Design and evaluation of a novel upper limb body-powered terminal device with voluntary opening and voluntary closing capabilities

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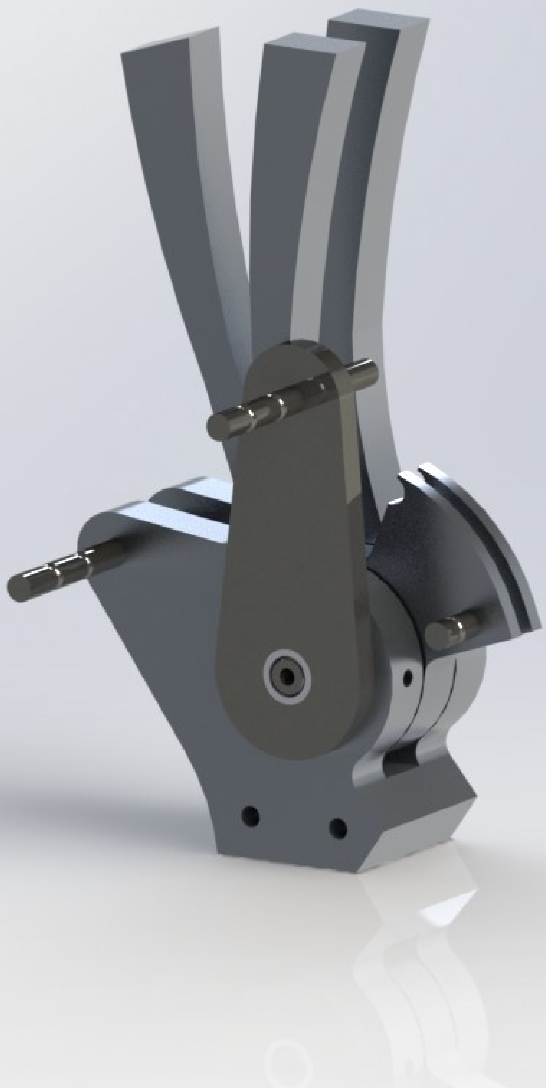

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Challenge the future

Design and evaluation of a novel upper limb body-powered terminal device with voluntary opening and voluntary closing capabilities

by

H.H. Coehoorn

in partial fulfillment of the requirements for the degree of

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Preface

Before the start of this thesis, back in December 2015, I mainly let myself be guided by my fondness for mechanisms while deciding on a thesis topic. The thought that the field of prosthetics improves the lives of countless individuals and would therefore be a worthy cause to spend my time on did not immediately cross my mind; I was more focused on meeting the design challenge. However, as the thesis process went on and graduation drew nearer my thoughts shifted towards the world beyond. One should spend their time wisely and honourably. Becoming an engineer opens up many possibilities, and with them comes the duty to do what is right and to do good. Duty requires a focus on what is necessary and one should not let their personal interests distract them from that focus. I am pleased to have contributed in my own way to solving significant problems of others, and I will always aim to do so in the future.

I have met many wonderful people during my time at Delft University of Technology and support was never far off, especially during the final thesis. I would like to thank my supervisor Prof. Dick Plettenburg for his guidance and enthusiasm throughout this project and for introducing me to the challenge of combined VO/VC terminal devices. I would also like to thank all members of the "Power Tower" studying group for listening to my complaining whenever things went wrong - something else than myself was always to blame, of course - and for the long-standing tradition of Broodje Leo. The trips throughout Europe with "The Men" helped to keep burnouts at bay. Also to thank are the VvA and DTS. And last but not least I should give thanks to the people that have made it possible for me to spend so many enjoyable years in Delft: my parents. Thank you very much.

H.H. Coehoorn
Delft, April 2017

Contents

Abstract

The field of upper limb prosthetics focuses on the development of artificial replacement devices for upper limb loss, from partial finger loss to amputation of the entire arm at the shoulder. Hand and hook prostheses are designed to replace the functionality of a missing hand and can be powered either by external sources (e.g. electricity) or by the wearer's body movements. Body-powered upper limb prostheses are as of yet preferred over electrical devices due to the possibility for extended physiological proprioception. In body-powered systems the user can generate force in only one direction, through pulling, so a choice must be made to either voluntarily open (VO) or voluntarily close (VC) the tongs. Both principles of operation have their own strengths and shortcomings in different situations and prosthesis users indicate that having both at their disposal would be preferred. Prehensors that offer both principles of operation are referred to as hybrid devices. A problem with current devices of both the VO and VC variety is that they do not offer the performance demanded by amputees which leads to rejection and abandonment of prostheses. A literature study indicates that a well-designed hybrid prosthetic prehensor might be able to offer amputees the performance they desire. However, of the eight known hybrid designs none perform well enough to become successful. The goal of this thesis is to find a new prehensor concept that incorporates both principles of operation and does so in a way that functions better than those already known.

The eight known hybrid devices are analysed for the individual advantages and disadvantages of their designs. This produced a set of three properties desired in any future prosthetic prehensor in addition to it being hybrid: a passive VO pinch force, change of principle of operation through cable excursion only, and a VC mode that is available without having to resist the VO spring element. None of the existing devices share all these three. Eight new concepts for gripper mechanisms are generated. All combine both principles of operation but only two possess all three desired properties. Of these two the simpler and most feasible mechanism was developed further. In the chosen concept the two tongs are allowed to move past each other instead of connecting at the tip, making it possible to apply grip onto objects in two different ways. During the first half of cable excursion the tongs move closer together until they overlap at the halfway point. During the latter half the tongs move away from each other. A spring works towards the initial opened gripper position with a second spring only activated in the second half of the tong movement. This leads to different spring forces in the two modes.

A first design of the concept is generated and a prototype is manufactured. A series of mechanical tests is performed with both the VO and VC modes of operation of the prototype in order to compare its performance with similar VO and VC hook devices. Its VO capabilities are slightly below the performance of the other examined prostheses. Its VC capabilities are comparable to the other examined devices. The functionality of the concept is assessed through the Southampton Hand Assessment Procedure (SHAP) and its score is compared with scores of body-powered hooks from literature. The SHAP tasks are performed in both VO and VC mode and the individual preferences are noted. Six out of 26 tasks could not be completed because of tong design. Users perform on average 4.4 ± 3.8 and 1.8 ± 2.3 points better when they could use their preferred mode on a task-by-task basis than when they were limited to only VO mode or VC mode, respectively.

This is the first instance of a hybrid prehensor scoring significantly better than either mode alone. The device is also the only prehensor that combines the VO and VC principles of operation and possesses all three desired properties. Design improvements are recommended for the tong shape to improve grip and performance.

1
Introduction

1.1. The field of prosthetics

Limb loss is a problem that has been occurring for thousands of years and around the world. Limb deficiency can be caused by congenital afflictions or forced amputation after physical injury, infection or dysvascular conditions, with conflict and limited healthcare increasing its prevalence worldwide. A person undergoing amputation of a limb will face far-reaching psychological, social and physical consequences. The field of prosthetics is focused on designing devices that can replace the missing limb, with the aim of improving amputee functionality and quality of life. Many prosthetic devices exist that replace missing limbs (feet, legs, fingers, hands or entire arms) but prosthetic replacements are also available for body parts such as hip or neck.

A subset of the prosthetics field deals with replacing lost upper limbs. The degree of limb loss differs between amputees and can range from partial finger loss to amputation of the entire arm at the shoulder joint. Within the Netherlands the prevalence of congenital and acquired deficiencies is approximately 0.8 and 1.5 per 10.000 inhabitants, respectively, leading to about 1350 congenital and 2400 acquired limb deficiency cases[1]. Of course, upper limb loss is a global affliction with amputees worldwide, where exact numbers depend on many factors, not least of all quality of health care. The research topic of this thesis is the upper limb prosthesis in particular, in part because of the great potential for functionality recovery that a device improvement offers.

1.2. Upper limb prostheses

The term 'upper limb prosthesis' encompasses a wide variety of devices designed for many different purposes, price ranges and levels of amputation, to name just a few variables. Among upper limb prostheses a broad distinction can be made into the two categories of passive and active prostheses, based on the measure of control the wearer has over their device. Passive upper limb prostheses cannot be controlled and are mainly to restore the body image and appearance of the wearer. They can be used to manipulate objects through simple acts like pushing, fixating against the body or supporting, often in cooperation with the sound hand. Some passive designs are incapable of movement altogether while others possess a clasping ability allowing the user to place an object in between the fingers. Active upper limb prostheses contain a system enabling the wearer to control the opening and closing of the hook-like or hand-like gripper at the end of the arm. A gripper fulfilling the function of the missing hand is also called a 'terminal device' (TD) or prehensor.

Active prostheses can be further split into two subcategories based on the power source used to move the gripper; a device can be either externally powered or body-powered. The most commonly used external power source is the electric battery. The prosthesis user carries a portable battery with them to power the electric actuators inside the device and provides the control signals, often through myoelectric signals measured in the residual limb. This way the prosthesis movements are dictated by local muscle activation. Figure 1.1 shows examples of different types of TD's.

(a) Passive prosthetic hand[2] (b) Externally powered hand[3] (c) Body-powered VO hook[4]

Figure 1.1: Examples of various types of upper limb prosthetic terminal devices.

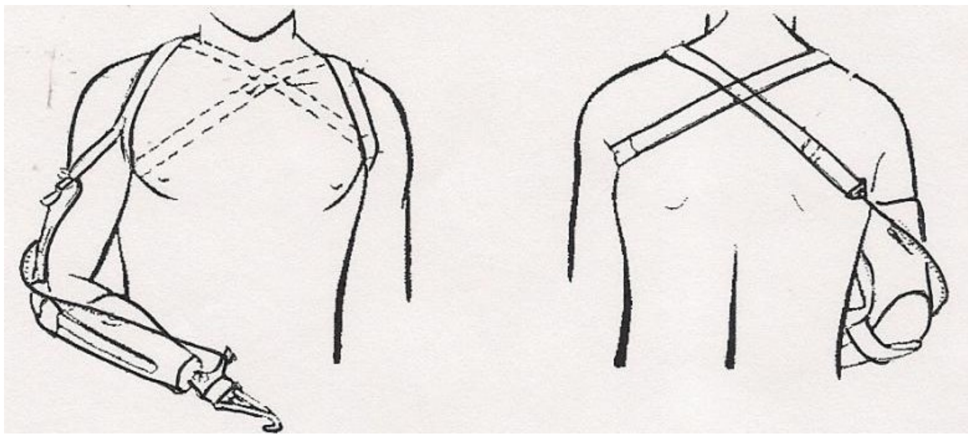

Figure 1.2: Illustration of a 'figure 8' type shoulder harness being worn around the amputee's shoulders. Contralateral shoulder movement and ipsilateral abduction and anteflexion of the arm create tension in the control cable, activating the terminal device.[6]

Body-powered upper limb prostheses have no external power source, instead relying on the wearer to supply power for movement and gripping force. Because no electric battery or gas tank is required the mass of this type of prosthesis is generally much lower than externally powered equivalents. TD control typically occurs through a harness worn on the shoulders and connected by a Bowden-type control cable to the prosthesis, where the wearer can utilize contralateral shoulder movement and ipsilateral abduction and anteflexion of the arm to generate tension in the cable and induce gripper movement. Figure 1.2 shows one type of shoulder harness being worn. Sometimes a hydraulic system is used instead of a Bowden cable[5]. Two alternatives to harness control are elbow control and cineplasty. The latter of these involves the cable being connected to a pin inserted through a surgically created tunnel in the biceps or pectoral muscle. Cineplastic methods have mostly fallen out of grace since the second half of the 20th century. Elbow control also is rarely applied.

For several reasons performance of the externally powered myoelectric prostheses was found to be lacking when compared to body-powered devices[7], despite high initial expectations. Body-powered hand prosthetics are described as inexpensive, durable, and easier and cheaper to maintain than myoelectric prosthetics[8]. Other stated advantages of body-powered systems are low weight and technical reliability, while electrical prostheses have superior grip strength and the benefit of a harness not being necessary in most cases[9]. A fundamental shortcoming of myoelectric devices is a lack of adequate proprioceptive feedback for the user. Available paths through which the amputee receives information regarding the state of the prosthesis are force feedback on the residual limb, visual feedback of the position in space and audio feedback through mechanical noise of electric actuators. However, no feedback is possible regarding applied grip force and grip velocity. Myoelectric control is therefore considered an open loop system and unsuited for grip force control[10].

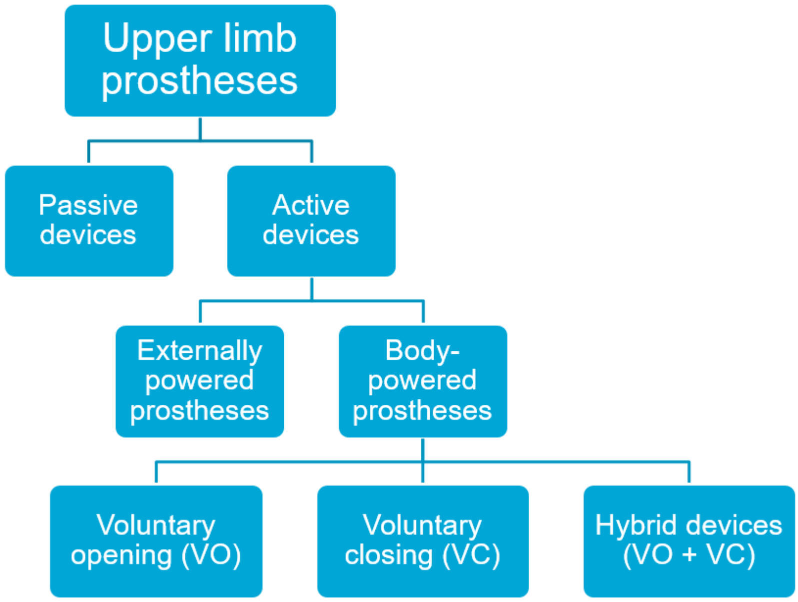

Figure 1.3: Overview of the different types of upper limb prosthetic devices and how they are related. This thesis is focused on those powered solely by the wearer's movement: body-powered prostheses.

Within the control of body-powered terminal devices two distinct principles of operation exist; generally the mechanism in a TD is of either the voluntary opening (VO) or voluntary closing (VC) type. A VO prehensor contains a passive spring that keeps its gripper or hand in a closed resting position while simultaneously providing pinch force. Putting tension on the Bowden operating cable causes the prehensor to open as the user works against the spring force, in a pull-to-open manner. Consequently, the maximum grip force a person can apply onto objects is limited and can only be changed by swapping out the spring element for one with a different stiffness. A VC TD works in the opposite manner, with a spring element keeping the prehensor in an open resting position until operating cable tension closes it, increasing the grip force after contact. These devices can be described as pull-to-close.

Many different terminal device design variations exist that employ one of the two aforementioned principles of operation. The principles perform differently and require different user control actions to operate. Due to these differences each has their characteristic advantages and drawbacks. Some attempts have been made to design "hybrid" mechanisms that combine VO and VC capabilities, ensuring that wearers can always use their preferred setting in all situations in a best-of-both-worlds approach. It would make sense to expect higher overall performance when users are given access to both methods of control instead of only one but a commercially successful hybrid prosthetic prehensor has yet to appear. An overview of the various types and subtypes of upper limb prosthetic devices and how they relate to each other is shown in figure 1.3.

1.3. Problems in the field

Persistent issues in the field of prosthetics are the high rejection and abandonment rates of prostheses by users: many amputees are dissatisfied with their prosthetic devices to such an extent that they stop using them altogether, opting instead for a life without any kind of limb replacement. Literature has reported mean rejection rates of upper limb body-powered prostheses of 45% and 26% in pediatric and adult populations respectively, with some studies reporting overall rates of rejection of body-driven prostheses as high as 66%[11]. Acceptance does depend on the type of TD, with body-powered hands having rejection rates as high as 87% while hooks are overall found to be more acceptable to users. Another study reported rejection rates of body-powered upper limb devices for transradial and transhumeral limb-loss levels of 35% and 52%, respectively[12].

These high rejection and abandonment rates are proof of dissatisfaction among prosthesis users and indicate that the performance of currently available upper limb body-powered prostheses is lacking. Arm amputees and professionals alike express their desire for improvements across the board, in general appearance, function, general comfort and the cable control system[13]. Despite the many currently available terminal devices based on the different principles of operation of either VO, VC or a VO/VC hybrid system there seem to be none that alleviate the feeling of dissatisfaction. The current problem can be stated as:

Current body-powered upper limb prostheses do not offer amputees the desired performance, leading to rejection and abandonment

There is a significant need for prosthetic devices of higher performance. An important factor in the performance of any upper limb prosthetic device is the principle of operation of its terminal device. Voluntary opening, voluntary closing, and hybrid devices require different control actions as input and produce different behaviour as a result of those actions. A prosthetic prehensor with a principle of operation that facilitates activities of daily living (ADLs) will perform to a greater satisfaction when compared to one whose principle of operation does not facilitate such activities. Therefore, the choice of principle of operation when designing a prehensor will have strong consequences for its performance and the extent to which it meets the demands of its user.

There is no clear agreement among prosthetists, amputees or device manufacturers on what should be considered the optimal principle of operation. Proponents of both the VO and VC principles have given arguments to support their preference, citing advantages in properties such as required energy to operate and amount of sensory feedback available to the user. In more recent years the supposed advantages and disadvantages of VO/VC hybrid prehensors have complicated the matter even further.

1.4. Literature study

In an attempt to clarify which principle of operation should be favoured to satisfy the need for higher performance devices much research has been performed throughout the years, though it cannot be said that a definitive answer was found. Furthermore, no clear and structured overview was available of the findings of this research. Such a document would facilitate the prosthesis design process. A literature study was performed by the author to collect all findings of known research into the possible advantages and disadvantages of both the voluntary opening and voluntary closing principle of operation, and to develop a structured overview of the current knowledge. The full literature study is enclosed as appendix .1. A short summary of its findings follows.

The literature study primarily analyses and compares the two working principles of VO and VC in terms of their known advantages and disadvantages to users. These are summarized in tables 1.1 and 1.2, respectively. Additionally, it presents a list of all known hybrid device designs and their advantageous and disadvantageous characteristics. The strengths and drawbacks of the VO and VC principles of operation seem to simultaneously oppose and complement each other. A shortcoming in one working principle is often opposed by a strength in the other. For example, the high spring tension that must be overcome with every operation in a VO device is opposite to the minimal input force that is required to initiate gripping in a VC device. Another example would be the exhaustion that occurs after prolonged VC operation compared to the fatigue-free VO gripping.

While moving to open or close the gripper the VC principle is inherently the more mechanically efficient of the two but this is only relevant for energy expenditure at the beginning and end of the gripping motion. During the gripping itself a VC device requires more energy to maintain grip. A well-designed holding assist function reduces metabolic cost of VC prehension by allowing the user to relax tension in the control cable, bringing it down to approximately the level of VO. Current holding assist mechanisms of which the performance is known are not well-designed however.

Table 1.1: VO strengths and weaknesses from literature.

Voluntary opening (VO) prehensors			
Advantages	ref.	Disadvantages	ref.
• Holds object without exertion	[14]	• Spring tension must be overcome with every operation	[15]
• No clutch needed to keep closed	[15]	• Only one grip force value	[15]
• Closed when not in use	[14]	• Cannot lock grip	[16]
		• Opposite in functional principle to normal prehension	[15]
		• Insensitive and lacking in neuromuscular control	[15]
		• Limited to a functional envelope closer to the body when picking up small objects	[8]

Table 1.2: VC strengths and weaknesses from literature.

Voluntary closing (VC) prehensors			
Advantages	ref.	Disadvantages	ref.
• Force and motion feedback	[10]	• Gripping for extended periods of time is fatiguing	[10]
• Active control over grasping force	[15]	• Open when not in use	[10]
• Input directly proportional to grip force	[17]	• Limited to a functional envelope that is away from the body when picking up small objects	[8]
• Reflexes have intended effect	[17]		
• Torso, limb muscles used more actively	[17]		

In various studies and works of literature amputees and prosthetists alike consistently agree that differences in operation render the working principles suitable for different types of tasks. Comparison studies into task preference support these claims, showing varying device preferences that not only depend on the type of task but also on individual preferences of the user.

Studies focused on performance time and prehension force found no significant differences between the principles, or were inconclusive. One group did find differences in variability and accuracy but no clear 'winner' can be appointed.

Position, velocity and force information is available to the user through proprioceptive feedback. This extended physiological proprioception (EPP) as a feedback signal available to the prosthesis wearer is vital in optimizing performance and in keeping the experienced mental load while operating manageable. A prerequisite for EPP is tension in the control cable. As long as tension is present a relationship exists between the state of the terminal device and that of the control joint, the shoulder. In this way the user is informed of the position, velocity and forces of the TD. For VC devices the control cable is tensioned during the entire duration of gripping, meaning the amputee always has EPP feedback when gripping. VO devices, however, only offer extended physiological proprioception when the internal spring is resisted and the gripping force reduced. An important strength of VO prehension is that it generates grip force without the energy of the operator. This strength is negated when a trade-off must be made between EPP and inexhaustive gripping.

The concept that the two principles each have their moments where they fare best has produced its results. Multiple prosthetic prehensor devices have been designed that, in a best-of-both-worlds approach, allow the user to choose between TD control in a voluntary opening or voluntary closing manner as the situation requires. Eight of such hybrid concepts have been found in literature, each combining VO and VC in a slightly different manner. Some have separate modes while others incorporate both continuously. Unfortunately, none of the hybrid concepts that were found have achieved commercial success with amputees. Their respective designers have attempted to identify the design flaws that may have caused this commercial failure. In the literature study focus on a favourable mechanical advantage, low mass and bulk and simplicity of the hybrid mechanism have been identified as important focus points when the design of a better hybrid prosthetic prehensor is to prove successful.

The study end with the conclusion that the hybrid VO/VC principle of operation convincingly possesses the potential to outperform either of the conventional principles. A recommendation is made to focus on realizing this as of yet unfulfilled potential in the quest for high performance prosthetic prehensors. The advice is included to accelerate the process by learning from the pitfalls of current hybrid devices, designing new iterations of current prehensors as well as entirely novel concepts. In this manner prosthetic prehensors may be generated that offer amputees a higher performance, thereby reducing rejection and abandonment rates.

1.5. Research Goal

Amputees have indicated a clear need for body-powered upper limb prosthetic devices that reach a higher level of performance. A literature study into the various principles of operation of terminal devices was performed, as design optimization of this device aspect has significant potential for performance improvement. The study concludes that pursuing the hybrid VO/VC principle of operation has a high potential for improved device performance over conventional devices. It also concludes that the eight hybrid device concepts that have been conceived in the past have failed to realize this high potential in its entirety. Therefore the goal of this thesis is:

The design, fabrication and evaluation of a novel upper limb body-powered terminal device with voluntary opening and voluntary closing capabilities

In the rest of this thesis the design process to reach this goal is documented. The design requirements, wishes and goals are stated. Within these boundary conditions a search is performed for novel and creative mechanisms, aided by the eight currently existing hybrid concepts. From the body of possible solutions produced through this search the optimal concept is chosen and expanded into a design that complies with the defined requirements. This design is then manufactured and the realized prototype is tested to verify that all requirements are met. In addition to mechanical tests a user test is also performed to investigate the subjective opinion of users. Concluding this thesis is a section focused on discussing the various test results, followed by conclusions that may be drawn from them and future work to continue this research project.

2
Methods

The goal of this project is now clearly stated. To succeed in this goal of designing a novel terminal device it is important to explicitly define all relevant design requirements, user demands, wishes and any further constraints that the prosthesis ought to comply with. In this report all these statements are divided into the two groups of requirements (section 2.1) and wishes (section 2.2). Where possible the requirements are expressed in explicit numerical values, with the remainder consisting of clear statements to comply with. Requirements have priority over wishes, which are all remaining entries not expressible in numerical values or clear yes/no properties. These are left as qualitative preferences (e.g. "the device should be affordable").

With a clear view of the design requirements and wishes a design process may yield a functioning terminal device design. Then, a prototype of this novel design is subjected to a series of tests to ascertain its compliance to the requirements, and to gauge its functionality. Section 2.3 presents the design of these validation tests.

2.1. Requirements

All design requirements and wishes are explained in the current and subsequent subsection.
Tables 2.1 and 2.2 provide overviews of respectively all requirements and wishes and their numerical constraints where applicable. The contents of the tables are categorized into the three categories of cosmesis, comfort and control, collectively known as "the three C's"; a commonly-used distinction of user demands in prosthetics.

Dimensions, appearance and shape

The size of the device in its entirety should be such that it is easy in use and does not get caught in its surroundings. Therefore a size close to the natural hand is chosen as requirement with a maximum total length of 185 mm and a maximum palm width of 100 mm[18]. A size and shape similar to a human hand would improve its appearance and therefore acceptance by the user, although studies have shown that amputees do not see a human-like presentation as a necessity[19]. Therefore a better criterion would be to wish for an aesthetically pleasing appearance.

Total mass

The mass of the device greatly influences the comfort during wear. Heavy prostheses are fatiguing to carry around for extended periods of time. Because prostheses cannot be fastened to the user's body like the natural hand its weight is experienced as more of a burden, further increasing the importance of a lightweight device. From literature the average mass of the human left hand was found to be 373.7 grams, with a standard deviation of 62.1 grams. The maximum allowable mass of the entire design is therefore chosen as 311.6 grams, one standard deviation below the mean. With mass minimization in mind emphasis can be put on mechanism simplicity to limit the number of parts.

Pinch force

The user should be able to generate sufficient pinch force without having to spend large amounts of energy. Otherwise, performing activities of daily living (ADL) throughout the day will become fatiguing and the prosthesis will be abandoned. Studies have been performed regarding the tasks that amputees wish to undertake on a daily basis, the role that their prosthetic device should fulfill during these tasks and the levels of pinch force required. Keller et al. states that a minimum pinch force of 7 lb. (approx. 31.14 N) is needed to accomplish 'standard activities'[20]. The requirement for this design will be that the user is able to generate at least 31.14 Newton of pinch force in either mode without being required to generate levels of cable force that are beyond reasonable. See subsection on activation force below.

Opening width

The maximum distance between the 'fingers' dictates the size of objects that users can grasp. A device whose opening width proves too small for daily activities will quickly be abandoned. Fletcher et al. found that an opening width of 1.5 inches (38.1 mm) is required for "about 90 percent of all common activities" and that an opening of 3 inches (76.2 mm) suffices for the remaining 10 percent[21]. With this in mind the minimum opening width of the terminal device is set to 76.2 mm.

Activation force

A TD in a body-powered upper limb prosthetic is commonly controlled through a Bowden cable and shoulder harness. Through body movements tension is created in the cable, resulting in the opening or closing of the prehensor. The opening spring force during VC mode of the new device should be only a low amount to minimize effort. Spring force of the VO mode should result in sufficient pinch force but should not be fatiguing for the user to open as the amount of cable tension that an amputee is capable of generating is limited. Care should be taken to ensure that the required activation force to generate adequate pinch force never rises above certain limits. Taylor et al. state that arm flexion is the preferred control movement for below-elbow amputees and that a typical mean control force value of 63 lb. (280 N) can be generated in this manner, with a 5.4 lb. (24 N) standard deviation[22]. Consequently, as an activation force requirement a maximum of 256 N is chosen, one standard deviation below the mean. It is noted that lower required activation forces are preferred, to keep energy expenditure low and preserve user comfort.

Cable excursion

In addition to the limiting cable force that can be comfortably generated by the user it is important to note the cable excursion a person is capable of inducing. Through select body movements the end of the Bowden cable will be moved away from the terminal device to which it is attached. This in turn will induce a movement of the tong(s) and will allow the wearer to control their device. The distance by which the end of the Bowden cable is displaced is referred to as the excursion. Taylor et al.[22] determined a mean maximum cable excursion by shoulder control that upper limb amputees are capable of generating of 53 mm, with a 10 mm standard deviation. The upper limit of cable excursion occurring in the prosthesis during normal operation is set to one standard deviation below the mean, resulting in a value of 43 mm.

Actuation

The goal of this project is to design a terminal device of the body-powered type. This choice was made mainly with the very limited capabilities for grip force feedback and grip velocity feedback of externally powered devices in mind. Shoulder control through the use of a shoulder harness and Bowden control cable can be described as industry standard.

Grip stability

Essential to any TD is the ability to grip objects in a stable manner. If a prosthetic device fails in this the user will certainly not wear it in everyday life. Stable gripping of objects of many different sizes and shapes should be possible. The natural hand employs several unique gripping patterns to do this. For an overview of hand prehension patterns see figure 2.1. Keller et al.[20] state that lateral, and particularly palmar grip are most often used in daily life. Especially palmar grip has large contact surfaces between digits and objects, ensuring stability. The ability to utilize palmar prehension is chosen as a requirement.

Table 2.1: An overview of all design requirements.

Requirements		
Cosmesis		
Dimensions	Maximum of 185 mm length, 100 mm width	[18]
Comfort		
Total mass	Maximum of 311.6 g	[23]
Control		
Pinch force	Minimum of 31.14 N (7 lb.)	[20]
Opening width	Minimum of 76.2 mm (3 in.)	[21]
Activation force	Maximum of 256 N	[22]
Cable excursion	Maximum of 43 mm	[22]
Actuation	Body-powered actuation through Bowden cable.	
Grip stability	Palmar prehension is required for stable gripping.	[20]

Table 2.2: An overview of all design wishes.

Wishes		
Cosmesis		
Appearance	Aesthetically pleasing, though not required to resemble the human hand.	[19]
Comfort		
Shape	Device does not get caught on objects, surroundings or clothing.	
Control		
Cost	The device is affordable.	
Line of sight	Objects that are to be grabbed are clearly visible.	
Locking option	The gripper can be locked in VC mode, retaining the applied pinch force.	

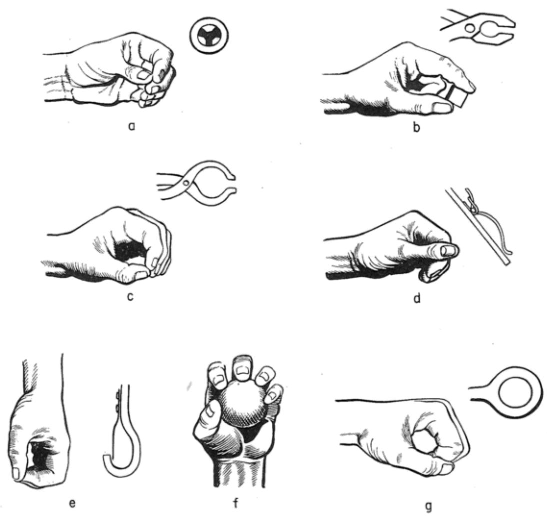

Figure 2.1: Overview of hand prehension patterns. *a*, palmar prehension. Opposition of thumb with digits II and III in the near-closed position gives a three-jawed chuck prehension. *b*, palmar prehension. At openings of 1 to 3 in., opposition between thumb and digits II and III is in the manner of a pliers grip. *c*, tip prehension. Distal phalangeal segments of digits II and III and of thumb are strongly flexed to bring the finger and thumb tips into opposition. *d* lateral prehension. Ball of thumb opposes lateral surface of digit II, usually the second phalanx. *e* hook prehension. Load supported by hooked terminal phalanges, thumb acting largely to prevent slipping volarly. *f*, spherical prehension. In addition to elements of grasp prehension, curving across the knuckle line permits conformity to spherical objects. *g*, grasp prehension. Digits curled about object, such as a handle; thumb curves and overlays finger tips to close the prehension "ring"[22]

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2.2. Wishes

Cost

Upper limb prostheses are commercial products paid for by the amputee themselves or, sometimes, their insurance provider. In both cases a lower price will be preferable to a higher one. A low cost price will enable more amputees to access prosthetic products, in countries around the world. Lower construction costs increase the opportunity to create an economically viable device. To lower costs care must be taken to simplify the TD mechanism where possible. Furthermore, minimizing internal forces and torques allows for designs composed of less material or less high-grade material.

Line of sight

No part of the device should obstruct the line of sight of the user to objects that they wish to manipulate. Objects should be clearly visible when approached with the prehensor, as well as when they are held.

Locking Option

A disadvantage of conventional VC terminal devices is the fact that holding an objects requires a constant effort from the user to supply grip force. A VO device, by contrast, requires no effort when gripping. To alleviate users from this fatiguing burden some VC devices have been equipped with a locking mechanism, which retains grip force after it has been applied by the user. While the need for a locking mechanism in a hybrid TD is much less than in a conventional VC device, the argument could still be made that a great multitude of 'effortless' gripping forces are available only by such a mechanism, while being unavailable in VO mode.

2.3. Experimental methods

An important step in any design process is the validation through testing of a prototype of the proposed design. The terminal device design generated in this thesis is tested in two ways: first, a number of mechanical properties of the prototype are measured and, where possible, compared to the predicted properties of a MATLAB software model of the design. Also they are compared to the measured values of the same mechanical properties for a selection of other terminal devices which are currently available to amputees. In this manner it can be approximated to what extent the mechanical behaviour of the prototype matches that predicted by the MATLAB model on which the concept choice (partially) depends, and also how the prototype fares compared to its 'competitors'. The design of these tests is further explained in subsection 2.3.1.

The second type of test that the prototype is subjected to is a user-performed functionality test. This is done because the success of a terminal device depends not only on mechanical properties but also on its functionality in use by amputees while performing activities of daily living. The Southampton Hand Assessment Procedure (SHAP[24]) is chosen to assess the functionality of the prototype. The experimental methods are explained in subsection 2.3.2.

2.3.1. Mechanical tests

In two published papers by Gerwin Smit et al. relevant mechanical properties of a number of popular commercially available prosthetic hands and hooks are measured and compared. One paper limited itself to voluntary opening devices[9], the other to voluntary closing devices[25]. This information on the mechanical performance of existing and commercially successful prosthetic prehensors provides a good indication of what is demanded of novel terminal devices. By replicating the Smit et al. tests with the separate VO and VC modes of the device of this thesis it becomes possible to compare the performance of the hybrid design prototype with a benchmark performance and subsequently gauge its future potential.

Due to significant differences in performance between hands and hooks[9][25][26], and the fact that the device developed in this thesis is more akin to a hook than a hand, the choice has been made to only include comparisons with the mechanical properties of VO and VC hooks.

VO tests

The test protocols used by Smit et al.[9] are also used to test the prototype of this thesis. Smit tested four body-powered hook terminal devices of the voluntary opening (VO) type:

- Hosmer model 5XA hook
- Hosmer Sierra 2 load VO hook
- RSL Steeper Carbon Gripper
- Otto Bock model 10A60 hook

For each device the mass and the maximum opening span of the gripper are measured. Furthermore, each device is subjected to three different tests using a simple test bench to measure the force in, and displacement of, the activation cable which connects the TD to the shoulder harness. The test bench is the same one Smit et al. used located at Delft University of Technology. In [9] its build is described: "The test bench was custom-built and consisted of standard components. A linear variable differential transformer (Positek Ltd; Cheltenham, United Kingdom) measured the displacements and a load cell (Zemic; Etten-Leur, the Netherlands) measured the cable activation force. We measured the pinch forces with a custom-built double leave strain gauge load cell. The voltage of each load cell was amplified with an amplifier (SCAIME; Annemasse, France). We recorded all data using a data acquisition system (National Instruments; Austin, Texas)."

Three different tests are performed using this test bench:

1. **Open and close test (full opening)**
   The gripper is moved from a fully closed state to full opening, by pulling the cable at a rate of circa 2 mm/s. Subsequently the gripper is closed with approximately the same velocity. Activation force and displacement are measured.
2. **Open and close test (50 mm)**
   Identical to test 1 except that the gripper is opened until an opening width between the fingers of 50 mm is reached before closing again.
3. **Pinch force test**
   A pinch force sensor is placed between the fingers and the pinch force is measured for opening widths of 10 mm, 20 mm and 30 mm.

