO	VC	VO	No	VO	VC	VO	VO	VO
Extension - Light	VO	VC	VC	VC	VC	VO	VO	VC	VC
Spherical - Heavy	VC	VC	VC	VC	No	VO	No	VC	VC
Tripod - Heavy	VC	VO	VC	VC	VO	VC	VO	VO	VO
Power - Heavy	VC	VC	VC	VC	VC	VC	VC	VC	VC
Lateral - Heavy	VC	VC	VO	VC	VC	No	VC	VC	VO
Tip - Heavy	No	VC	VO	VO	VO	VC	VC	VO	VO
Extension - Heavy	VO	VC	VO	VO	VC	VO	VC	VC	VO
Pick up Coins	VC	VO	VO	VO	VC	VC	VO	VO	VC
Button Board	VC	VO	VO	VO	VO	No	VO	VO	VO
Simulated Food Cutting	-	-	-	-	-	-	-	-	-
Page Turning	VC	VO	VO	VO	VC	VC	VO	VO	VO
Jar Lid	VC	No	VC	VC	VO	No	VC	VO	VC
Glass Jug Pouring	VO	VC	VO	VC	VO	No	VO	VO	VC
Carton Pouring	VO	VC	VC	VO	VO	VC	VC	VC	VC
Lifting a Heavy Object	-	-	-	-	-	-	-	-	-
Lifting a Light Object	-	-	-	-	-	-	-	-	-
Lifting a Tray	No	VC	VO	VO	VO	VO	VC	VC	VO
Rotate a Key	VO	VC	VO	VO	VO	VO	VO	VO	VO
Open/Close Zip	VO	VO	VO	VO	VO	VO	VO	VO	VO
Rotate a screw	VO	VO	VO	VO	VO	VO	VO	VO	VO
Door Handle	VC	VO	No	VO	VO	VO	VC	VO	VC

3

Appendices

A

Requirements

In this appendix, the design requirements for a new terminal device hook are listed. These are based on the earlier set requirements by Coehoorn [8], on the findings from the performed literature study [13] and other literature findings. Besides requirements, wishes for the design are shown. The design requirements are classified to one of the three main requirements; comfort, cosmesis and control [14]. An overview of the requirements can be found in Table A.1.

A.1. Comfort

Mass: The mass of a normal hand is 373,7 ± 62,1 gram [15]. Taking the mass of the normal hand minus one SD, the maximum mass of the hook should be 311,6 gram [8]. But body-powered hooks are often classified as heavy and weight is one of the main areas of improvement [16]. The weight of the APRL hook (248 gram, [11]), was classified by over 95% as satisfactory [17]. This weight will be taken as maximum for the new device. The terminal device should be as light as possible, which relates to a target of 100 gram.

A.2. Cosmesis

Dimensions and appearance: The new hook should fit in pockets and match the size of the sound hand. That is why the dimensions should be the size of a normal hand minus one SD. The hand length is 184 ± 14mm and the width (without thumb) is 84 ± 8mm, which leads to terminal device dimensions of 170mm length and 76mm width [18].

Since cosmesis is one of the three main factors in prosthesis design, the appearance of the hook should be taken into account. According to the literature review [13], users are often dissatisfied with the cosmesis of their hook. The terminal device should not exactly represent the hand but a hook based on the anatomy of the hand is ranked higher in appearance than the metal finger hook. A requirement for the hook is that it should have an appealing appearance [8].

A.3. Control

Pinch Force: The literature review [13] shows that for performing daily life activities, a pinch force of 31N is useful. For performing all activities, a pinch force of at least 67N should be available. Existing VO hooks have a pinch force ranging from 9-37N [10] (which can be even higher with adding bands) and for VC hooks the pinch force depends on the force generated by the shoulders. Earlier research showed that a pinch force between 15 and 20N was not enough to perform all the SHAP tasks [19]. Berning et al. [9] concluded that a pinch force of 14N was a good choice because it was too low for some SHAP-tasks and too high for others.

A lower pinch force in VO mode is appreciated when looking at activation force since this will be lowered as well. The new design will be able to switch between VO and VC, which leaves the option to use VC when high forces are needed. A reasonable pinch force in VO mode is 14N.

Cable Force: Women can produce a maximum cable force of 188 ± 87 N and men of 332 ± 117N [20]. Since only 20% of the maximum muscle force can be used fatigue-free [21], women can provide a force of 38N and men of 66N. It can, therefore, be said that to open the prosthesis to 50mm (VO mode), the maximum cable activation force should be 38N.

It is shown that for a VC prosthesis the optimal operation force is between 10 and 20N [22]. It is furthermore shown that with higher cable forces, control is worse [23]. But, to create a pinch force of 15N, the lowest cable force for hooks was found to be 33N [11]. Taking all results into account, the requirement should be that the cable force should be maximum 38N to create a pinch force of 15N. Thereby the target is added, that a pinch force of 15N can be reached with a cable force between the 10 and 20N. According to Hichert [23], the fatigue-free boundary can be exceeded without further consequences when a higher pinch force is required in a VC prosthesis just once.

Opening Width: According to the results of the literature study, the opening width of a prosthetic hook should be between 83mm and 100mm. But, it should be noted that 90% of the objects can be grasped with an opening of 38mm.

Since the user should be able to grasp as many items as possible, the opening width should be at least 83 mm for one mode. It applies for VC that smaller objects require a longer stroke and can, therefore, be better controlled [23]. This is the other way around for VO devices, where pinch force on larger objects can be better controlled. This suggestion implies that a large opening (min. 83mm, target 100mm) is more suitable for the VO mode. In VC mode, the prosthesis should at least be able to grasp 90% of the objects, which leads to an opening width of at least 38mm. However, a difference in opening width would force the user to pick up large objects in VO where VC might be preferred. Since the choice of the user should not be influenced, the requirement is a opening width of 83mm for both modes.

Cable Excursion: According to Taylor [24], the cable excursion should be 53mm for fully opening and closing a terminal device. This is based on shoulder measures. Maximum cable excursions were measured and concluded that the cable excursion should not exceed 80mm [23]. This length, however, might be impractical since objects should be grasped far away from the body to put tension on the cable.

Besides, a study shows that increasing cable excursion helps create the desired pinch force [23]. This leads to the requirement that the cable excursion should have a maximum of 70mm.

Grip: An important field of improvement is 'holding an object' [13]. Different types of surface design were used to improve this. Taking the grip into account when designing is important. The grip should be functional for objects of all sizes and shapes.

Prehension Type: To be able to grasp as many objects as possible, hand prehension types should be adopted in the prosthesis. According to Keller et al. [25], the ideal situation should include the three most popular types of prehension. First is tip prehension, used for picking up small objects (needles, pencils) and cylindrical larger objects (drinking glass, apple). The other types of prehension are lateral and palmer, which are harder to distinguish. Palmer prehension can do anything lateral prehension can (not the other way around), but lateral is more convenient for some activities. For example, holding a fork or spoon. Palmar prehension can be used for grasping coins, pencils, small blocks and more. The design should at least focus on palmer prehension and tip prehension. The target is added to include lateral prehension as well.

Additional: A hook is chosen for several reasons. These advantages should be taken into account when designing a new hook. According to the literature review [13], these advantages are roughness, durability, the easiness of cleaning and good sight on items when grasping. As said before, the hook should be able to grasp different sized objects. Besides that, the hook should be able to grasp items of different stiffness. Special attention is needed for grasping soft items. The above-mentioned requirements are mainly regarding the grasping of items, also called prehensile movements. But, the literature review [13] showed that the hook is more often used for non-prehensile movements, which are movements like pushing and pulling objects without grasping. The hook should be able to perform these movements and assist in two-handed tasks.

Table A.1: Requirements for the new VO/VC device

Measure	**Requirement**	**Target**
Mass	max 248g	$\pm$ 100g
Dimensions	Length: max 170mm, width: max 76mm	
Pinch Force VO	min 14N	
Cable Force VO	max 38N	
Cable Force VC (for a 15N pinch)	max 38N	10-20N
Cable Excursion	max 80mm	$\pm$ 53mm
Opening width	min 83mm	$\pm$ 100mm
Prehension type	Palmar and Tip	Addition of Lateral

B

Finger design

The shape of the prosthetic fingers is highly important for the functioning of an upper limb prosthesis [13]. They should be able to provide a certain grip on objects, be able to grasp objects of different sizes and they should have an attractive appearance. More requirements are mentioned in appendix A. The goal of this study is to improve the novel VO/VC device as explained in section 1.4. It was first analysed why the used fingers did not perform well. Thereafter, new designs were created and incorporated with the mechanism. The two concepts and the use of frictional material were evaluated with Matlab [26].

B.1. Western curlew theory

The fingers of the hook were designed based on the beak of a Western Curlew bird. The theory is presented in a lecture [27] and further explained in the report [8].

