A voluntary closing mechanism for the WILMER appealing prehensor

Master of Science Thesis

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September 4, 2020

Master of Science: Biomedical Engineering

Department of Biomechanical Engineering

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Introduction

Today is probably a regular day for you. You were woken up by your alarm clock, got up, took a shower, brushed your teeth and dressed yourself. You made yourself breakfast and had a cup of coffee. You left your house and drove to work, maybe you stopped by a gas station to fill up your tank. At work you greeted your colleagues and got your work done. After work you maybe met with friends or went exercising. Back at home you cooked dinner and enjoyed your meal. And after a relaxed evening with a movie or a book, you made yourself ready for bed for a good night of sleep. Nothing special right? Now, think about this day while missing a hand. Suddenly, your day is not as easy as it seemed.

Our hands are incredibly important. We constantly use our hands in our everyday living. Not only to perform our activities of daily living, but also to emotionally express ourselves [1, 2]. Usually, we are not aware of the importance of our hands. But for people with an upper limb deficiency, this is totally different. The missing limb heavily impacts their everyday live, because many functions of their upper limb are lost.

Upper limb prosthetics

In order to replace the missing limb, people with an upper limb deficiency can use a prosthesis. Prostheses are designed to restore some of the lost functions and to support the user in activities of daily living [3, 4, 1, 5, 6, 7]. Currently, three types of prostheses are available for people with an upper limb deficiency: cosmetic, externally powered (EP), and body-powered (BP).

Cosmetic prostheses are passive devices mainly chosen for aesthetic reasons. The appearance of a cosmetic prosthesis is often comparable to a human-like hand, providing the user with a more natural look and feel. For many users cosmetic prostheses fulfil a functional role as well, especially in stabilizing objects. However, cosmetic prostheses do not provide a grasping function which can be actively controlled by the prosthetic user [4, 8, 9, 10].

EP and BP prostheses do offer prosthetic users an actively controllable grasping function. EP prostheses are powered by an external energy source, such as electricity. A common control type for EP prostheses is myo-electric control. Prehension of a myo-electric prosthesis is activated by electromyography (EMG) signals from muscles present in the stump or other body parts of the prosthetic user [11, 4, 12]. BP prostheses are controlled entirely mechanical. Prehension of a BP prosthesis is directly coupled to the movement of an intact joint. BP prostheses can either be harness-controlled, in which the movement of the contra-lateral shoulder is captured by a figure-nine shoulder harness (Figure 1), or elbow-controlled, in which the flexion/extension of the ipsi-lateral elbow is captured by an elbow-pad (Figure 2). The captured movement of the intact joints is then transferred via a Bowden-cable to the terminal device, which replaces the function of the hand [13, 14, 7, 15, 2, 16, 17, 18, 19]. The force and displacement in the Bowden-cable are directly coupled to the force and displacement of the terminal device. Therefore, BP prostheses have the ability to provide the prosthetic user with direct feedback through proprioception. EP prostheses, on the other hand, rely mainly on visual feedback. Proprioceptive feedback is much faster and easier to interpret than visual feedback. The presence of proprioceptive feedback is a clear advantage of BP prostheses, resulting in a preference for BP control [14, 20, 7, 2, 21, 17, 19].

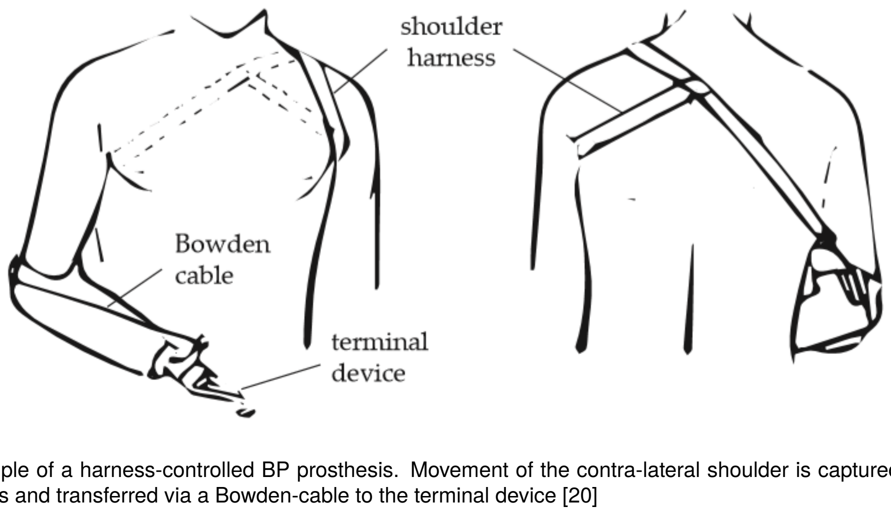

Figure 1: Example of a harness-controlled BP prosthesis. Movement of the contra-lateral shoulder is captured by a figure-nine shoulder harness and transferred via a Bowden-cable to the terminal device [20]