The newly developed prototype will undergo these tests while solely acting as a VO device. This way the equivalent mechanical properties are found. The rationale for test 2 is to account for the varying opening spans of the inspected devices in the original study. Both tests 1 and 2 are preceded by two initial runs to account for transient behaviour in the mechanism and are subsequently performed four times. Results are then averaged. The properties resulting from test 3 are not dependent on motion and therefore do not have to be repeated.

Measurements on pinch force, activation force and cable excursion during operation are acquired from the tests performed using the test bench. Data of the latter two can be used to calculate both the amount of work needed to close the device, as well as the amount of hysteresis occurring during a full cycle of opening and closing. This is done through integration of the force-displacement curve. A complete list of all measured mechanical properties of the VO mode is:

- Mass of the device
- Maximum opening span
- Maximum cable excursion required for full and 50 mm opening
- Maximum activation force required for full and 50 mm opening
- Work required for full and 50 mm opening
- Hysteresis occurring during a full, and 50 mm opening, cycle
- Pinch force generated with a 10 mm, 20 mm and 30 mm opening width

VC tests

To test the VC mode of the novel design, the test protocols of Smit et al.[25] are used as well. The two body-powered terminal devices of the voluntary closing (VC) type tested by Smit were:

- Hosmer APRL VC hook
- TRS VC Hook (Grip 2S)

Again for each device the mass and maximum opening span are measured. Of course, the device of this thesis will have values identical to those measured as part of the Voluntary Opening tests. The test bench is again used here, for three different tests:

1. **Closing test**
   The control cable was pulled until the gripper tightly gripped a steel plate of 1 mm thickness.
2. **Pinch test**
   The pinch force sensor (approx. 10 mm wide) was placed in the fully opened gripper. The cable was operated until a pinch force of 15 N was reached.
3. **Pull test**
   The pinch force sensor was again placed in the gripper. This time the cable was operated until the activation force in the cable reached 100 N.

The terminal device developed as part of this thesis undergoes these tests while solely acting as a VC device, with the voluntary opening function never being utilized. This way it is possible to compare the acquired mechanical performance data with that of tested commercially available VC devices. Similar to the VO test protocol the closing and pinch tests are preceded by two initial runs to account for transient behaviour and are performed four times, after which the resulting measurements are averaged. The pull test is performed a single time as its results are not dependent on possible varying behaviour of elastic spring elements.

As in the VO testing, the required work and occurring hysteresis during VC mode operation can be calculated through integration of the force-displacement data produced by the test bench. A full list of all measured mechanical properties of the VC mode is:

- Mass of the device
- Maximum opening span
- Excursion range of the activation cable
- Work required for closing the device
- Hysteresis occurring during one full cycle (closing and reopening)
- Work required to close the gripper and pinch 15 N
- Activation force required to generate a pinch force of 15 N
- Generated pinch force at an activation force of 100 N

One mechanical property investigated by Smit et al. is the amount of pinch force drop that occurs once a locking mechanism is activated that locks the operating cable, effectively maintaining pinch force without requiring the user to continuously deliver cable tension. This property is not investigated if the final thesis prototype does not facilitate such a locking function.

2.3.2. User functionality tests

The previous subsection discussed how the mechanical properties of the novel design can be measured and subsequently compared to those acquired of comparable body-powered hook terminal devices of the VO and VC varieties. However, in addition to its mechanical quality it is of great importance that the functionality of the device during a wide variety of tasks suffices as well. It is not impossible for a prosthesis to mechanically be capable of high performance while still having a low functionality when used by an amputee. Therefore, the user functionality of the concept design is also assessed.

Multiple alternative procedures have been created that have the aim of assessing the functionality of upper limb prostheses. For this thesis the Southampton Hand Assessment Procedure (SHAP[24]) is chosen. The SHAP is an oft-chosen procedure and multiple studies have published the scores they obtained through testing their chosen prosthetic devices, enabling comparison. Four sets of SHAP scores have been found in literature; two regarding VO devices[27][28], one of a VC device[27], and one hybrid VO/VC prehensor[29]. This last study also lists its separate VO and VC scores.

The Southampton Hand Assessment Procedure consists of a total of 26 tasks that a participant should perform as demonstrated to them and as fast as reasonably possible. Each task is self-timed, meaning that the participant starts and stops a timer at the beginning and end of each task. The first series of 12 tasks involve the manipulation of lightweight and heavyweight versions of six abstract objects, requiring the use of six different grasps: spherical, tripod, power, lateral, tip and extension grasps. The remaining 14 tasks resemble a collection of activities of daily living (ADLs): picking up coins, undoing buttons, simulated food cutting, turning a page, removing a jar lid, pouring from a glass measuring cup, pouring from a carton, lifting a heavy jar, lifting a light can, lifting a tray, rotating a key, opening and closing a zipper, rotating a screw, and using a door handle. In this thesis a total of 10 participants undergoes the procedure, all of which are unimpaired and make use of a Body Powered Prosthetic Simulator by TRS Inc. This device allows for control over body-powered upper limb prosthetic devices in a manner similar to upper limb amputees and is deemed a good approximation of eventual amputee use.

The SHAP website produces a final participant score when a set of 26 completion times is entered. This score is a single number normally between zero and a hundred, although higher scores are possible. The score expresses the functionality of the participant relative to an unimpaired individual, e.g. a score of 75 indicates that a person has 75% of unimpaired hand function.

As the terminal device designed in this thesis possesses both a voluntary opening mode and a voluntary closing mode each task of the SHAP can be performed in two ways. Similarly, each participant can produce two SHAP scores; one where all tasks are performed using VO mode, and another one where all tasks are performed using VC mode. During the SHAP session a participant performs each task first in one mode, directly followed by the other. The order of modes is randomized to minimize influence. After a task is completed using both modes the participant indicates which mode they preferred for that particular task, as well as the motivation for their preference. Through this it becomes possible to produce a third SHAP score dependent on the task completion times related to the *preferred* mode of each task. With these three SHAP scores per participant and a total of 10 participants some insight is gained into the relative functionality advantage(s) of having a choice of modes over either one on its own. A one-tail repeated measures t-test is used to determine whether possible detected advantages are significant.

The mean SHAP score attained using only the VO mode can be compared to SHAP scores of other VO hook devices. Two studies have been found in literature. Dalley[28] reports the data of a 33-year old male bilateral transradial amputee performing the SHAP four times, using a Hosmer-Dorrance Corp. 5XA (VO) split-hook. Berning et al.[27] provide data regarding 31 subjects using a Hosmer Dorrance Corp. Sierra 2-Load VO hook. In the same study Berning et al. also tested a Hosmer Dorrance Corp. APRL VC hook in identical experimental conditions. This data can be used in a comparison with the mean VC mode SHAP score of this thesis. Finally, Sensinger et al.[29] developed a hybrid prosthetic prehensor that also possesses the ability to switch between VO and VC modes. A prototype of the design was tested in a SHAP-based experiment very similar to the tests of this thesis. The 'preferred mode', VO mode and VC mode SHAP scores can all be compared to the scores of Sensinger.

3
Concept generation

With the goal in mind of designing a high-performance terminal device it is important to carefully choose its working principle, ensuring that sufficient effort is put into exploring all perceivable possibilities. A hybrid prehensor's working principle dictates the design of virtually every part of the entire device and therefore has significant consequences for the final functionality. In this chapter a search is performed with the aim to generate as many unique hybrid prehensor working principle concepts as possible. Subsequently the collection of novel concepts can be compared with one another and with currently existing hybrids to find the single concept that shows the most promise for improved functional performance. The design requirements and wishes defined in chapter 2 help in this concept choice where applicable.

Generating a collection of novel hybrid concepts is a challenging task. Before the search is started, first all hybrid devices that are currently known in literature are analysed. In a literature study preceding this thesis (appendix .1) a total of eight hybrid VO/VC terminal devices has been found:

- Dalisch[30]
- LeBlanc[31]
- Nelson[19]
- Veatch[32]
- Kuniholm1[33] (based on a pin and slot)
- Kuniholm2[33] (based on bevel gears)
- Sullivan[8]
- Sensinger[29]

Each of these eight prosthetic devices employs a working principle enabling the combination of both principles of operation, voluntary opening and voluntary closing, within a single gripper mechanism. Appendix .1 includes detailed explanations of the devices.

3.1. Analysing existing hybrid concepts

When the many designs of body-powered VO and VC prehensors are abstracted and broken down into their basic parts, it can be said that all conventional prehensors consist of only five essential elements:

1. An input, most often an operating cable
2. A passive tong, or 'finger', that is unmoving
3. An active tong, of which the movement is controlled
4. A rotation point around which the active tong rotates
5. A spring element or elastic band

For VO and VC devices these five parts are in slightly different arrangements but both can be constructed from them. See figure 3.1. The eight known hybrid prehensor designs can all be viewed as variations on the conventional five-part prehensor as introduced just now. It is these variations that allow the prehensor to incorporate both principles of operation instead of just one. In total four distinct *methods of hybridization* - variations that turn a standard gripper into a hybrid one - are identified.

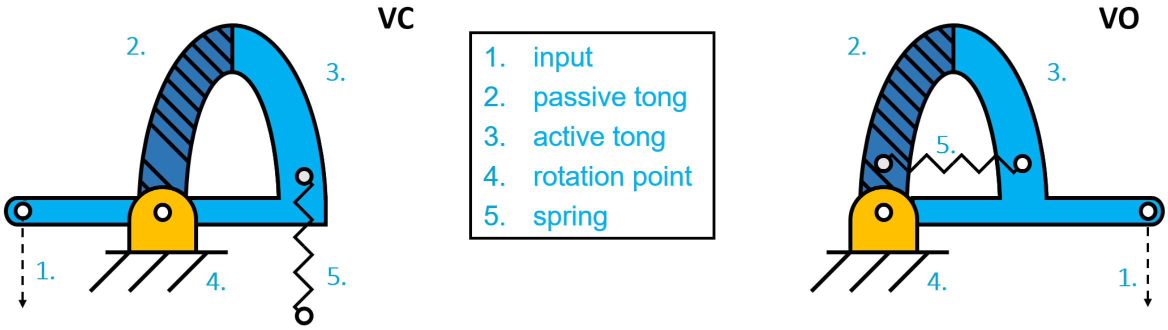


Figure 3.1: A schematic representation of the five essential prehensor elements forming a voluntary closing (left) and voluntary opening (right) mechanism.

Method 1 The first method to hybridize the standard gripper introduces a second input. This approach is seen in the device of Dalisch, where the opening of the artificial hand is directly linked to the elbow angle of the wearer. When the elbow moves from full flexion to full extension the prosthetic hand first opens up from a closed starting position before proceeding to close once more. As the user has control over both flexion and extension of the elbow, this translates into a double input that can 'pull' on the active tong in both the opening and closing directions.

Method 2 The second hybridization method adds a second passive tong to the set of five elements. The two passive tongs are placed on opposite sides of the active tong, creating two gripper openings instead of only one. As one gripper opening is enlarged by the actions of the user through the input cable, the other gripper opening becomes smaller until the two tongs eventually meet. In this way the device possesses both a VO and a VC gripper opening. Both the designs of LeBlanc and Nelson function in this manner.

Method 3 One hybrid prehensor design, that of Veatch, has its control cable connect with both tongs. Through two actions the user can lock the active tong and unlock the passive tong, effectively switching their roles. This can be classified as either 'switching the roles of the tongs' or 'introducing a second active tong'. The latter classification is chosen in this analysis.

Method 4 Hybridization method 4 introduces the option of reversing the input-output polarity of the relationship between the input cable and the active tong. In both designs of Kuniholm as wel as in those of Sullivan and Sensinger a mechanism connects the control cable (input) and active tong (output). The mechanism has two settings, making the active tong either move towards or away from its passive counterpart when the control cable is tensed. This is different from the previous approaches as none of the five basic elements are doubled.

Regarding the four distinct known methods, one thing stands out. The first three methods involve doubling one of the five designated parts that a conventional gripper consists of: either input, passive tong or active tong. This raises the question of whether it would also be possible to create a hybrid mechanism by instead introducing either a second rotation point or spring, the remaining elements. Regarding springs; three of the known hybrid designs (Veatch, Kuniholm1 and Sensinger) already require multiple springs in order to function. The Kuniholm2 concept might share that requirement as well, though its design stage is too early to say for certain. Furthermore, no concept could be generated by the author which used multiple springs while not falling into one of the previously mentioned categories. Due to these two reasons it is decided to omit this method from the list. Still, there is potential for at least one additional method of hybridization: one that introduces a second point of rotation to switch prehension mode. This is dubbed hybridization method 5.

Table 3.1: Overview of identified methods of hybridization.

#	*Hybridization methods*	*Design*	*Implementation*
1	Use a second input	[30] Dalisch	Elbow control provides two-way input
2	Use a second passive tong	[31] LeBlanc	Two passive tongs flank the active tong
	(create second gripper opening)	[19] Nelson	Active tong rotates around passive tong
3	Use a second active tong	[32] Veatch	Active control switched between tongs
4	Reverse input-output polarity	[33] Kuniholm1	Pin and slot impose active tong path
		[33] Kuniholm2	Change gears
		[8] Sullivan	Additional gear is activated
		[29] Sensinger	Adaptable four-bar linkage
-	*Use a second spring*	-	-
5	Use a second rotation point	NEW	*To be determined*
6	Reverse approach direction active tong	NEW	Active tong passes passive tong

In addition to the five hybridization methods already introduced, a sixth one was devised during concept generation. This approach, dubbed hybridization method 6, involves the active tong being allowed to pass the passive tong in a manner similar to scissor blades. The two tongs do not lie in the same geometric plane and never touch, but instead lie in parallel planes with the 'fingertips' close to grazing one another as the gripper closes. As the control cable is pulled the initial VC gripper opening first decreases in size until it disappears, after which a secondary VO gripper opening grows in size. Thus the active tong can approach the passive tong from two different directions. Table 3.1 offers a full overview of the six methods identified in this chapter, along with a categorisation of the eight known devices and a very brief note on their particular implementation of the method.

3.2. Generating new concepts

After analysis of all currently known hybrid designs a categorisation is constructed, with a total of six identified methods for combining the VO and VC principle of operation in a single prehensor mechanism. Four of these methods come from the devices found in literature while two are novel, in the sense that up until now no hybrid prehensor has been designed that belongs to either one.

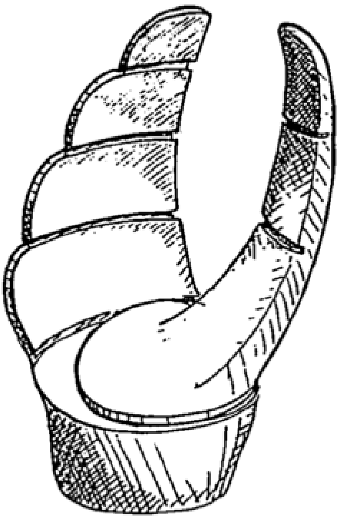
The next step in the process of finding a novel, high-performance terminal device is to generate new concepts of hybrid gripper mechanisms. In the course of this thesis the author has succeeded in creating eight concepts. Some are (believed to be) new and different from those known in literature while others are proposed improvements upon designs already presented. All are thought possibly useful to implement in a terminal device. They are described below. For an overview see table 3.2.

Concept 1

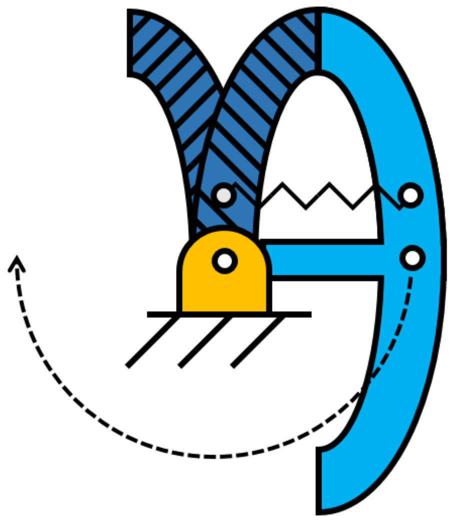
The first concept is a proposed improvement upon Nelson's prehensor. The original design is shown in figure 3.2a with figure 3.2b showing a schematic representation of both the original device and the proposed improvement. Nelson's prehensor was experienced as graceful and simple to use. Two of its described weaknesses were the awkward angles of grasp the user had to deal with when picking up objects, and the tongs not facilitating fine grasping due to poor shape. These shortcomings can be corrected through a design iteration of the finger shapes and positions, possibly unlocking the concept's full potential. This concept is classified as using hybridization method 2 with the wide passive tong, both sides being used, as two simple passive tongs fused.

Concept 2

Concept 2, like concept 1, is another variation upon Nelson's prehensor (figure 3.2a). In this concept the passive tong is split into two to improve angles of grasp, with the active tong situated in between the two tongs. This also solves the issue in Nelson's original design where, between zero and full excursion, a large part of the cable excursion resulted in no notable pinch force occurring, as the tongs would move parallel with respect to one another. See figure 3.3.

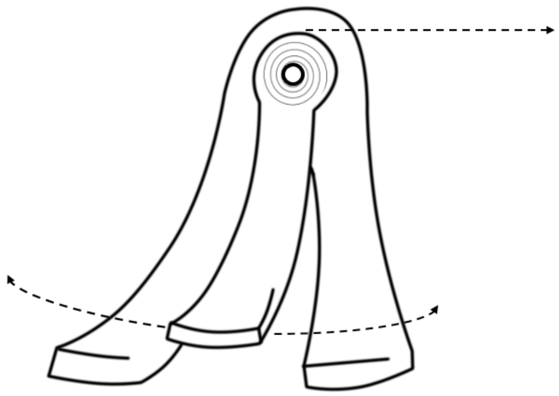


(a) Illustration of Nelson's prehensor[19]

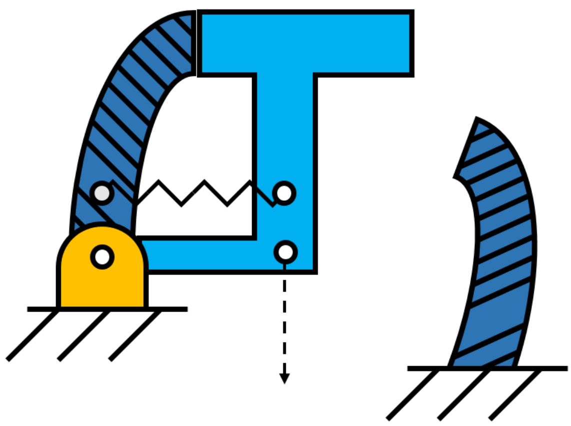


(b) Schematic view of concept 1.

Figure 3.2: Through cable pull the user rotates the active tong against the spring force in VO mode. At full excursion the tongs connect again on the other side in VC mode. This is interpreted as the introduction of a second passive tong.

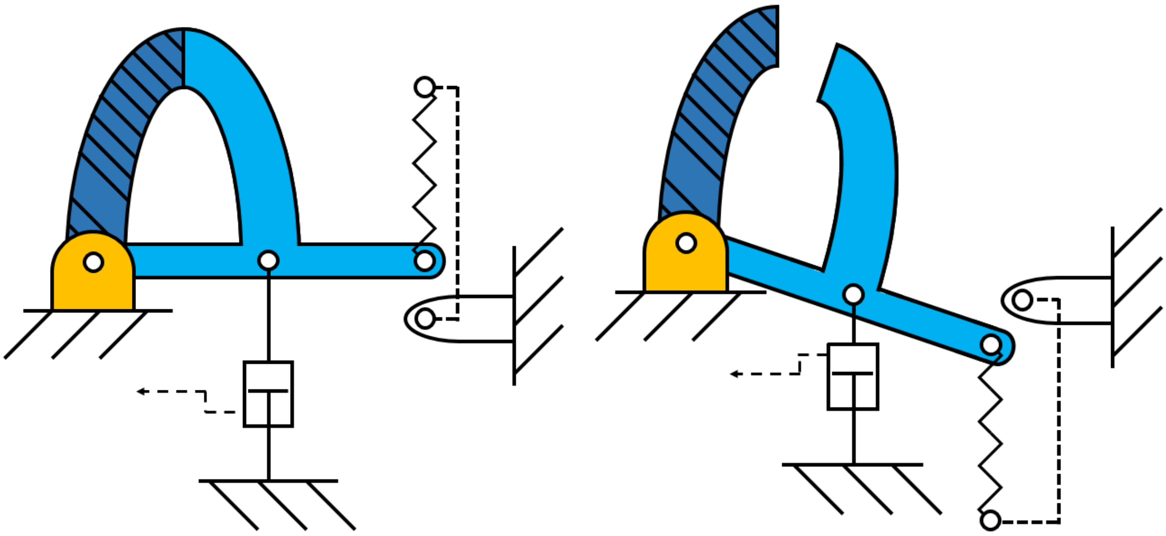


(a) A torsion spring opposes user input, with both a VO and VC gripper opening existing simultaneously.



(b) Schematic view of concept 2.

Figure 3.3: Through cable pull the user rotates the active tong against the torsion spring force in VO mode. Simultaneously it approaches a second passive tong in VC mode.



(a) Schematic view of concept 3 in VO mode.

(b) Schematic view of concept 3 in VC mode.

Figure 3.4: Concept 3. A mode switch is enacted through the rotation of the spring element and a hydraulic valve switch at the input, causing the user to generate either push force or pull.

Concept 3

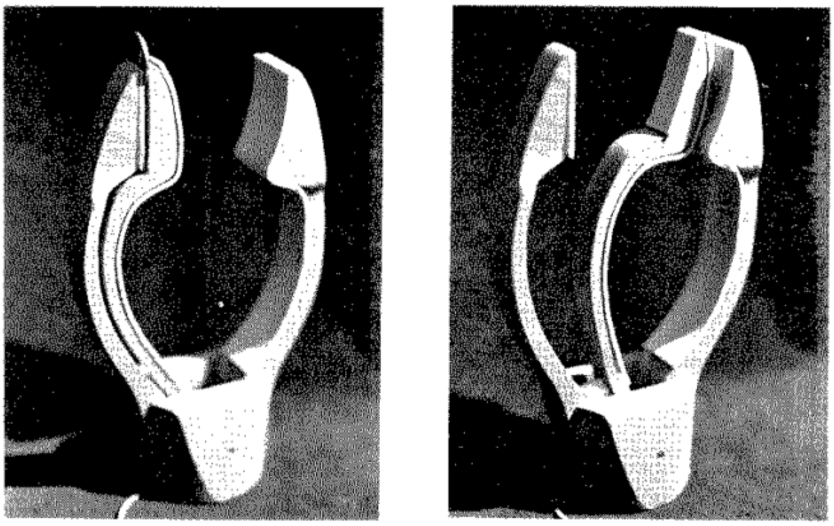
Concept 3 incorporates a hydraulic input as opposed to a more conventional Bowden cable input for the user. This type of input is not limited to one connection to the gripper mechanism but can be made to exert pressure at multiple locations. The pressure can be either at those locations simultaneously, or it can be diverted through valves from one to another. In this concept a valve is used in such a way that the input, normally only capable of exerting pull forces, can now also be made to push. By making it possible to change the spring element orientation between a closing and an opening force a mode switch between VO and VC is possible. Figure 3.4a shows a schematic overview of the mechanism in VO mode, where movement by the user causes the cylinder to pull down on the active tong. Figure 3.4b has the mechanism in VC mode instead. The spring element is flipped to provide an opening force on the gripper, while piston pressure causes a pushing force that closes the gripper. An alternative to this one-cylinder approach would be to utilize two cylinders on opposite sides of the rotation point, where a valve determines the cylinder that expands and thus the direction of rotation. The spring element would still have to be flipped manually. Hybridization method 4 is employed here (mechanism to reverse polarity between input and output).

Concept 4

This concept is also an improvement onto an existing device, this time LeBlanc's prehensor[34]. The existing terminal device (figure 3.5a) has the active tong moving away from one passive tong and moving towards the other. This way the voluntary opening and voluntary closing modes can be used at the same time. Negative feedback from amputees, prosthetists, occupational therapists and laypersons that tested the prototype, mainly regarding the shape, ultimately lead to a halt in development. The proposed improvement is to shape the tongs after those of conventional 'lyre'-shaped hook prostheses (figure 3.5b), as this shape is highly functional and has proven to be very popular since its conception. Although schematically concepts 2 and 4 are identical the decision was made to treat them as two unique concepts instead of one. This was done because the shape of the devices is fundamentally different, with the active tong rotating in concept 2, while it translates in concept 4.

Concept 5

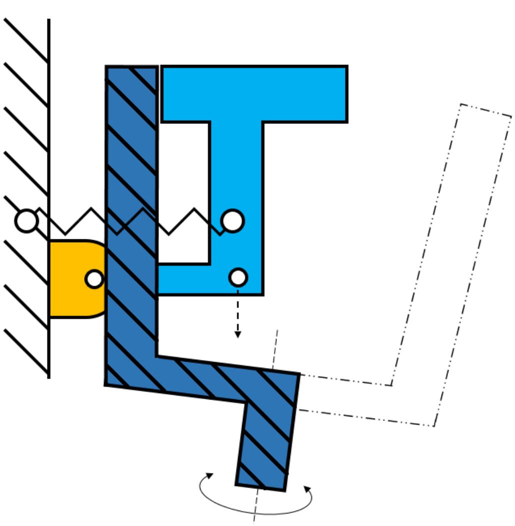
In this concept the user is able to pick from two possible positions of the passive tong. In one position the active tong is pulled against it by the spring element, effectively creating a VO mechanism as illustrated in figure 3.6a. If the user decides to rotate the passive tong to its position at the other end, the gripper will have an open starting position and pulling the control cable will voluntarily close it as in figure 3.6b.



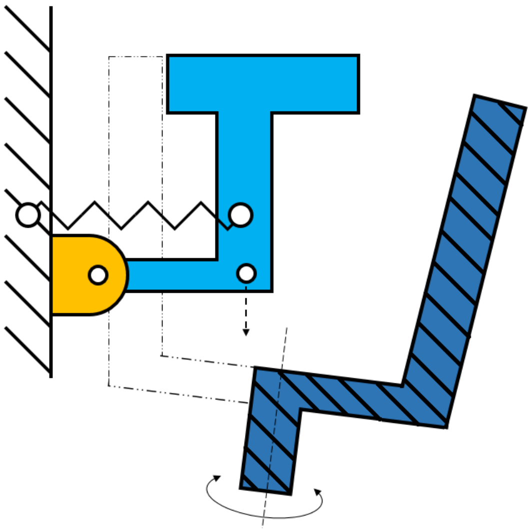
(a) LeBlanc's prehensor[34] in starting position and when closed by the user; the active tong has a gripper opening on both sides.

(b) A conventional 'lyre'-shaped hook.

Figure 3.5: Concept 4 involves the use of LeBlanc's approach, but the tongs are shaped like a conventional 'lyre'-type prosthetic hook. The rationale being that this shape has been functionally optimized for many years. Schematically it is virtually identical to figure 3.3b.

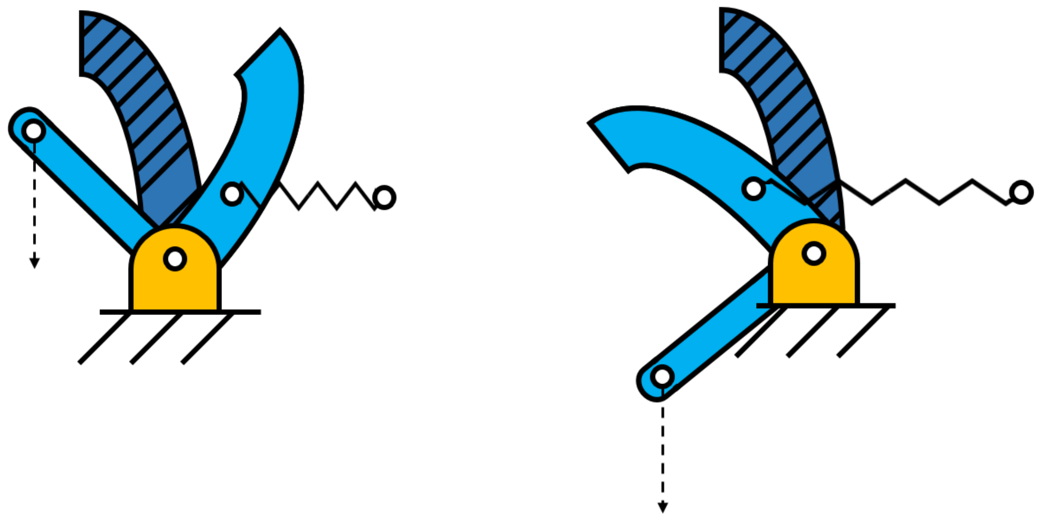


(a) Concept 5 in VO mode.



(b) Concept 5 in VC mode.

Figure 3.6: The two modes of concept 5. The passive tong can be manually rotated to opposite sides of the active tong to switch.



(a) Concept 6 in VC mode.

(b) Concept 6 in VO mode.

Figure 3.7: In voluntary closing mode the active tong approaches the passive tong from the right, while in VO mode the active tong moves away towards the left, having just passed in front of the passive tong.

Concept 6

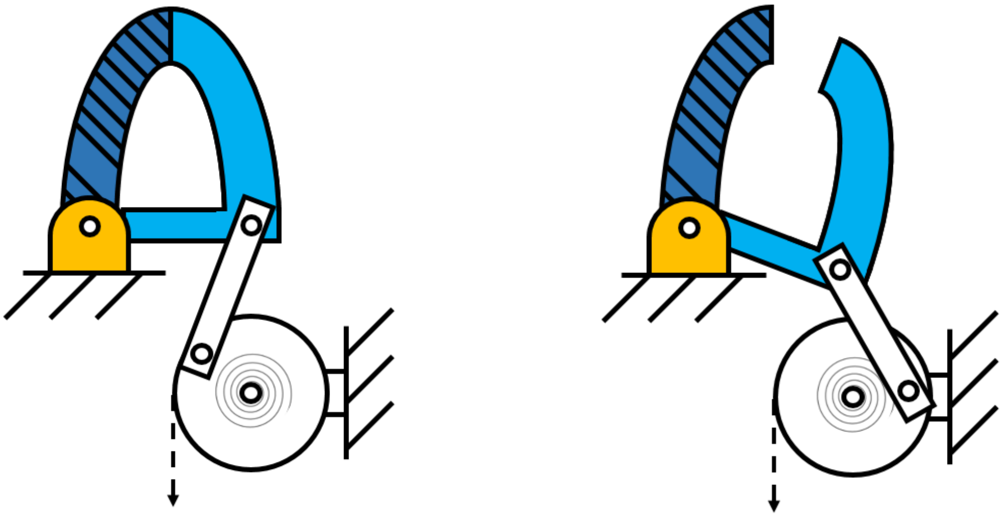
The hybridization method of the sixth concept is one unlike previously encountered, and thus does not fit within any of the first four categories defined in section 3.1. Instead it has been dubbed method 6 (concept 8 uses method 5, see below). The defining property that sets this concept apart from others is the fact that the two tongs do not touch, but rather slide past each other. Table 3.1 states that the approach direction of the active tong is reversed. As the input cable is pulled and the initial gripper opening decreases, the active tong will eventually pass the passive tong and a second gripper opening will appear. This opening occurs between the backsides of both tongs, therefore exact tong design is very important. The prehension patterns that can be used with this gripper might be different than those of conventional grippers and most of the other concepts in this section. Although not illustrated in the figure this mechanism offers straightforward opportunities to set separate values for the VO and VC spring forces. This is done by adding a second spring that catches the active tong once it passes the passive tong.

Concept 7

This concept incorporates a crank and shaft. It turns the rotating movement of unwinding the control cable from the shaft into a reciprocating motion, where the active tong goes down, then up again as the gripper moves. A torsion spring connected to the shaft resists its rotation across the entire excursion range, meaning the user initially experiences a spring force keeping the gripper shut which gradually shifts to a force keeping it opened. See figure 3.8. The crank-and-shaft mechanism gradually reverses the polarity between the cable input and output, the movement direction of the active tong, and thus this concept falls into the category of designs employing method 4.

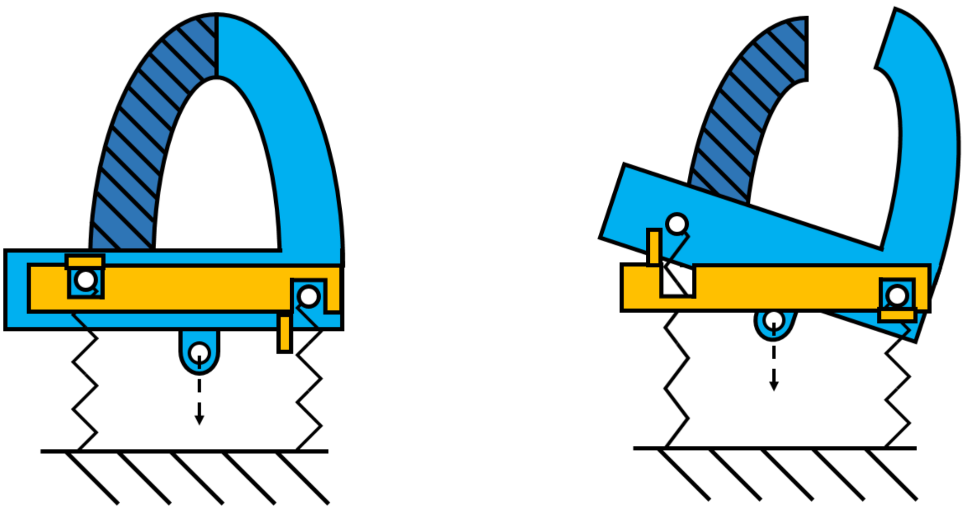
Concept 8

The eighth and final generated concept is the second one that cannot be categorized using the initial four methods of hybridization. In this mechanism a second rotation point is introduced, making it the only concept employing method 5. The active tong is connected to two rods that can be translationally locked in slots independently of each other. Doing this turns the rod into an axle around which the active tong can rotate. See figure 3.9. Each rod is associated with one mode of prehension, VO or VC. When both rods are locked the gripper is locked in its position. This quality could be used as a locking mechanism. Locking and unlocking of rods can only be done while the gripper is in its closed position and both rods are in their slots, which means the user is required to pull the prehensor shut to switch from VC mode to VO mode. Although less than ideal the spring which the user has to work against is a relatively weak VC spring. This locking of the rods might have to be done by the user's other hand if no mechanism can be found that switches modes purely through cable excursion.



(a) Concept 7 in VO mode. (b) Concept 7 in VC mode.

Figure 3.8: The two modes of concept 7. The wound control cable, when pulled, unwinds from the shaft and moves the crank downward, thereby opening the gripper. The shaft itself is connected to a torsion spring that resists this movement and supplies VO pinch force. Once the crank is beyond its lowest point it moves back up and starts closing the gripper again, while the torsion spring now labours for it to remain open.



(a) Concept 8 in VO mode. The left slot is locked. (b) Concept 8 in VC mode. The right slot is locked.

Figure 3.9: The two modes of concept 8. The two springs are compression springs. The mechanism has two possible rotation points, where a rod (in white) falls into a slot which can be sealed, translationally locking the rod. The rotational degree of freedom is still available. By switching which slot is sealed the rotation point can be chosen, and thus the prehension mode.

Table 3.2: List of new concepts and the hybridization method categories they belong to.

Concept no.	Hybridization method
1	2 - second passive tong
2	2 - second passive tong
3	4 - input-output polarity reversal
4	2 - second passive tong
5	2 - second passive tong
6	6 - reversal of active tong approach direction
7	4 - input-output polarity reversal
8	5 - second rotation point

4

Concept choice

The previous chapter has introduced eight new hybrid prehensor concepts that have been generated. Now it is time to determine which of these has the most potential of resulting in a high-performance and functional prosthetic prehensor. Before the new concepts are analysed, first the pros and cons of the eight known hybrid devices will be summarized. This is done for two reasons. Firstly it is valuable to identify possible structural strengths or shortcomings in any of the hybridization methods or other groups of devices. A second motivation is to find out whether any of the newly generated concepts manage to avoid these pitfalls while maintaining the strengths, or whether previously unknown strengths can be identified. Section 4.1 lists the pros and cons from literature regarding the eight known hybrid devices and derives three important properties of an ideal terminal device. In section 4.2 these desired properties are laid next to the new concepts to determine which show potential to outperform current devices and which concepts can be ignored.