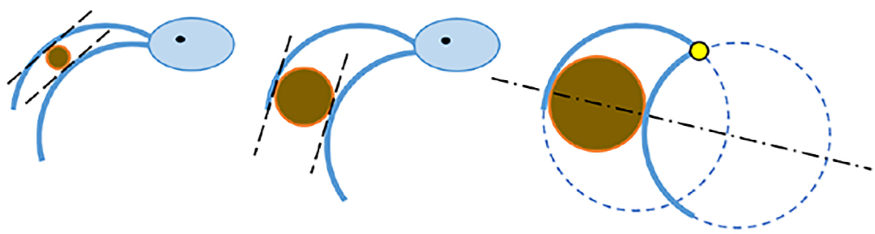
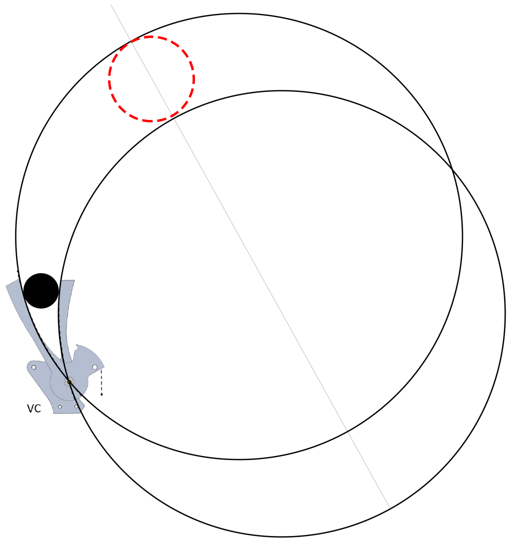


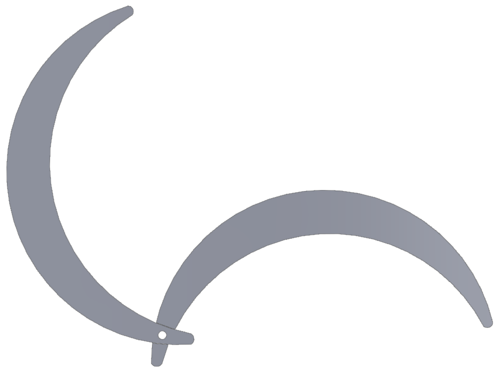
Figure B.1: Western Curlew Theory. Adapted from [27]

The beak of this bird consists of two equal curved parts. According to Coehoorn: 'Objects will settle where the contacts forces align' (page 28 of [8]). From the images used in the slides, it becomes clear that the centre of the (circular) object should align with the two centres of the beak parts. These centres are found by extrapolating the radius used for the beak parts, see the drawing on the right in Figure B.1. Because the radius is the same for both jaw parts, it is an ideal use for the fingers of this new terminal device, since both fingers are used on both sides.

The theory sounds reasonable and applicable to the design of the hook fingers. However, it did not work in the novel design. Since the radius, used for the shape of the fingers, is not mentioned in the report [8], the circles were constructed based on of the images given. This reconstruction can be found in Figure B.2(a). As shown, the chosen radius is quite large. When constructing the circles, as shown in the lecture slides, the object (red dotted circle) will settle outside the fingers. This reconstruction shows that the theory was not applied correctly. The centres of the circles align at a point where no fingers were created.



(a) Reconstruction of the existing hook with the western curlew theory

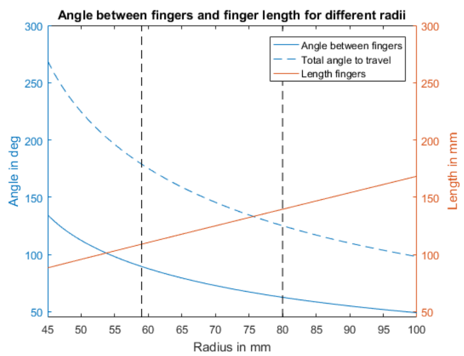


(b) Impression of correct constructed fingers

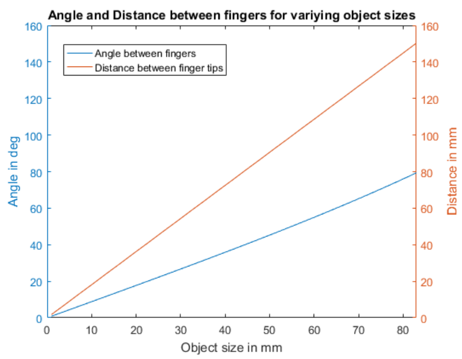
Figure B.2: The existing fingers compared to the correct constructed fingers

B.2. New designs

New western curlew design Since the theory is applied wrong in the prototype, it could be applied well in a new design. An impression of correct constructed fingers is shown in Figure B.2(b). Several important parameters are influenced by the radius of the circles: the width and length of the fingers and the opening angle between the two fingers. For finding the optimal radius, Matlab [26] was used to find the corresponding parameters and some advantages and disadvantages were taken into consideration.



(a) The angle between the fingers and the length of the fingers plotted against the different radii.



(b) The distance between the finger tips and the opening angle of the fingers for fingers with a radius of 65mm, plotted against different objectsizes.

Figure B.3: Resulting plots form the mentioned Matlab script. Figure B.3(a) shows the length of the finger and the angle between the fingers for grasping a 83mm object, for several radii used to construct the finger. The black dotted line on the right, shows the boundary given by the requirements for maximum length. The left black dotted line shows the limit before the opening angle becomes unrealistic. Figure B.3(b))gives the angle between the fingers and the distance between the fingertips for several object sizes

Table B.1: Parameters of the fingers when the radius is 65mm

Parameter	Object diameter 38mm	Object diameter 83mm
Finger length	117.7mm	117.7mm
Opening angle	34 deg	79.4 deg
Width when closed	37.4mm	37.4mm
Width when open	65.8mm	115.7mm

To choose a specific radius, some advantages and disadvantages were summed up.
Advantages for a smaller radius are:

- The fingers will become almost halve a circle and can be used as a hook to carry a bag or alike
- When the fingers are shorter, less material is needed and the fingers will be lighter

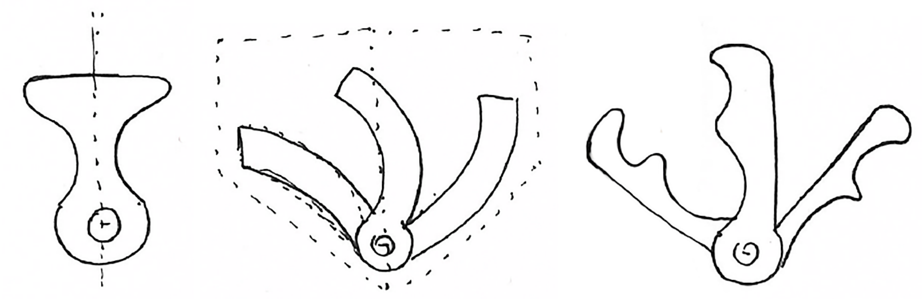
Disadvantages for a smaller radius are:

- The fingers should travel far for grasping a large object
- A longer part of the curvature is needed when the radius is small, which is less appealing than longer but straighter fingers

As the strength and weaknesses are the other way around for a large radius, they are not summed up. Based on the advantages and disadvantages mentioned, an optimal radius of 65mm was chosen. This results in the second plot (Figure B.3(b)). The resulting values for the earlier mentioned parameters can be found in Table B.1.

A major drawback of this design is the appearance, which is not aesthetic. Furthermore, for grasping an object, it should be perfectly aligned with the centres of the circles. As this is not always the option, new ideas are generated.

New ideas Based on the different designs found in an earlier performed literature study [13], lots of ideas for finger shapes were generated. These ideas could be classified into three types: Mirrored Finger, Equal Grasp and Different Grasps. In the first class, designs of which one finger is equal on both sides are included. To the second class belong the designs where both fingers are equal, leading to an equal grasp in both VO and VC mode, but the finger itself is not mirrored. The third class consists of designs where both VO and VC have a different type of grasp. Examples are shown in Figure B.4.

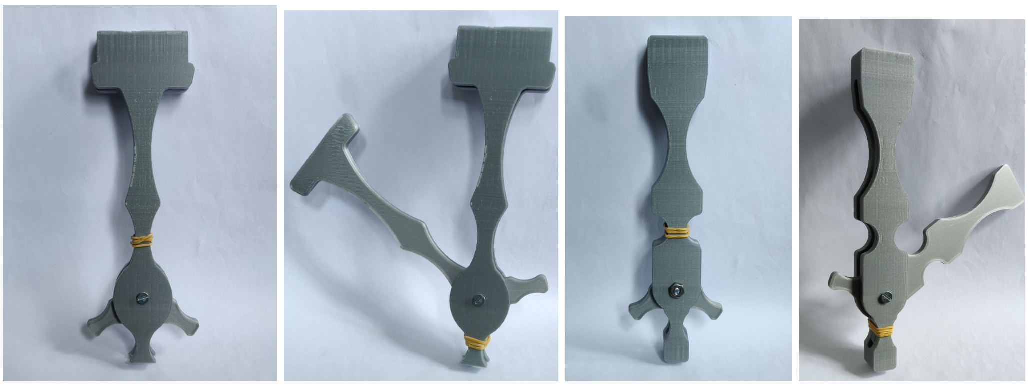


(a) Mirrored finger (b) Mirrored Grasp (c) Different grasp

Figure B.4: The three categories for new finger ideas

Different grasps for VO and VC (class three) will make the final design less valuable. Instead of switching when a mode is preferred, the user is forced to switch mode because of the shape of an object. This is unwanted, so concepts were only generated with the first and second class.

Due to the design of the mechanism, the maximum angle for the moving finger is 110°. As the fingers need to grasp an object with a diameter of 83mm, the choice in finger design is limited. Based on these requirements, two ideas were chosen as concepts and prototyped.