4.1. Strengths and drawbacks of current devices

From literature an overview (table 4.1) is constructed of the strengths and shortcomings of the known hybrid prehensor designs. All these are either mentioned in literature or observed by the author of this thesis. The shortcomings are the reason why development on most of these designs was halted. The listed advantages, together with the known advantages of combining principles of operation, are the motivation to pursue functional hybrid prostheses.

A significant disadvantage of the Dalisch device is the absence of springs or other elastic elements to provide passive pinch force during use of the voluntary opening principle of operation which forces the wearer to generate their own. The prehensor developed in this thesis should offer users a passive VO pinch force. Several devices possess a button or switch(es) that the user has to operate with their other hand before the alternative principle of operation becomes available to them. This is the case in those of Veatch, Kuniholm (#2), Sullivan and Sensinger. Ideally the two principles of operation are available to the user without any required actions beyond cable excursion, which is the sole control input. Having to drop any held objects from the gripper and have a free unimpaired other hand to switch modes is inconvenient and sometimes not possible, as in the case of bilateral amputees. The remaining devices that do not incorporate any such buttons are those of LeBlanc, Nelson and Kuniholm (#1) (excluding Dalisch). In these mechanisms the VO and VC modes are sequential in nature, meaning the amputee can move between principles of operation by changing the amount of cable excursion. A flaw in the design of all three is that the user must extend the VO spring to reach VC mode. As the VO spring stiffness is generally relatively high it becomes a fatiguing act to initiate the voluntary closing principle of operation. It would be preferable to have a terminal device where the voluntary closing principle of operation can be accessed with very little effort and the VO spring is only extended when the switch is made to a voluntary opening mode.

Table 4.1: Overview of strengths and shortcomings of all eight hybrid concepts found in literature. Where indicated these are taken from the assessment of the designers or of peers. When no source is given the judgement comes from the author of this thesis.

Dalisch	⊕ Large excursion allows favourable mechanical advantage	
	⊖ Singular input joint inhibits the moveability of the user	
	⊖ Due to lack of a spring the user is required to generate pinch force	
LeBlanc	⊕ Simultaneous modes allow a favourable mechanical advantage	
	⊕ Simplicity in use as no mode switching is required	[19]
	⊖ Empty, robot-like appearance	[19]
	⊖ The VO and VC spring forces are the same	
Nelson	⊕ Graceful, non-threatening appearance	[19]
	⊕ Simplicity in use as no mode switching is required	
	⊖ VC mode at extreme end of cable excursion leads to awkward control	[31]
	⊖ Awkward angles of grasp	[19]
	⊖ ”Fingers” coming together do not facilitate fine grasping	[19]
	⊖ The VO and VC spring forces are the same	
Veatch	⊕ Variable mechanical advantage during grip cycle	[32]
	⊖ To change modes the user must operate two switches in sequence	
	⊖ Too heavy and bulky for comfort	[29]
	⊖ Either the lateral or medial tong moves, depending on mode	[29]
Kuniholm1	⊕ Wide range of slot and pulley shapes gives flexibility in mechanical advantage	[33]
	⊖ Slot length is limited by maximum dimensions of the device	[33]
	⊖ Less favourable mechanical advantage due to sequential modes	
	⊖ VO spring force must be overcome to reach VC mode	
Kuniholm2	⊕ Potential compactness and simplicity	[33]
	⊖ Large internal forces	
	⊖ Switching modes requires pushing a button	
	⊖ Switching from VO to VC requires the user to put energy into the spring	
Sullivan	⊕ *No notable strengths*	
	⊖ Too heavy and bulky for comfort	[29]
	⊖ Large internal forces	[8]
	⊖ Low mechanical efficiency of gear system	[29]
	⊖ Bowden cable attachment site not the same between modes	[29]
	⊖ Switching modes requires pushing a button	
	⊖ Switching from VO to VC requires the user to put energy into the spring	
Sensinger	⊕ Compact mechanism	[29]
	⊖ Switching from VO to VC requires the user to put energy into the springs	[29]
	⊖ Switching modes requires pushing a button	

Table 4.2: Three properties desired in a body-powered terminal device and an overview of which of the new concepts possesses them. Only concepts 6 and 8 possess all three and thus come out on top.

Property	new concept nr.							
	1	2	3	4	5	6	7	8
Passive VO pinch force	✓	✓	✓	✓	✓	✓	✓	✓
Principle of operation switch possible through cable excursion only	✓	✓	✘	✓	✘	✓	✓	✓
VC mode available without extending VO spring	✘	✘	✘	✘	✘	✓	✘	✓

4.2. Evaluation of new concepts

Section 4.1 presents the known strengths and shortcomings of the current hybrid devices in table 4.1 and describes three properties that the ideal terminal device should possess. Each of the eight existing hybrids fails on at least one of these three points. This information will facilitate the concept choice. The design requirements also help decide.

Encouragingly all eight new concepts offer a passive pinch force in VO mode. However two concepts, numbers 3 and 5, require some external action in order to change the principle of operation. Concept 3 utilizes a hydraulic valve that must be switched as well as a spring that must be rotated 180°. In concept 5 the user is forced to manually flip the passive tong to the opposite side of the active tong. Because it is desired to limit the control actions of the terminal device to only cable excursions these two concepts are dropped from consideration. In the description of concept 8 it is stated that a mode switch button might or might not be required depending on future development of the mechanism. The assumption is made here that a mechanism variant exists that functions with only cable excursion.

The third desired property mentioned in the previous section is access to the voluntary closing principle of operation that does not require the user to extend the VO spring. Tied to this is a desire to have separate and different spring forces in the two modes; a modest amount of spring force keeping the gripper opened in VC mode and sufficient passive pinch force in VO mode. Here many of the newly generated concepts fall short. All concepts except for numbers 6 and 8 incorporate only a single spring, leading the passive VO pinch force to be what the user must surmount to start using the prosthesis as a voluntary closing terminal device. This characteristic is what stopped several of the existing hybrid devices from being successful and therefore these new concepts with the same flaw cannot be deemed superior. Concepts 1, 2, 4 and 7 are dropped from consideration and 6 and 8 are left. See table 4.2.

4.2.1. Final concept choice

The conclusion is drawn that concepts 6 and 8 both possess advantages over the range of currently known hybrid prosthetic prehensors and that a design process involving the best of the two has a high change of resulting in a high-functioning prosthetic prehensor. The last step in determining which of the eight new prehensor concepts has the most potential is choosing between concepts 6 and 8. This is complicated by the two sharing a number of properties. Both allow separate VO mode and VC mode spring forces. Both have to split the total amount of available cable excursion between the modes as one mode of prehension always comes after the other, which might negatively impact mechanical advantage. As the tongs in concept 6 slide past each other this changes their relative orientation, which is not favoured as it might make manipulations more confusing for the user. However the unusual movement of the active tong in concept 8 also leads to different positions. One definite disadvantage of concept 8 is the challenging bearing of the two rotation points. Also it is uncertain whether this mechanism can generate sufficient pinch force and whether a way can be found to avoid a button in order to switch modes. Limited stable grip capabilities might be a disadvantage of concept 6.

A 2D kinematic MATLAB[35] computer model is created of concept 8 to assess its capabilities regarding pinch force generation. The concern is that the requirements and restrictions regarding size, mass and operating effort will render the design too challenging. Furthermore, the elongation of the springs might prove unrealistic. The MATLAB model describes the motions of the active tong in the plane and determines the spring properties necessary to generate desired pinch force values. Design requirements regarding operating force demanded from the user, cable excursion, gripper opening width and total size and mass of the device are incorporated. Three separate models were made; one utilizing compressive springs, one using extension springs and one where a single extension spring attaches to the active tong at a point in between the two points of rotation. In this design variant the single spring supplies both the pinch force during VO mode and an opening force in VC mode. Differences in spring elongation and moment arm between the modes cause the spring to generate different torques nonetheless.

The MATLAB model results show that the mechanism behaves as initially expected, but indicate that all three design variants require unrealistic behaviour of the elastic spring elements if the design requirements of this thesis are to be met. The variants incorporating compressive springs, extension springs and a single extension spring require spring deformations up to 92, 200 and 285%, respectively. Activation forces demanded from the amputee respectively reach up to 190, 300 and 150 Newton for full VO opening; all three quite high. More information regarding the model and its results can be found in appendix .2. This information, together with the fact that concept 8 is relatively complex, makes concept 6 the best choice to be made into a full design and accompanying prototype.

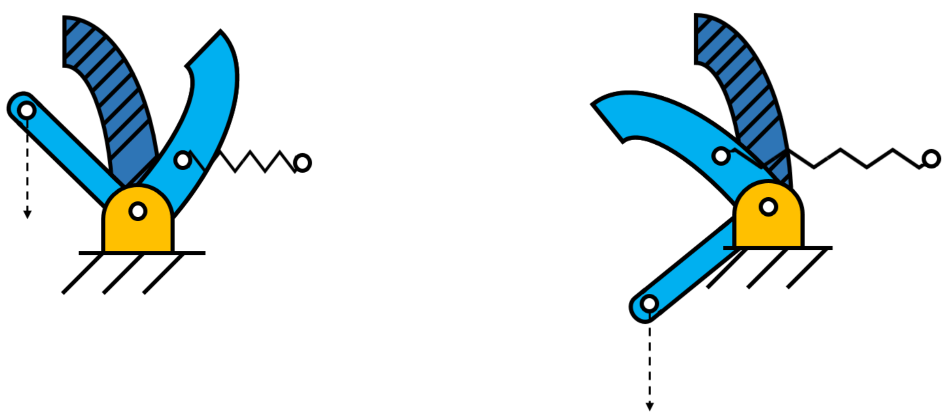
5 Final design

Chapter 4 concludes that concept 6 has the most potential of resulting in a high performance terminal device. In figure 5.1 the conceptual depiction of this concept from chapter 3 is shown once more. The mechanism only employs one spring here but a two-spring variant is proposed that will allow for separate spring forces in the two modes. The current chapter covers the design process from this very simple illustration to a fully functioning physical prototype. The main design choices that are made during this process are summarized in section 5.1. Section 5.2 presents images of the final prototype design in SolidWorks as well as photographs of the finished product.

5.1. Design choices

Tong number, size and shape

A considerable point of concern regarding this prehensor is the unconventional grip it applies to objects. A consequence of the two tongs sliding past each other is that the pinch forces acted upon a held object will not be in line with each other, causing a torque. The object will have an unfortunate tendency to shift when grasped. This effect is exacerbated when the object is less rigid. The decision is made to have two passive tongs that flank one central active tong. This results in the applied grip being a stable three-point grip very close to a three-jawed chuck palmar prehension pattern (pattern *a* in figure 2.1). While this will increase the mass of the device it is less of an issue than the introduction of additional tongs in other concepts, because increasing the number of tongs here allows each to be designed slighter.



(a) Concept 6 in VC mode.

(b) Concept 6 in VO mode.

Figure 5.1: In voluntary closing mode the active tong approaches the passive tong from the right, while in VO mode the active tong moves away towards the left, having just passed in front of the passive tong.

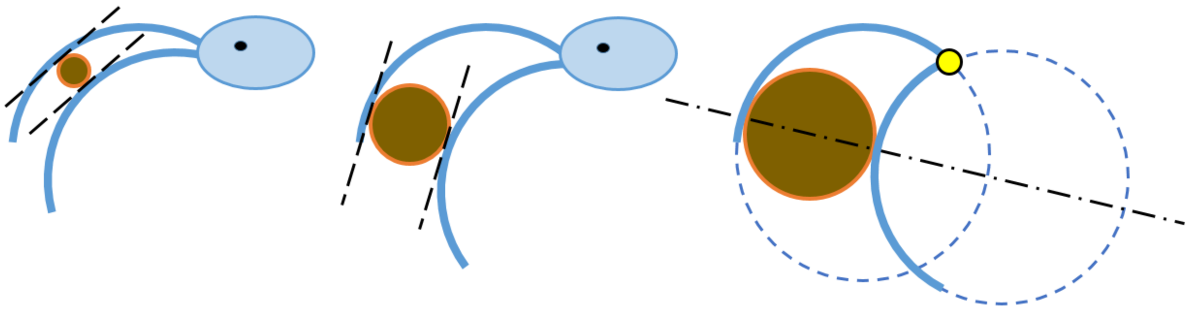


Figure 5.2: A simplified sideways view of the Western Curlew's curved beak when holding two differently sized object, and an abstract representation (right). Both parts of the beak are arc-shaped with the same curvature. Objects will settle where the contact forces align. Adapted from [36].

The gripping of small objects such as coins must be possible. To facilitate this type of action the tongs should be quite close to one another while not touching. Furthermore, the width of the middle tong is a deciding parameter for which objects can still be gripped using the three-point grip. In this case thinner is better, and it will keep the mass of the device low as well. However, too thin a width risks fracture or deflection in use. Tongs made of aluminium with a width of 8 mm are chosen to balance these factors.

The shape of the tongs is very important to the quality of grip. If they were simply straight beams any object would fly from their grasp as soon as some pinch force was applied. A tong shape is required that will always result in stable gripping, no matter the mode used. Compared to the tong design of conventional terminal devices this is more challenging as both the front and back of the tongs will be used for gripping. The voluntary closing mode uses the front of the active tong and the backside of both passive tongs, and the opposite happens in voluntary opening mode. The shape that is chosen is bio-inspired as it has its roots in nature, in the form of the beak of a specific type of bird: the Western Curlew[36]. Its arced beak facilitates the stable gripping of many differently sized objects purely through pinching. The principle is illustrated in figure 5.2. Both parts of the beak are arc-shaped and have the same curvature, causing most objects with near-circular profiles to shift to a stable point in the beak where contact forces align. The object will not move from that spot, no matter the pinch force applied. The tongs of the novel design are given an arc shape on both sides as well so that both modes offer similar grip stability.

Spring location and type

The type of elastic spring element defines the device design to a large extent. Torsion and extension springs are available for use, consisting of metal or elastomer. At first glance torsion springs have potential when combined with the rotating parts of the concept, but after consideration no straightforward way could be found to incorporate them. With hysteresis minimization in mind metal extension springs are chosen over elastomers. Hysteresis is an unwanted phenomenon in any mechanism and more so in this prototype, where a clear assessment of the mechanism's performance is desired with as few complicating influences as can be managed.

The concept as depicted in figure 5.1 only has a single spring and therefore the spring force is nearly constant across the two modes. Although the force will increase due to spring extension and its moment arm around the rotation point will change as well, the spring force in the two modes is still too similar. It has been stated that ideally the voluntary closing mode has a low spring force keeping the gripper opened, and the voluntary opening mode has a high spring force keeping it shut. A graph of this ideal pinch force behaviour is shown in figure 5.3 plotted against the percentage of rotation of the active tong and with the mode transitioning exactly halfway to maximum rotation. Zero percent rotation means the user has not moved the active tong yet, closely resembling figure 5.1a. Maximum rotation resembles the position in figure 5.1b. A negative pinch force is present during VC mode as the user has to overcome this force to begin pinching. Ideally the value of this force is constant and as close to zero as possible to minimize fatigue. A value of 3 Newton is chosen after comparison with Sensinger's prehensor. Over the entire VO mode the ideal applied pinch force is the required value of 31.14 Newton.

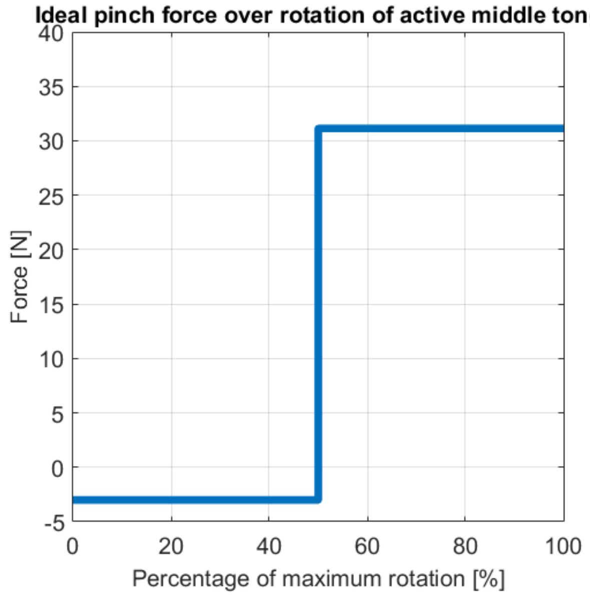


Figure 5.3: Idealized pinch force behaviour plotted over the full rotation of the active tong, from the starting state at zero percent rotation to full cable excursion at 100 percent rotation. Voluntary closing (VC) mode comes first, starting at 0%, followed by VO mode from the 50% mark onward. User has to overcome negative VC pinch force before actual pinch force is generated.

To achieve a pinch force profile similar to that in figure 5.3 some changes have to be made to the mechanism. A new conceptual design is shown in figure 5.4. A lever (in white) sharing its fulcrum with that of the active tong is added to the mechanism and connected to two springs. Spring *A* is attached to the base of the device, spring *B* to a lever extending from the active tong. Also at this end the input cable is attached. Due to the force of spring *A* the lever rotates counter-clockwise until it stops against the passive tong. In this figure a red rectangle stopping the rotation is shown instead. When the input cable is pulled spring *B* will provide the VC spring force while spring *A* provides no resistance. Only after the active tong has passed between the passive tongs does spring *A* start resisting further movement. The active tong comes in contact with the lever and together they rotate further clockwise. The spring force that the user now encounters is the sum of both springs. By choosing appropriate spring parameters the behaviour of figure 5.3 can be approximated. The effect of changing moment arms for both spring forces should be taken into account. The control cable is attached to an extension of the active tong for sufficient moment arm. This extension is designed to maximize moment arm so the required activation forces are lower.

5.2. Final design of prototype

After all design choices have been made in the course of multiple design iterations a final design of all parts is made using SolidWorks 3D-modelling software. A few of the more unique and interesting parts are highlighted in this section. A side view of the active tong (figure 5.5a) shows that both sides of the actual 'finger' section have an arc shape starting from the flat tip and going down until a point is reached where further tapering would make the part too weak. The paths of both arcs eventually intersect right in the center of rotation of the tong. Both passive fingers also have this shape (figure 5.5b). Because of this the curved beak principle illustrated in figure 5.2 can be used irrespective of whether objects are gripped with the front or backside of the tongs (figure 5.5c). In figure 5.5a the dash-dot line indicates the path the control cable will follow, ensuring a constant moment arm in VO mode to lessen the activation force requirement.

Figure 5.6a shows the passive and active tong together, points of rotation aligned on a single axle. The white lever introduced in figure 5.4 is added, albeit in a slightly more rounded shape. Both springs *A* and *B* are connected to it near the top. This is also where the lever is stopped from passing the

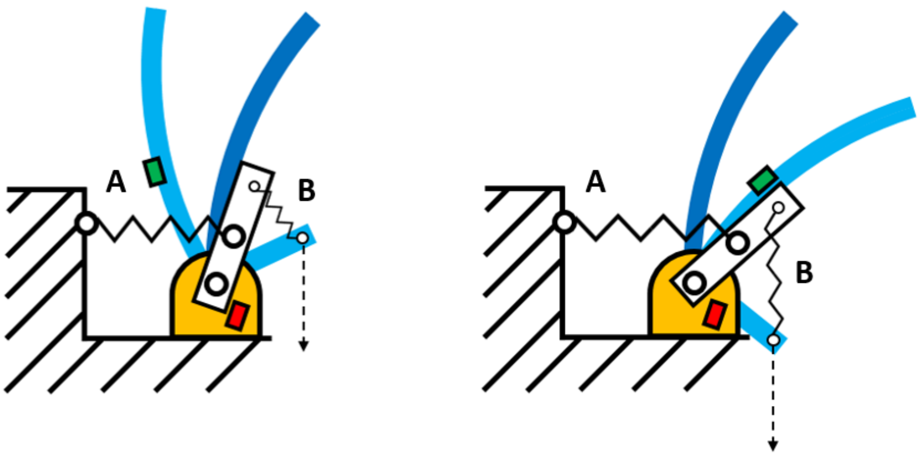
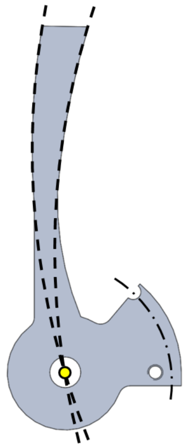
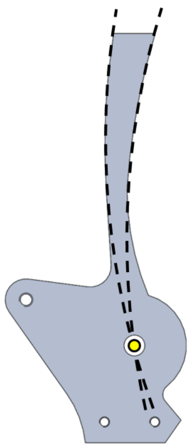


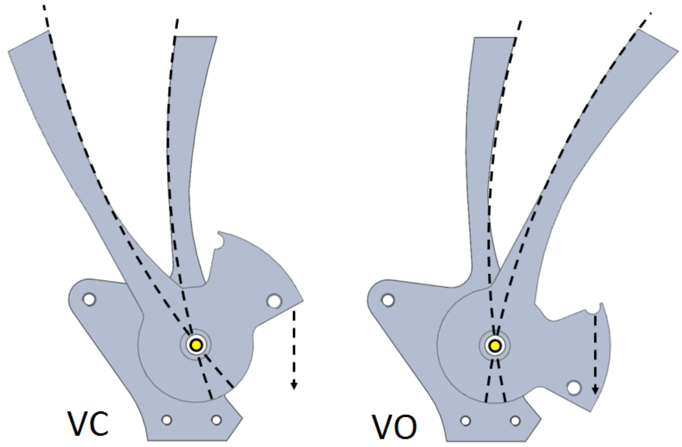
Figure 5.4: A more elaborate conceptual design with curved tong shape and lever allowing for separate spring forces.



(a) Active middle tong.

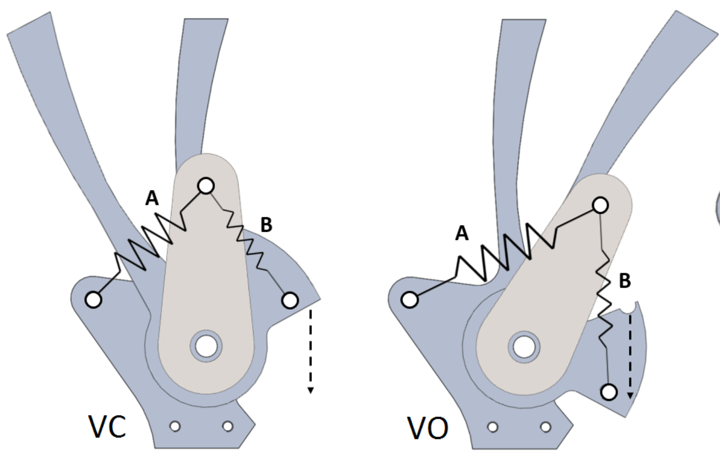


(b) Passive outer tongs.

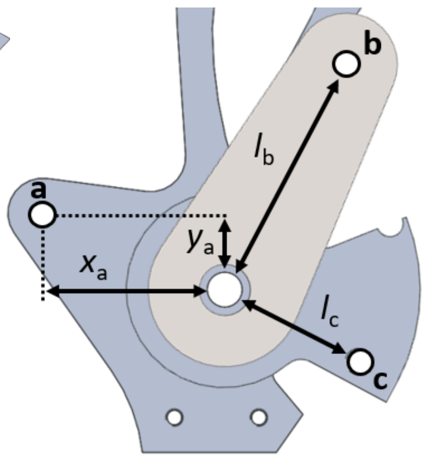


(c) The tongs in VC mode (left) and VO mode (right).

Figure 5.5: Side views of the passive and active tongs with dashed lines highlighting the arced shapes of their functional sides, enabling the application of the Curlew beak gripping method. Both sides of both tong designs have the same curvature so the tongs can function together in VO and VC mode.



(a) Passive and active tong with lever and springs included. The second passive tong is omitted for better viewing.



(b) An overview of the spatial design parameters optimized through the MATLAB model.

Figure 5.6: A schematic side view of the mechanism, showing the working of the lever and springs *A* and *B*. In (a) on the left VC mode is depicted, where the lever rests against the passive tong and only spring *B* is active. In VO mode on the right spring *A* has been activated now that the active tong takes the lever along with it. In (b) the spatial design parameters are displayed.

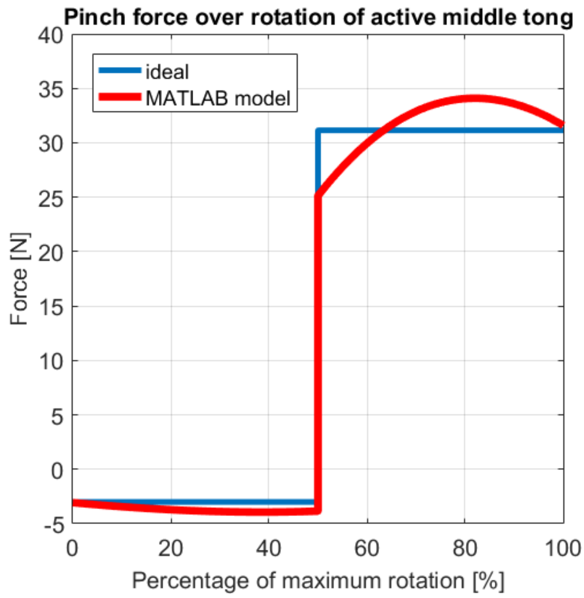


Figure 5.7: The idealized pinch force behaviour plot from figure 5.3 is now extended to include the pinch forces predicted by the MATLAB model. The favoured 'pinch force' in the left half of the curve (VC mode) remains below zero, as the user first has to overcome this force before any actual pinching can occur.

passive tongs. This is better visible in a digital rendering of the assembly as a whole in figure 5.9a and a photograph of the physical prototype in figure 5.9b.

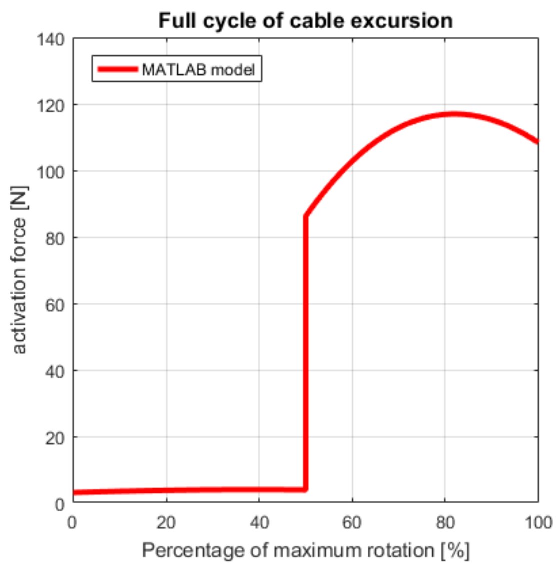
The exact dimensions of the mechanism shown in figure 5.6a together with the spring parameters of springs *A* and *B* determine the final pinch forces of both modes. Figure 5.6b shows the four spatial design parameters (x_a, y_a, l_b and l_c) that determine the three spring attachment points a, b and c. Point a is freely placed while point b is located along the longitudinal axis of the lever and point c lies along a line perpendicular to the active tong. Both springs have three parameters each: their spring constant *k*, initial length l_0 and preload F_0. Tong length l_{tongs} is also a factor. A kinematic model of the mechanism is created in MATLAB to determine appropriate values for all five spatial and six spring parameters. Favoured are values that will result in an accurate approximation of the idealized pinch force behaviour curve of figure 5.3 while keeping required activation forces below the set threshold and as low as possible. The MATLAB code is included in this report as Appendix .3.

Figure 5.7 combines the idealized pinch force curve (blue) with the curve predicted by the MATLAB model (red). The effects of the non-linearly changing moment arms and spring extensions are clearly noticeable in the shapes of the graph. The left halves of the two curves are quite similar despite these effects. The right halves, however, are much less alike. The non-linearity of the system results in the pinch force being far from a single constant value. In the end a compromise is made between matching the MATLAB-produced and ideal curves, and the activation force demanded from the wearer. Ensuring the entire VO pinch force would not fall below the 31.14 N threshold would result in much effort.

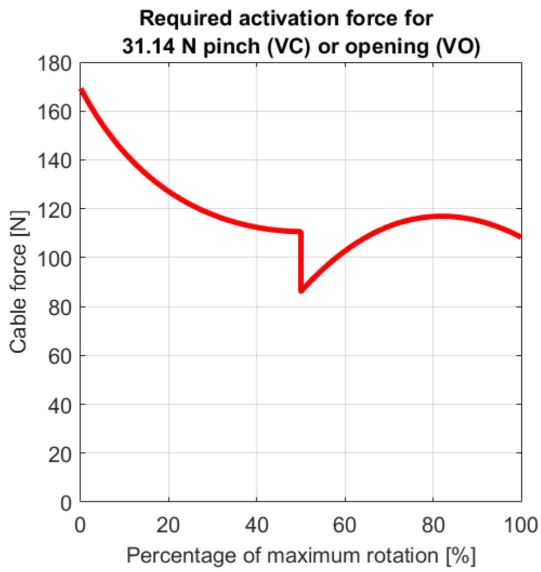
The pinch force curve shown in red in figure 5.7 is produced by the MATLAB model for specific values of the eleven design parameters. Table 5.1 lists these values. The model also calculates the amounts of activation force required from the user for a range of different positions of the gripper. Figure 5.8a shows this curve in a graph. The curve constitutes the amount of activation force a user has to generate to hold the gripper still with a certain opening width. The transition between the modes at 50% rotation shows a clear difference in required activation force. In figure 5.8b the MATLAB-predicted activation forces are plotted that are needed to produce the threshold pinch force of 31.14 Newton. For VO mode this is the same curve as figure 5.8a, but VC mode requires more effort. The maximum allowable activation force value set as a requirement in chapter 2 is 256 Newton. As the curve never exceeds 170 N (pinching at full VC opening) the parameter values in table 5.1 are deemed valid.

Table 5.1: Optimal values for the eleven design parameters of the mechanism; five spatial parameters, four of which are illustrated in figure 5.6b, and two sets of spring parameters.

Parameter	value	unit
l_{tongs}	90	mm
x_{a}	30	mm
y_{a}	14	mm
l_{b}	40	mm
l_{c}	25	mm
k_{A}	4.74	N/mm
$l_{0,\text{A}}$	37.1	mm
$F_{0,\text{A}}$	9.56	N
k_{B}	0.17	N/mm
$l_{0,\text{B}}$	20.2	mm
$F_{0,\text{B}}$	0.94	N

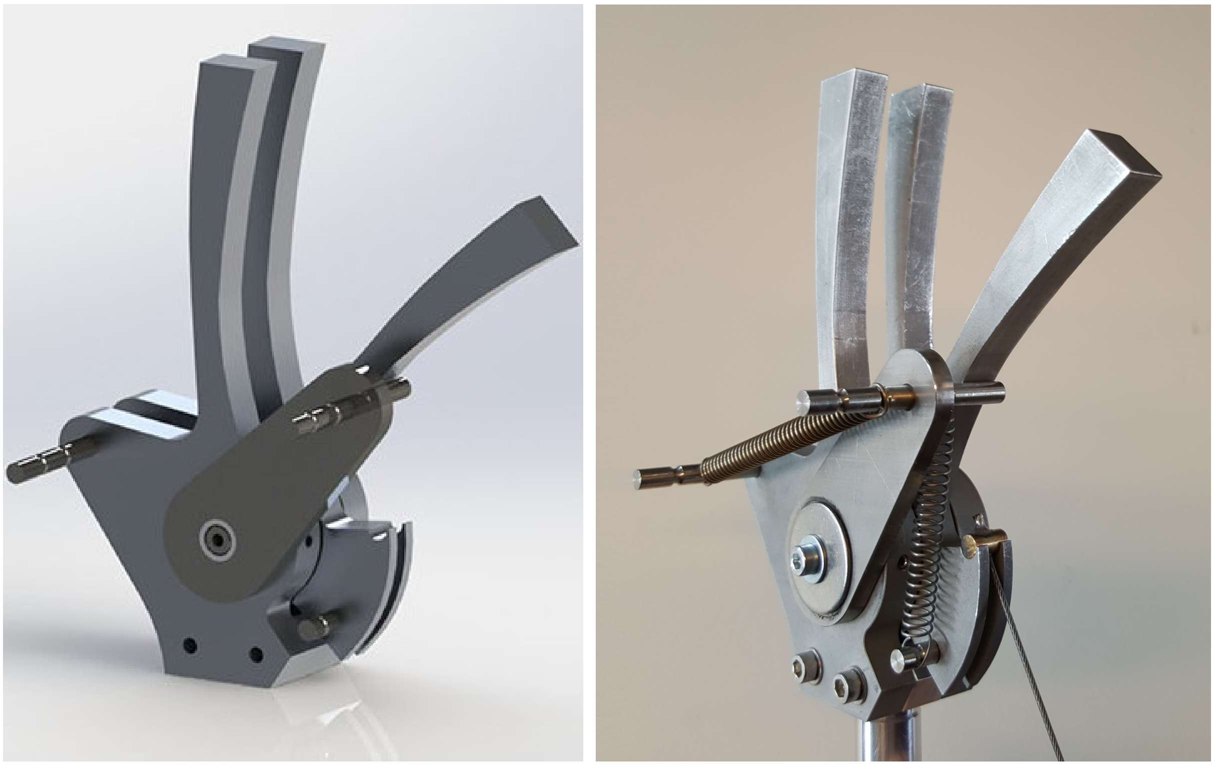


(a) Model-predicted activation force required to hold a range of possible gripper positions.



(b) Model-predicted activation force needed to reach the pinch force threshold in either modes.

Figure 5.8: Graphs produced by the MATLAB model. Figure (a) shows the predicted activation force that the user must generate in the input cable to move the active tong from its opened starting position, first through VC mode to a closed position, and then through VO mode into another fully opened position. Figure (b) shows instead the activation force required to make the gripper pinch with a force of 31.14 N in VC mode (0-50%), and again how much activation force it takes to keep the gripper opened in VO mode (50-100%). Pinching 31.14 N in voluntary closing mode with a fully opened gripper requires the most effort from the user (170 N).



(a) A rendering in SolidWorks of the entire assembly. (b) The physical prototype in VO mode, with springs.

Figure 5.9: The final design of the novel device is rendered in SolidWorks PhotoView 360 and a prototype is manufactured for testing.

Optimized values for the main design parameters have now been found and are supported by the MATLAB model. Assuming the model is correct the values in table 5.1 will result in a pinch force behaviour that closely resembles the ideal case while keeping the activation force demands well below what a user can manage. The entire prehensor is designed in SolidWorks with these parameter values in mind. A digital rendering of the SolidWorks assembly in a voluntary opening position is found in figure 5.9a. In this image the springs are omitted. The physical prototype that is manufactured based on the SolidWorks drawings is pictured in figure 5.9b, including springs this time. All three tong parts are fashioned of aluminium 7075 while the lever, central axle and the rods around which the springs are hooked consist of steel. Design drawings of all custom-designed parts are enclosed as appendix .4.

6

Results

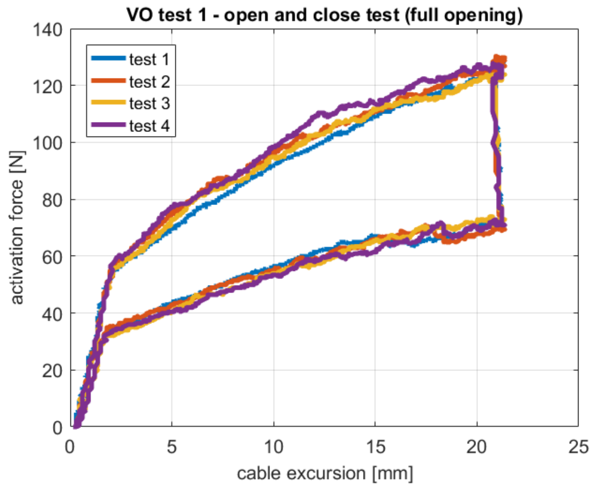
The final design of the prototype is finished and the device is manufactured. Now comes the validation of the proposed novel design through testing. In chapter 2 section 2.3 the experimental methods have been introduced of two types of tests: mechanical and functional. A number of mechanical tests is performed in order to assess the mechanical properties of the mechanism. See subsection 2.3.1 for details. The experimental design of Smit[9][25] is followed so the results can be compared with other VO and VC devices already available to amputees. The presentation of the experimental results and comparison with Smit's data is done in section 6.1. After the mechanical performance of the prototype becomes known the compliance with the design requirements of chapter 2 is checked in section 6.2. Section 5.2 presented three curves produced by the MATLAB model of the final design: the pinch force behaviour (figure 5.7) and required activation forces (figures 5.8a and 5.8b) along the whole range of rotation were predicted. These predictions are evaluated in section 6.3 using the measurement data. The functional tests are user performance tests in the form of the Southampton Hand Assessment Procedure (SHAP). The procedure is explained in detail in subsection 2.3.2. The ten participants that perform the SHAP will each produce three scores: one VO mode score, one VC mode score, and one hybrid mode score. The scores are compared with each other to investigate the relative functionality advantage(s) of having a choice of modes over either one on its own. The mean values of the three types of scores are also compared with SHAP scores of two VO devices, one VC device and one hybrid device. All this is done in section 6.4. The feedback of the participants regarding the novel device and its performance are included as appendix 2.

6.1. Mechanical tests

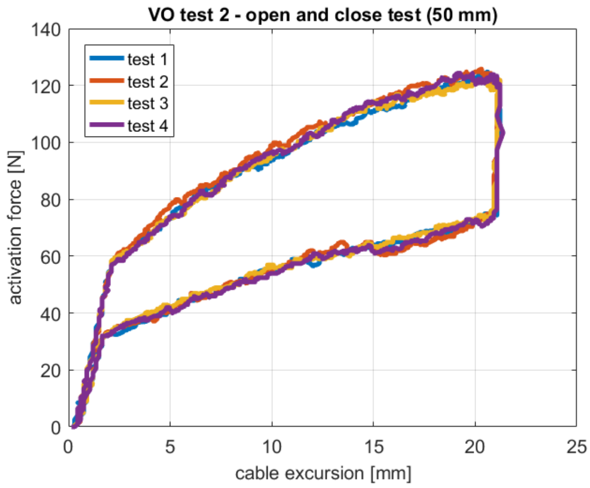
VO tests

A series of mechanical tests have been performed with the prototype to assess its mechanical properties and performance. Its voluntary opening mode is assessed through three tests:

1. **Open and close test (full opening)**
   The gripper is moved from a fully closed state to full opening, by pulling the cable at a rate of circa 2 mm/s. Subsequently the gripper is closed with approximately the same velocity. Activation force and displacement are measured.
2. **Open and close test (50 mm)**
   Identical to test 1 except that the gripper is opened until an opening width between the fingers of 50 mm is reached before closing again.
3. **Pinch force test**
   A pinch force sensor is placed between the fingers and the pinch force is measured for opening widths of 10 mm, 20 mm and 30 mm.



(a) Graph of four trials of VO test 1.



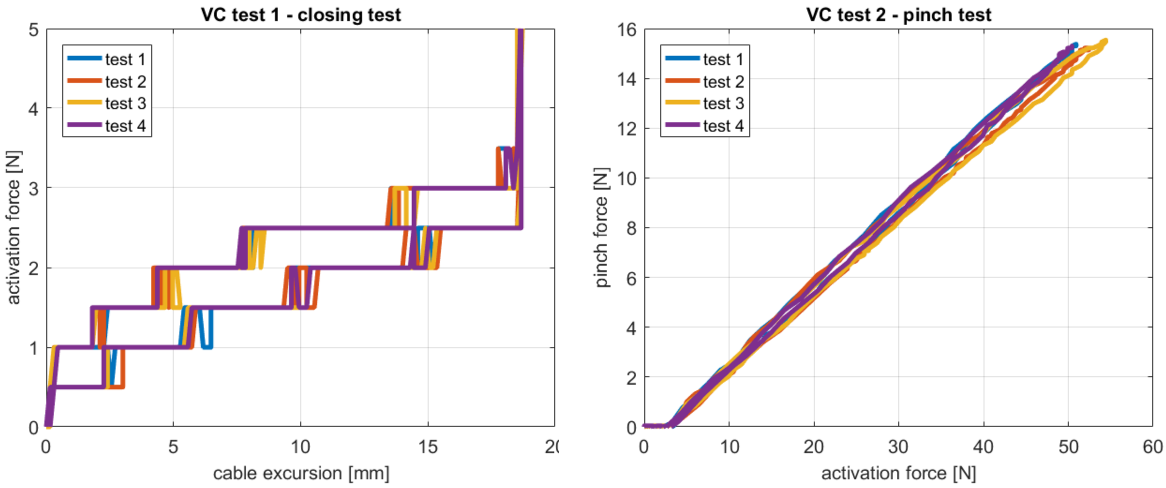
(b) Graph of all four trials of VO test 2.

Figure 6.1: Two graphs showing the measured activation force and cable excursion during tests 1 and 2 for the VO mode of the prototype. In test 1 the gripper starts out closed and is first fully opened and subsequently closed again. Test 2 also opens and closes the gripper but here the reversal point is where the gripper opening first measures 50 mm. Both tests are performed four times.

Table 6.1: Table containing all measured and derived mechanical properties of four currently available VO hook devices, as published by Smit[9]. The last row, in gray, is added and shows the equivalent properties of the new prototype. Activation force is called cable force here to match Smit's paper.

VO Terminal Device	Mass (g)	Max. Open (mm)	Max. Cable Excursion (mean ± SD, *n* = 4)		Max. Cable Force (mean ± SD, *n* = 4)		Open and Close Test 1: Full (mean ± SD, *n* = 4)		Open and Close Test 2: 50 mm (mean ± SD, *n* = 4)		Pinch Force Test 3		
			Test 1: Full (mm)	Test 2: 50 mm (mm)	Test 1: Full (N)	Test 2: 50 mm (N)	Work (Nmm)	Hysteresis (Nmm)	Work (Nmm)	Hysteresis (Nmm)	10 mm (N)	20 mm (N)	30 mm (N)
Hosmer Model 5XA Hook													
1 band	87	88	45 ± 0.2	24 ± 0.1	48 ± 12.0	25 ± 0.3	1,128 ± 14	290 ± 3	574 ± 3	120 ± 4	9	9	9
2 bands	90	88	46 ± 0.1	25 ± 0.1	72 ± 3.5	50 ± 0.2	2,248 ± 10	394 ± 6	1,173 ± 6	154 ± 3	14	19	20
3 bands	92	88	46 ± 0.1	25 ± 0.0	95 ± 4.2	71 ± 0.2	3,206 ± 18	458 ± 4	1,684 ± 4	186 ± 4	24	29	33
Hosmer Sierra 2 Load VO Hook													
Setting 1	242	66	34 ± 0.1	26 ± 0.0	67 ± 7.9	40 ± 0.3	1,243 ± 11	379 ± 1	868 ± 1	245 ± 3	9	11	11
Setting 2	242	66	35 ± 0.0	26 ± 0.0	117 ± 6.4	82 ± 0.1	2,642 ± 14	571 ± 2	1,820 ± 2	337 ± 2	24	27	29
RSL Steeper Carbon Gripper													
Setting 1	171	97	43 ± 0.2	28 ± 0.1	70 ± 0.4	43 ± 0.3	1,619 ± 2	487 ± 4	846 ± 4	267 ± 4	11	11	11
Setting 2	171	97	43 ± 0.1	28 ± 0.1	75 ± 0.2	48 ± 0.1	1,848 ± 7	510 ± 2	992 ± 2	272 ± 6	14	13	14
Otto Bock Model 10A60 Hook (2 × 2 Springs)													
Setting 1	223	67	35 ± 0.1	27 ± 0.0	36 ± 0.0	32 ± 0.5	1,002 ± 3	482 ± 5	775 ± 5	353 ± 6	11	11	11
Setting 2	223	67	35 ± 0.1	27 ± 0.2	101 ± 0.5	94 ± 0.3	2,752 ± 6	555 ± 15	2,033 ± 15	421 ± 16	24	31	37
Novel design	213	65	21 ± 0.0	19 ± 0.1	128 ± 2.3	124 ± 1.5	1,827 ± 69	767 ± 18	1,624 ± 20	698 ± 9	20	24	27

The four sets of measured activation force and cable displacement (excursion) during the full opening of test 1 are plotted together in a graph in figure 6.1a. All four are largely similar in shape and magnitude. The four datasets of test 2, also activation force and cable excursion, are graphed in figure 6.1b. Again the four trials produce similar results. Test 3 produced three single pinch force values for different opening widths and therefore no graph is made. A collection of mechanical properties of the voluntary opening mode of the prototype are measured and derived from test results. These are collected in the bottom row of table 6.1. This table (apart from the added bottom row) is taken directly from Smit[9].



(a) Graph of four trials of VC test 1.

(b) Graph of all four trials of VC test 2.

Figure 6.2: Two graphs showing the measured activation force and cable excursion during tests 1 and 2 for the VC mode of the prototype. In test 1 the gripper is slowly closed starting from its fully opened resting position, and then opened again. The large spike on the right signifies the gripping of the steel plate. Test 2 involves the pinching of a sensor until a pinch force of at least 15 Newton was reached. Both tests are performed four times.

Table 6.2: Table containing all measured and derived mechanical properties of two curently available VC hook devices, as published by Smit[25]. The last row, in gray, is added and shows the equivalent properties of the new prototype. Activation force is called cable force here to match Smit's paper.

Prosthesis	Mass (g)	Opening width (mm)	Maximum cable excursion (mm), n = 4	Work closing (Nmm), n = 4	Cycle hysteresis (Nmm), n = 4	Work closing and pinching 15 N (Nmm), n = 4	Required cable force for a 15 N pinch (N), n = 4	Pinch force at a cable force of 100 N (N)	Pinch force drop at a 15 N pinch (N), n = 4
Hosmer APRL hook, 52601 (R)	248	73 (33**)	38 ± 0.1	720 ± 6	138 ± 3	687 ± 2	62 ± 0.0	30	10 ± 1.5
TRS hook, Grip 2S	318	72	49 ± 0.1	284 ± 3	52 ± 1	243 ± 3	33 ± 0.2	58	–
Novel design	213	65	20 ± 0.4	41 ± 0.3	11 ± 0.3	65 ± 0.8	51 ± 1.6	31	–

**Hook adjusted to small range.

VC tests

The mechanical properties of the voluntary closing mode of the hybrid design are assessed as well. This is done through three tests, following the experimental design of Smit[25].

1. **Closing test**
   The control cable was pulled until the gripper tightly gripped a steel plate of 1 mm thickness.
2. **Pinch test**
   The pinch force sensor (approx. 10 mm wide) was placed in the fully opened gripper. The cable was operated until a pinch force of 15 N was reached.
3. **Pull test**
   The pinch force sensor was again placed in the gripper. This time the cable was operated until the activation force in the cable reached 100 N.

Figure 6.2 shows two graphs displaying measurements of tests 1 and 2. In both cases the four trials show curves that are only marginally different. Smit summarized the mechanical properties of two existing VC hook devices in a table. This table is copied here and extended with the properties of the novel device in gray. See table 6.2.

Table 6.3: The overview of all design requirements given in table 2.1 is now extended with the properties and data of the prototype.

Parameter	Unit	Requirement	Prototype
Cosmesis			
Dimensions	mm	max. 185 (length)	117.8
	mm	max. 100 (width)	52.25
Comfort			
Total mass	g	max. 311.6	213
Control			
Pinch force	N	min. 31.14	20
Opening width	mm	min. 76.2	65
Activation force	N	max. 256	128
Cable excursion	mm	max. 43	43
Actuation	-	Bowden cable	Yes
Grip stability	-	Palmar prehension	Yes

6.2. Compliance with design requirements

The extent of compliance with the design requirements discussed in chapter 2 can now be determined. Table 6.3 offers an overview of the requirement values as well as the actual properties of the prototype. The length is taken as the vertical distance from the flat base to flat end of the passive tongs. The side of the tongs is the widest dimension, wider than the frontal side even with the jutting rods that hold the springs. The stated mass includes all springs. The 20 N pinch force is the lowest pinch force measured in voluntary opening mode, in pinch force test 3. This occurs when the gripper opening is 10 mm. The largest opening width of the gripper is measured between the tips at full opening and is identical for both modes. The largest activation force required is the highest value occurring during the full opening in the first VO mode test, which is 128 N (figure 6.1a). Larger activation forces are possible if one pinches exceedingly hard in VC mode but these scenarios are ignored, especially because the pinch force threshold of 31.14 N can be reached with only 100 N (table 6.2). Total cable excursion can be read from figure 6.4a. The control method is a shoulder harness with Bowden cable and it has proven possible to make the gripper exert a palmar grasp onto objects.

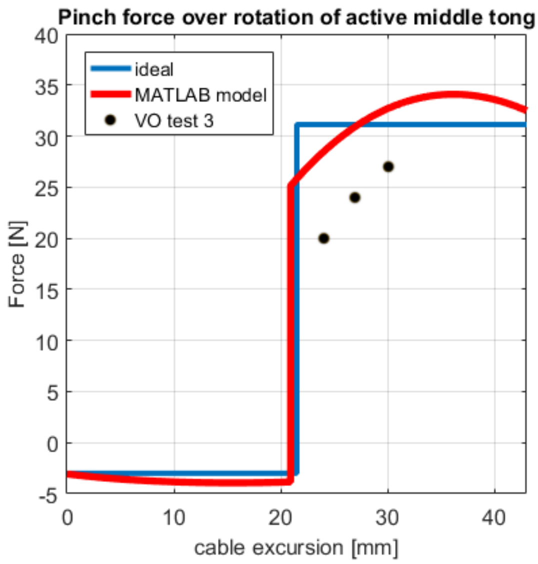


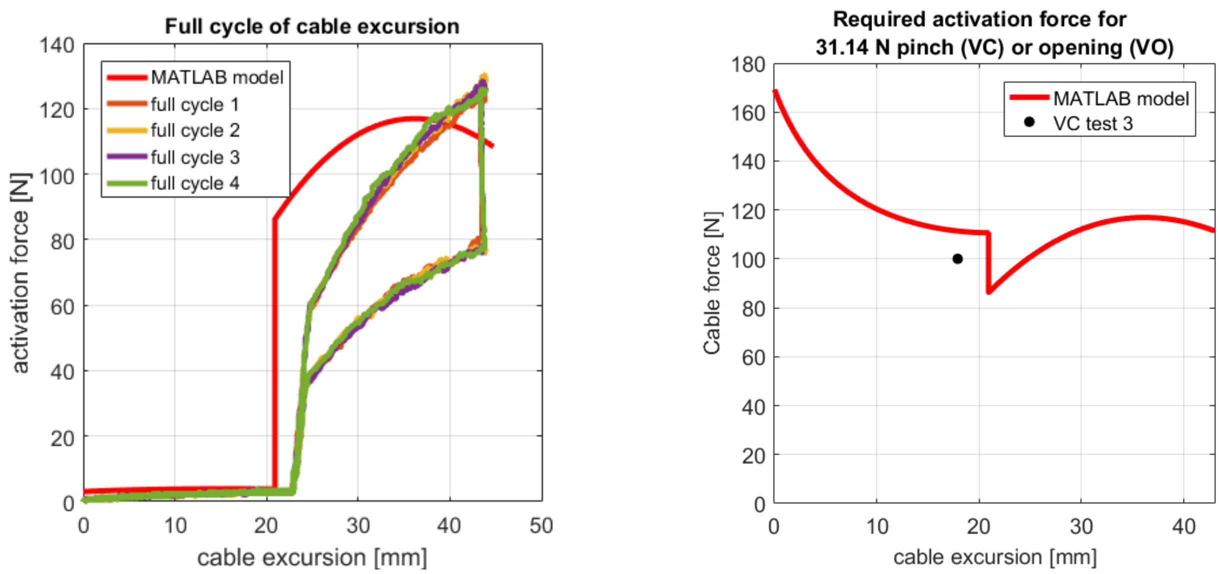
Figure 6.3: The idealized and MATLAB-predicted pinch force curves from figure 5.7 with three data points from the third test of the prototype's voluntary opening mode. These points lie at the excursion values related to VO mode gripper opening widths of 10 mm, 20 mm and 30 mm.

6.3. Comparison with MATLAB model results

The kinematic model of the prehensor mechanism made in MATLAB has been used to optimize the final design in chapter 5. To help interpret the experimental data and determine the quality of the model it is useful to compare measurement data with model predictions where possible. The three curves in figures 5.7 and 5.8 can be verified to some extent. VO test 3 measured the pinch force for opening widths of 10 mm, 20 mm and 30 mm. These three data points can be inserted into the graph of figure 5.7 and results in figure 6.3. A complete cycle of cable excursion, from zero to full and back to zero, is performed four times and the required activation force throughout is added to figure 5.8 to create figure 6.4a. These full cycle tests are not part of the three VO test or the three VC tests. As a fortunate accident VC test 3 found that gripping the pinch force sensor with an activation force of 100 N resulted in a pinch force of almost exactly 31.14 N, making it possible to add this data point to the graph in figure 5.8b. See figure 6.4b for the result.

6.4. User performance tests

The functionality of the novel device is assessed with help of the Southampton Hand Assessment Procedure, or SHAP. A participant performing the SHAP produces an index of functionality (IOF) as a score, based on their completion times of its 26 tasks. In this thesis each participant produces three SHAP IOF scores: one associated with the functionality of the prototype while its voluntary opening mode is used, one when voluntary closing mode is in use, and a functionality score when the user is free to choose their preferred mode for each task individually. For all ten participants in this thesis the three scores are listed in the first three rows of table 6.4. Two things should be noted: firstly, during the process of the SHAP it became clear that not all of the 26 tasks could be performed with the newly designed terminal device. Ultimately six tasks could not be completed by any of the participants, leaving 20. These six tasks were Light and Heavy Spherical, Heavy Power, Jar Lid, Full Jar and Empty Tin. Secondly, it quickly became clear that the stiffness of the prototype's VO spring was far too high. Participants indicated that it took too much effort to open the gripper in VO mode and to keep it in an opened position. The pinch force was also described as 'far too much'. The decision was made to replace the spring for one with exactly half the original stiffness value listed in table 5.1. This was done for the SHAP only. The mechanical tests used the original spring.



(a) Model-predicted activation force required to hold a range of possible gripper positions (red), and the measured values from the physical prototype.

(b) Model-predicted activation force needed to reach the pinch force threshold in either modes, and a data point from the third VC mode testing of the prototype.

Figure 6.4: The activation force requirement curve produced by the MATLAB model is laid next to the four graphs of a full excursion cycle, where the control cable is pulled to full excursion and back to zero (a). As an additional opportunity for comparison a data point from the third VC test is added to the predictions from figure 5.8b (b).

Table 6.4: Index of functionality (IOF) scores for ten participants with intact arm. Each produces three scores: VO, VC, and Preferred. The VO and VC scores indicate how well the participant can function using either mode. The Preferred score signifies the scenario wherein the user is allowed to employ the mode they think is best for the task at hand. Additionally the differences in score between the Preferred mode scenario and the separate modes are assessed.

	1	2	3	4	5	6	7	8	9	10	Mean $\pm$ SD	p-value
VO	35	31	36	48	42	40	34	46	31	34	37.7 $\pm$ 6.0	-
VC	35	31	39	50	37	46	33	51	40	41	40.3 $\pm$ 6.8	-
Preferred	36	35	38	50	43	50	35	50	41	43	42.1 $\pm$ 6.2	-
Preferred - VO Mode	1	4	2	2	1	10	1	4	10	9	4.4 $\pm$ 3.8	0.0025
Preferred - VC Mode	1	4	-1	0	6	4	2	-1	1	2	1.8 $\pm$ 2.3	0.0175

Along with the scores of the VO, VC and preferred modes the mean values and standard deviations of the three types of IOF scores are also listed. The mean IOF score when the ten participants perform the SHAP in voluntary opening mode is 37.7 $\pm$ 6.0. The mean score for the voluntary closing mode is slightly higher, 40.3 $\pm$ 6.8. The equivalent mean IOF score based on the completion times associated with tasks done in preferred mode is 42.1 $\pm$ 6.2, again higher. The last two rows in table 6.4 present the differences in IOF scores between the preferred mode scenario and the two conventional modes, for all participants. The means of these differences show that, on average, participants score higher when they can choose their preferred mode on a task-specific basis compared to being restricted to only one of the principles of operation. The mean increase in score of preferred mode over VO mode is 4.4 $\pm$ 3.8 while the mean increase over VC mode is 1.8 $\pm$ 2.3. The p-values produced by the one-tailed repeated measures t-test signify that both observed effects are significant ($p = 0.0025$ and $p = 0.0175$, respectively).

Regarding the difference of the prototype as hybrid device over only its VO capabilities the following can be stated: VO mode and preferred mode scores were strongly and positively correlated ($r = 0.806$, $p = 0.005$). There was a significant average difference between preferred mode and VO mode scores ($t_9 = 3.655$, $p = 0.0025$). On average, preferred mode SHAP scores were 4.4 points higher than VO mode scores (95% CI [1.68, 7.12]).

Table 6.5: Overview of all relevant studies regarding the SHAP assessment of body-powered hook prehensors. In total three index of functionality (IOF) scores have been found for voluntary opening (VO) devices, or in the case of Sensinger's device its VO mode. Two IOF scores of a VC device or mode. Only one of the eight known hybrid designs has been submitted to the SHAP; Sensinger's device. The table lists the SHAP IOF score of the preferred modes of both hybrids.

Prehensor type	Source	IOF results: Mean ± SD	Nr. of participants	Healthy participants	Impaired participants	Nr. of trials each
VO	[27]Berning	53.6 ± 10.9	31	29	2	1
	[28]Dalley	88.8 ± 3.9	1	0	1	4
	[29]Sensinger	50.2 ± 7.3	7	5	2	4
	Novel design	37.7 ± 6.0	10	10	0	2
VC	[27]Berning	55.4 ± 11.5	31	29	2	1
	[29]Sensinger	53.8 ± 11.0	7	5	2	4
	Novel design	40.3 ± 6.8	10	10	0	2
Hybrid	[29]Sensinger	57.4 ± 6.2	7	5	2	4
	Novel design	42.1 ± 6.2	10	10	0	2

Regarding the difference of the prototype as hybrid device over only its VC capabilities: VC mode and preferred mode scores were strongly and positively correlated ($r = 0.943$, $p < 0.001$).
There was a significant average difference between preferred mode and VC mode scores ($t_9 = 2.475$, $p = 0.0175$). On average, preferred mode SHAP scores were 1.8 points higher than VC mode scores (95% CI [0.15, 3.45]).

One advantage of utilizing the SHAP to assess the functionality of the prototype is that the IOF scores can be compared to those of other devices. Table 6.5 summarizes the SHAP information of all relevant studies that could be found in literature by the author. It gives an overview of the mean scores and standard deviations and includes the number and composition of participants in the studies and the number of times each participant performed the SHAP. The scores are grouped according to prehensor type with the scores of the novel design of this thesis indicated in gray.

After a participant had completed each SHAP task in both modes they indicated their preference for that particular task; either VO mode or VC mode. They were also asked for the motivation behind their preference. Figure 6.5 shows a histogram of the ratios of user preference for the 20 executable SHAP tasks. A score of zero indicates all ten participants preferred VO mode for a particular task, and a score of one indicates all ten participants prefer VC mode. Scores between zero and one indicate that some participants prefer VO mode and some prefer VC mode. An example: the histogram shows that five tasks have a user preference ratio of 0.4, indicating that for five out of twenty SHAP tasks there are four participants that prefer VC mode and the remaining six prefer VO mode. The design of this figure is chosen such that it facilitates comparison with a similar figure found in Sensinger et al.[29].

A different way of visualizing the same user preference information as in figure 6.5 is given in figure 6.6. This image shows twenty bars; one for each of the SHAP tasks that could be performed. The colouration indicates the distribution of preferences with cyan showing the amount of participants preferring the VO mode for a particular task and yellow representing a preference for VC mode. The tasks are sorted by the amount of preference for VC mode and thus the order is not related to the standard procedure order. For example: there are two tasks where nine out of ten participants preferred VC mode (top of figure), and only one where nine out of ten preferred VO mode (bottom). A dashed vertical line indicates the middle of the chart where the user preference ratio would be 0.5, or 50/50. The bold red line shows the ratio averaged over all participants and tasks. It lies right of centre, indicating a slight overall preference for voluntary closing mode to perform the SHAP tasks. The mean user preference ratio is 0.572 and signifies that, on average, participants chose VC mode over VO mode in 57.2% of the cases. For each task the participants gave the motivation for their preference. All motivations are compiled and presented in appendix .5.

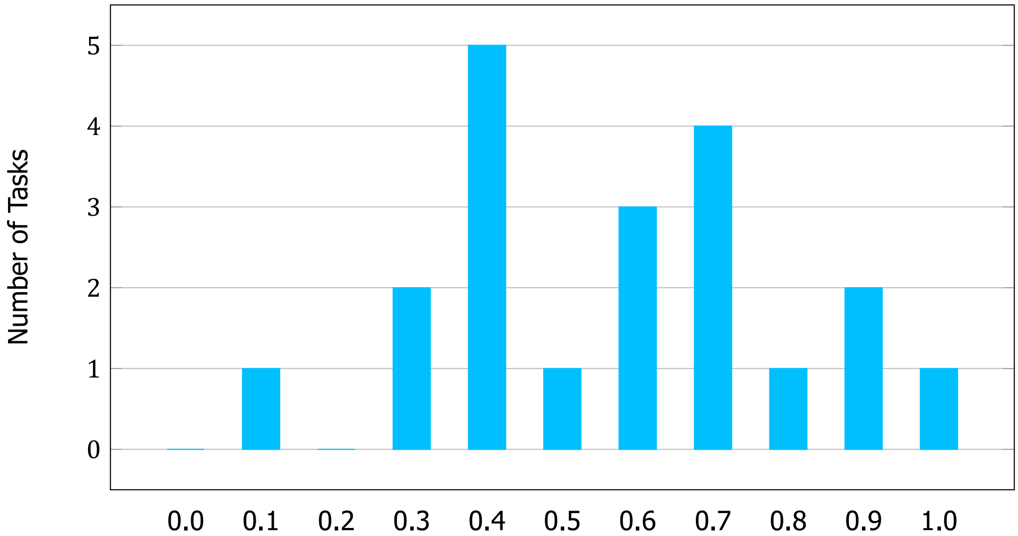


Figure 6.5: Histogram of ratios of user preference for the 20 SHAP tasks that can be executed by participants. A score of zero indicates all ten participants prefer VO mode for a particular task, and a score of one indicates all ten participants prefer VC mode. Scores between zero and one indicate that some participants prefer VO mode and some prefer VC mode. Compare with equivalent user preference histogram of Sensinger's experimental results[29].

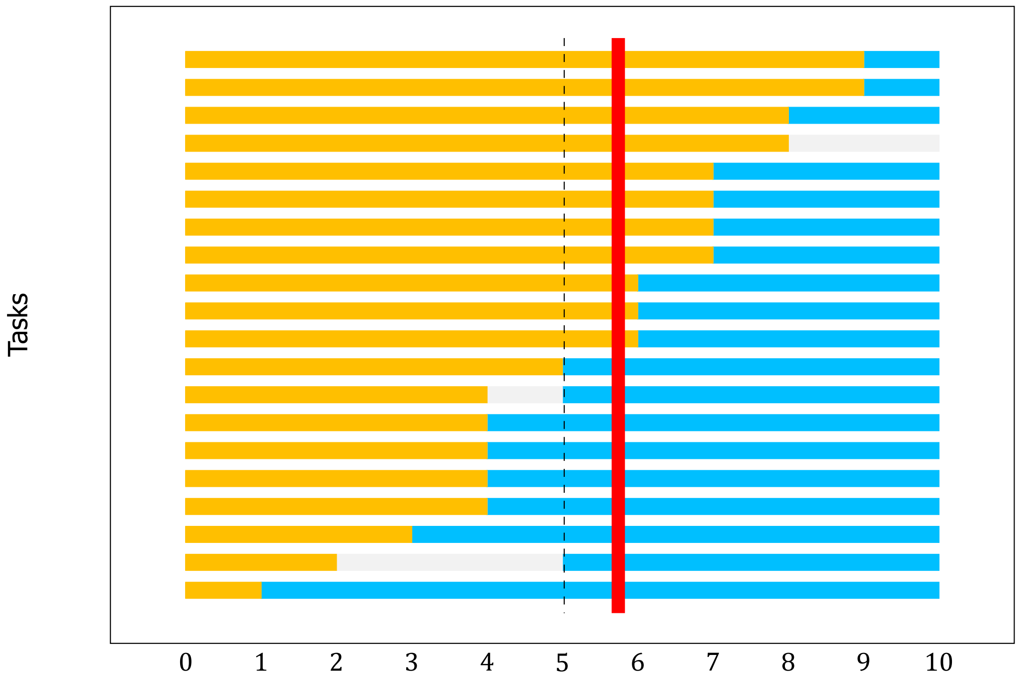


Figure 6.6: Stacked bar chart showing user preferences for the 20 SHAP tasks that can be executed by participants. Yellow indicates a preference for VC mode, cyan relates to VO mode. Gray means a user failed to complete the task. Bars are sorted by amount of preference for VC mode. The dashed vertical line indicates the middle. The bold red line indicates the user preference ratio averaged over all users and tasks and lies at 0.572.

7
Discussion

Value of the concept

Out of eight novel concepts for terminal device mechanisms one was ultimately chosen as 'the best'. It showed the most potential of resulting in a highly functional prehensor that could eventually improve the quality of life for upper limb amputees. The concept has four properties that are deemed very valuable to the overall performance of the device:

1. It offers the wearer both voluntary opening and voluntary closing principles of operation
2. The VO principle of operation includes a passive pinch force
3. Deciding on the principle of operation is done through cable excursion only
4. The VC principle of operation is available without having to resist the VO spring element

It is important to emphasize that none of the many terminal devices existing today possess all four of these properties. Only eight TD's possess the first property. These are the hybrid prehensor designs found in literature. The Dalisch device contains no springs and thus cannot offer passive VO pinching force. The mechanisms of Kuniholm (#2), Veatch, Sullivan and Sensinger all require the wearer to operate at least one switch or button to change the mode of operation. And though the prehensor concepts LeBlanc, Nelson and Kuniholm1 share the first three properties they all require the wearer to extend the VO spring before the VC mode can be used. For Nelson and LeBlanc the VO spring and VC spring are even one and the same. The VO spring has a high stiffness for the purpose of generating sufficient passive pinch force and extending it will therefore be fatiguing to the user. Fine object manipulation and pinch force control in VC mode will also be hampered if the user has to strain to stay in this mode. Being the only device that offers the advantages of all four properties is convincing ground for future research and additional design iterations for the new terminal device of this thesis.

It might be valuable to remember that concept 8 also possesses all four desired properties, and that it was dropped from consideration for three main reasons: the challenging bearing of the rotation points, the mechanism being more complex than concept 6 while offering similar performance, and kinematic modelling in MATLAB confirmed unrealistic demands from the springs. If the pinch force requirements would be reduced to a lower value the concept might still be realistic, although this does not solve all challenges.

Mechanical tests

The contents of tables 6.1 and 6.2 are discussed. The mass of the device is not particularly different from the prostheses studied by Smit. Of the four tested VO hook devices two are heavier while two are lighter. Both tested VC hook prostheses are heavier. Nevertheless it would prove useful to further reduce the mass to optimize wearing comfort. The maximum opening width unfortunately is the lowest of the examined hook devices of both modes. This is in part caused by a design error while calculating the mechanism dimensions needed to achieve a sufficiently large gripper opening where the width of the tongs was not taken into account. Because of this the maximum width is 65 mm instead of the intended 76.2 mm.

Compared to the four VO hook devices the prototype has significantly less cable excursion available. This is inherent to the concept as the total cable excursion has to be allocated between the two modes. Here the decision was made to split it evenly but in future designs this could be different. The amount of activation force necessary in VO tests 1 (full opening) and 2 (50 mm opening) exceeds that of all the others, possibly due to a mechanical advantage that is relatively less advantageous. The required work in those same two tests is near the average however. This is because the larger activation forces are somewhat counteracted by the lower amount of excursion, bringing total work down to a value comparable to others. Cycle hysteresis is the highest out of the group of five. Why this high amount of hysteresis occurs is not fully understood. In the kinematic MATLAB model the dry frictional moment on the axle is estimated[37] to lie between 4.5% and 5.5 % of the operational torsional moment generated by the user during gripper movement. This cannot be the full explanation. Inadequate bearing of the central axis is suspected of being a major contributor. Reduction of the amount of hysteresis should be a focus point in possible future development. From the results of VO test 3 it appears that the generated pinch force is less than the values predicted by the MATLAB model. The measured pinch force are 20 N, 24 N and 27 N and never reaches the value of 31.14 N that was aimed for. A suspected cause for this is a mismatch between the assumed and actual spring properties. The two Hosmer devices and the Otto Bock model all have settings that generate higher amounts of pinch force than the new prototype, with only the RSL Steeper Carbon Gripper being inferior in this aspect. Presently the mechanical properties of the prototype's voluntary opening mode are slightly below the performance of the other examined prostheses.

The prototype's VC capabilities are compared to the Hosmer APRL hook and the TRS hook. Again its maximum cable excursion is much lower as only half of the total excursion is available in this mode. The work that the user must generate to close the gripper (test 1) and pinch 15 N (test 2) is very much lower for this device than the two 'competitors' and so is the hysteresis during the cycle. Unfortunately the hysteresis value is quite high relative to the work (26%). The amount of required activation force for a 15 N pinch force lies in between the two other values and 100 N of activation force results in 31 N of pinch force. These measurements again indicate that the mechanical advantage is adequate but a good candidate for further improvement, especially compared with the TRS hook. Overall the mechanical properties of the prototype's voluntary closing mode are in the vicinity of the other two devices, with a particularly low amount of work needed in operation but a mechanical advantage lower than that of TRS.

Compliance with design requirements

Table 6.3 shows that most design requirements are met. The criteria for the dimensions, total mass, activation force, cable excursion, actuation method and grip stability are all satisfied. The pinch force requirements which was set to 31.14 N is not met however. The highest pinch force value found in the tests for VO mode was 27 N for a gripper opening of 30 mm. This is below the values predicted by the MATLAB model. An unknown flaw in the kinematic model could be the cause of the mismatch between prediction and experiments. Another possibility is a mismatch between the actual spring parameter values and the values that the spring manufacturer presented. This last explanation for the unexpected results is deemed most probable. If future research is attempted it is advised to thoroughly verify all spring parameters. The other design requirement that is not met is the maximum opening width of the gripper. The minimum requirement was set to 76.2 mm and taken from literature. Due to an error during the design phase the final maximum opening width fell short of this goal with a value of 65 mm. A future version of the device can easily comply with the requirement by changing either the tong length or range of rotation.