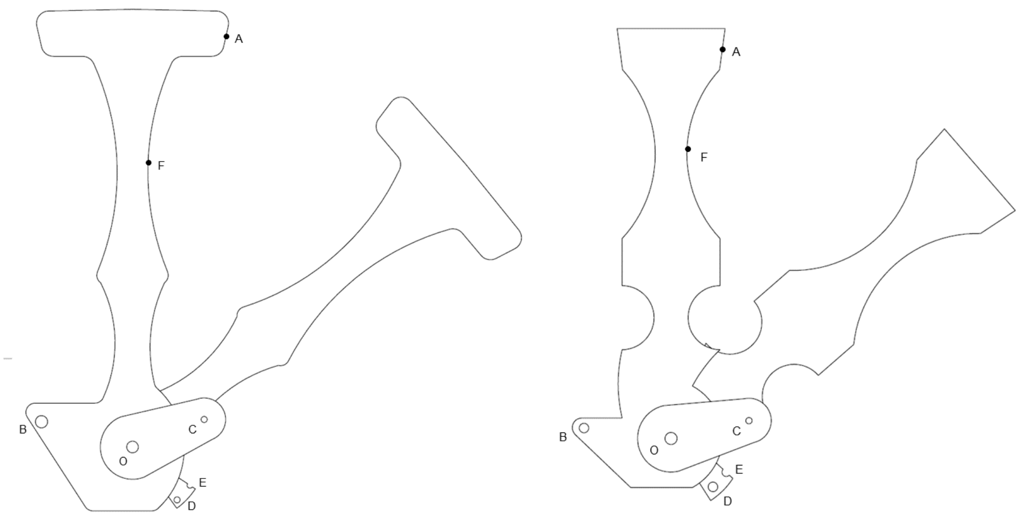
(a) Concept 1 VO (b) Concept 1 VC (c) Concept 2 VO (d) Concept 2 VC

Figure B.5: 3D prints to evaluate shape functionality. The prototypes are a bit longer than the design, which was necessary to create enough strength in the 3D print.

B.3. Evaluation of designs

The prototypes (Figure B.5) where evaluated by grasping the following objects (the diameter is shown between brackets): pencil (10.5mm), glue stick (26.5mm), adhesive tape roll (48.1mm), cup with rubber band (79.6mm) and larger cup with the same rubber band (84.7mm). The prototypes were able to grasp all the objects. However, concept 1 could not grasp the cups when entering from the front, it could grasp the cups when entering from above.

Also, Matlab [26] was used to evaluate the other requirements like pinch and cable force. To do so, the mechanism was incorporated. Figure B.6 shows both concept 1 and 2, with the mechanism as used in the novel VO/VC device [8]. The springs are not shown.



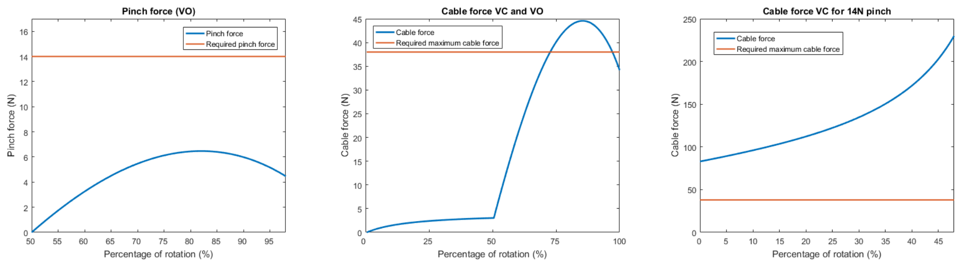
(a) Concept 1 (b) Concept 2

Figure B.6: Concepts 1 and 2 shown with mechanism, without springs

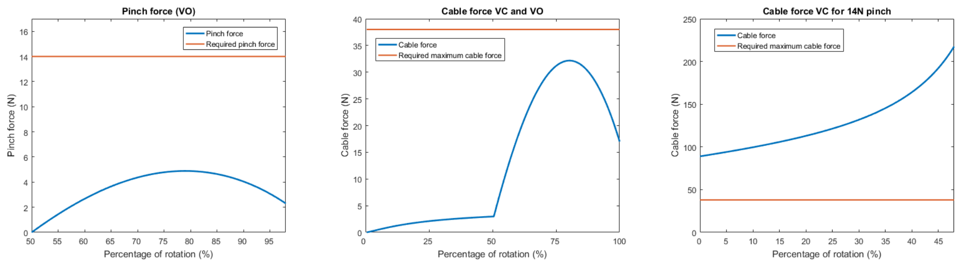
Using some chosen distances and the original springs, pinch and cable force could be found. Figure B.7 shows the results for both concept 1 and 2. The pinch force in VO is much lower than required and the cable force in VC to provide a pinch force of 14N is too high.

To respectively increase and decrease these forces, some parameters where changed. The points used for optimization are indicated by the characters in Figure B.6. Table B.2 summarizes the results. These lengths were increased and/or decreased to check their influence on cable and pinch force.

Concluded can be that increasing the length between the rotation point and cable connection (E_x) and decreasing the finger length (l_AOy) has a positive influence on both pinch and cable force.



(a) Pinch force in VO, Cable force for both VC and VO and Cable force for a pinch of 14N in VO for the first concept



(b) Pinch force in VO, Cable force for both VC and VO and Cable force for a pinch of 14N in VO for the second concept

Figure B.7: Graphs showing pinch and cable force for Concept 1 and Concept 2

Table B.2: Influence of decreasing or increasing a parameter on the pinch and cable force. An x in the name indicates the horizontal distance to point O and y indicates the vertical distance to point O.

Action	**VC/VO**	**Influence on cable force**	**Influence on pinch force (VO)**	**Influence in cable force of 14N pinch (VC)**
Increasing l_OC	VO	Large, negative	Large, positive	-
Increasing l_OC	VC	Small, negative	-	Small, negative
Increasing B_y	VO	Medium, negative	Medium, positive	-
Increasing E_x	VO	Medium, positive	No influence	-
Increasing E_x	VC	Medium, positive	-	Medium, positive
Decreasing l_AOy	VO	No influence	Small, positive	-
Decreasing l_AOy	VC	No influence	-	Small, positive
Increasing l_OD	VC	Medium, negative	-	Medium, negative

Increasing the length of the lever (*l_OC*) and the width to the spring connection (*B_y*) have a positive influence on pinch force but negative on cable force and the lengths of these parameters should be chosen according to other parameters. Increasing the distance to the other spring connection (*l_OD*) has a negative influence and should not be done.

Decreasing the length of the fingers (*l_AOy*) is easier said than done. The two concepts were chosen because they had an optimal grasping design and were able to grasp a circular object of 83mm. Decreasing the length of the finger together with the limitation from the mechanism that the movable finger has a maximum angle of 110°, makes it impossible to create fingers which can grasp an object of 83mm firmly. As the next step, it was studied whether frictional material on straight fingers could give enough strength to hold objects.

B.4. Straight fingers with frictional material

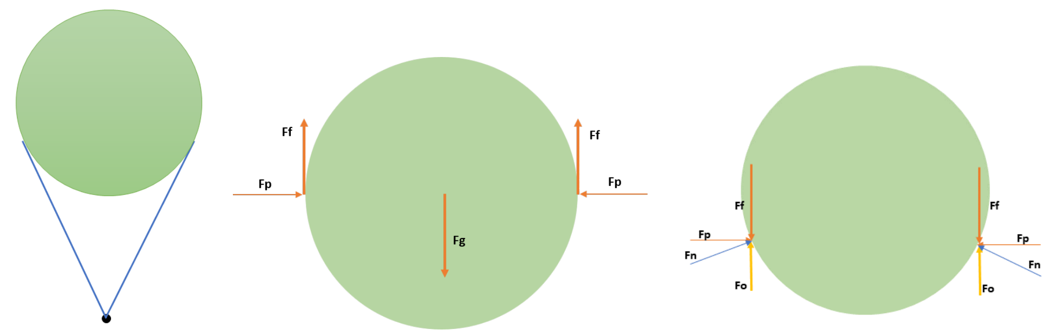
Until now, grasping was improved with different finger shapes. This is preferred because the user is not dependent on the material of an object which should be grasped. Furthermore, prosthetic hooks made of one metal are more durable than fingers with added materials. However, this approach did not work together with the used mechanism. Therefore, the option to use a frictional material is studied.

Table B.3: Parameters used when finding the needed friction force

Finger Length	90 [mm]	**k_CD**	0.17 [N/mm]
B_x	27.27 [mm]	**k_BC**	2.37 [N/mm]
B_y	18 [mm]	**l_OC**	40 [mm]
l_OD	20 [mm]	**l_OE**	35 [mm]
theta	55 [deg]	**alpha**	55 [deg]
angle_DE	20 [deg]		

For finding the needed friction force, the parameters presented in Table B.3 are used and it is assumed that the fingers are straight. The friction calculation was based on [28]. In figure B.8(b) the gravitational force of the object (*Fg*), the pinch force created by the fingers (*Fp*) and the friction force (*Ff*) on the grasped object are shown. The friction force can be determined by $F_f = \frac{1}{2} * F_g$ and the friction coefficient μ can be determined by $\mu = \frac{F_g}{2F_p} = \frac{F_f}{F_p}$. This results in a friction coefficient of 0.2453 for VC and 0.4035 for VO.

Since the force applied by the fingers is not perfectly in the direction of the pinch force, there is a force present which pushes the object out of the fingers. This force is *Fo* in Figure B.8(c). This force is opposite to *Ff* and therefore, the friction coefficient can be found by $\mu = \frac{F_o}{F_p}$. For VC, a coefficient of 0.5206 was found and 0.8564 for VO. These friction coefficients were compared with the contact table [29] which shows that when using rubber as friction material, a coefficient of 0.8 can be achieved, depending on the material of the grasped object. This might lead to a problem in VO, where larger objects are shot away because of the high pinch forces.



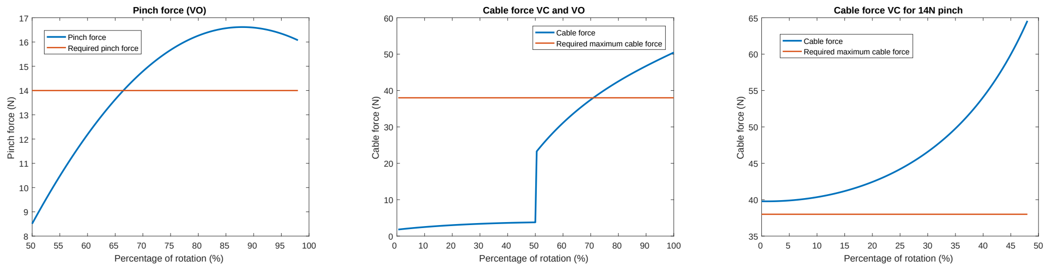
(a) Top view, grasping object (b) Front view (c) Top view, 'pushing' force in yellow

Figure B.8: Forces used to find the needed friction coefficient

It is shown that only using friction to hold the objects will not work in this situation. Furthermore, the lengths of the fingers used for this calculation are not able to grasp an object of 83mm. With an opening width of 64.9mm, an object with a diameter of maximum 69.5mm can be grasped. The resulting pinch and cable forces, shown in Figure B.9, do not fulfil the requirements. With the current parameters, the requirements are not met. Therefore, it can be concluded that only using friction is not enough.

B.5. Conclusion

In this appendix is shown that the optimization of the fingers on the novel VC/VO design is limited. With another, better-grasping finger design, requirements for aesthetics, pinch force or maximum length cannot be met. The overall performance of the hook will probably increase with using frictional material but not enough. It is concluded that with only changing the fingers, the prosthesis will not fulfil the requirements. A next step is taken to find other areas of improvement for this VO/VC device.



(a) Pinch Force in VO (b) Cable force for VC and VO (c) Pinch Force in VO

Figure B.9: Pinch and Cable forces for the straight finger design

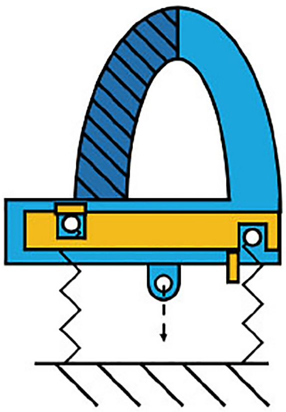
C

New mechanism

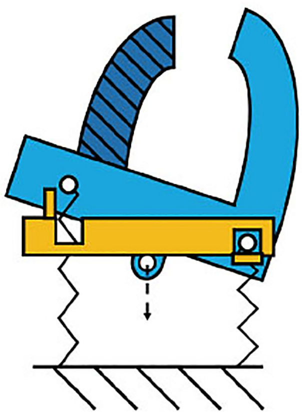
Appendix B explains why changing the fingers of the novel VO/VC device as presented in section 1.2 is not enough to meet the requirements set for a prosthetic hook. More focus is placed on the change in mechanism design. Where pinch and cable forces might be improved by adding extra mechanisms or external power, the grasp can only be enhanced by a different design. It was, therefore, decided to take another step back. The study done by Coehoorn [8] presents a total of eight concepts. Of these concepts, two were classified as promising. The first one is developed into the novel VO/VC device, mentioned in section 1.2. The other promising concept was dismissed because it was difficult to reach the high pinch forces. Since the requirements for pinch force have been lowered (see appendix A), this concept might be appealing. In this appendix, the feasibility of this concept is studied. Additionally, parts which were not yet defined, are embodied.

C.1. Feasibility of the concept

It is stated [8] that the idea of the concept has not been found in other VO/VC prototypes before. In this concept, an extra rotational point is used. Changing between these points of rotation gives a change in using VO or VC. When both axes are active, the gripper is locked. Changing between axes can only be done when the prehensor is closed, which might lead to an additional closing movement for the user. A mechanism to switch between axes should still be found, preferably done with only the movement of the cable.



(a) The concept in VO mode. The left axis is locked, the right axis is free. With pulling the cable, identified by the arrow, the prosthesis will open.

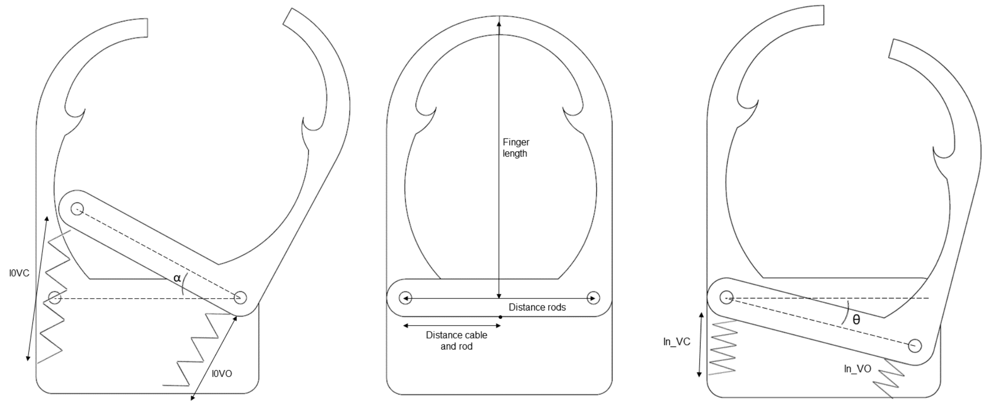


(b) The concept in VC mode. The right axis is locked, the left axis is free. Pulling the cable, identified by the arrow, will close the prosthesis.

Figure C.1: The concept in the two output modes. Adapted from [8]

Table C.1: Parameters used in the concept

Finger Length	90 [mm]	**Distance cable and rod**	30 [mm]
Distance rods	60 [mm]	**k_VC**	0.11 [N/mm]
l0VC	65 [mm]	**lnVC**	17.4 [mm]
k_VO	20 [N/mm]	**l0VO**	150 [mm]
lnVO	25 [deg]	**theta**	47.3 [deg]
alpha	54 [deg]		



(a) The concept in VC, with lengths and angle α.
(b) The concept when closed, with lengths.
(c) The concept in VO, with lengths and angle θ.

Figure C.2: Parameters in the concept.

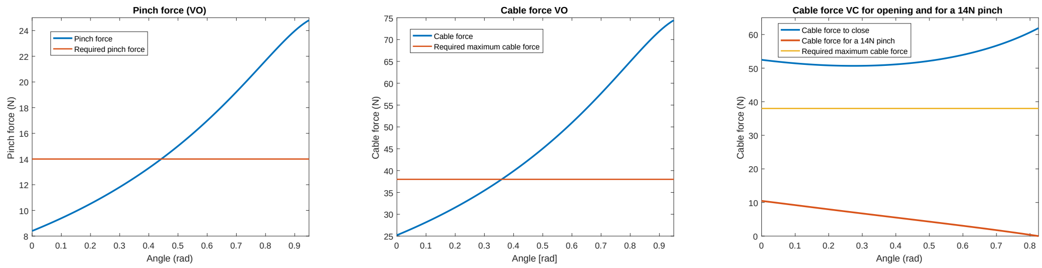
Because the concept was found as one of the two best options, a calculation was made to prove the feasibility [8]. Three models were thought of: one as drawn in Figure C.1 with two compression springs, a second model with extension springs (the Bowden cable should be replaced by something which makes the user able to push) and a third model with only one extension spring. The evaluation in Matlab [26] shows that the concept functions as expected but that requirements for the spring become unrealistic when meeting all the concept requirements. Since concept requirements are changed in this thesis, the concept might be more realistic. A new calculation was made with the current requirements, using model 1. This was chosen because for model 2 and 3 an extra mechanism should be incorporated which makes the device more complicated.

Optimization of the first novel VO/VC prosthesis showed that length of the fingers and distance between the cable connection and the rod are of large influence on the cable and pinch force (see appendix B). Optimizing these distances by trial and error within the limitations of the requirements was done, followed by trying some spring parameters based on existing springs. This resulted in the parameters shown in Table C.1 and Figure C.2 and the pinch and cable forces shown in Figure C.3. Since the results look promising, it was chosen to continue with developing this concept, model 1.

C.2. Switching axes

As explained in section C.1, the new mechanism is based on using two different pivot points. In order to make the idea work, the device should be able to switch between axes and in an ideal situation both axes can be activated, creating a lock. It is important to take into account that always one axes should be active. If the option exists that both axes become loose, the device will break. The device should improve on earlier presented VO/VC devices. It should, therefore, be possible to switch without the use of the intact hand. Switching should be done by the movement of the cable or other parts present in the device.