Comparison with MATLAB model results

Although no experiments were performed with the explicit goal of verifying the MATLAB kinematic model some of the measurement data of the mechanical tests can be compared to model predictions. Figures 6.3 and 6.4 graph predicted and measured values. The first figure (6.3) plots the VO pinch forces for three positions of the gripper, along with the modelled curve for all positions. The three data points lie below the predicted curve but do seem to show a similar shape. More data points are necessary to confirm this. It seems the stiffness coefficient of the VO spring is lower than assumed in the MATLAB model, leading to model output that is too high. A more sophisticated kinematic model, one that more accurately represents the final design of the prototype, will most probably also increase accuracy. In figure 6.4a the MATLAB-predicted required activation force in the control cable to move the active tong or to keep it at an arbitrary fixed position are initially higher, but the actual required force exceeds the model curve at around 38 mm cable excursion. The measured curve never stops increasing while the model peaks near 36 mm of excursion and decreases beyond. This discrepancy in fundamental shape between model and experiment curves cannot fully be explained by faulty spring parameters if the springs are assumed to be linear. The VO spring actually exhibiting non-linear behaviour with a lower initial stiffness which increases as elongation increases could explain the measurements. Another discrepancy is the moment of sharp increase in required activation force. The model places this almost exactly halfway of full cable excursion, at approximately 21 mm. The experimental data indicates VO mode starts at 22.5 mm excursion, with the increase not instantaneous but slightly drawn out. Slack in the control cable and cable attachment might have contributed here. Figure 6.4b includes the single point of data from test 3 of the VC mode into a MATLAB model prediction. The model shows the expected activation force to pinch 31.14 N for a range of tong opening widths. The force required in VC test 3 is less than expected; 100 N as opposed to approximately 110 N. This somewhat small difference can also be explained by the VC spring stiffness being slightly less than assumed.

User performance tests

Something that became clear during the SHAP testing was an inability of the participants to successfully perform 6 of the 26 tasks. The Light and Heavy Spherical, Heavy Power, Jar Lid, Full Jar and Empty Tin tasks could not be completed by any of the ten users. The shape of the tongs was to blame for this inability. All six tasks involve the manipulation of either spherical or cylindrical objects which proved to be too large for the user to get a good grip. Only the Heavy Power object fit into the gripper at all. Failing to complete roughly a quarter of the task set has a substantial negative effect on the IOF scores. A redesign of the tongs to accommodate these types of tasks will likely result in higher SHAP scores and, hopefully, in a higher functionality.

As stated it was decided to replace the high-stiffness VO mode spring after feedback from the participants. Originally, the MATLAB kinematic model was used to calculate a spring stiffness coefficient that would result in a passive VO pinch force close to 31.14 N. This value (4.74 N/mm, see also table 5.1) was experienced as too high by the participants, who wished for a gripper that could be fully opened in VO mode with less effort. They also felt that the applied passive pinch force was far beyond sufficient to perform the various tasks. Because of this feedback the VO spring was replaced with one with a stiffness coefficient reported as 2.37 N/mm by the manufacturer, exactly half of the stiffness of the original spring. VO test 3 found that the original spring resulted in pinch forces of up to 27 N, leading to the assumption that the prototype will offer up to approximately 13.5 N with the new spring installed. With this the SHAP has been performed. Participants were satisfied with this amount of VO pinch force during all tasks except for the Heavy Lateral task, where the object could not be picked up without slipping. This is mainly the result of the low-friction metal-to-metal contact and can probably be solved by adding a rubber coating to the tongs. It is the opinion of the author that the originally desired pinch force level of 31.14 N (7 lb.) as recommended by Keller et al.[20] is too high and exceeds the amount needed by quite an amount. The participants also saw the reduction in required activation force to operate the VO mode as positive. VO test 1 found that it took 128 N of activation force to fully open the gripper (figure 6.1a). This is apparently too much and should be more similar to the other VO hook devices tested by Smit. The Hosmer Model 5XA, Hosmer Sierra 2 Load and Otto Bock Model 10A60 achieve VO pinch forces comparable to those of the prototype through activation force levels between 95 and 117 N. Future prosthesis design attempts should consider an activation force upper threshold much lower than the 280 $\pm$ 24 N stated by Taylor and used in this thesis.

The IOF scores of the SHAP (table 6.4) show that use of the 'preferred mode' - where the user is allowed to use their preferred principle of operation for each task - results in a significantly higher functionality score than either VO or VC mode on their own (VO IOF: 37.7 $\pm$ 6.0. VC IOF: 40.3 $\pm$ 6.8. preferred IOF: 42.1 $\pm$ 6.2). This is the first time such a significant SHAP IOF increase is found for a hybrid prehensor. The only other SHAP data available for such devices is that of Sensinger[29] who only found a significant IOF improvement of preferred mode over VO mode, but not over VC mode. Offering a choice of principle of operation to the user within a single device does indeed seem to increase functionality, as is established through this SHAP data. User tests with a large representative group of participants with upper limb amputations could confirm this observation.

The data in table 6.5 allows for some comparisons of the functionality of different body-powered hook prehensors as assessed using the SHAP. For both the voluntary opening and voluntary closing modes of operation the thesis prototype scores lower than the other devices. This is a reasonable consequence of the more complicated design goals of a hybrid prehensor; the device has to facilitate two principles of operation instead of just one. Neither of the two can be optimized as some compromises have to be made. Future design iterations can still result in higher IOF scores for both modes however, especially if the tong shape is altered to facilitate the six tasks currently not possible. It seems that the other hybrid terminal device in the table, that of Sensinger, scores higher than the prototype in all three of the IOF scores: its VO mode, VC mode and the preferred mode. However the significant disadvantage in functionality of having to operate a button to switch between principles of operation is not reflected in these IOF scores. The ability to change modes through cable excursion only is valuable and should not be underestimated.

One final observation from figures 6.5 and 6.6 is that the mean user preference ratio of these tests is 57.2%, indicating that the participants have a slight preference for the voluntary closing principle of prehension when faced with the SHAP tasks and this prototype. The findings reported in Sensinger's paper would result in a mean user preference ratio of 61.5% and support a very similar conclusion. Both ratios lie fairly close to 50% which supports the added value of incorporating both modes into one device. By contrast, if the user preference would be near 90% or even higher the addition of a VO mode to the very much preferred VC mode would be harder to justify.

8 Conclusions

A body-powered terminal device is designed with several favourable properties facilitating high functionality and performance. The single device can be used in the manner of a voluntary opening (VO) prehensor as well as a voluntary closing (VC) prehensor. The user can switch between these two principles of operation by changing the amount of cable excursion. No additional actions are required. When the device is in its voluntary opening configuration a passive pinch force is generated by an elastic spring element. During operation of the prehensor as a voluntary closing mechanism the user experiences no resistance from this spring. No other terminal device possesses all these same properties.

The functionality of the terminal device is assessed through the Southampton Hand assessment Procedure (SHAP) and three different Index Of Functionality (IOF) scores are calculated. As a device where the amputee can choose their preferred principle of operation per individual task the IOF score becomes 42.1 ± 6.2. This 'preferred mode' functionality score is significantly higher than the other two: 4.4 ± 3.8 higher than purely VO mode and 1.8 ± 2.3 higher than purely VC mode. This is the first time a significant improvement in functionality of a combined VO/VC device over both its separate VO and VC modes is established.

These two observations are grounds for further research into this terminal device concept to optimize its design and maximize its potential. A clinical study can be performed with an optimized design to verify the results of this thesis.

9 Recommendations

The design of the prototype generated in the course of this thesis is only a first design to prove that the concept functions as expected and can indeed be utilized as a terminal device. It can still be improved in many ways to optimize function and performance. One part of the design that has a large potential for improvement is the shape of the tongs. The current shape was inspired by the curved beak of the Western Curlew with the aim of achieving stable grip on a range of objects. However, not all objects featured in the tests could be gripped in a stable way. Large spherical and cylindrical objects in particular are difficult to grip and hold. To significantly improve the performance of the device a better design of the tongs should be found. Perhaps the current tapering shape of the space between tongs should be avoided. Participants also felt that the metal tongs had too little friction with metal objects. To further improve grip a rubber coating can be applied as is common with prostheses. The next design iteration should ensure that the maximum opening width reaches a sufficient value. The requirement of 76.2 mm is not reached in this design due to a design error. After a tong redesign deals with these challenges a new phase of (SHAP) tests will give a better view of the device's full potential. Clinical trials can be considered to investigate its performance when used by actual amputees.

The cause of the large amount of hysteresis should be identified and remedied. Care should be taken than the bearing of the central axle is sufficiently stable. Furthermore any future design iterations should include efforts to lower the amount of work needed through increasing the mechanical advantage. The amount of available cable excursion in the two modes of operation is about half that of conventional devices so any improvement in the mechanical advantage is valuable.

The requirement thresholds concerning pinch force and activation force used in this thesis should be reconsidered. Feedback from the participants that wore the prosthetic prototype indicate that the level of pinch force originally desired (31.14 N) would have been excessive. Some tasks are hampered by the high pinch forces and it leads to more effort than strictly necessary due to higher activation forces and thus work.

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Appendices

.1. Literature Study

Delft University of Technology

Literature Study

Comparison of voluntary opening, voluntary closing and hybrid working principles of body-powered upper limb prostheses

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Abstract

Amputees that have partially or entirely lost their upper limb can make use of upper limb prostheses to restore some of their capacity for prehension (handling objects). Externally powered and body-powered prosthetic devices are available, with body-powered prostheses offering advantageous proprioceptive feedback that externally powered devices currently lack. High rejection and abandonment rates, where amputees stop wearing their devices due to disappointing performance, are a present and persistent problem. To help reduce this and improve amputee quality of life the functionality of body-powered upper limb prostheses must be improved. One design parameter that greatly influences upper limb prosthesis performance is its working principle. Currently it is unknown which principle will result in the best performance.

Traditionally, the two known working principles are voluntary opening (VO) and voluntary closing (VC) prehension. VO mechanisms resemble a clothing pin in that an internal spring keeps the gripper closed until the user puts tension on the control cable. VC mechanisms resemble tweezers in that the gripper is opened unless the control cable is used to close it against the internal spring force. A third working principle is the hybrid type, which includes mechanisms enabling users to choose between VO and VC modes on a task-by-task basis in a single device.

This literature study analyses and compares the three working principles in terms of their known advantages and disadvantages. The strengths and drawbacks of VO and VC seem to oppose but also complement each other. VC is inherently more mechanically efficient than VO but this only influences energy expenditure while the gripper is in motion at the beginning and end of the gripping motion. User preferences strongly depend on type of task and personal preference with both being suited to different daily tasks. Position, velocity and force information is available to the user through proprioceptive feedback with both types of devices, but VO feedback ceases when control cable tension is stopped while VC feedback is always present. Eight known hybrid VO/VC concepts and their strong and weak points are discussed. None of these have become successful prostheses. The recommendation is made to realize the full potential that hybrid VO/VC devices possess by learning from the pitfalls of current devices, designing new iterations as well as entirely novel concepts and in this manner reduce rejection and abandonment rates.

Contents

Chapter 1

Introduction

1.1 Upper limb deficiencies

The field of upper limb prosthetics deals with replacing lost upper limbs. An upper limb deficiency can be either congenital or acquired through amputation due to dysvascular conditions, physical injury, infection, or some other affliction. The degree of limb loss differs between amputees, ranging from partial finger loss to amputation of the entire arm. Within the Netherlands the prevalence of congenital and acquired deficiencies is approximately 0.8 and 1.5 per 10.000 inhabitants, respectively, leading to about 1350 congenital and 2400 acquired limb deficiency cases[1]. Of course, upper limb loss is a global affliction with amputees worldwide, with conflict and limited healthcare increasing its prevalence.

1.2 Upper limb prostheses

Within the field of prosthetics a distinction can be made between the two categories of passive and active prostheses. Passive upper limb prostheses are mainly to restore the body image and appearance of the wearer but can also be used to manipulate objects through simple acts like pushing, fixating against the body or supporting, often in cooperation with the sound hand. Some passive designs are incapable of movement altogether while others possess a clasping ability allowing the user to place an object in between the fingers. Active upper limb prostheses contain a mechanism through which the wearer is able to operate a terminal device (TD) taking over the role of the missing hand.

Active prostheses can be further divided into externally powered and body-powered devices, based on the power source used when opening and closing the TD. The most commonly used external power source is the electric battery, while compressed carbon dioxide is a formerly popular alternative that has been largely abandoned in recent times. The prosthesis user carries the portable battery with them at all times to actuate the device while they provide the control signals, often through myoelectric signals measured in the residual limb. This way the prosthesis movements are dictated by local muscle activation. While much was expected of these myoelectric prostheses their performance was found to be lacking when compared to body-powered devices[2], for several reasons. Body-powered hand prosthetics are described as inexpensive, durable, and easier and cheaper to maintain than myoelectric prosthetics [3]. Other advantages of body-powered systems that are mentioned are low weight and technical reliability, while electrical prostheses have superior grip strength and the benefit of a harness not being necessary in most of the cases [4]. The primary shortcoming of myoelectric devices however, is that they lack good (proprioceptive) feedback for the user. The available paths are force feedback on the residual limb, visual feedback and audio feedback through mechanical noise. However, no feedback is possible for the grip force and grip velocity. Myoelectric control is therefore considered an open loop system and unsuited for grip force control [5].

Body-powered upper limb prostheses have no external power source, instead relying on the wearer to supply power for movement and gripping force. Because no electric battery or gas tank is required this type of prosthesis can be designed much lighter than externally powered ones. Operation typically occurs through a worn shoulder harness connected by Bowden cable to the prosthesis, where the wearer utilizes contralateral shoulder movement, ipsilateral abduction and anteflexion, or a combination of these three to induce TD movement. Sometimes a hydraulic system is used instead of a Bowden cable [6]. Two alternatives to harness control are elbow control and cineplasty. The latter of these involves the cable being connected to a pin inserted through a surgically created tunnel in the biceps or pectoral muscle, but this method has mostly fallen out of grace since the second half of the 20th century. Elbow control also is rarely applied.

Within the control of body-powered terminal devices two distinct principles of operation can be discerned. Traditionally, a TD is either a voluntary opening (VO) or a voluntary closing (VC) mechanism. A VO prehensor has a spring force keeping its gripper or hand in a closed resting position. Pulling on the cable causes the prehensor to open as the wearer works against the spring force. Consequently, the grip force a person can apply to objects is constant and can only be changed by swapping out the spring element for one with a different stiffness. A VC TD works in the opposite manner with a spring element keeping the prehensor in an open resting position until cable tension closes it, increasing the grip force after contact.

Many different designs for terminal devices exist but both VO and VC prehensors have their characteristic strengths and weaknesses. Some researchers, in a best-of-both-worlds approach, have attempted to design "hybrid" mechanisms combining VO and VC capabilities so that wearers can change to their preferred setting per situation as they see fit. It would make sense to expect higher overall performances when users are given access to both methods of control instead of only one, but as of yet no real success stories have occurred.

1.3 Problem statement

Major issues that have continuously plagued the field of prosthetics are the high rejection and abandonment rates of prostheses by users: amputees are dissatisfied with their devices to such an extent that they stop using them altogether. Literature has reported mean rejection rates of upper limb body-powered prostheses of 45% and 26% in pediatric and adult populations respectively, with some studies reporting overall rates of rejection of body-driven prostheses as high as 66% [7]. Acceptance does depend on the type of TD, with body-powered hands having rejection rates as high as 87% while hooks are, overall, found to be more acceptable to users. Another study reported rejection rates of body-powered upper limb devices for transradial and transhumeral limb-loss levels of 35% and 52%, respectively [8].

These high rejection and abandonment rates clearly show that the performance of currently available upper limb body-powered prostheses is severely lacking. Arm amputees and professionals alike express their desire for improvements accross the board, in general appearance, function, general comfort and the cable control system [9]. Despite the plethora of available terminal devices based on the different principles of operation of either VO, VC or a VO/VC hybrid system none seem to solve these rejection issues. A problem statement can be formulated as follows:

Current body-powered upper limb prostheses do not offer amputees the desired performance, leading to rejection and abandonment

1.4 Research goal

It is clear that better prosthetic devices are needed. One step towards realizing this is the design of better terminal devices. However, researchers are divided regarding which TD working principle trumps the others in terms of performance and all three principles (VO, VC, hybrid) continue to be employed. The strengths and weaknesses of each have never been categorized in a systematic and complete manner. Particularly for the VO/VC hybrid TD designs, where structured performance analysis is complicated by the great variety in mechanisms, a clear overview of the qualities and shortcomings of each is very valuable. Knowing this, a research goal can be formulated:

To categorize the advantages and disadvantages of the three types of working principles of an upper limb body-powered terminal device, focussing on identifying pathways to improve prosthesis performance

Chapter 2

Methods

For this study a search is performed for all relevant literature on the web, and the websites Scopus, Pubmed and the Orthotics & Prosthetics Library (O&P Library) are consulted. Scopus is the primary source of papers while Pubmed and O&P Library are primarily used to find the files of papers whose titles appear on Scopus but which are not directly available there.

It is noted that all literature concerning upper limb prostheses makes use of the terms "*voluntary opening*" and "*voluntary closing*" and that no synonyms or variant terms are used when discussing these working principles. Thus, a confident claim can be made that all relevant literature is found by inputting these two search terms into the mentioned websites. The term "*extended physiological proprioception*" is another search term used once it was found that this phenomenon plays an important part in prosthesis design and the comparison discussion surrounding VO and VC. Finally, the fourth search term used is "*hybrid*", combined with Boolean keywords to restrict to relevant results ("prosthe*" AND "upper extremity"). This fourth search term is intended to find hybrid working principles. It should be noted that no singular term is used when addressing this type of prehensor with both VO and VC capabilities, with the terms "hybrid"[3][10], "VOVC"[11], "VO/VC"[12][3] and "Voluntary opening-closing"[13] being used interchangeably. In the remainder of this report the term "hybrid" will be used.

Entering these four search terms into the specified websites yielded a total of 151 hits. After a selection based on title and abstract contents this number was reduced to 26 unique relevant papers. Only papers in the field of upper limb prosthetics were retained, and all studies concerning myoelectrics or other external power sources were omitted also. From these initial 26 an additional 25 relevant references were extracted that were not found in the initial search. Furthermore, this study's supervisor supplied 4 more relevant pieces of literature. In total this amounts to 55 pieces of literature found to be valuable to this study. See also table 2.1.

Table 2.1: An overview of the number of pieces of literature found in this study, and their origin.

Literature search	Number of papers
Total hits	151
Title and abstract based selection	26
Relevant references	25
Recommended by supervisor	4
Total	55

Chapter 3

Results

A word on hooks versus hands Terminal devices generally come in three varieties: hands, hooks and tools. A hand-type prosthesis attempts to simulate the look and function of the natural hand as much as possible, often including a palm, four fingers and a thumb. Most include a cosmetic glove to give the device a more natural appearance. The hook TD variety does not attempt to mimic the human hand but instead favours optimizing performance. As a result these devices look quite unlike hands and can have a variety of shapes. Tool TD's are designed for single purposes, like mountain climbing. These generally don't move and are excluded from this study.

As this literature study primarily focuses on the working principles of various TD's there is no inherent reason to only focus on TD's of one type or the other. However, in reality it is clear that hook-type body-powered prehensors have always far outperformed hand-types in many, if not all, aspects. Hand-type terminal devices are utilized to a limited extent compared to hook-types[14]. Among the upper limb prosthetics users that do use hands the acceptance rate has been found to be very low, ranging from 21% for below-elbow amputees to as little as 6% for the higher levels[15]. On average body-powered hand prosthetic prehensors are used for fewer hours per day when compared to body-powered hooks. Users generally describe them as "difficult to operate, awkward, and heavy". One study on commercially available VO hands found them to have a mass 1.6 to 5.1 times higher than that of comparable VO hooks[4]. A lack of durability and a weak grip were other complaints. Pinch forces in all common hand models were found to be too low, being outperformed by hooks delivering higher pinch forces at lower required activation forces[4][16][17]. In other words, mechanical efficiencies of body-powered hands, both VO and VC, are less than those of hook TD's[18]. This is mainly due to friction in the internal hinges of the hands as well as glove attachments[17], resulting in a mechanical work requirement (for VC devices) 1.5-8 times higher than hooks, and an energy dissipation up to an alarming 27 times higher[16].

This limited performance of hand-type terminal devices is the reason why research and development of upper limb prosthetics has primarily focused on hook-type TD's. As a result most of the literature found in this study concerns itself with hooks.

3.1 VO vs. VC

Terminal devices can be subdivided into the voluntary opening (VO), voluntary closing (VC) and VO-VC hybrid design types. The last of these three is only a recent addition still in its infancy and so every prosthetic prehensor prescribed for upper body amputees has been of either the VO or VC type. In the past voluntary opening systems have been strongly favoured by prosthetists and other professionals. A two-year study ending in 1967 in the USA showed that the VO hook was prescribed in 87% of the cases involving above-elbow amputation and in 90% of below-elbow amputation[14]. Recently, however, the popularity of VO hook prehensors is declining among new comtemporary fittings (in the US)[19]. In the next few subsections the strengths and weaknesses of both systems are analysed. First, in subsection 3.1.1 for VO, and then for VC in subsection 3.1.2. After both types have been treated the attention is shifted towards studies comparing the two on various fronts in subsection 3.1.3.

3.1.1 Voluntary opening prehensors

The voluntary-opening prehensor has for many years been the norm for body-powered prostheses. In essence it is a spring clamp, where a tongs-like hook is kept closed by means of one or more springs or elastic bands. Typically the user is able to open the device through a harness worn around the contralateral shoulder and connected to the TD by a cable, through which the movements are transmitted. Either by contralateral shoulder movements such as shrugging or pectoral contraction or by relative movement of the arm away from the body is the device opened.

Advantages Compared to more complex prostheses (e.g. those utilizing myoelectrics) the control of these prehensors is intuitive and simple to learn[20]. After initial gripping of the object the user is free to move their prosthesis any way they want, as long as the control cable is kept slack. The primary advantage of voluntary opening prehensors, however, is the fact that objects can be held for extended periods of time without exhaustion. Once the object is gripped and tension is removed from the cable the user can relax while the springs or elastic bands deliver grip force. No additional clutch or brake system is necessary to relieve the wearer of having to generate constant tension in the operating cable as is the case for voluntary closing devices. Finally, another advantage is the fact that VO TD's, hook or hand, remain closed when not in use. This makes it more manageable performing certain activities such as donning and doffing long-sleeved items of clothing and prevents the device from accidentally getting caught behind objects.

Disadvantages VO's greatest strength lies in its elastic elements alleviating the user from having to apply constant tension when holding objects. However, this method has its limitations. A typical voluntary opening prehensor is able to provide just a single amount of grip force through its spring or elastic band. Common activities occurring in daily life obviously require a broad range of grip force levels, from handling a fragile plastic coffee cup to swinging a hammer. To prevent situations where the available grip force is insufficient often a high grip force is chosen. However, light grasps are used much more often than heavy grasps, which means that in most situations the grip force will be far beyond what is required. Two major difficulties can be identified here[21]:

1. **Spring tension must be overcome with every operation** The user must generate more force and expend more energy than is strictly necessary for most tasks as he counteracts the grip force to open the prehensor. Higher cable forces negatively impact the service life of prosthesis components and also cause greater fatigue and discomfort due to pressure applied to the skin through the harness.

2. **Only one grip force** There is no directly controllable continuously progressive range of forces and so holding an object gently is very difficult. The only way to do this and reduce grip force is to maintain cable tension while gripping, which directly counteracts the primary strength of VO prehension.

An additional disadvantage of VO prehension is the inability of locking on an object. The prehensor grips, but there is always the possibility of external forces opening it again. The user cannot prevent this. Furthermore, a complaint often heard is the seemingly unnatural relationship between muscle activation and grip strength, where an increase in effort of the user results in a grip reduction and vice versa[22]. Still, the legitimacy of this complaint has never been fully proven. Because the ongoing discussion is quite relevant to this study it has been decided to dedicate a separate section to discussing the impact of muscular effort-grip force polarity. For this, see section 3.2. Also, gripping an object with a VO TD does not give any neuromuscular feedback or other information to the user when gripping with full force, as no muscular effort is needed to maintain the grip[22]. Only when restraining the grip force will proprioceptive feedback be available. Lastly, the fact that opening the prehensor is correlated to moving the device away from the body means that the user is limited to a functional envelope that is closer to

Table 3.1: VO strengths and weaknesses from literature.

Voluntary opening (VO) prehensors			
Advantages	ref.	Disadvantages	ref.
• Simple to operate	[20]	• Spring tension must be overcome with every operation	[22]
• Holds object without exertion	[23]	• Only one grip force	[22]
• No clutch or brake needed	[22]	• Cannot lock on an object	[20]
• Closed when not in use	[23]	• Opposite in functional principle to normal prehension	[22]
		• Insensitive and lacking in neuromuscular control	[22]
		• Limited to a functional envelope closer to the body when picking up small objects	[3]

the body when picking up small objects[3]. See table 3.1 for an overview of all mentioned advantages and disadvantages.

Adjustable grip force

Some attempts have been made to offer the amputee the option of a voluntary opening prosthesis with more than one single grip force level. This can be achieved in three possible ways. The most straightforward method is to vary the stiffness of the elastic element in the TD. The Hosmer Sierra 2-load VO hook, Stanford Children's Hospital adjustable prehension device and LeBlanc's Adjustable Prehension Device (APD) are all examples of voluntary opening hooks that allow the user some control over their grip force in this manner. The Sierra 2-load employs two torsion springs of which the user can choose to disengage one, giving a low and high grip force setting. Despite being easy to adjust and similar in size to other Hosmer hooks it has failed to gain wide acceptance, possibly due to its high weight or limited number of settings. The Stanford hook allows the addition and removal of modules containing pre-stretched elastic bands, but these actions require a fair amount of effort and the modules need to be carried separately and can be lost[21]. LeBlanc's APD made similar use of pre-stretched modules[24]. A second method to change the grip force level would be to increase the tension in the elastic element, but adding any considerable amount of energy to the system would result in either an exhausting or time-consuming process. Therefore this method is deemed unsuitable. The third and final way in which the grip force of a voluntary opening terminal device can be altered is found in varying the angle between the elastic element and the gripper. The fact is utilized that the torque generated by the elastic element depends on both its elongation and its angle relative to the gripper. If the elongation remains the same no additional energy needs to be added to the system and the angle can be changed with little effort. This concept has been dubbed the "vector prehensor" by Frey et al. due to the exploitation of the vector nature of the elastic force[21]. A simple design, little added weight, easy adjustment and a great multitude of settings over a wide range are advantages of this approach. Ottobock Adult Hooks also include two distinct grip force settings in this manner, by changing the orientation of two parallel strings[25].

Table 3.2: VC strengths and weaknesses from literature.

Voluntary closing (VC) prehensors			
Advantages	ref.	Disadvantages	ref.
• Force/motion feedback	[5]	• Gripping for extended periods of time is fatiguing	[5]
• Active control over grasping force	[22]	• Open when not in use	[5]
• Input directly proportional to grip force	[26]	• Limited to a functional envelope that is away from the body when picking up small objects	[3]
• Reflexes have intended effect	[26]		
• Torso and limb muscles utilized more actively	[26]		

3.1.2 Voluntary closing prehensors

For a long time the VO mechanism type was the working principle of choice for prosthetists and amputees alike, as mentioned in the previous chapter. Researchers in favour of VC TD's have credited this to early VC designs being clumsy and mechanically inefficient, counteracting the inherent benefits of VC over VO and leading amputees to choose the simpler system of the two[22]. Recent improvements in VC design have since resulted in them being a serious alternative again.

Advantages There are some important advantages to utilizing the voluntary closing working principle in upper limb prostheses. First of all it provides inherent, good quality feedback of force and motion. The user is able to sense the position and motion of the prehensor, as well as the pinch force exerted and the texture and stiffness of the object held[5]. Secondly, the amount of grasping force that is exerted can be actively controlled, resulting in an entire range of available force levels as opposed to the single value for VO devices[22]. Furthermore, this chosen grasping force level is directly proportional to the muscular effort required, as an increased contralateral shoulder movement results in a more forceful grip. This is deemed a more natural feedback pattern[27]. Section 3.2 discusses the relevance of muscular effort-grip force polarity in greater detail. An additional advantage of VC is the fact that reflexes still have their intended effect, in the sense that letting go of gripped objects still entails ceasing muscle activation. Besides this, muscles in the torso and limb are used more actively and continuously, leading to healthier and stronger muscles.

Disadvantages The main disadvantage of voluntary closing terminal devices is the fact that the user must continuously provide tension in the control cable while holding an object, as opposed to VO devices where the elastic element provides the pinch force and the user can relax. If an object is held for an extended period of time this will cause muscle fatigue, increased mental loading, discomfort and irritation, particularly in the axilla when using a shoulder harness[9]. To lighten this physical load most VC devices are provided with some form of locking mechanism or holding assist, but oftentimes mechanical inefficiency and design errors prevent these from performing well. See subsubsection 3.1.2 for more information.

A second disadvantage is the TD's open default position as a result of its elastic elements. This causes trouble when the hook gets caught behind objects or parts of clothing. One design, the TRS VC hook, has solved this problem by incorporating a 'controlled tension' harnessing of the user and achieving a nearly closed neutral position[26]. Another has a hand which does not automatically return to its fully opened resting position without the user's assistance[28]. A third downside compared to VO is the partial coupling between the prosthesis' distance to the body and the opening width of the prehensor device, causing the user to be somewhat limited to a functional envelope farther away from them when picking up small objects[3].

Holding assist functions and locking mechanisms

In an effort to improve the performance and target its main disadvantage designers have incorporated locking mechanisms into voluntary closing terminal devices. These mechanisms, that also go by the names of clutches or holding assists, free the user from having to supply constant tension to the control cable when holding objects for extended periods of time, thereby significantly reducing muscle fatigue and mental load. The ability to keep the prehensor in its fully closed position when not in use is an additional advantage. Others claim that an automatic lock completes simulation of the natural process of hand prehension that the voluntary closing principle started.[29].

Despite their importance however, most current locking mechanisms in VC TD's demonstrate a truly poor performance. The pinch force significantly dropping after the wearer locks the mechanism and removes tension from the cable is a common occurrence. This phenomenon is called *backlash.* The opposite phenomenon, where pinch force increases when tension is removed, is called *frontlash.* In some voluntary closing devices the locking mechanism had so much backlash that, after it was set, the object grasped would simply be dropped[22]. One study found a drop in pinch force varying in magnitude from 50-90% of the initial pinch force for different popular VC hook and hand devices[16].

An additional downside to current locking mechanisms is the inability to quickly remove pinch force and drop carried or held objects in case of emergency. Most locks are released when operating cables are tensed to a certain threshold. If a user instinctively removes all tension from their device, intending to cease gripping, the opposite will in fact happen.

A third problem regarding certain types of locking mechanisms is the number of additional motions the user must perform in operating the mechanism. Chapter 7 of Klopsteg and Wilson's "*Human Limbs and their Substitutes*" (see figure 3.1) offers an overview of the differences in required control operations between voluntary opening devices and voluntary closing terminal devices equipped with a locking mechanism demanding additional actions. The secondary control operations to release the lock are marked with an asterisk. Comparison between prostheses with intact or removed locking mechanisms showed that performance with VC locking devices was considerably slower on all tests[30]. A consideration should therefore be made whether the ability to adjust the grip force to each task outweighs the decrease in speed accompanying VC TD's equipped with locking mechanisms.

Finally, a fourth problem with conventional locking mechanisms today is their tendency to wear out relatively quickly, often before the prehensor itself requires maintenance[31].

Operation	Voluntary-closing hand or hook	Voluntary-opening hook
Preparatory..............	Normally closed. Control motion unlocks,* and hook opens by spring action to the prehension position	Normally closed. Control motion opens hook to clear the block
Prehension................	Control actively closes hook on the object	Spring or rubber band closes hook on the object
Opening.................	Active control motion disengages lock,* and hook opens under spring action	Active control motion opens hook against spring or rubber-band tension
Return to resting position....	Active control motion closes to preparatory position	Spring or rubber band closes hook to preparatory position

Figure 3.1: Overview of required control operations for VO terminal devices and VC TD's equipped with a locking mechanism that unlocks when a tensile force threshold is reached[29].

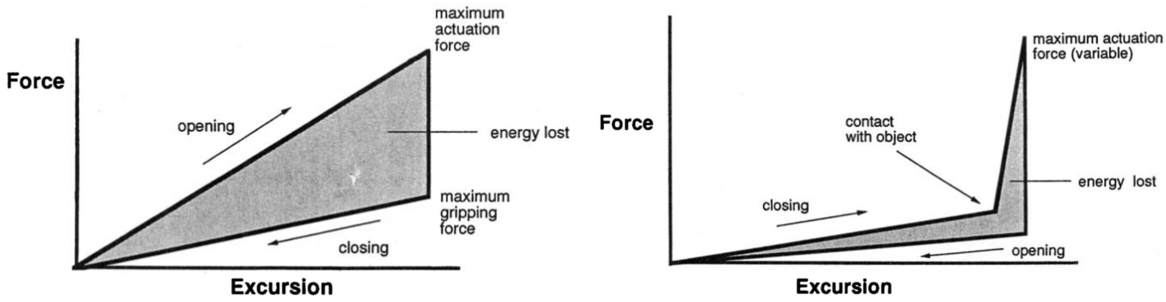
Not all locking mechanisms and holding assists are sub-par, however. There are some that do manage to perform their intended task successfully. The APRL VC hook, for example, offers a locking function with an anti-backlash mechanism which can be adjusted to give frontlash. Closing the prehensor around an object engages the lock while a second pull releases it again. In this way the backlash problems of other locking mechanisms are avoided but concerns regarding safety and additional motions are still present[32].

Veatch et al. designed a holding assist allowing the user to reduce cable tension by as much as two thirds while preserving 95% of their initial applied grip force[33]. Fully releasing cable tension does result in grasp release.

The Sure-Lok cable system offered by TRS also seems a viable locking mechanism but this system had not yet been clinically tested[34].

Frey et al. created a body-powered prehensor with a variable mechanical advantage gripping mechanism that simultaneously acts as a holding assist[27]. It initially operates at low mechanical advantage during sizing of the object, reducing cable excursion requirements, and shifts into high mechanical advantage after initial contact with the object, reducing cable tension requirements. The created prototype provided a mechanical advantage of 2.4, nearly five times that of conventional VC devices. To deal with exceedingly compliant objects a switch was incorporated to avoid the holding assist mechanism and use the device as a conventional VC prehensor.

Finally, de Visser et al. took a different approach to the problem of alleviating users from continuous gripping[28]. Research has shown that humans use their ring finger and little finger to support hand-held objects, reducing required grip force. By giving prosthesis users this option a similar goal is achieved as with a locking mechanism, without the unwanted occurrence of backlash. Objects can quickly be dropped in case of emergency and the mechanism does not wear out quickly. Furthermore, the designers made sure to give the prosthesis a nearly closed resting position, which was another advantage of a locking mechanism on conventional VC devices. An additional control action is still necessary however, as the ring finger and little finger are manoeuvred into place by the sound hand. Also, holding objects with a hand orientation where these two fingers are not on the bottom side negates the support function.



(a) Voluntary opening

(b) Voluntary closing

Figure 3.2: Graphs qualitatively showing actuation force versus cable excursion for the two types of working principles. Energy lost per operating cycle is shown in grey[18].

3.1.3 Comparison studies

Studies have been performed comparing VO and VC with each other, on various fronts. In the following sections the inherent differences in mechanical efficiency, task preference, time and grip force, and accuracy and variability are discussed.

Inherent efficiency differences

The prosthesis system is comprised of three parts that all contribute to the overall mechanical efficiency. These three are the prehensor mechanism itself, the shoulder harness and the control cable and housing connecting those two. The choice of prehensor working principle is relevant in terms of system efficiency as VO and VC are close to opposite principles with markedly different force-excursion profile and resulting energy losses. Figure 3.2 shows qualitative force-excursion graphs for both, for one full cycle of opening and closing the TD[18]. It is clearly visible that the energy lost per cycle, marked in grey, is significantly greater for voluntary opening mechanisms when compared to voluntary closing, indicating an inherent lower mechanical efficiency.

It is important to keep in mind that the mechanical efficiency of these prostheses only influences energy expenditure while the gripper is in motion. This happens at the beginning and end of the gripping motion when the user proceeds to pick up an object and the moment they put it back down. The period of time where the object is being held costs metabolic energy in the case of a VC prehensor, but this cost is not related to the mechanical efficiency but instead depends on the mechanical advantage of the mechanism.

Carlson and Long[35] compared both types of devices and came to a similar conclusion, with the results showing that the tested voluntary opening device required close to five times as much mechanical work to operate (4.4 Joules versus 0.9 Joules). Here, mechanical work is the area under the force-excursion graph and a better comparative measure than force or cable excursion alone.