Activation Because the switch should be activated by the movement of the cable or the finger, this movement was identified and illustrated in Figure C.4. The active pivot point is shown in black and



(a) Pinch Force in VO mode (b) Cable Force in VO mode (c) Cable Force in VC mode

Figure C.3: Pinch and Cable forces after optimization

the rectangle represents the part to which the moving finger is connected. The movement starts at Fig C.4-a with closing the prosthesis. After switching (b-c), the prosthesis can be opened in VO (d). Then the cable is relaxed (e) and the prosthesis will close (f) where , after switching (f-g), the prosthesis will open again by the VC spring (h). This analysis shows that the first switch should take place when the prosthesis is closed after pulling the cable (VC to VO) and the second switch should be done after closing the prosthesis with a relaxed cable (VO to VC). This difference in pulling and relaxing of the cable makes it difficult to incorporate the switch in the cable movement and, thereby, it is difficult to switch based on cable movement as the switch should take place when the device is closed. Therefore, it was chosen to generate ideas with the switch in the moving plate (rectangle in Figure C.4). Ideas with a rotating motion and a flipping pin were thought of.

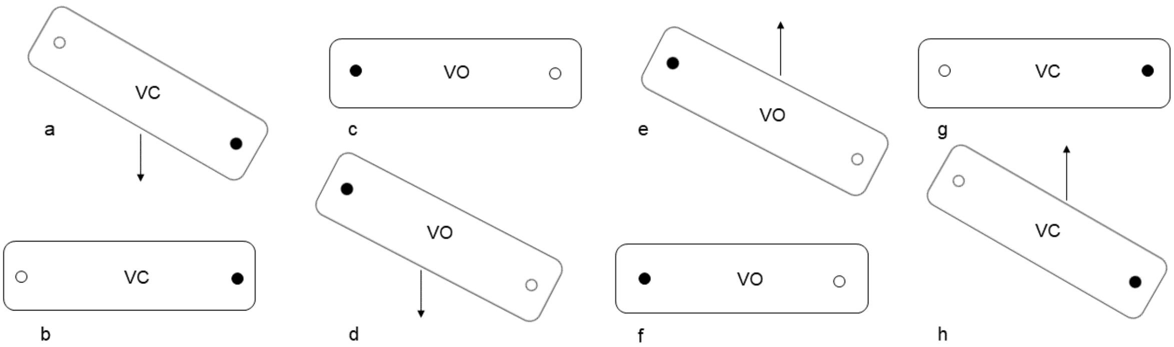
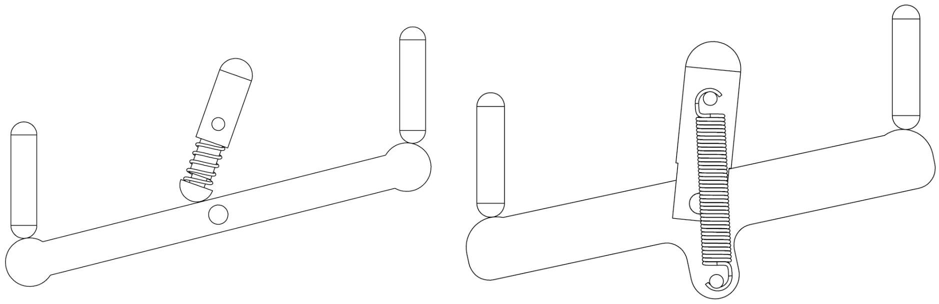


Figure C.4: Movements made when using the prosthesis

Switching The device makes use of two alternating pivots. The user should be able to shift between the use of these axes. Two ways of switching were identified: using two steady axes and open slots, as illustrated in Figure C.1 or moving the axes themselves. For opening slots, the mechanism should be placed in the moving part. For switching pivots, the mechanism can be placed in both parts. Another characteristic of using slots is that the axis is not fully enclosed which leads to unwanted movements. Thus, it was chosen to use the switching axes.

Switching between the axis should be fast to make sure that the movable finger is always supported and that a wrong movement of the user during the switch will not lead to a locked or jammed system. For this fast switching, inspiration was found in a light switch. With the help of a loaded spring, the part that needs to be flipped, will be pulled to the other side which prevents that the switch sticks in a dangerous position. This is better known as a bi-stable mechanism. Introducing this idea in a prototype was first done with a compression spring (Figure C.5(a)). With a small test set-up, it was shown that this did not work well and the system was changed to a tension spring (Figure C.5(b)). In the test set-up, the spring was a bit to weak and the arm a bit to short which led to insights for the final design. At least, the test set-up demonstrated that the mechanism worked as wanted. It should be noted that with this system, using a lock is not possible. This was accepted since the presence of a lock was not a requirement.

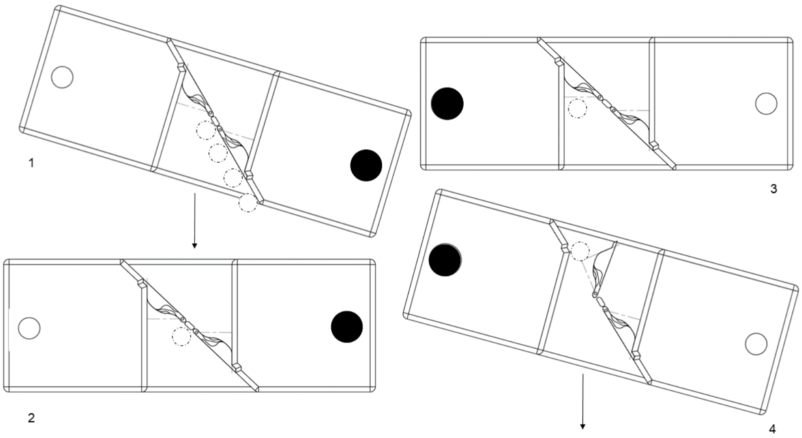


(a) First bi-stable mechanism (b) Second bi-stable mechanism

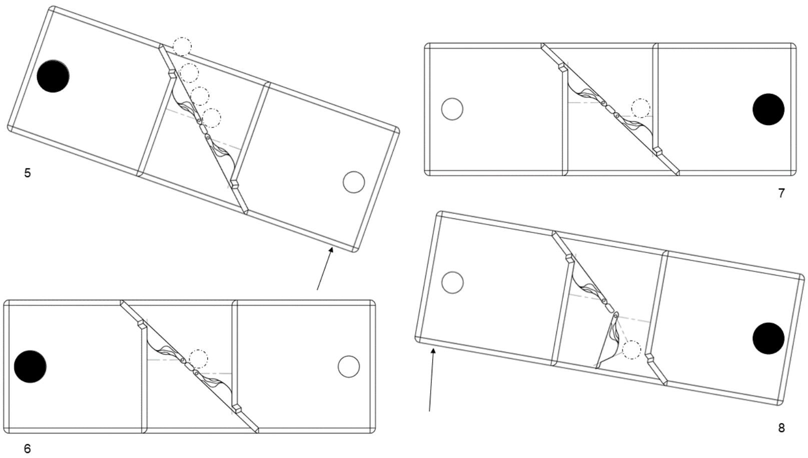
Figure C.5: The two mechanism used for switching the pivot points

C.3. Complete design

For combining the activation and the switching movement, it was chosen to use the flipping of the pin as activation movement. The pin, connected to the spring in the bi-stable mechanism, can be flipped from one side to the other by the movement of the illustrated plate. To guide this movement, a pattern is designed in this plate. The working principle of this pattern can be found in Figure C.6.



(a) VC to VO movement



(b) VO to VC movement

Figure C.6: The pattern in the plate to flip the pin of the bi-stable mechanism. The configuration presented is the same as in Figure C.2 and the plate is made transparent. The dotted circle is the pin and the black dot the activated pivot. Closing in VC mode will slowly move the pin to the middle of the plate, were it will flip because of the bi-stable mechanism (Fig 1-3). Than the pivots are switched and when opening in VO, the pin can stay in its position because of the opening flap (Fig 4). This flap closes again by a small torsion spring. When closing the device in VO, the pin moves again to the middle, were the pin will flip and the pivots switch again (Fig 5-7). The device can open again in VC, because of the flap (Fig 8).

D
Prototype

As shown before, the prototype will have two compression springs for use in VO and VC and it will be possible to switch the axes by flipping a pin. In this appendix, it is shown which springs will be used, what the sizes of the prototype will be and of which materials it will be made. The working principle of the final prototype is shown in Figure D.1.

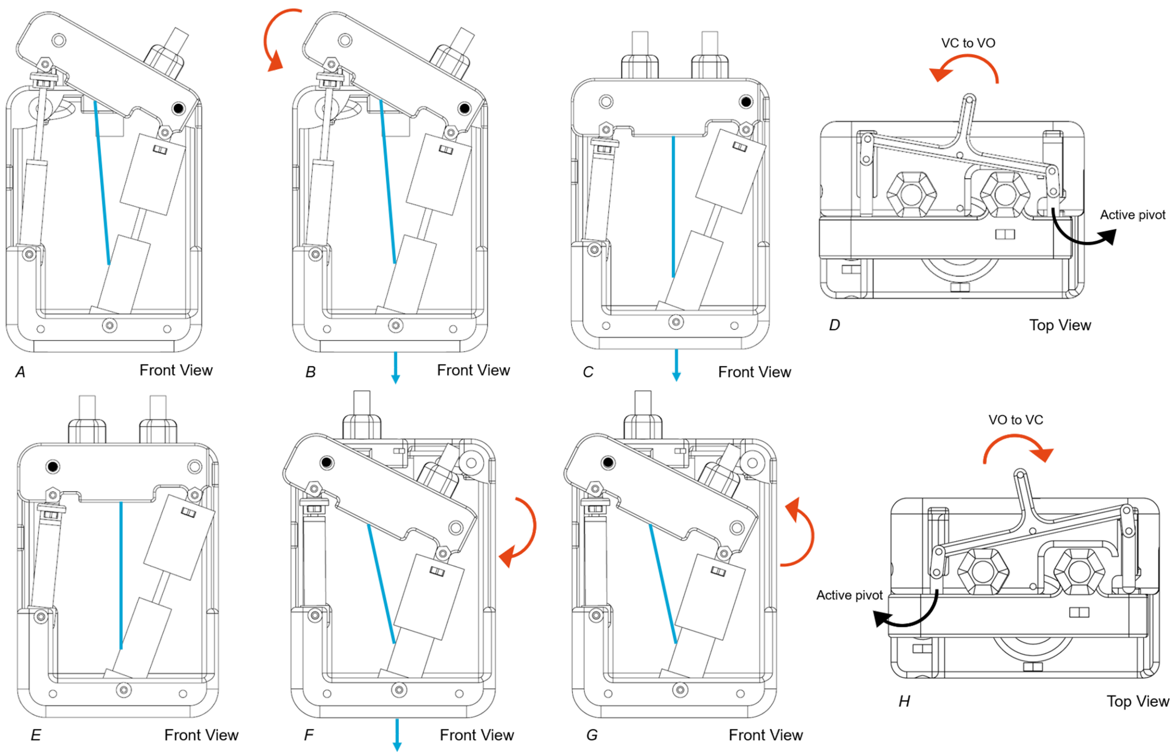


Figure D.1: Movements of the terminal device. The connections to the fingers are shown on top of the device, with two nuts. On the top row, the VC movement is shown. When the cable (shown in blue) is pulled, the device starts rotating (B). When it is fully closed (C), the activated pivot (indicated by the black dot) can be switched to VO (D). When the cable is pulled in VO, the device opens (F). When the cable is relaxed, the prosthesis closes (G). When fully closed, the pivot can be switched again (H).

D.1. Bi-stable mechanism

The design as described in section C.2 is incorporated, but some changes had to be made. It was decided to build a prototype to evaluate the use of two pivot points and the bi-stable mechanism.

Flipping the pin with the movable finger is not included. A first test with a bi-stable mechanism and a moving finger with pattern showed that creating the perfect pattern, which flips the pin when the pivot points are aligned, would be difficult to make. In addition to that, the flaps as described in section C, where to small to incorporate in a 3D print. For those reasons, it was chosen to first evaluate the use of two pivot points and the bi-stable mechanism. Flipping with the movement of the finger or cable are left for future research. In this prototype, the pin is placed on the backside of the device, which makes it easy for the user to flip the pin with the intact hand.

Second, because of this change, the bi-stable mechanism was changed a bit again. Because now it does not matter which side of the pin relates to VO or VC (it did matter because of the movement made by the moving finger), the pin is now one part together with the lever. The spring is still connected to the pin but now also to the stationary part of the design. As shown in Figure D.2, where the loose axis head is connected to the stationary part of the design. This configuration makes flipping possible with a shorter pin.

Third, in Figure C.5, the axes are not connected to the lever. A test with the bi-stable mechanism revealed that the axes had difficulties with going back to their lowest position. To make sure that the axes move as they should, links were added. They connect the axes to the lever but still provide the needed range of motion for the axes.

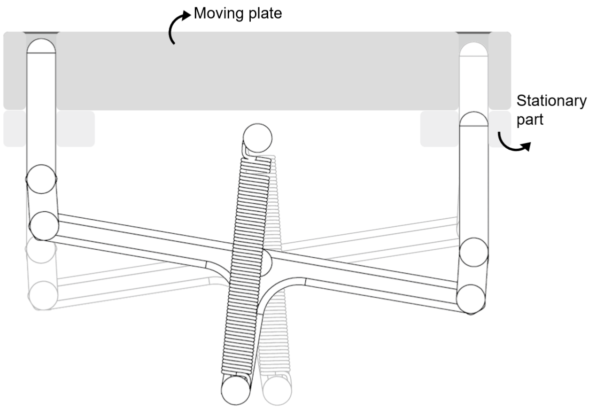


Figure D.2: Bi-stable mechanism used in the final design. The spring is connected to the stationary part (indicated in this figure as a loose axis head) and to the lever which connects the axes.

D.2. Compression springs

For choosing the compression springs, several parameters are of importance. First of all, the pinch force in the tip in VO mode and the force needed to open the prosthesis is determined by the VO compression spring. The VC spring influences the closing force of the prosthesis and lowers the pinch force, which needs to be taken in to account as well. Second, the maximum travel of the compression spring determines the opening angle and thereby the opening width of the prosthesis. Third, to save time and complexity it was chosen to use off-the-shelve springs which limits the choice.

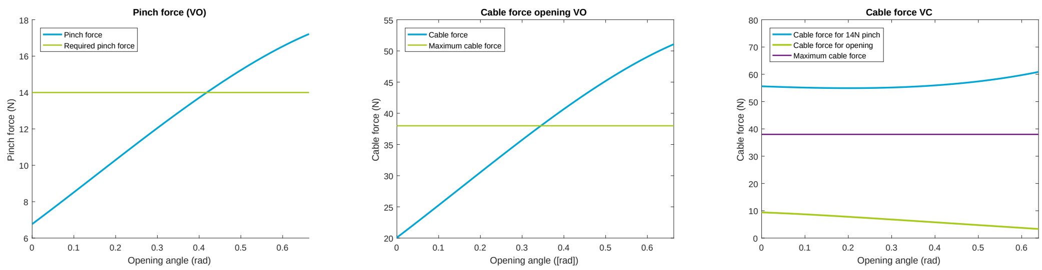
Because the spring is compressed when opening the prosthesis (VO) or closing the prosthesis (VC) the amount of force applied by the spring changes over the opening. The ideal spring should have a large initial force and a low spring constant, which decreases the influence of the compression during the movement. To create an initial force in VO, a long spring will be used and added to the system under some compression. In this way, there is already a force present when opening the prosthesis only a bit. Because long compression springs have the urge to buckle, the total length is limited and guiding parts are used to prevent buckling.

After identifying all the needs and wishes for the springs, several springs from Tevema [30] were evaluated in Matlab [26]. Taking into account the sizes of the device which are explained in section D.3, led to the choice of the springs described in Table D.1 Using these springs in combination with the fingers described in section D.4, an opening width of 67 mm in VO is reached and 65 mm in VC. This opening width is relative small compared to other devices. The lengths of the springs were limited by the guiding systems. Since 3D printing was used as manufacturing technique, telescopic systems

Table D.1: Compression spring parameters

VC spring	D21841
Middle diameter	10 [mm]
Spring constant	0.16 [N/mm]
Max. length	96.5 [mm]
Min. length	27.08 [mm]
Max. length in design	78.4 [mm]
Min. length in design	40 [mm]

VO spring	D22335
Middle diameter	16 [mm]
Spring constant	0.28 [N/mm]
Max. length	140 [mm]
Min. length	33.93 [mm]
Max. length in design	75.2 [mm]
Min. length in design	35 [mm]



(a) Pinch Force in VO (b) Cable Force in VO (c) Cable Force in VC

Figure D.3: Modelled pinch and cable forces for the final design

could not be produced. Because of this, the guiding parts need half the length of the spring. This limits the total length and compression of the spring and leads to a smaller opening width.

D.3. Lengths and sizes

It was chosen that the maximum distance between the pivots can be 60mm because of the appearance as mentioned in appendix C. The distance between the cable connection and a pivot point should be as large as possible to create mechanical advantage. This applies to both VC and VO and therefore it was chosen to place the cable connection in the middle (30mm from both pivot points). The VO spring is placed under an angle, the bottom is located 30mm to the left from the top. This was done because when opening the device, the top location of the spring will move to the left. To prevent a change in the direction of the spring force, the bottom of the spring is placed to the left. The same applies to the VC spring, where the connection to the bottom of the spring was shifted only 5mm.

The lengths and sizes, in combination with the chosen springs, lead in Matlab [26] to a pinch force and cable forces as shown in Figure D.3.

D.4. Fingers and material

In Figures C.1 and C.2, the fingers are illustrated in approximately the same way. They start at the widest point of the prosthesis and with a curvature, they move to the middle where they touch. The fingers which are shown in Figure C.2 are inspired by the TRS hook. The literature study [13] indicates the importance of good finger design. This, together with the problems found in the earlier described novel VO/VC device, puts doubt on designing new fingers for this prototype. For the first VO/VC device, designing new fingers was necessary because of the new mechanism. In this situation it is not, standardized fingers can be connected to the moving and stationary part. With using standardized fingers, the evaluation of the prototype is focussed on the new mechanism design and not on both finger and mechanism design. Since APRL fingers are sold separately, they will be used in the prototype.