Task preference

The average person's day is filled with a multitude of different tasks that require them to perform grips of various strengths, durations and hand positions, to name a few. A prosthesis working principle may lend itself well to performing some of these tasks while being less suitable for others. It would make sense, then, to expect the ranges of suitable tasks to differ between principles, due to their significant intrinsic differences. Sullivan et al., for example, claimed that VO devices are better for tasks that require precision, viewing, and continuous holding, while VC devices are better for pinching, pulling, and holding large objects[3].

Sensinger et al. performed a study regarding the preference of subjects for either VO or VC prehension when attempting a range of tasks commonly encountered in daily life[10]. Both amputees and physically healthy individuals (via prosthesis simulator) participated and the prosthesis used was Sensinger's own hybrid design offering the user both methods of prehension, ensuring prosthesis bulk and weight were identical during trials. Each participant performed a total of 26 tasks using both modes and their preferred mode for each individual task was recorded.

From the resulting data it became clear that the average participant chose to perform a task using VC mode in 62% of the cases. Two important observations can be made regarding these results. Firstly, every participant made use of both modes that the hybrid prosthesis offered when faced with the various tasks, and only a slight preference towards VC was noticed. This implies that, assuming the 26 tasks of this study accurately reflect those encountered in daily life, a demand for both working principles is present among users and thus that a hybrid device would mean an improvement in performance. A second observation was the fact that for only two out of 26 tasks participants unanimously agreed on the preferred mode of prehension. This indicates that personal preference strongly influences working principle employability. Therefore, restricting users to only one out of two working principles will inevitably result in suboptimal performance.

Berning et al. also compared prosthesis performance regarding various tasks, this time with a larger participant group of 29 healthy individuals and two amputees[31]. Surveys produced subjective results. For example, many subjects preferred the VO prehensor for tasks that required object rotation such as pouring water or using a screw driver. Some of the tasks where the VC prehensor was preferred were lifting heavy objects or undoing buttons. Most subjects expressed the desire for a device allowing them to switch modes because "each had their own strength".

Performance time and prehension force

Two advantages of voluntary closing prehension that are often stated in literature are its compatibility with normal neuromuscular patterns, and its ability to permit grading of prehension force. Groth et al. were unconvinced, however, that these characteristics resulted in a better performance, as is often claimed[30]. The hypothesis tested in their study was that "a voluntary closing type of prosthesis control system will lead to superior psychomotor performance for arm amputees when compared with a voluntary opening type of system because of the closer 'imitation of natural function' said to be provided by the former system". To test this, three simple manipulation tests were performed with performance time as a criterion measure. Results indicated that there was no significant difference between the VO and VC nonlock hooks, but that the tested VC device with locking mechanism performed significantly slower than the VO device. The latter was to be expected due to the additional operational steps required. Thus, the mode of TD control seems unrelated to the criterion of performance time. One important point of criticism that has been raised regarding Groth's research has to do with the particular VC device used in testing. The APRL hook with disengaged locking mechanism was said to "suffer partially from the limitations of the very high return spring force which had originally been found necessary to pull the inner wire out of the Bowden cable housing to assure full opening of the hook and hence recocking of the locking mechanism"[32].

Berning et al. also looked at a possible difference in performance time between VO and VC devices and did find that VC was slightly faster (14.0 s versus 15.3 s averaged across tasks and subjects), but this did not equate to significantly higher performance[31].

In addition to performance time, Groth et al. also studied output force, that is, the grip force applied to objects during tasks. Again the aim was to dispel the supposed benefit of two oft-repeated characteristics of voluntary closing prostheses. Proponents of the VC principle state that the variable prehension force and wider range of useful force make it superior to the VO principle. Groth retorts that prehension force can be adjusted equally well with VO and VC mechanisms and that in realistic situations the additional utility of a wider range of forces available in VC devices is not of practical significance to the user. Manipulation tests showed no significant difference in absolute level of prehension force exerted between VO and VC hooks. Holding tests showed there was no difference in mean prehension force either. A questionnaire found that all participants in the study preferred the VO hook over a VC hook during the experiments. However, multiple participants noted that they feared damaging the VC hook, which was made of aluminum. The steel VO hooks did not have this problem. Four out of ten VC wearers claimed they had damaged their hook during the study. Therefore, it is fair to assume that this large difference in structural toughness contributed in their prehensor preference, invalidating the questionnaire results.

Variability and accuracy

Wallace and Trujillo performed multiple studies focusing on the variability and accuracy of applied pinch force when gripping with either type of prehensor. Theirs is the 'muscular effort-grip force compatibility hypothesis' which claims that the control of prosthetic prehensors based on the voluntary closing working principle resembles the anatomical hand more closely, and that these are therefore superior to VO devices. One study involving 10 able-bodied participants using a prosthetic simulator tested this hypothesis[36]. The tests involved participants gripping a dynamometer with the simulator while a nearby monitor provided visual feedback through a force output tracing. Results showed that VC was significantly less accurate than VO for low pinch force levels (1 N) but significantly more accurate for high pinch force levels (12 N). Furthermore it was found that VO was significantly less variable for both levels. Removing the visual feedback exacerbated the effects. The authors, at least, see these results as proof of the superiority of the voluntary closing principle.

Trujillo et al. performed similar tests with a quadruple congenital amputee participant with nearly 38 years[37] of VO experience. This opposed to the ten participants of the previous study that were able-bodied and thus inexperienced with any kind of prosthetic device. Due to the participant's extensive experience it could be expected that grip force is produced more accurately and with a lower variability with a VO device. However, results indicated that the VC principle was more accurate for both high and low force targets and both with and without visual feedback. Furthermore, use of the VC device resulted in a lower variability when visual feedback was unavailable, possibly meaning that VC proprioceptive feedback is of higher quality. Lastly, the participant was more on-target with the VC device when visual feedback was omitted, and also when it was still available for high pinch force targets. According to the authors these results showed the superior proprioceptive feedback of VC prehension, most apparent when the accuracy of force output was examined in the no-vision condition, and that "compatibility was more important than specificity training".

3.2 Extended physiological proprioception

The concept of extended physiological proprioception was first proposed as an efficient prosthesis control method by D.C. Simpson in 1974[38]. He observed that humans effortlessly control their natural limbs with their many degrees of freedom while struggling with the control of even a two degrees of freedom machine, deducing that a control system different and more efficient than usual man-made systems is operating in the biological situation, reducing the control load to such an acceptable level that unconscious operation is possible. Humans have physiological proprioception, a sense that provides force, position and velocity information of their body. Instead of hoping to mimic or replace this biological system in a prosthesis it is suggested to create a position control system where the movement at a joint in the artificial arm corresponds proportionally to the movement of a joint somewhere in the body. This way the efficient biological control system still present in the body can be harnessed. One of the joints in the shoulder girdle is mentioned as suitable. This proprioceptive feedback of a mechanical system outside of the body is labelled as extended physiological proprioception, or EPP.

It is worth noting that the EPP phenomenon occurs in many ways and is not limited to prosthetics only. A simple example outside of prosthetics would be a tennis racket. Even though it is a simple object without sensors the wielder is aware of its position and velocity in space, as well as the forces acting on the racket and the forces it acts upon its environment. The tennis player has access to this information because of the interface, in this case the hand gripping the handle. Prosthesis designers wish to give amputees access to this type of information in a similar manner.

Simpson never specifically mentioned terminal devices when proposing EPP as a prosthesis control method. However, multiple papers use EPP as an argument in favour of the voluntary closing principle over voluntary opening. For example, Plettenburg states that a simple and direct relationship should exist between the position of the control joint and the position of the prosthesis, between the velocity of the joint and the velocity of the prosthesis, and between the joint force and the force of the prosthesis, and proceeds to claim that optimal controllability can only be reached if the polarities of movements, velocities and forces correspond to physiology (i.e. VC)[39][5]. De Visser and Herder call the increase in pinch force with increasing operating force that occurs in voluntary closing devices "logical force feedback"[28]. Wallace and Trujillo advanced the "muscular effort-grip force compatibility" which proposes that the voluntary closing prehensor should allow the inexperienced user to perform similar to the anatomical hand, and possibly better than the voluntary opening prehensor, in tasks requiring grip force modulation[40]. Stated was that this hypothesis was based on the conceptualization that "the functioning of the VC prosthesis more closely resembles that of the anatomical hand in which there is higher compatibility between muscular effort used and the resultant grip force".

The control cable connecting the prehensor and the control joint allows for the user's physical proprioception to extend to the prosthesis. Information regarding the position and velocity, as well as forces are available to the wearer as long as cable tension is maintained. Without cable tension only visual feedback is available. As VC TD's require cable tension to maintain pinch force this means that EPP is always present during gripping actions. In VO devices proprioceptive feedback is only available when the internal spring is partially counteracted by the wearer and the subsequent grip force is reduced, and is lost once objects are gripped with full grip strength as cable tension disappears[12].

3.3 Hybrid systems

The voluntary opening and voluntary closing working principles have been around for a long time, and for nearly just as long prosthetists have been trying to decide which one is “the best”. The various comparison studies listed in subsection 3.1.3 are testament to this. However, amputee prosthesis users, when asked, consistently indicated that they would very much like a device that could offer them both principles and the option to easily switch from one to the other[31][12][41]. A total of eight upper limb prosthesis designs have been found during this literature study that are designed with the aim of exceeding VO and VC devices through employing hybrid working principles, and each manages to do so in a unique manner. Unfortunately, some of these eight are no more than conceptual designs while others have never made it past the prototype phase. In the following subsections each prehensor design is explained.

3.3.1 The Hand of Dalisch

The earliest mention of a terminal device combining both types of working principle was an elbow-operated hand prosthesis developed in 1872[42]. It was intended for amputees that had lost pronation and supination abilities of the lower arm. The device linked elbow angle and mechanical hand such that the hand was closed when the elbow was either at a right angle or fully extended, while moving between these two positions caused it to open. Access to the VO and VC modes is sequential, in that the user cannot switch between them at will but instead must move through one mode to reach the other. Details on the mechanism design could not be found however. Figure 3.3 shows a schematic drawing of the elbow mechanism.

This elbow-operated type of hand prostheses is uncommon but does offer an advantage compared to the more common cable-operated versions regarding the hybrid working principle. When a cable-operated hybrid prosthesis has its VO and VC modes accessible in sequence, either mode is restricted to only half the cable excursion it would otherwise have in a standard prosthesis. This halves the mechanical advantage of the mechanism, as the same amount of gripper movement has to be achieved with half the cable excursion. Elbow-operated designs have a relatively large amount of ‘excursion’, almost 180° of rotation, so splitting this between the two modes has a lesser negative impact. A disadvantage of elbow control is the limiting single input joint the wearer can use to control their prosthesis, as opposed to the multiple control movements available in harness control that offer more freedom (contralateral shoulder movement, ipsilateral abduction and anteflexion).

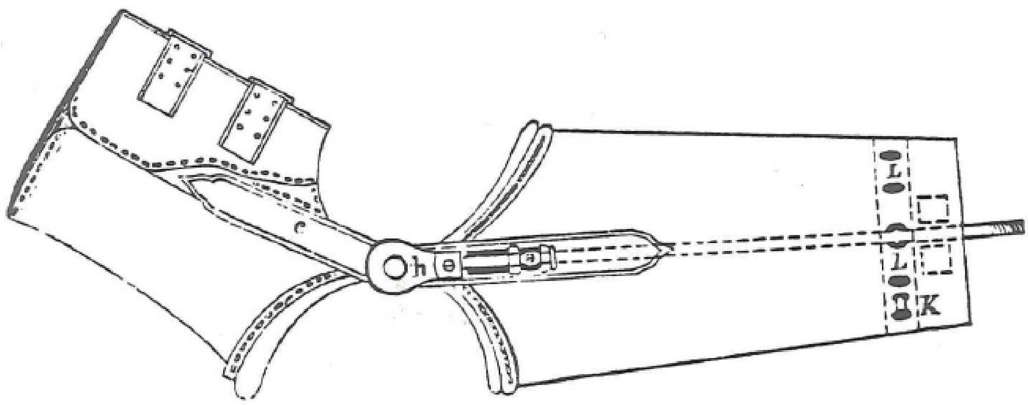


Figure 3.3: Schematic of the elbow mechanism used to operate the Hand of Dalisch[42].

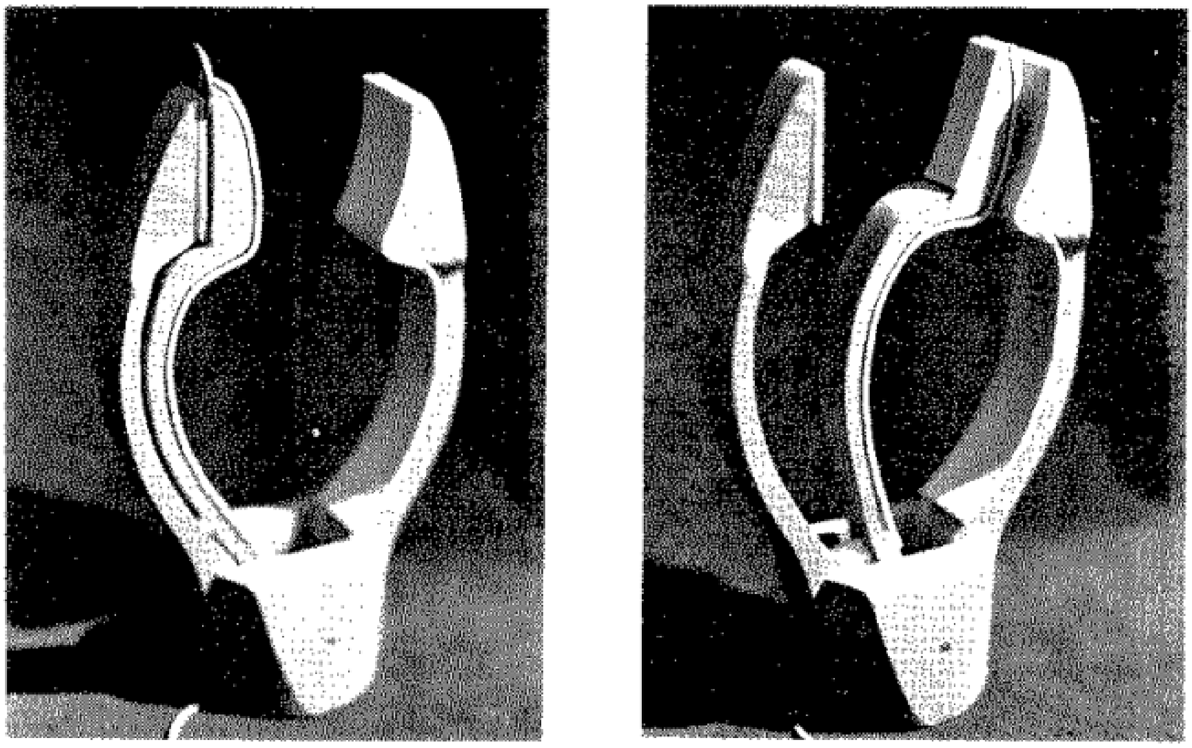


Figure 3.4: LeBlanc's prehensor, showing the VO mode on the left and VC mode on the right[44].

3.3.2 LeBlanc's prehensor

Leblanc's prehensor is the result of a study attempting to create a terminal device that is functional, attractive, and that does not neccesarily have to look like a hand[43]. This prehensor was designed primarily with function in mind. It is shaped somewhat like a two-fingered claw with a central third finger moving to either end to grip objects, see figure 3.4. An internal torsion spring forces the central finger towards the left, offering VO fingertip grasp. Operating the control cable causes the finger to rotate towards the right so that VC palmar grasp takes place.

The VO and VC modes here are simultaneous, as pulling on the control cable results in both voluntary opening one grasp while voluntary closing the other. This prevents the problem of reduced mechanical advantage mentioned in the previous subsection. A questionnaire discovered that subjects praised the small bulk and simplicity in use of the device, but disliked the claw-like, 'empty' appearance. This design was not further developed and instead efforts were focused on a second hybrid device that originated from this study: Nelson's prehensor, described in subsection 3.3.3.

3.3.3 Nelson's prehensor

Both this design and LeBlanc's prehensor, described in subsection 3.3.2, originated from the same study[43]. Nelson's prehensor came out as the best concept out of three after a questionnaire among amputees, prosthetists, occupational therapists and laypersons regarding appearance, function and acceptance. Based mainly on aesthetics, it is unique in utilizing a rotary thumb that offers VO fingertip grasp at the beginning of its cable excursion and VC palmar grasp at the end of excursion. See figure 3.5. Thus, the modes are sequential. The position at rest of the thumb is shown on the left in the figure and pulling on the control cable causes a clockwise rotation, widening the VO gap. By pulling far enough against the internal spring the thumb meets the palm at the other end.

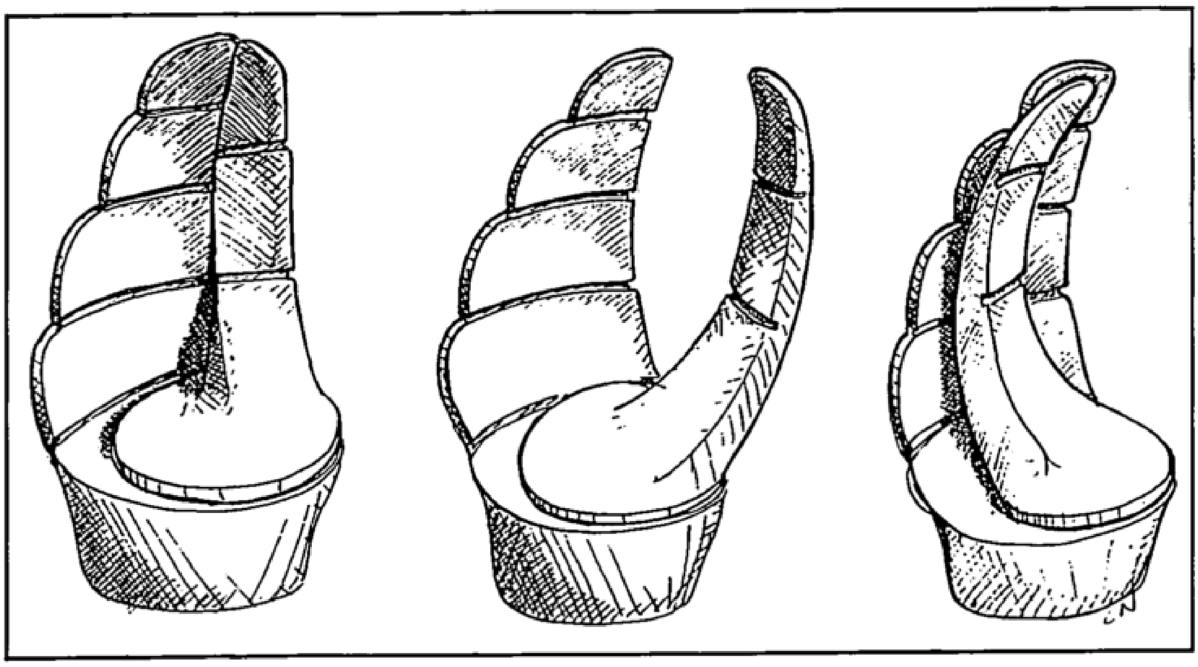


Figure 3.5: Nelson's prehensor, showing the rotating thumb[41].

Participants of the initial study liked the concept's appearance, describing it as artistic, graceful and non-threatening. A follow-up study compared its performance to the participants' existing prostheses that had standard hooks. Appearance-wise the new design was preferred, but its function was deemed inferior in general. It was noted, however, that the shape facilitated certain tasks that were more difficult to perform using a standard hook. Unfortunately, the hybrid quality of the prototypes was never used due to the VC mode being at the very end of the excursion. In reality Nelson's prehensor was only used as a VO device with an alternative shape. It was experienced as very awkward to move the TD sufficiently far from the body to reach the VC mode[41].

3.3.4 LESA prehensor

The LESA (Low Energy Sequential-Action) prehensor was designed with the problem of mechanical advantage in mind[12]. Conventional prostheses have a fixed mechanical advantage with an average value of around 0.5[27]. Some users with impaired strength or limited movement have trouble generating sufficient cable tension or excursion to operate these devices. The LESA borrows the variable mechanical advantage (VMA) concept found in the normal gripping cycle: two distinct phases of sizing and gripping, each with a different mechanical advantage. During sizing the advantage is low, reducing the excursion requirements. After initial contact with the object the mechanical advantage shifts to a higher value which reduces cable tension requirements. As a result of this wear, skin chafing and harness pressure are reduced as well. Compare with Frey et al. who applied the same concept[27].

In this hybrid design the wearer has to operate switches to select their working principle of choice, which are discrete and separate from one another. A small lever on top of the gripper and a latching tab on the upper digit have to be moved, either by pressing the TD against nearby objects or the user's own body. This mode switch requirement could be seen as a downside since it interrupts tasks. Design flaws to the LESA were its mass and bulk, caused by its complicated mechanism[10].

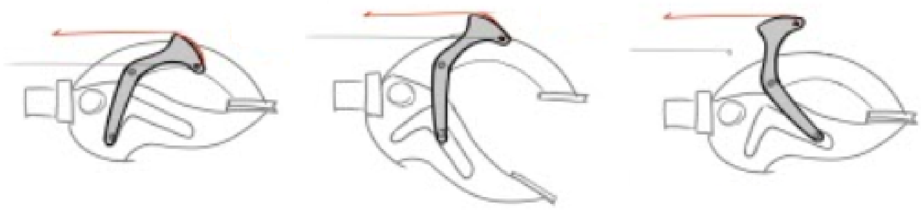


Figure 3.6: Kuniholm's concept #1 depicted in three stages of operation[46]. The position when not in use is shown on the left.

3.3.5 Kuniholm's prehensor #1

The Open Prosthetics Project (OPP) is an online platform intended for sharing prosthetics experiences, suggestions and new designs. Currently, two concepts for hybrid terminal devices are explained on their website, though neither have as of yet been converted into a physical product[45]. The working principle of the first of these two concepts is depicted in figure 3.6, showing the gripper opening and closing again as the control cable is pulled back and a pin moves through the curved slot. The second concept is explained in subsection 3.3.6.

Two opposing spring are used. A closing spring tries to pull the hook closed and a return spring tries to pull the cable back to its neutral position shown on the left in figure 3.6. Shaping the slot and the pulley around which the cable winds allow for some control over the mechanical advantage. The OPP website mentions the length of the slot as a practical problem, as the maximum length is limited if this TD is to be interchangeable with others on the market. Furthermore, the problem mentioned in subsection 3.3.1 plaguing hybrid mechanisms with sequential modes is also an issue here: because both a full opening motion and a full closing motion of the gripper are coupled to a limited amount of cable excursion, this results in an unfavourable mechanical advantage. Overall it is most likely the problem of dimensions that has prevented this concept from becoming popular.

3.3.6 Kuniholm's prehensor #2

A second concept for a hybrid working principle is mentioned on the website of the Open Prosthetics Project (OPP), described as their "most successful idea so far" that allows the user to manually switch between discrete VO and VC modes. The potential compactness is noted. A combination of bevel gears and a pulley offers a simple way of changing the direction of rotation. Figure 3.7 shows voluntary opening mode on the left, indicated by the number 1, where the cable turns a pulley which drives the moving finger (blue) through the pinion on the right. On the right the voluntary closing mode is depicted where the same pulley is rotated, but this time the pinion on the left drives the moving finger. This VC mode is indicated by the number 2. Switching between modes only involves sliding the shaft. The website notes that they not yet know whether small gears will be able to bear the loads but it is known that another gear-based hybrid concept, Sullivan's prehensor in subsection 3.3.7, experienced design problems due to high internal forces in the gears.

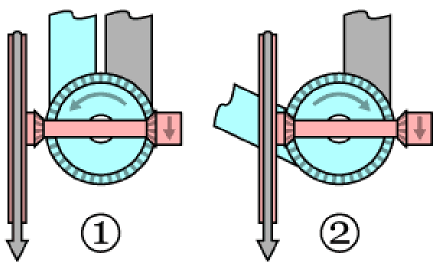


Figure 3.7: Kuniholm's second concept shown in both VO mode (1) and VC mode (2)[45].

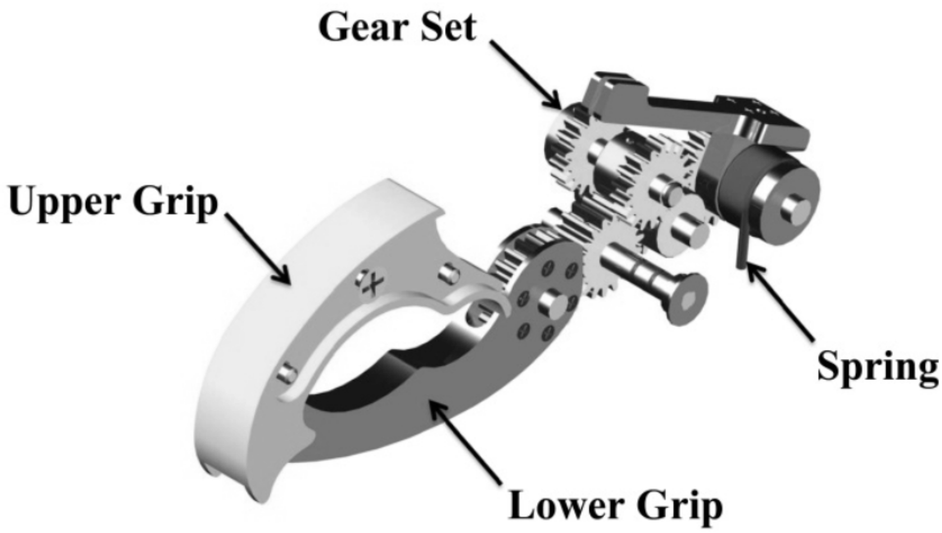


Figure 3.8: Image showing the inner workings of Sullivan and Teh's TD[3]. By operating a knob an additional gear is introduced to the gear set and the direction of movement of the lower grip is reversed.

3.3.7 Sullivan's prehensor

Sullivan and Teh designed a terminal device that uses a set of gears to translate cable excursion to gripper movement, where an additional, laterally moving gear can be added to the set by operating a knob[3]. Doing this will reverse the direction of rotation and switch the mode from a voluntary opening working principle to voluntary closing or vice versa. Thus, the two modes are discrete and separate.

The mechanism chosen here to allow for both working principles to be available brings with it several disadvantages. The design is bulky and heavy, leading to low wearing comfort. Inefficiencies due to the gears[10] negatively influence proprioceptive feedback and required operational power. Large internal forces necessitate strong gears fashioned from titanium. Sullivan and Teh admit that they constructed their prototype from less expensive materials that are easier to machine, indicating that the production costs of the prosthesis are high. Moreover, the Bowden cable attachment site does not remain the same in the two modes, requiring the wearer to adjust harness tension with every mode switch[10].

3.3.8 Sensinger's prehensor

The hybrid TD designed by Sensinger et al. also offers two separate modes[10]. The mechanism relies on a singularity that occurs in a three-link linkage when three joints align. This is illustrated in figure 3.9. By operating the control cable the leftmost link is pulled towards the left and the connected rightmost link will move. The direction of movement depends on the position of the linkage. One particular configuration of the three links exists where the movement direction of the rightmost link is uncertain, which is known as a singularity and is shown in figure 3.9b. Through a switch connected to the linkage the user can set its position, bringing the mechanism through the locked state of the singularity and reversing the output movement direction. This way the mode can be switched while requiring only a small amount of force and displacement. This type of hybrid mechanism stands out as both light and compact, although the user still has use their other hand in order to switch modes. As of yet no clinical trials have been performed with this design, but after the Southampton Hand Assessment Procedure (SHAP) was performed it was found that subjects obtained higher SHAP scores when they could choose their preferred mode on a task-specific basis than when they were forced to use either VO or VC mode. A hand version is also being developed by Sensinger et al.[11]

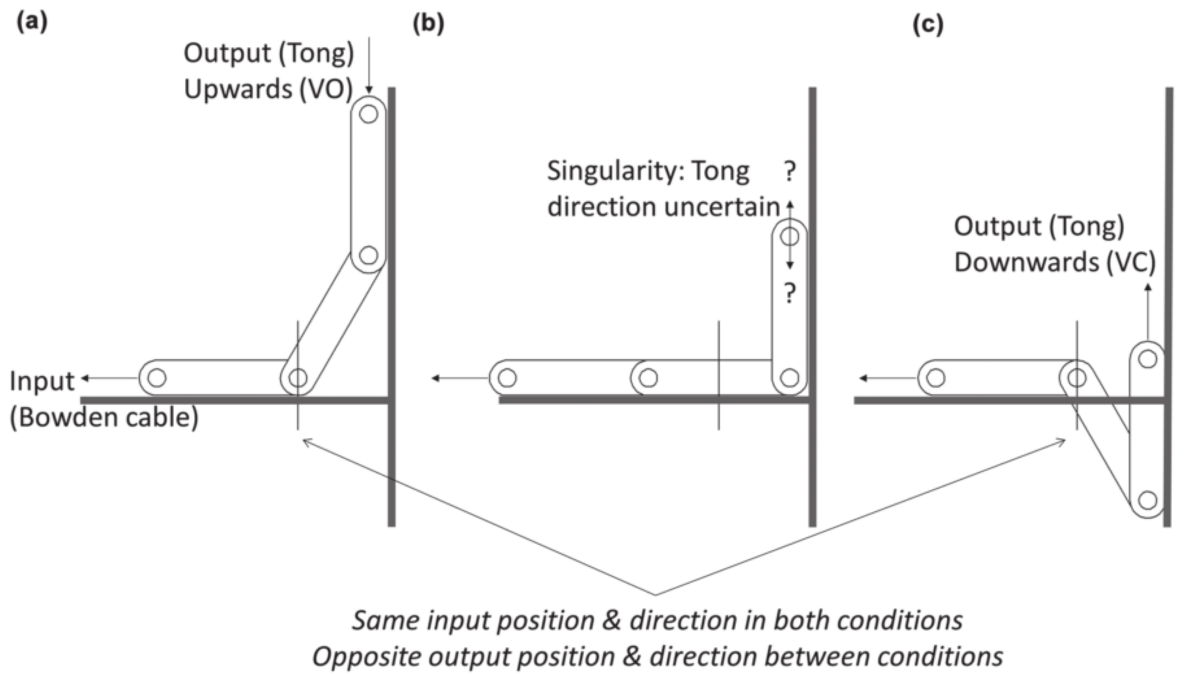


Figure 3.9: The three link linkage in Sensinger's prehensor allows for contrary movement directions through a small adjustment of its position[10].

3.3.9 Overview of strengths and weaknesses

All eight hybrid prehensor concepts found in this literature study have been discussed in the current section. Table 3.3 gives an overview of all mentioned strengths and weaknesses of the various designs. Due to the wide variety of hybrid solutions their advantages and disadvantages are also very varying, however some general observations can be made.

Mechanical advantage is important in terms of functionality and occurs multiple times, both as a strength and a weakness. In concepts where the VO and VC modes occur sequentially, such as Kuniholm #1, cable excursion must be split between the two which negatively impacts mechanical advantage. Nelson's prehensor also has sequential modes but in initial testing no mention was made of such problems. Concepts where the user actively switches between modes or where both modes are simultaneous (LeBlanc) offer the user more favourable mechanical advantage values, or even values that change during the gripping cycle (LESA).

Additionally, large bulk and mass are noted multiple times as design weaknesses (LESA, Sullivan). Very much tied to the choice of hybrid concept, it is important to keep mass and size of the mechanism and total device as low as possible. Both have been stated as factors influencing rejection and abandonment. Kuniholm #2 and Sensinger's prehensor have the explicit strength of compact, simple and therefore lightweight mechanisms.

Mechanism simplicity generally reduces mass and bulk as well as cost of manufacture and maintenance due to fewer parts. This also improves system efficiency, and robustness as fewer parts can break. Especially Sullivan's prehensor suffers from mechanical inefficiency because of its complex gear system. A low mechanical efficiency not only requires more operational force from the user but also degrades useful proprioceptive feedback.

Table 3.3: Overview of strengths and weaknesses of all eight hybrid concepts found.

Hybrid design	Strengths	Weaknesses
Dalisch	Large excursion to distribute between modes achieves good mechanical advantage	Singular input joint limits user moveability
LeBlanc	Simultaneous modes lead to favourable mechanical advantage, no switching, simplicity in use	‘Empty’, robot-like appearance
Nelson	Graceful, non-threatening appearance	VC mode at very end of cable excursion causes awkward control and non-use
LESA	Variable mechanical advantage during grip cycle	Mode change requires two switches, heavy, bulky
Kuniholm #1	Shaping slot and pulley allows for design control of mechanical advantage	Slot length is limited by maximum dimensions of the device, unfavourable mechanical advantage due to sequential modes
Kuniholm #2	Potential compactness, simplicity	High internal forces can be expected, resulting in higher costs
Sullivan	None worth mentioning	Bulky, heavy, inefficient gears, large internal forces
Sensinger	Lightweight, compact mechanism	None worth mentioning

Chapter 4

Discussion

Section 3.1 sums up and explains the various advantages and disadvantages that the voluntary opening and voluntary closing working principles offer to the user. When comparing the two sets of pros and cons it becomes apparent that they are not so much opposites as they are complementary to one another. A shortcoming in one working principle is often opposed by a strength in the other. Examples include the high spring tension that must be overcome with every operation in a VO device whereas VC requires minimal input force to initiate gripping, or the exertion that occurs after prolonged VC operation compared to the fatigue-free VO gripping.

It may seem that the VC working principle outright trumps VO concerning inherent mechanical efficiency, but this higher efficiency is only relevant during gripper movement at the beginning and end of object gripping. A well-designed holding assist function reduces metabolic cost of VC prehension by allowing the user to relax tension in the control cable, bringing it down to approximately the level of VO. Current holding assist mechanisms of which the performance is known are not well-designed however.

In various studies and works of literature amputees and prosthetists alike consistently agree that differences in operation render the working principles suitable for different types of tasks. Comparison studies into task preference support these claims, showing varying device preferences that not only depend on the type of task but also on individual preferences of the subject. Studies focused on performance time and prehension force found no significant differences or were inconclusive. One group did find differences in variability and accuracy but no clear 'winner' can be appointed.

Extended physiological proprioception (EPP) as a feedback signal available to the prosthesis wearer is vital in optimizing performance and in keeping the experienced mental load while operating manageable. A prerequisite for EPP is tension in the control cable. As long as tension is present a relationship exists between the state of the terminal device and that of the control joint. In this way the user is informed of the position, velocity and forces of the TD. For VC devices the control cable is tensioned during the entire duration of gripping, meaning the amputee always has EPP feedback when gripping. VO devices, however, only offer extended physiological proprioception when the internal spring is resisted and the gripping force reduced. An important strength of VO prehension is that it generates grip force without the energy of the operator. This strength is negated when a trade-off exists between EPP and inexhaustive gripping.

The thought that the two working principles each fare better in different situations has produced its results. In a best of both worlds approach multiple prosthetic prehensor devices have been designed that offer the user both voluntary opening and voluntary closing capabilities. Eight of these hybrid concepts have been found in literature, each with a different method of combining VO and VC. Some have separate modes while others incorporate both continuously. Unfortunately none of the concepts have been adopted by amputees, owing to different design flaws. The most recent design of Sensinger might have potential of success but large scale testing has not taken place yet. Focus on a favourable mechanical advantage, low mass and bulk and simplicity of the hybrid mechanism are important focus points when attempting to design a better hybrid prosthetic prehensor.

Chapter 5

Conclusions

It can be concluded that a well-designed prosthetic prehensor with a hybrid working principle would offer amputees a higher quality functionality than either a VO or VC device alone. In the scenario where users solely prefer one type of principle for all their tasks and activities this device will be able to perform just as well as a traditional prosthesis, while in all other scenarios the hybrid provides an unbeatable advantage by giving amputees any mode desired. Studies indicate the latter scenarios are far more likely to take place. Thus, a well-designed hybrid prehensor will improve the quality of life for many amputees that are currently dissatisfied with their prostheses.

Although eight hybrid designs have been developed, none of these have become successful products despite the predicted improvements in performance. This failure can be attributed to design flaws. Each hybrid concept manages the combination of VO and VC prehension in a different manner and each design suffers from a slightly different range of shortcomings. It is noted that mechanical advantage, mass and bulk and hybrid mechanism simplicity are important factors that strongly influence prosthesis performance. There are still possibilities for improving these existing concepts, applying them in different ways, or generating entirely new ways to combine VO and VC prehension. There is no reason to assume that the currently known number of hybrid concepts is the total amount, nor should it be assumed that performance cannot be improved further.

One of the causes of the high rejection and abandonment rates of upper limb body-powered prostheses is that the functional performance of currently available devices does not meet the expectations of users. With limited functionality causing disappointment, amputees opt to stop using their prosthesis altogether and leave it at home. Designs with better performance that do meet user expectations will help reduce rejection and abandonment rates.

The problem statement that was arrived at in the introduction of this report read:

Current body-powered upper limb prostheses do not offer amputees the desired performance, leading to rejection and abandonment

With this problem statement and all the above in mind it is the concluding recommendation of this literature study to both research ways of improving currently available hybrid terminal device designs as well as new hybrid concepts which avoid the pitfalls plaguing current hybrids. Particular focus should be put on ensuring favourable mechanical advantage in the mechanism, keeping its mass and bulk low and utilizing hybrid mechanisms that are as simple as possible. Doing so will yield new prosthetic devices that surpass contemporary voluntary opening and voluntary closing TD's in function and that will have a reducing effect on the rejection and abandonment phenomena. It is the opinion of the author that the full potential of hybrid terminal devices has yet to be reached.

Chapter 6

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.2. MATLAB model concept 8

Introduction

The final design choice consists of two options: concepts 6 and 8. A kinematic model of concept 8 is created in MATLAB to assess its suitability and potential. Concept 8 utilises a hybridization method distinct from existing hybrid TD designs and thus creates a category of its own. The active tong does not have a single point of rotation but instead a mechanism operated by the user locks one of two possible rotational points while simultaneously unlocking the other. A locked point still allows for rotation but prevents translation of the active tong at that location. Choosing the right attachment points for operating cable and springs on the active tong will result in the direction of rotation being opposite between the two settings. Attaching the two springs to either rotational point causes them to only produce torque in one of the two modes, having a zero moment arm in the other. The pinch and operating forces for each mode are wholly separate from one another, allowing the springs to be chosen separately. If desired a third mode can be added which keeps the prehensor in its closed position by locking both points of rotation. The mechanism can function with either extension springs or compression springs, with the case of compression springs illustrated in figure 1.

Matlab models

Using MATLAB, a simple 2D kinematic model of the concept is created describing the motions of the active tong in the plane. The model allows to decide which spring properties are necessary in order to generate the required pinch forces. In addition to these forces, design requirements regarding operating force demanded from the user, cable excursion, gripper opening width and total size and weight of the device have to be kept in mind. Three models are made in total. The first assumes compressive springs and a Bowden cable pulling on the active tong towards the user, as depicted in figure 1. The second instead assumes extension springs and a push input force away from the user. Finally, the third model simulates a conceptual design where, instead of two springs, a single extension spring attaches to the active tong at a point located in between the two points of rotation. In this design variant the single spring supplies both the pinch force during VO mode and a force holding the gripper opened in VC mode. Differences in spring elongation and moment arm between the modes cause the spring to generate different torques nonetheless. See table 1 at the end of this report for a full overview of the spring parameter values used as inputs for the models.

Model 1

The first model incorporates two compressive springs. Appropriate spring properties are found using trial and error until the pinch forces meet certain criteria. VO mode requires a pinch force (in black in figure 2) of at least 31.14 Newton[20] that is fairly independent of rotation angle. The requirements concerning VC mode are less specific. Eventually, a minimum input force of circa 3 Newton was chosen as requirement. This means that the user must generate a tensile force (shown in green in figure 2) of around 3 Newton to overcome the VC spring and start closing the gripper. This spring force should also be fairly independent of rotation angle.

To achieve the force behaviour seen in figure 2 a considerable amount of preload has to be stored in the compressive springs. When the gripper is closed the rightmost VO spring has a maximum length of only 20% of its original uncompressed length and is compressed until it is 8% of the original length at full VO opening. Similarly, the leftmost VC spring is compressed by up to 80%. Realistically there are no helical springs capable of such large compressions. An additional worrisome observation is the high required tensile force to fully open the gripper in VO mode; up to 190 Newton is demanded from the amputee. This approaches the maximum activation force of 256 Newton found in literature[22].

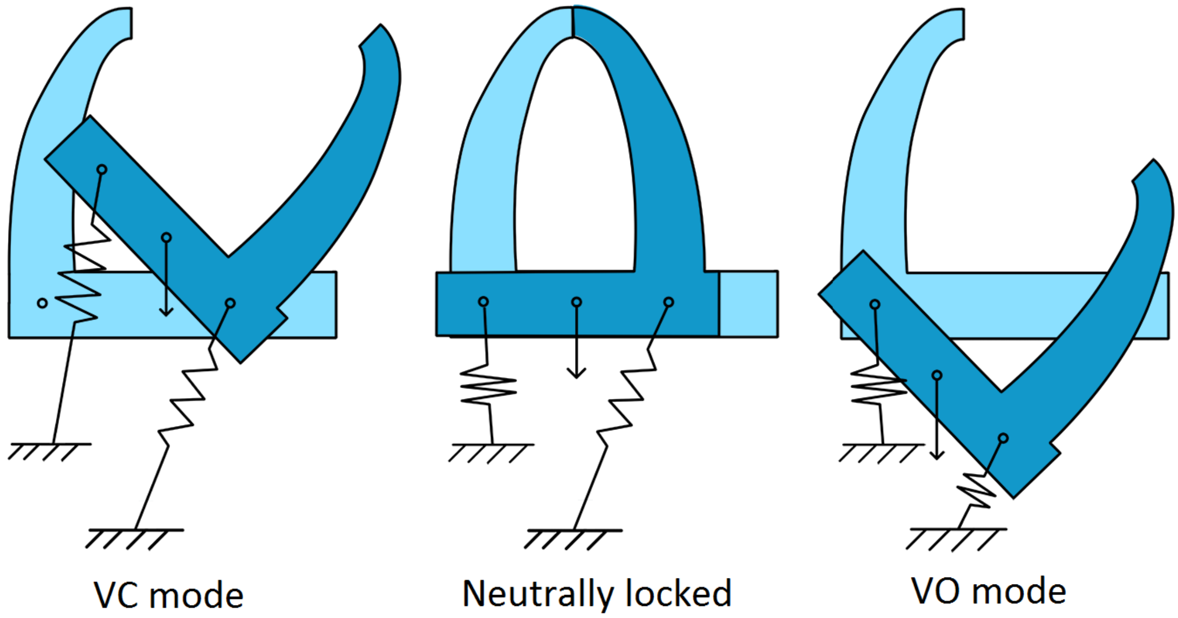


Figure 1: Conceptual design of concept 8 in three distinct phases of operation, with dark active tong and brighter passive tong. Here, spring elements are compression springs and the input force of the user is directed downwards.

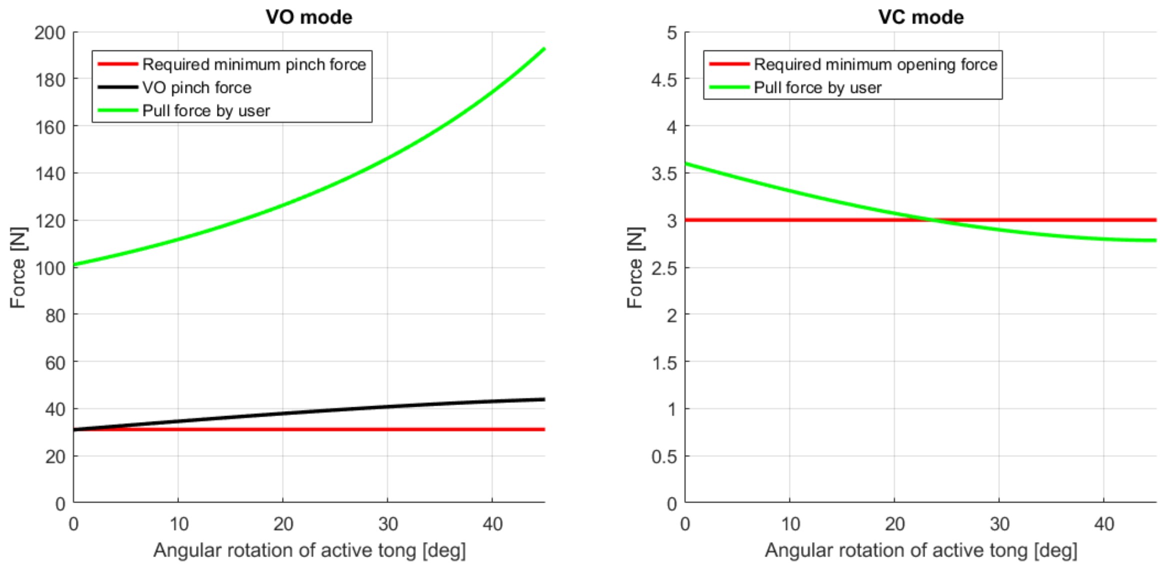


Figure 2: Graphs produced by model 1 showing, for both modes, spring and pinch forces against rotation angle of the active tong.

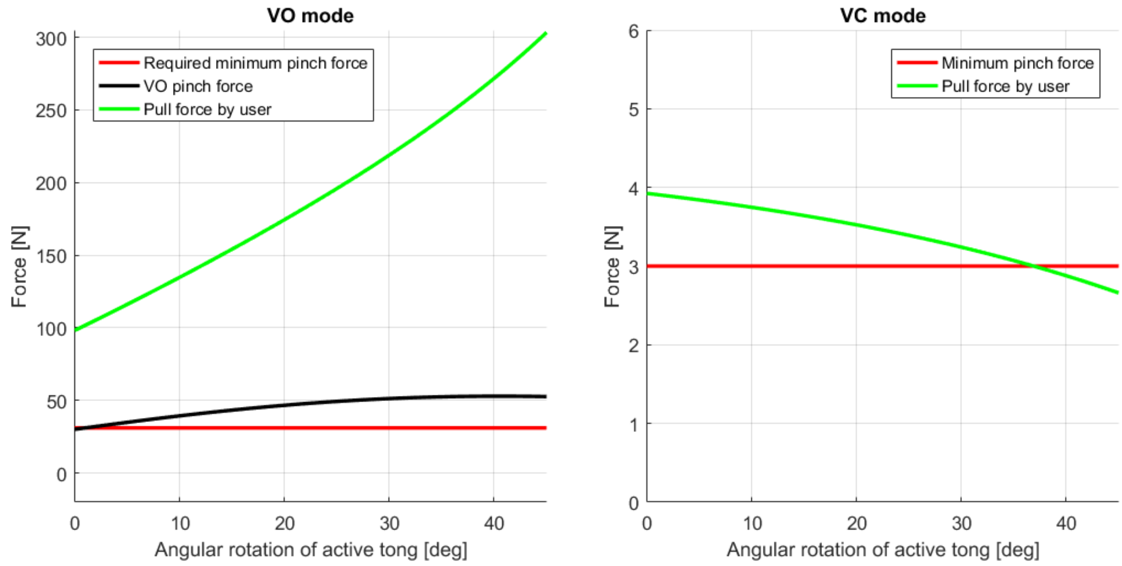


Figure 3: Graphs produced by model 2 showing, for both modes, spring and pinch forces against rotation angle of the active tong.

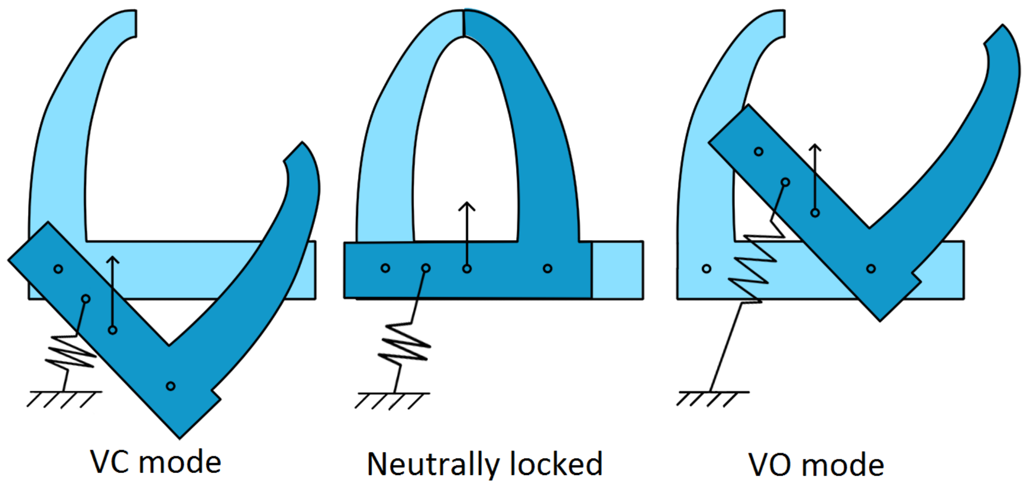


Figure 4: Model 3 variant of concept 8, only containing a single extension spring.

Model 2

A second model is made to research a version of concept 8 that utilizes extension springs. It is assumed that the user is capable of pushing against the active tong; something that is not directly possible with a Bowden cable but certainly feasible with some additions to the mechanism. The pinch force requirements remain the same. Again appropriate spring parameters were found through trial and error. Figure 3 shows spring and pinch force graphs for both modes with these parameters as input.

To achieve the results of figure 3 both springs undergo elongations of almost 200%. They are elongated to three times their original length, which seems extreme. Elastomer bands may prove suitable due to their tolerance to large elongations but hysteresis is an undesirable side-effect of this type of material. Moreover, just as in model 1 the input force to be provided by the prosthesis user in VO mode surpasses their abilities, as over 300 Newton is required for full opening.

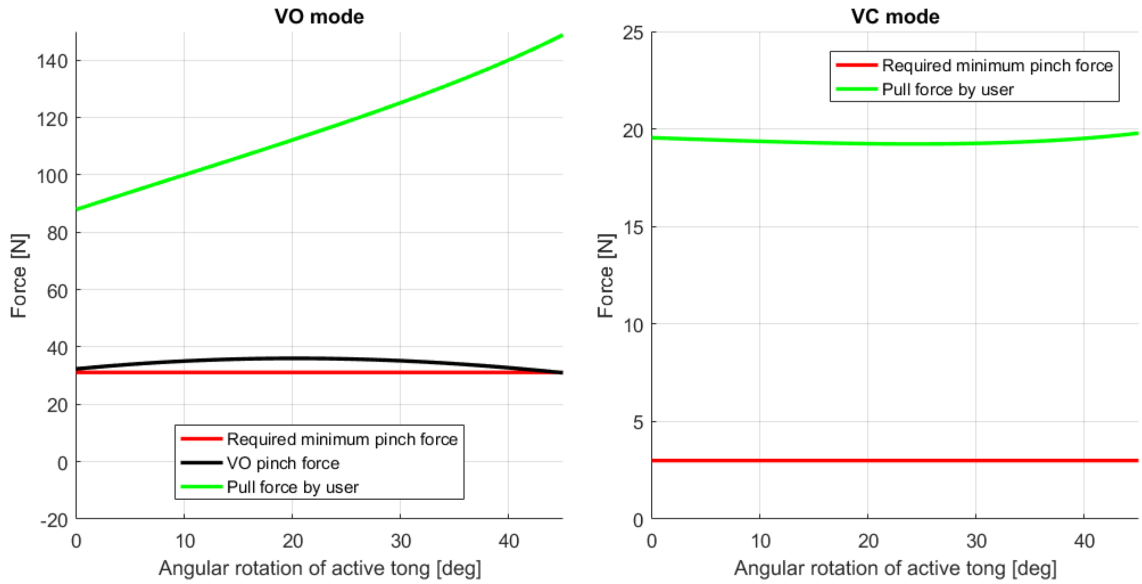


Figure 5: Graphs produced by model 3 showing, for both modes, spring and pinch forces against rotation angle of the active tong.

Model 3

A variant on the two-spring design is pictured in figure 4. A single extension spring is attached to the active tong, providing the necessary spring forces in both VO and VC modes. Differences in spring elongation and moment arm result in different torques experienced by the user, avoiding the common pitfall of identical spring forces between modes that most current single-spring hybrid terminal devices suffer from. Figure 5 presents the spring and pinch forces in both modes as produced by model 3. Only one spring stiffness, initial length and lower spring attachment point can be defined now, but the upper spring attachment point on the active tong is now also free to optimize.

A downside to reducing the number of springs from two to one is that the spring forces of both modes can no longer be optimized independently. While it may still be possible to get the various relevant forces near their ideal values it will prove tougher to do so. In figure 5 the VO input force (in green), while still high, is lower than the equivalent curves in figures 2 and 3. This was achieved at the expense of the input force in VC mode, which is now much higher than desired. Elongation problems are expected to be more difficult to resolve due to the dual role of the spring. With current properties the spring reaches a maximum elongation of 285% during VO opening and 168% when the gripper is closed.

Conclusions

Three variants of concept 8 have been kinematically modelled in MATLAB. The first variant seems to require compressive springs that shorten to unrealistically short lengths. The second and third variants utilize compressive springs and instead induce quite severe spring extensions. User input forces also approach undesired values in most cases. The models indicate that the mechanism functions as expected but cannot realistically be used within the set of requirements of this thesis.

While developing the three MATLAB models sets of spring parameter values were found through trial and error which resulted in force curves that approached desired shapes. Table 1 offers an overview of these parameter values that resulted in figures 2, 3 and 5. They are by no means optimal values but do offer some initial insights.

Table 1: List of spring parameters yielding approximately desirable results when inserted into the three MATLAB models. Listed are the values of spring stiffness *k*, initial spring length l_0, x- and y-coordinates of the lower spring attachment point P as measured from the left rotational point and maximum spring elongation or shortening Δl. As model 3 has only one spring the lower half of the column is empty.

		model 1	model 2	model 3
left spring	k [$\frac{N}{m}$]	15	1557	1200
	l_0 [mm]	150	40	30
	P [mm]	0, -30	-20, -70	15, -80
	Δl [%]	80	192	285
right spring	k [$\frac{N}{m}$]	200	30	
	l_0 [mm]	370	40	
	P [mm]	20, -60	0, -100	
	Δl [%]	92	189	

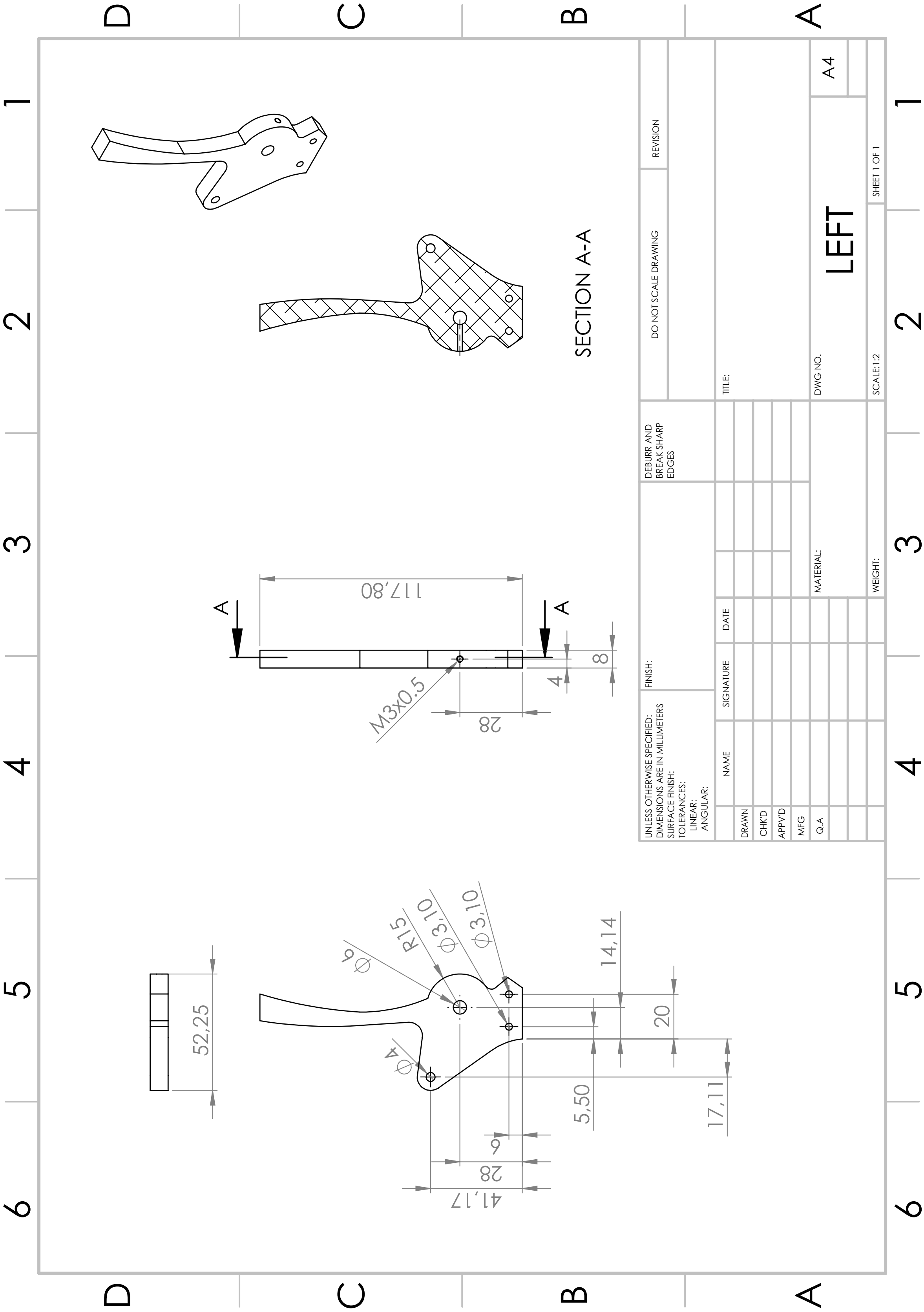
.3. MATLAB model of final design

```
clc
close all
clear all

%% Coordinates and Dimensions to Choose
% Requirements
Fpinch_req = 31.14;      % [N] minimum required pinch force (VO and VC)
VC_Fcable_req = 3;       % [N] estimated cable tension threshold in VC mode

l_fingers = 0.09;        % [m] length of all three fingers
w_middlefinger = 0.01; % [m] width of middle finger (as seen from side)
w_hookerbeam = 0.005;    % [m] diameter hooker beam (catches middle finger)

max_ang_bkwd = 50;       % [deg] -> VC action
max_ang_fwd  = 50;       % [deg] -> VO action

l_OB = 0.04;             % [m] length of hooker
l_OE = 0.02624;          % [m] distance rot. point to cable attachment point

VC_mech_advantage = l_OE/l_fingers; % [-] maximum mechanical advantage

% resulting opening widths using stated max angles and finger lengths
% (should be about 76.2mm)
opening_width_backwards = ...
    pdist([0 l_fingers; l_fingers*[sin(max_ang_bkwd*pi/180)...
    cos(max_ang_bkwd*pi/180)]],'euclidean'); % [m]
opening_width_forwards  = ...
    pdist([0 l_fingers; l_fingers*[sin(max_ang_fwd*pi/180)...
    cos(max_ang_fwd*pi/180) ]],'euclidean'); % [m]

theta0 = asin( (w_hookerbeam+w_middlefinger)*.5 / l_OB );
    % [rad] angle of hooker with vertical when at rest
theta0deg = theta0 *180/pi;

%% Spring Parameters to Choose

% VO spring (on the right) -> T31720 times two
k_AB  = 2.37*1000*2;% [N/m] strong VO spring stiffness
l0_AB = 37.1/1000;  % [m]    initial length
F0_AB = 9.56;       % [N]    initial force

A_x = 0.030;        % [m] location where VO spring connects to base
A_y = 0.014;        % [m] "

% VC spring (on the left) -> TR200
k_CD  = 0.17*1000;  % [N/m] weak VC spring stiffness
l0_CD = 20.20/1000; % [m]    initial length
F0_CD = 0.941;      % [N]    initial force

l_OC = 0.025;     % [m] distance rot. point to where VC spring attaches

%% FORWARDS (VO) Movement
theta = linspace(0, max_ang_fwd*pi/180)'...
    + theta0;                                 % [rad] hooker rotation fwd
thetadeg = theta*180/pi;

B_x = l_OB * -sin(theta);                     % [m] x-coord. of B fwd
B_y = l_OB * cos(theta);                      % [m] y-coord. of B fwd
AB_dist = sqrt((A_x-B_x).^2 + (A_y-B_y).^2); % [m] dist. A to B fwd

alpha = sin( (B_y-A_y) ./ (AB_dist) );        % [rad] spring force AB angle
alphadeg = alpha*180/pi;                      %             with horizontal

thetax = linspace(0, max_ang_fwd*pi/180)';
thetaxdeg = thetax*180/pi;
```

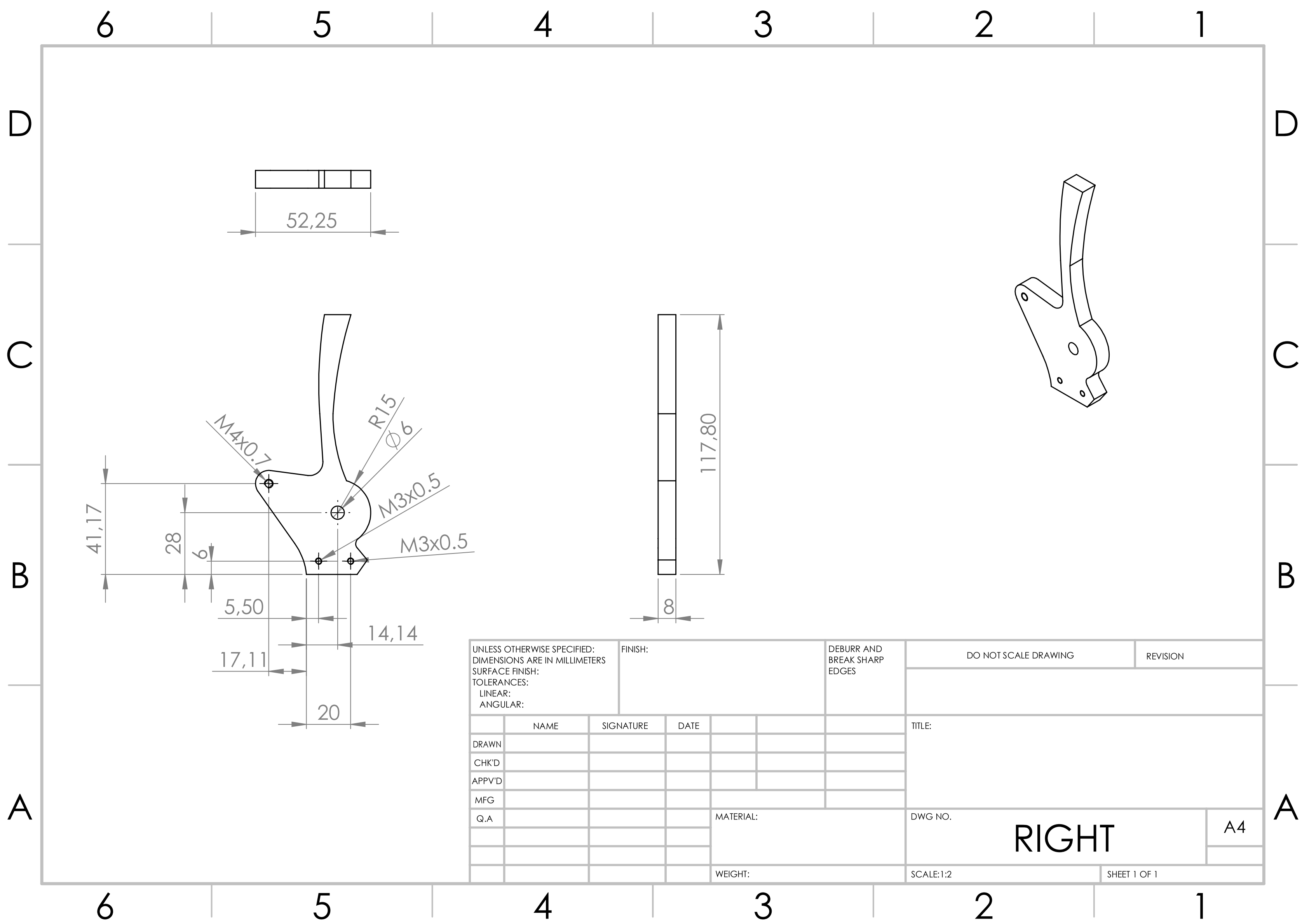
```
%% BACKWARDS (VC) Movement
phi = linspace(0, max_ang_bkwd*pi/180)';     % [rad] rotation backwards
phideg = phi*180/pi;

C_x = l_OB *-sin(theta(1));   % [m] location of point C (static)
C_y = l_OB * cos(theta(1));   % [m] "

D_x = l_OC *-cos(phi);                           % [m] x-coord. point D
D_y = l_OC * sin(phi);                           % [m] y-"
CD_dist = sqrt((C_x-D_x).^2 + (C_y-D_y).^2); % [m] dist. C to D

beta = sin( (C_y-D_y) ./ (CD_dist) );          % [rad] angle spring force CD
betadeg = beta*180/pi;

%% BACKWARDS (VC) Resulting Forces and Torques
F_CD_tang= (k_CD*(CD_dist + w_hookerbeam - l0_CD) + F0_CD ).*sin(phi+beta);
T_VC = F_CD_tang*l_OC;
F_cable_downward_BKWD = T_VC./(l_OE*cos(phi)); % [N] downward cable force
                                                % (approx. VC_Fcable_req)

% What downward cable tension is needed to generate 31.14N of pinch force?
F31N_VC = ( Fpinch_req*l_fingers + T_VC ) ./ (l_OE*cos(phi));

%% FORWARDS (VO) Resulting Forces and Torques
F_AB_tang= (k_AB*(AB_dist + w_hookerbeam - l0_AB)+F0_AB).*cos(theta+alpha);
T_VO = F_AB_tang*l_OB  +  T_VC(1);

F_cable_vertical_FWD = T_VO./l_OE;       % [N] vertical pull force

% hysteresis explanation
Fc = F_cable_vertical_FWD;
Fs = k_AB*(AB_dist + w_hookerbeam - l0_AB) + F0_AB;
Fsx = cos(alpha).*Fs;
Fsy = sin(alpha).*Fs;
Fw = sqrt( (Fc+Fsy).^2 + Fsx.^2 );
Tw = 0.25*Fw*(0.006/2);                  % [Nm] dry friction torque on axle
VO_friction_ratio = Tw./T_VO;


%% BACKWARDS (VC) Figures

figure
h1 = plot(phideg, F_cable_downward_BKWD);
grid on
hold on
h2 = line([phideg(1) phideg(end)], VC_Fcable_req*[1 1],'Color','k');
h3 = plot(phideg, F31N_VC);
axis([ [0 max_ang_bkwd] 0 180]);
title('Voluntary Closing Mode');
xlabel('angle phi of middle finger, backwards [deg]');
ylabel('Force [N]');
legend([h1 h2 h3],{'Downward cable tension to oppose spring',...
                   'Desired cable tension',...
                   'Downward cable tension required to pinch 31.14N'},...
                   'Location','NorthWest')

%% FORWARDS (VO) Figures

figure
h3 = plot(thetadeg, F_cable_vertical_FWD);
grid on
hold on
h4 = plot(thetadeg, T_VO/l_fingers);
h5 = line([thetadeg(1) thetadeg(end)], Fpinch_req*[1 1],'Color','k');
axis([ theta0deg+[0 max_ang_fwd] 0 210]);
title('Voluntary Opening Mode');
xlabel('angle theta of middle finger, forwards [deg]');
ylabel('Force [N]');
legend([h3 h4 h5],{'Downward cable tension to oppose spring',...
                   'Pinch force by spring','Desired pinch force'},...
                   'Location','NorthWest')
```

```
%% MISCELLANEOUS FIGURES

F_c_downward_COMBO = [flipud(F_cable_downward_BKWD); F_cable_vertical_FWD];
angles_COMBO = [phideg; thetaxdeg+phideg(end)];

F_netpinchforce_COMBO = [-flipud(F_cable_downward_BKWD); T_VO/l_fingers];
F_activationforce_31N = [flipud(F31N_VC); F_cable_vertical_FWD];

angles1 = phideg;
angles2 = thetaxdeg+phideg(end);
excursion1 = abs(20.913 - 27.3*sin( (50-angles1)*pi/180 ));
excursion2 = 20.913 + ((angles2-50)/50)*27.3*(50*pi/180);
excursion_COMBO = [excursion1;excursion2];

figure
h6 = plot(excursion_COMBO, F_c_downward_COMBO,'Color','r');
hold on
grid on
axis([0 50 0 140])
axis square
title('Full cycle of cable excursion', 'FontSize', 12);
xlabel('cable excursion [mm]');
ylabel('activation force [N]');
set(h6,'LineWidth',3);

figure
h8 = plot(angles_COMBO, F_netpinchforce_COMBO,'Color','r');
axis([0 100 -5 40]);
axis square
title('pinch force something');
xlabel('rotational angle of middle finger [deg]');
ylabel('Vertical cable force [N]');

figure
h88 = plot(angles_COMBO, F_activationforce_31N,'Color','r');
set(h88,'LineWidth',3);
grid on
axis([0 100 0 180]);
axis square
set(gca,'FontSize',12);
title(char('Required activation force for',...
      '31.14 N pinch (VC) or opening (VO)'), 'FontSize', 12);
xlabel('Percentage of maximum rotation [%]', 'FontSize', 12);
ylabel('Cable force [N]', 'FontSize', 12);

figure
h99 = plot(excursion_COMBO, F_activationforce_31N,'Color','r');
set(h99,'LineWidth',3);
grid on
hold on
plot(17.9, 100,'.','MarkerSize',20,'Color','k');
axis([0 43 0 180]);
axis square
set(gca,'FontSize',12);
title(char('Required activation force for',...
       '31.14 N pinch (VC) or opening (VO)'), 'FontSize', 12);
xlabel('cable excursion [mm]', 'FontSize', 12);
ylabel('Cable force [N]', 'FontSize', 12);
legend('MATLAB model','VC test 3','Location','NorthEast')
```

.4. Design drawings



LEFT
SECTION A-A
A
117,80
M3X0.5
28
4
8
52,25
R15
⌀9
⌀3,10
⌀3,10
⌀4
14,14
20
5,50
17,11
6
28
41,17
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
MATERIAL:
DWG NO.
A4
WEIGHT:
SCALE:1:2
SHEET 1 OF 1