Prosthetic hooks are often made of metal, because of its strength and durability. For the final prototype, it was chosen to use a combination of metal and 3D printed plastic parts. This was chosen for two reasons: small tests were already made with 3D prints which made it easier to create the device in plastic compared to metal and since 3D printing is less time consuming than creating metal parts it was more attractive for the scope of this project. The fingers and the connecting parts will be metal.

The moving plate, the casing, the lever for the bi-stable mechanism and the spring guiding parts will be made of plastic. By creating thick walls and rounded corners the prototype was made strong enough for user testing.

E

Evaluation

E.1. Built prototype

The device is manufactured with the design features mentioned in Appendix D. Most parts were 3D prints, except for connecting parts and the fingers, which were machined or bought. The prototype was assembled in house. In this appendix, the differences between the design and the prototype are mentioned and explained. The results for both the mechanical and user tests are elaborated, in addition to the results presented in the scientific paper, chapter 2.

Functioning of the switch The bi-stable mechanism was placed in the design to ensure rapid switching between the two pivot points. But, it did not function correctly. The switch is working and makes it possible to shift between VO and VC. The spring, included to make the system bi-stable, makes switching more efficient. Though, the spring is not able to guide the second half of the movement by itself. Several parts of the prototype make this switching movement difficult. The first problem found, is the misalignment in the pivot point holes. The axis connects two different parts and when these are not perfectly aligned, pushing the axis through becomes difficult. This misalignment is probably due to the high tolerances in 3D printed parts, but it is even more difficult to align the pivots since spring force, from the VO and VC springs, is constant pressing on the axes. This leads to the second problem, when the spring force is pressing on the axes, it is difficult to pull them down. More force is needed in the switching movement to pull the axis out. A third reason for the difficult switching, is the fact that the axes move to the side when they are not in use. The picture in Figure E.1 presents the skew axis which is not in use. During the user test, this axis was pushed in a straight position before flipping the switch. To conclude with, switching is not as easy as wanted, but it is possible to switch between the two modes.

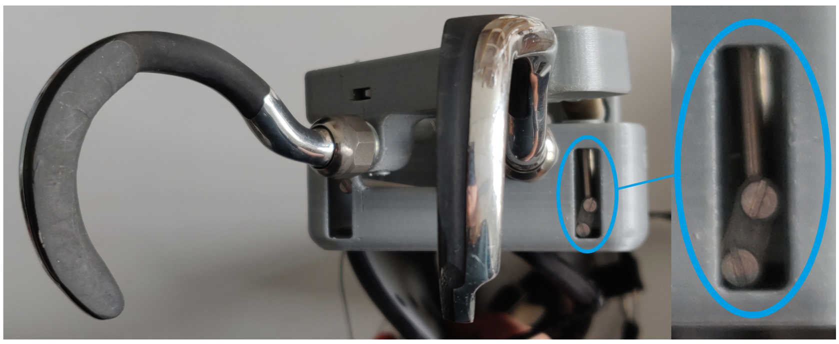


Figure E.1: The pivot (cyan circle) is moved to the side which makes the switching more difficult.

Cable location The direction of the cable was modelled as presented in Figure D.1. The cable would leave the device in the middle and would there connect to the prosthetic simulator, needed for user testing. This led to some problems. The cable could not leave the device exactly in the middle, as the VO spring was connected at that location. For that reason, a hole for the cable was created in the middle, close to the backside of the prosthesis. This, however, led to unwanted forces in this direction and made it impossible to open the prosthesis with the cable. Therefore, it was decided to relocate the cable, as mentioned in the scientific paper. This led to unwanted forces too, but these forces were of less influence and the relocation made it possible to open the device with pulling the cable. The influence of the cable location is further analysed in section E.2.

Friction Friction was not only a problem found in switching the pivots. As mentioned before, compression springs buckle. Guiding parts were created to prevent buckling. But, since the compression springs still tend to buckle, friction is created between the spring and these guiding parts. Furthermore, the guiding system consists of a metal axis sliding in a metal bearing. The force is not applied in a perfect direction on the top, so the axis is also pushed in a sideways direction. This leads to extra friction in the complete spring guiding system. Other sources of friction, probably of less influence than the spring system, are the friction around the axis when in use in a specific mode and the friction between the moving and stationary part when moving. An elaborate analysis of the friction in the device is given in section E.2.

E.2. Mechanical test

The mechanical test was performed to evaluate the mechanical properties of the device. In this section is discussed how the device complies with the requirements and how this influenced the performance, how the device compares to existing devices and an explanation is given for the amount of hysteresis found. This section is an addition to the results discussed in the scientific paper, presented in chapter 2.

Comply with the requirements The scientific paper in chapter 2 presents a table in which the results are shown next to the requirements. It is shown that the device did not meet the requirements, which influences the functioning. The short cable excursion presented leads to less control over the pinch force in the tip of the device [23]. Because of the high cable forces, the prosthesis cannot be used fatigue-free [23], which was taken into account during the user test. The spring was shortened which decreased the cable activation force and users were warned for discomfort in the shoulder muscles and enough breaks were introduced during the test. The resulting pinch forces in VO are not enough according to the requirements (see A). Due to the shortening of the spring, the pinch force was lowered to 5.4N for user testing. This influenced the user test, since 'Simulated Food Cutting' could not be performed as the knife could not be held. The performance in the user test were furthermore influenced by the small opening width. This made two other tasks in the test impossible to perform.

Comparison to other devices The appendix of the scientific paper (chapter 2) shows the results found for the presented device compared to existing terminal devices. The device has a high weight, a small opening span and a short cable excursion compared to other VO devices. Additionally, the pulling force is relatively high. But since the cable travel is short, the amount of work and hysteresis are similar to other devices. The pinch force is low, as expected in the model. The high weight, small opening width and short excursion are also present when comparing the VC mode to VC devices. But compared to VC devices, the hysteresis and work are also unfavourable. Furthermore, the device needs a high cable force for pinching with 15N.

The prototype presented is a proof-of-principle. For some properties, it was already accounted for that they would be lower than existing devices. The low pinch force in VO was accounted for since other springs were not available on short-term. Even as for the short cable excursion, as increasing the distance to the cable would increase the width of the device. That friction would be present, was expected as well. However, with such high amounts, the device is not competitive at all compared to other devices.

Hysteresis The graphs obtained in the mechanical tests presents a high amount of hysteresis. This reveals that energy is lost in the system. This is probably due to friction, which is present around the

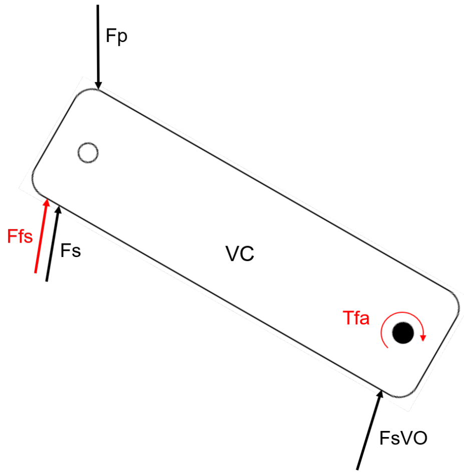


Figure E.2: The forces present in the system when measuring the pushing force (Fp) in VO. Fs = spring force, Ffs = friction force in the spring guidance system, Tfa = friction around the axis and FsVO = forces created by the VO spring.

axis, in the spring and its guiding system and between the cable and the wall which it is pushing against to.

Expected is that the largest part of the hysteresis is obtained in the spring and its guiding system. A test was done with applying a pushing force on the top of the prosthesis instead of pulling the cable. The forces which were present in the system are shown in Figure E.2. With this experiment, the hysteresis was obtained and compared to the hysteresis found in the original study by pulling the cable. Since the travelled distance in the experiment was larger because of the longer moment arm to the axis, the distance was adjusted based on the cable excursion found in the mechanical test. The experiment was only performed in VC, but since the direction of the cable is almost equal in the VO movement, no large differences between the two modes were expected.

The found hysteresis is 111N which should be compared to the 142N found in the mechanical tests. This result indicates that most of the energy (78%) is lost in the system due to friction and that only a small part is lost in the cable. It should be noted that these results are based on one experiment run and that adjusting the travel is not perfect.

E.3. User test

The Southampton Hand Assessment Procedure (SHAP) was performed with 9 subjects. This procedure is designed to assess hand functionality but the test is also used to evaluate prostheses. Using the new device, participants were only able to perform 23 of the 26 tasks as explained in the paper.

IOF-scores With the device in VO, the IOF-score found is 41.2 $\pm$ 5.0, which is higher than the 37.7 $\pm$ 6.0 found in [8] but lower than the other two devices. The found IOF-score in VC is 37.4 $\pm$ 7.9, which is the lowest of all compared devices. The score for using the prosthesis in both modes is 46.3 $\pm$ 6.3, which is higher compared to the 42.1 $\pm$ 6.2 found in [8] but lower compared to the 57.4 $\pm$ 6.2 found in [12].