52,25
117,80
8
R15
Ø6
M4x0.7
M3x0.5
M3x0.5
41,17
28
6
5,50
17,11
14,14
20
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
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NAME
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DATE
DRAWN
CHK'D
APPV'D
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Q.A
TITLE:
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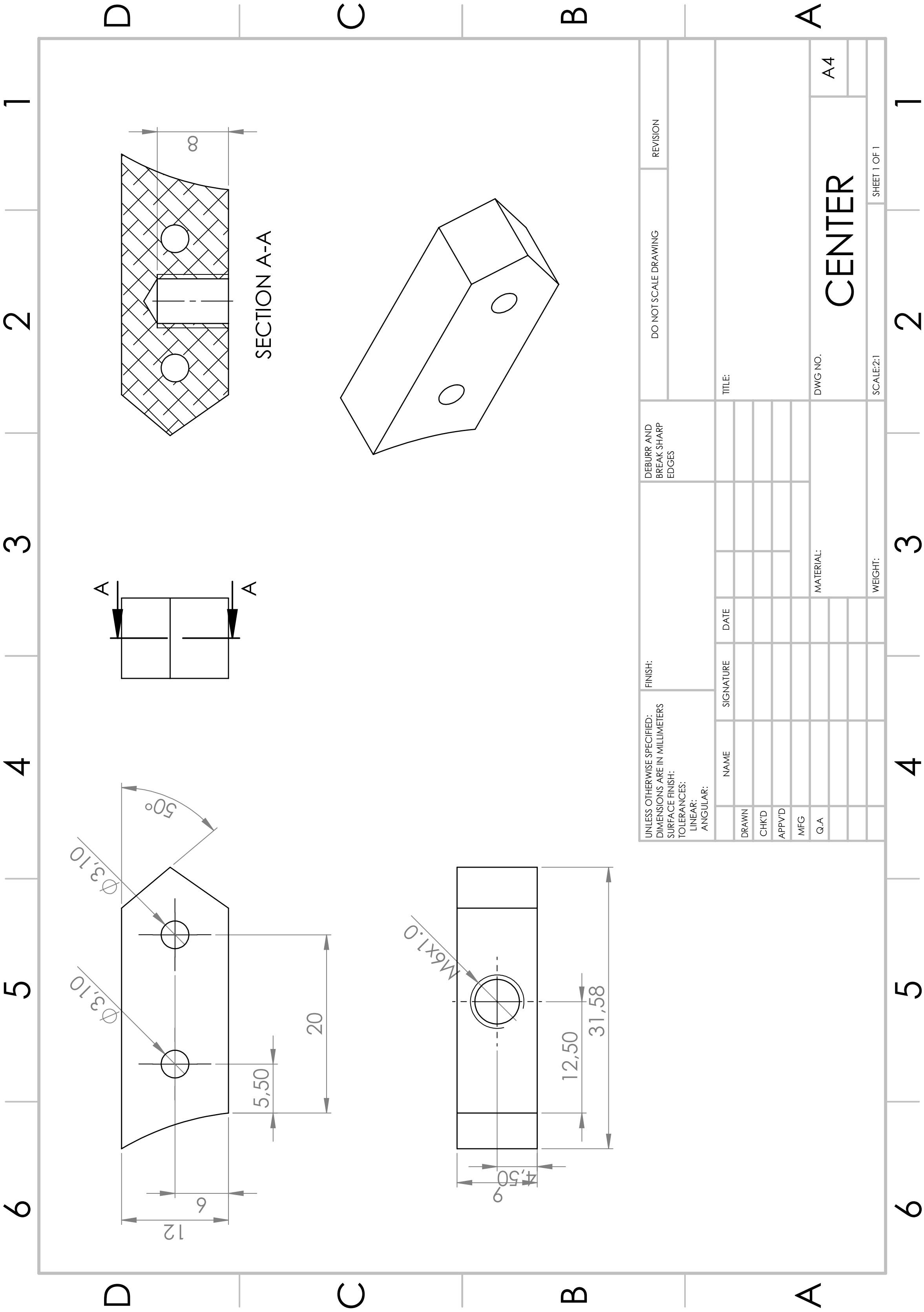
DWG NO.
RIGHT
A4
WEIGHT:
SCALE:1:2
SHEET 1 OF 1


SECTION A-A
A
A
8
20
5,50
12
6
Ø3,10
Ø3,10
50°
M6x1.0
12,50
31,58
4,50
9
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
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NAME
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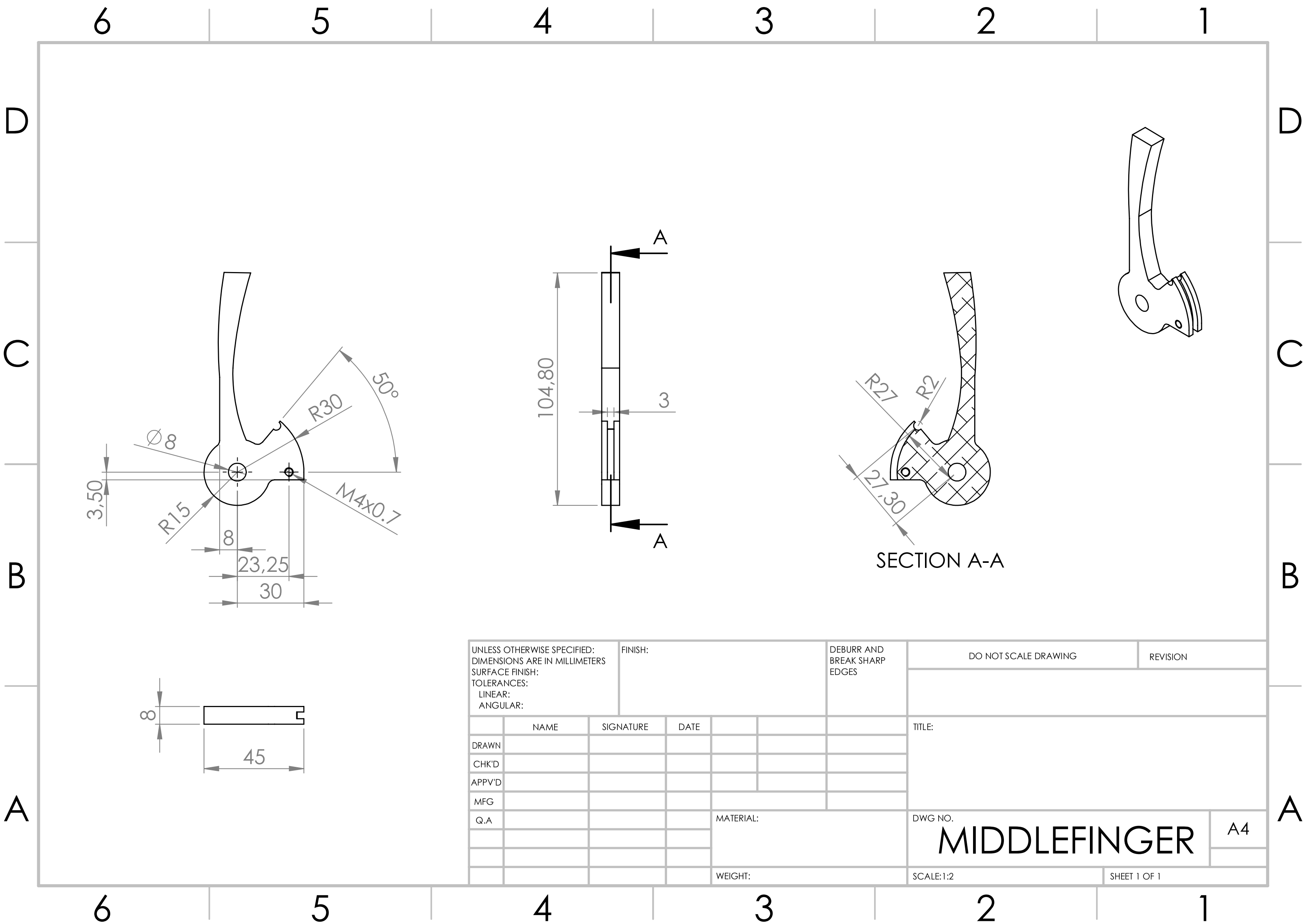
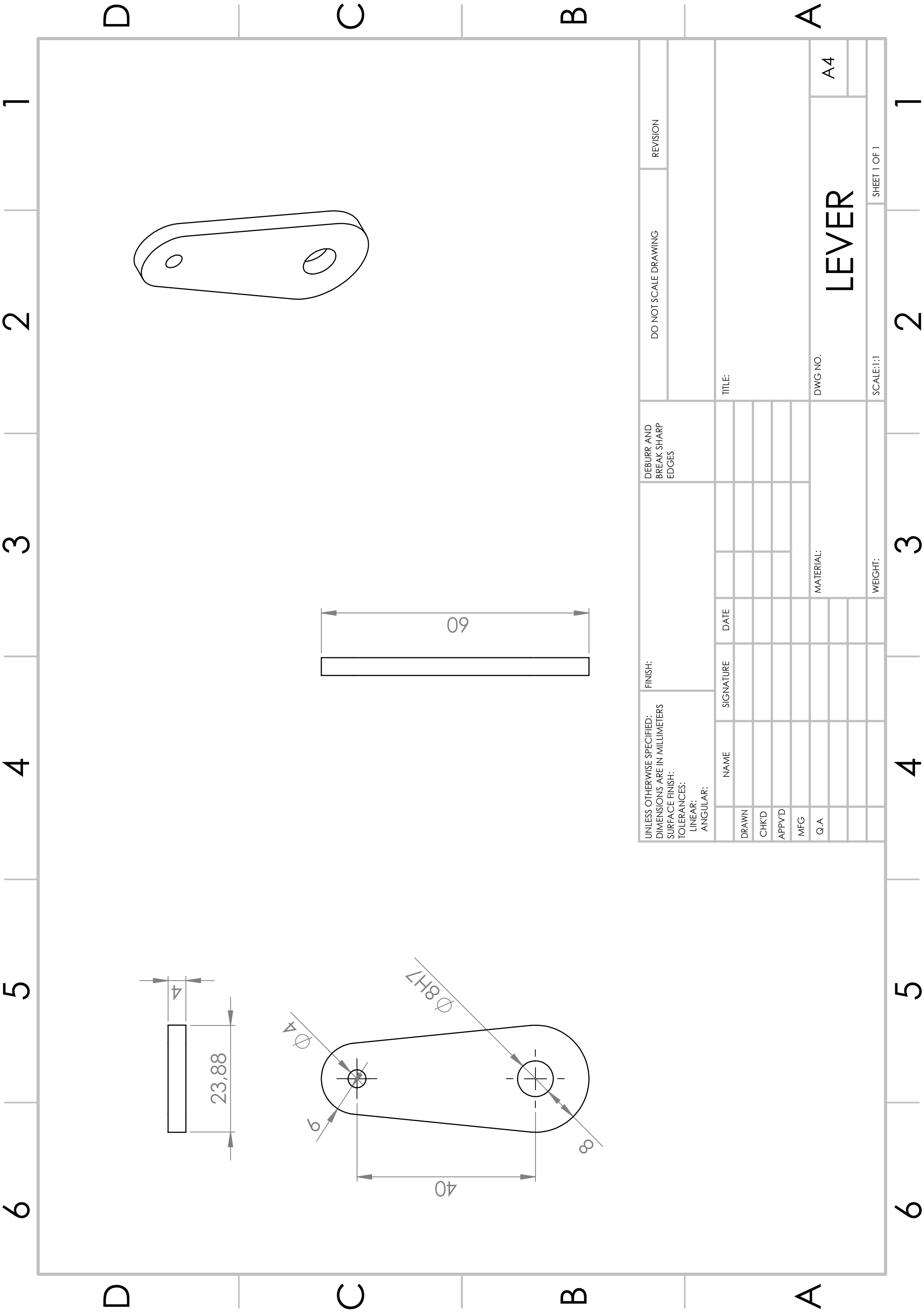
DATE
TITLE:
DRAWN
CHK'D
APPV'D
MFG
Q.A
MATERIAL:
DWG NO.
CENTER
A4
WEIGHT:
SCALE:2:1
SHEET 1 OF 1


Ø8
R30
50°
3,50
R15
M4x0.7
8
23,25
30
8
45
104,80
3
A
A
R27
R2
27,30
SECTION A-A
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
MATERIAL:
DWG NO.
MIDDLEFINGER
A4
WEIGHT:
SCALE:1:2
SHEET 1 OF 1


DO NOT SCALE DRAWING
REVISION
UNLESS OTHERWISE SPECIFIED:
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SURFACE FINISH:
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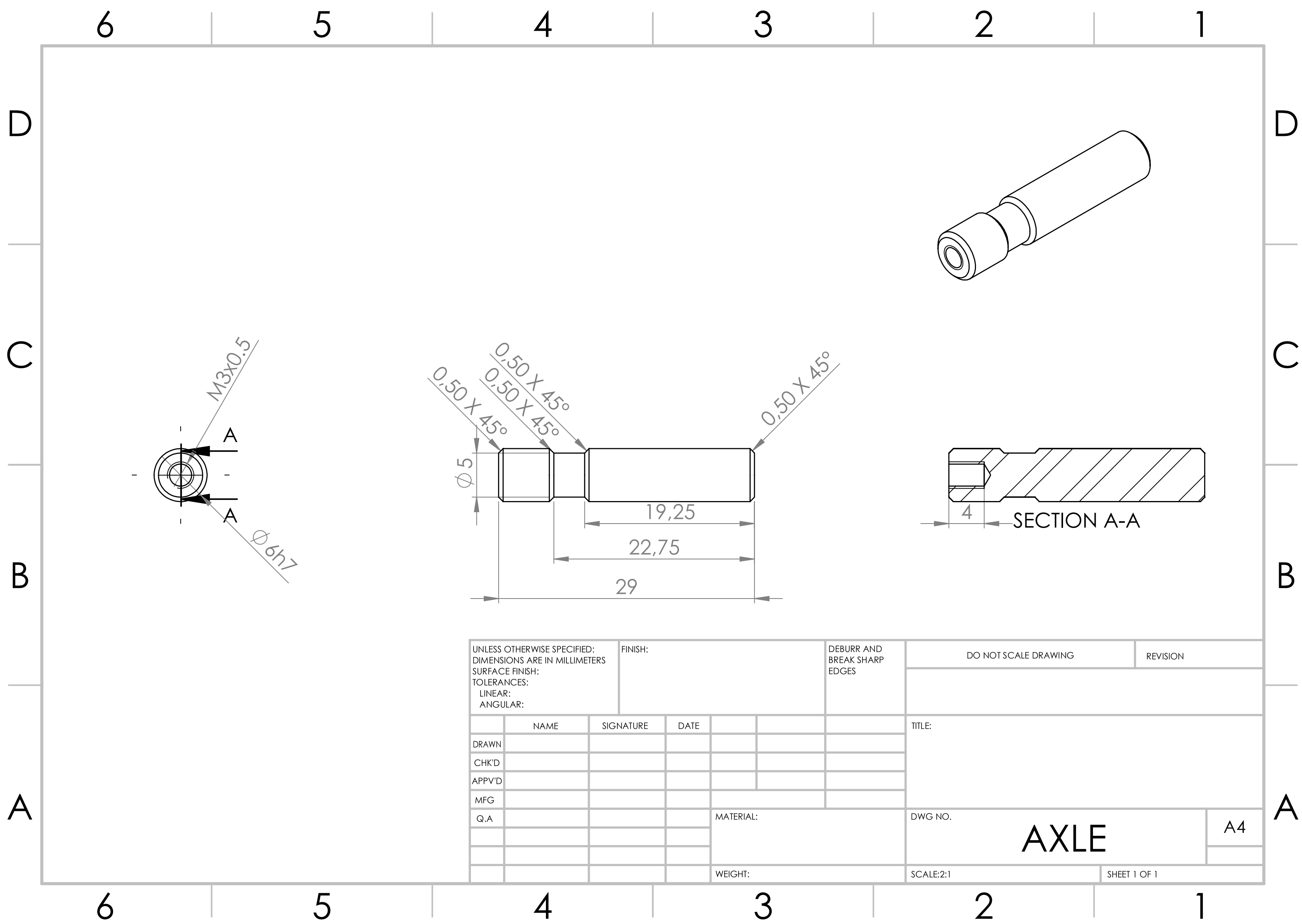
LINEAR:
ANGULAR:
FINISH:
DEBURR AND BREAK SHARP EDGES
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
MATERIAL:
WEIGHT:
TITLE:
DWG NO.
LEVER
SCALE:1:1
SHEET 1 OF 1
A4
60
4
23,88
Ø4
Ø8H7
6
8
40


M3x0.5
A
A
⌀6h7
0,50 X 45°
0,50 X 45°
0,50 X 45°
0,50 X 45°
⌀5
19,25
22,75
29
4
SECTION A-A
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
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NAME
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DATE
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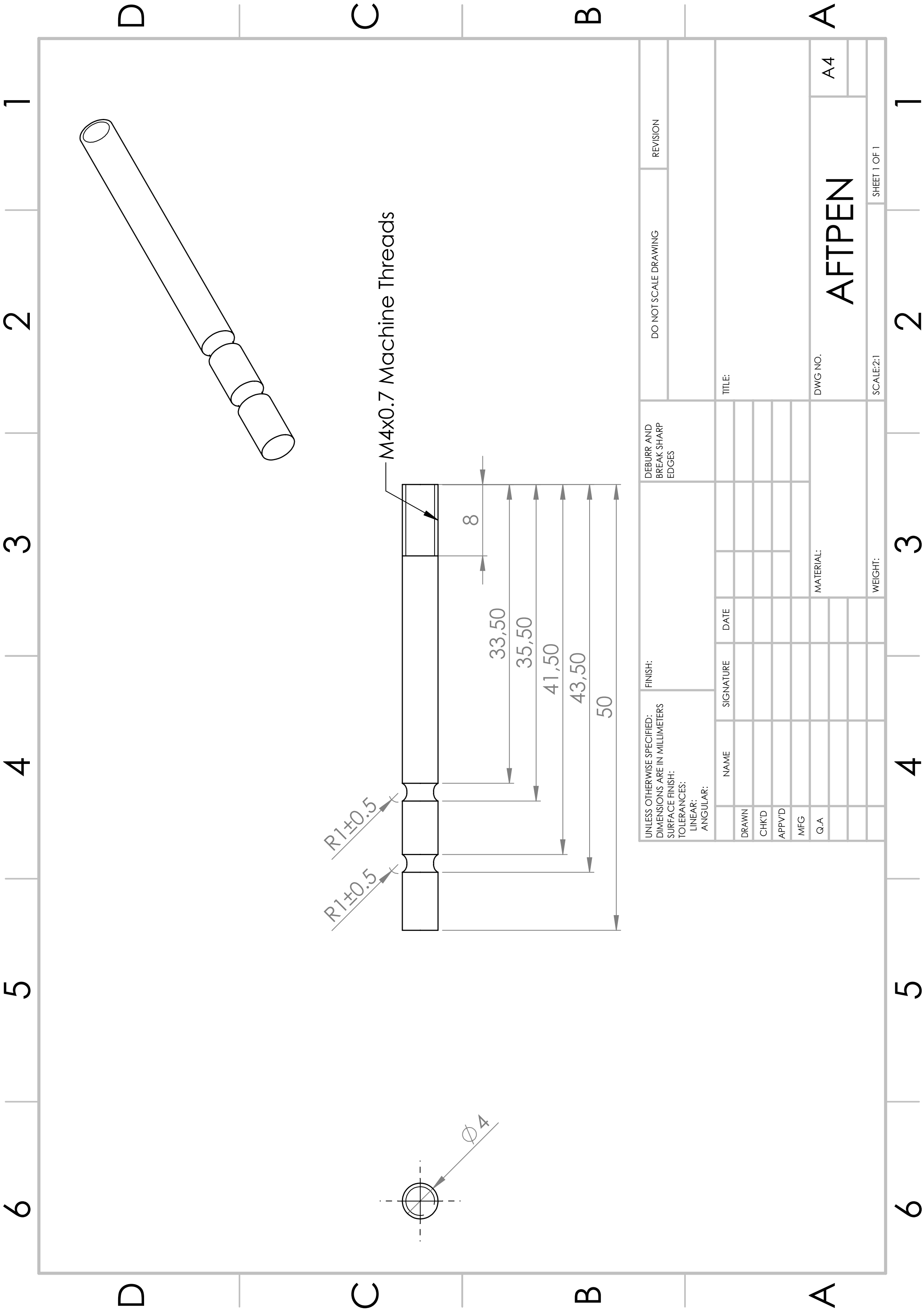
CHK'D
APPV'D
MFG
Q.A
TITLE:
MATERIAL:
DWG NO.
AXLE
A4
WEIGHT:
SCALE:2:1
SHEET 1 OF 1
6 5 4 3 2 1
D C B A


M4x0.7 Machine Threads
8
33,50
35,50
41,50
43,50
50
R1±0.5
R1±0.5
⌀4
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
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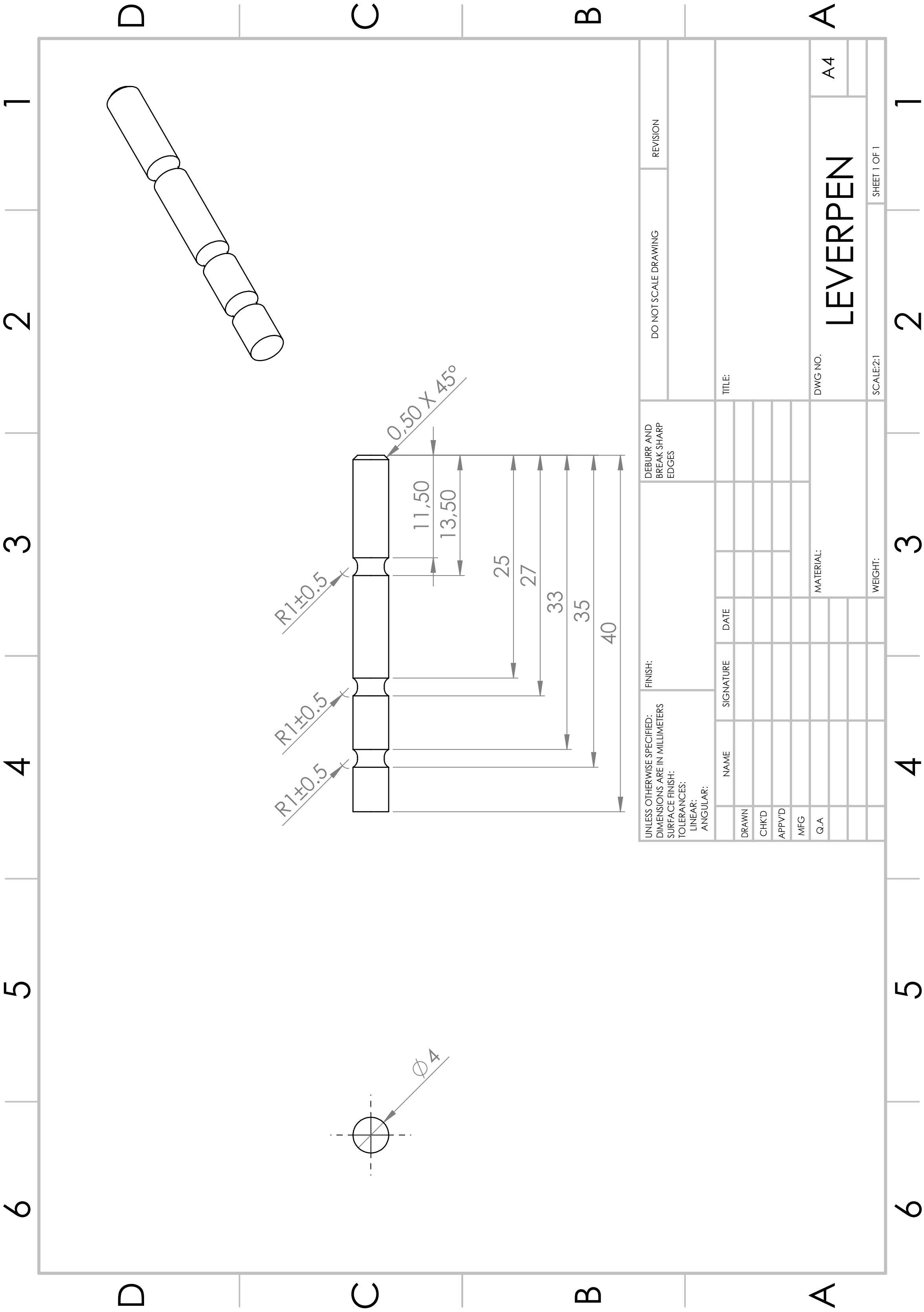
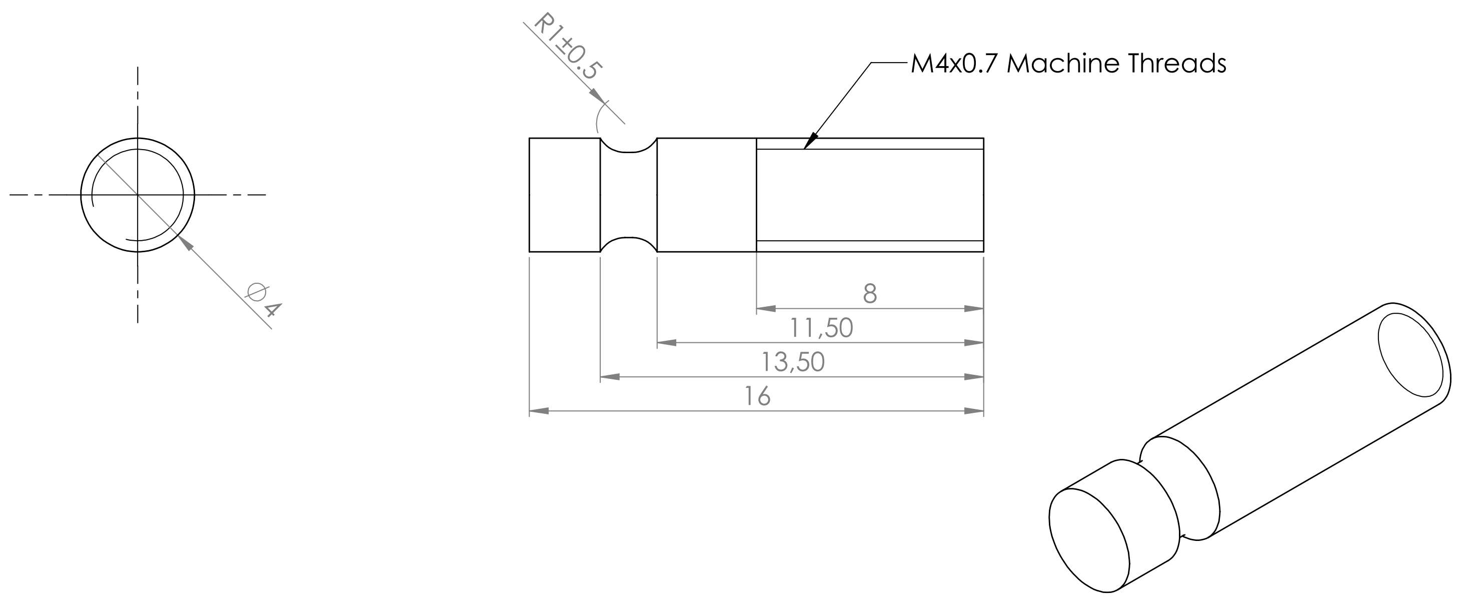
TITLE:
MATERIAL:
DWG NO.
AFTPEN
A4
WEIGHT:
SCALE:2:1
SHEET 1 OF 1


LEVERPEN
0,50 X 45°
11,50
13,50
25
27
33
35
40
R1±0.5
R1±0.5
R1±0.5
Ø4
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
MATERIAL:
DWG NO.
A4
WEIGHT:
SCALE:2:1
SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
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ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

WEIGHT:

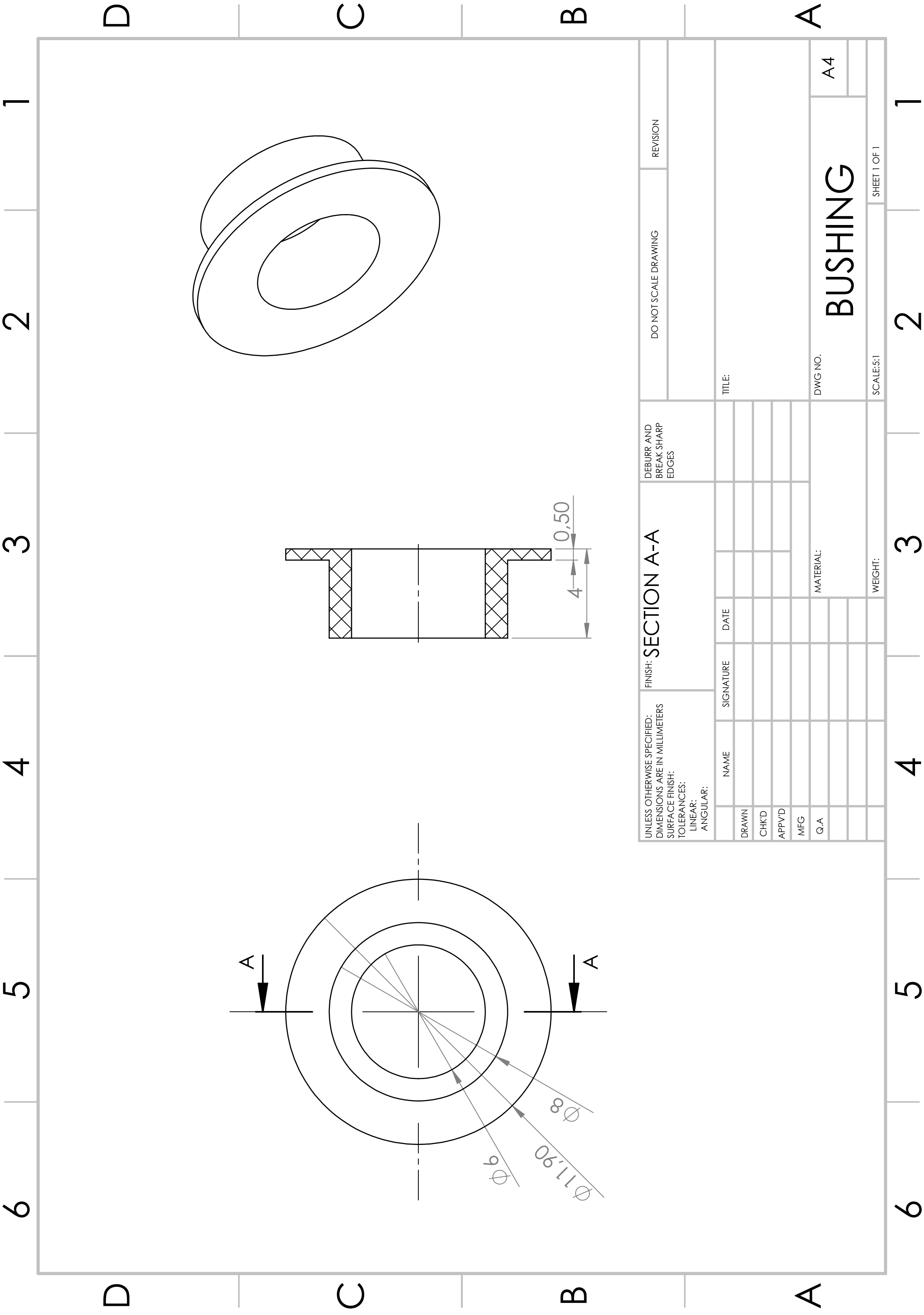
DWG NO.

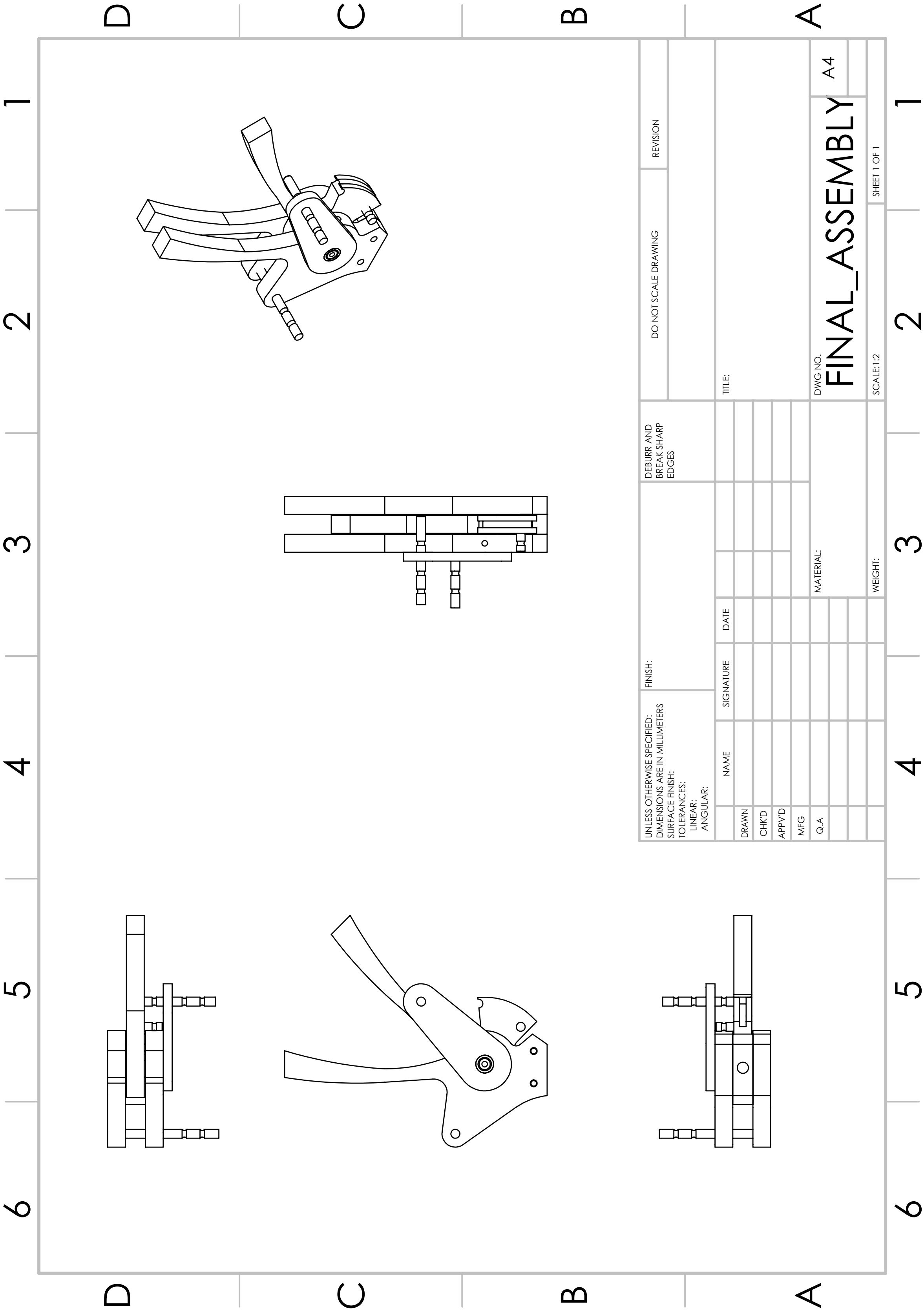
FANPEN

A4

SCALE:5:1

SHEET 1 OF 1


BUSHING
SECTION A-A
DO NOT SCALE DRAWING
REVISION
DEBURR AND BREAK SHARP EDGES
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
DWG NO.
MATERIAL:
WEIGHT:
SCALE:5:1
SHEET 1 OF 1
A4
0,50
4
Ø8
Ø9
Ø11,90
A



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
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FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
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DRAWN
CHK'D
APPV'D
MFG
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TITLE:
MATERIAL:
DWG NO.
FINAL_ASSEMBLY
A4
WEIGHT:
SCALE:1:2
SHEET 1 OF 1

.5. User preference motivations

Table 2: Compilation of the various motivations participants have given for preferring one mode over the other. Also listed are the total amount of times a particular motivation has been mentioned.

Preferred mode	Reason given for preference	Amount
VO	Less mental effort required to maintain grip	22
	More grip, or better grip	20
	Less physical effort required to maintain grip	13
	Location/orientation of tongs facilitates action	11
	Static tongs can be used as support	6
	No extra effort required to maintain grip during complex movements	6
	Easier to let go	6
	Object fits better into gripper	2
	Passive tongs stay in the right spot while active tong moves	1
	Easier to get a large gripper opening	1
VC	Finer control over object	31
	Letting go of objects requires less effort/movement	20
	Location/orientation of tongs facilitates action	16
	Able to exert more pinch force	14
	The pinch force needed to lift the object is modest	11
	Better tong placement possible	10
	Better control over pinch force	9
	Static tongs can be used as support	7
	less effort required	6
	Less excursion needed	2
	More clear when to let go	1
	Starting position better facilitates pronation/supination	1