Reasons for this low score were already mentioned in the scientific paper, but will be elaborated in this section. The mechanical and users tests are used to assess if using two pivot points is a good method to create a VO/VC device. This design influences the way in which an object could be grasped. With a pivot point on the side, the moving fingers opens over another trajectory compared to standard hooks. This affects the forces applied to the objects which needs to be grasped. If this is the reason for the low IOF-score, it could be concluded that using two pivot points has a bad influence on the grasping properties of the hook. However, more reasons were found which influenced the performance of the prototype. The device was not able to close in VC, which affected the results when thin objects were involved. Furthermore, the device had a smaller opening width compared to other devices for both VC and VO. This had effect on the performance for several tasks in the SHAP-test. It should also be mentioned that using the tip of the prosthesis could only be done when moving the body in an

Table E.1: IOF-score for each grasping pattern for VO, VC and Hybrid

Pattern	VO	VC	Hybrid
Spherical	45.8 ± 12.0	51.2 ± 15.0	61.7 ± 19.2
Power	17.7 ± 4.8	18.1 ± 3.2	21.2 ± 5.3
Tip	29.6 ± 6.8	24.1 ± 10.5	37.8 ± 16.2
Tripod	23.2 ± 7.1	20.6 ± 8.5	26.0 ± 6.7
Lateral	49.6 ± 15.7	50.9 ± 14.0	62.1 ± 10.1
Extension	51.4 ± 18.0	49.4 ± 17.0	58.7 ± 15.3

uncomfortable position. Due to the location of the cable, the terminal device could not be used in all positions over a range of 180°. Users more often used the back of the prosthesis, as shown in Figure E.3(a). The last reason for the bad performance could be the high cable forces, which makes using the device an exhausting activity.

All in, it cannot be said if the different gripping pattern influences the performance of the hook. To support this hypothesis, a prototype which is more alike current available prosthesis (with opening width, range of motion and cable forces) should be created.

(a) Using the back of the prosthesis

(b) Lateral grasp for the prosthesis and the human hand [31]

Figure E.3: Pictures during the user test. Presenting the use of the device on its backside and using the device in lateral grasp compared to a human hand lateral grasp.

Preferred Mode It is shown that using the device in both modes contributes to higher IOF-scores. This confirms the need for a hybrid device. It is furthermore shown that users prefer different modes for specific tasks. This result is equal to other studies [8] [9] [12]. However, the quality of the prototype might be of influence in this result. Because the device could not close in VC, tasks with flat objects were difficult to perform. This might have affected the choice in the task 'open/close zip', were everyone chose VO as preferred mode since grasping the zip in VC mode was more difficult. On the other hand, Berning et al. [9] described that tasks which need simultaneous movement (which is needed for opening and closing a zip) were often preferred in VO mode. So, the result is still in line with other research. Additionally, the prosthesis could open further in VO than in VC. Every subject chose the mode VC for the task 'Heavy Power' which involves a large cylindrical object. It was difficult to put the device in VO mode around this object, because of its small opening. This might have influenced the result, but again, Berning et al. [9] found that heavy objects were preferred in VC mode because of the extra power which can be applied. So, this result is equal to other studies too.

All together, the prototype might have influenced the choice for a specific mode but it can still be concluded that using a hybrid device has a positive effect on the IOF-scores.

Grasp The SHAP-test provides a total IOF-score for the functioning of the hand, but additional to that, a score for each grasping pattern is given. The six patterns are: spherical, power, tip, tripod, lateral and extension. As mentioned in appendix A, a prosthesis should provide three of these patterns: palmer (spherical), tip and lateral. Table E.1 gives the mean ± SD IOF-scores for the six grasping patterns. The patterns were scaled relative to the overall score to compare the functionality. Figure E.4 presents these normalized scores. If the prosthesis is more functional in a pattern, the score is above one [32].

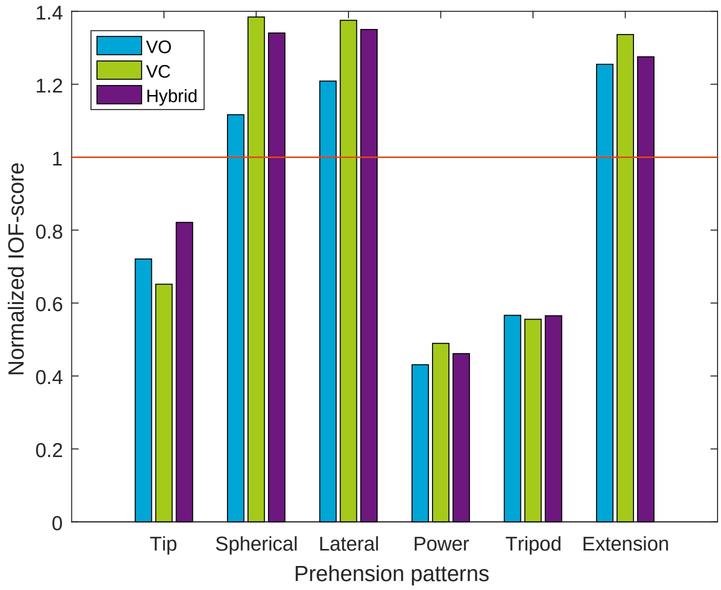


Figure E.4: The normalized IOF score per mode and prehension pattern

For spherical, lateral and extension an normalized score above 1 was obtained in each mode. This indicates that these grasping patterns are somewhat functional in the prosthetic device, where the other three; power, tip and tripod are not. The tip of the prosthesis was difficult to use, which could explain the worse performance for this pattern. Since the device has only two fingers, a three point grasp (tripod) is challenging and because the opening width was small, the power grasp was difficult to perform too. This power grasp is often lacking in terminal devices, as indicated in the literature study [13]. A good score for both lateral and extension grasp are explicable since a grasp between the two fingers of the prosthesis is very alike these two patterns, indicated in Figure E.3(b). The high performance for spherical should be discussed. The large spherical ball could not be grasped and was 'scooped' over the small wall. Other tasks belonging to this grasping pattern are 'Remove jar lid' and 'Pour water from carton'. The lid could not be grasped because of the opening width so the lid was often swept of the jar. Additionally, the carton could be easily grasped in VC but since the opening width in VO is smaller, the carton could only be grasped when it was indented a bit. Concluded can be that the only spherical task executed well, is the 'Pour water from carton'-task in VC mode. Therefore, it can be concluded that the high score for spherical is not representative for this prosthetic device. The results on grasping patterns available in the device are relative. The patterns which score above one are more functional than others. However, since the device had a low overall score, it might be discussed if the patterns are 'present' in the device.

F

Recommendations

The main recommendations are mentioned in the scientific paper, presented in chapter 2. Some of the recommendations will be elaborated here. Furthermore, switching without the intact hand is something left for future work. The implementation of this in a new device will be discussed in this appendix.

F.1. Improving the built device

Metal design A 3D printed prototype was used to easily evaluate the working principle of this new concept. Printed parts have more design freedom compared to metal parts since a 3D printer can more easily make difficult shapes and fill up hollow spaces with water-soluble material. To create hollow spaces in a metal part, the material should be removed by a machine.

Nonetheless, plastic is not a durable material which could be seen during the user tests. Additionally, if the prosthesis needs to be used for several years, the design should be made of metal or strong carbon fibre. Due to the strength of this material, the size of the device can be decreased. There are two main changes which need to be made when changing the plastic design to a metal one: the shape of several parts needs to be changed since machining gives less design freedom compared to printing and bearings around de switching axes should be added to ensure easy sliding of the pivots. Bushings might be enough but if not, (linear) ball bearings might be needed.

Custom or tension springs The springs used were taken off-the-shelve. The choice was thereby limited in length and spring constant. A custom-created spring could improve the spring force in VO and create a larger opening width. A higher initial force, a lower spring constant and a larger travel are needed. But, custom springs have their limits too. Therefore, it might not be possible to reach a perfect pinch force in VO with compression springs. In that case, a study into the use of tension springs would be valuable. This leads to large design changes and it might be necessary to implement a system where the user can push. However, tension spring do not buckle which improves the mechanical advantage of the device and tension springs are easier to connect.

F.2. Future work

Switching without the intact hand A method to flip the pin without the use of an object or intact hand was created. However, due to difficulties in the production of this idea and time limitations, it was not used in the final prototype. Since 3D printed parts are too weak to test the working principle of the idea, another way of evaluating this design should be thought of.

It was mentioned before that, because of the difference in pulling and relaxing the cable during the switching movement, it was not possible to activate the switching with the cable. However, a new idea came across, where the pushing of the cable against the wall of the device, could be compared to the pressing of a pencil. When the prosthesis is closed in VC, the cable should be pulled a little bit more to press the button. This should lead to a switch of the pivots. Then the cable can be relaxed again, while the pivots stay in this VO position. The prosthesis can be used in VO mode, but when doing that, the cable will be pulled again and the button is pressed. When the cable is relaxed again, the prosthesis is closed and the pivots are again able to switch (because the cable is relaxed and the button can move back again).

Two ideas are generated to switch between the two output modes without use of the intact hand or a stationary object. The ideas were not further evaluated. Furthermore, both ideas have the disadvantage that they switch every time the prosthesis is used in one mode because the button is pressed or the pin is flipped. For that reason, it might be valuable to gather more information about the need for switching with only the device itself and for which limitations. It can be imagined that switching every time the prosthesis closes is not beneficial. However, if ideas could be generated without the disadvantage of switching every movement, it will be beneficial to introduce them to the device.

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