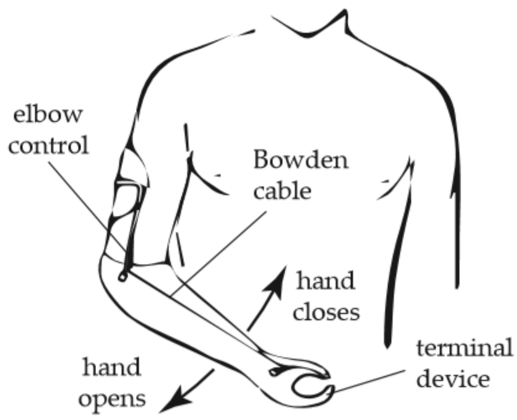

Figure 2: Example of an elbow-controlled BP prosthesis. Flexion/extension of the ipsi-lateral elbow is captured by an elbow-pad and transferred via a Bowden-cable to the terminal device [20]

The WILMER appealing prehensor

The WILMER appealing prehensor is a BP prosthesis for people with a trans-radial upper-limb deficiency [22]. The prosthesis is currently also known as the Tweezer. The design of the prosthesis is based on the standard split-hook prosthesis (Figure 3) [22, 23, 24]. The split-hook prosthesis owns its name to its terminal device, which is a cloven hook. The cloven hook consists of a stationary and a rotary finger. Movement of the rotary finger is harness-controlled. The rotary finger is connected to a figure-nine shoulder-harness via a Bowden cable. Motion of the rotary finger is achieved by tensioning the Bowden cable through movement of the contra-lateral shoulder [16, 18].

Unfortunately, the standard split-hook prosthesis was often rejected by prosthetic users. Although hook-like terminal devices in general show better mechanical efficiency than hand-like terminal devices [25, 26], the necessary input forces to operate the prostheses were still experienced as too high. Furthermore, the standard split-hook prosthesis had a deterring outward appearance [22, 23, 24]. To tackle these flaws, some important adjustments have been made to the mechanism and design of the standard split-hook prosthesis, eventually resulting in the WILMER appealing prehensor (Figure 4) [22].

Various aspects of the split-hook have been adjusted in order to improve the outward appearance. First of all, the volume and length of the finger tips and position of the rotary finger were adapted to an anatomical hand. Second, the connection to the forearm was made smooth and harmonic. Furthermore, all the mechanical parts were placed into the frame and therefore out of sight. This not only improved the outward appearance, but also reduced the wear and tear of clothing. Lastly, the frame was enclosed by a cosmetic cover. This cover can have any color preferred by the prosthetic user. Furthermore, the cover can be easily removed to be interchanged if another color is preferred. The mechanism underneath the cover remains easily accessible if maintenance is necessary [22, 23]. In order to improve the force transmission ratio, a four-bar linkage mechanism was applied to the prosthesis. Figure 5 shows the cross section of the WILMER appealing prehensor, exposing the four-bar linkage mechanism. The four-bar linkage mechanism resulted in a reduction of the necessary input forces and a constant output force over the full range of motion [22, 23]. Currently, the WILMER appealing prehensor is highly appreciated because of its functionality and appearance [22, 23].

Prehension

The terminal device of a BP prosthesis is operated with only one cable. Therefore, BP prostheses have only one controllable degree of freedom. In order to enable the ability to grasp, the controllable degree of freedom is used to either open or close the terminal device. Prehension of the terminal devices is then referred to as voluntary opening (VO) or voluntary closing (VC), respectively (Figure 6) [20].

A VO terminal device is kept closed by a spring in its default state. In order to grasp an object, the prosthetic user actively opens the terminal device by tensioning the Bowden cable. Once the prosthetic user releases the tension in the Bowden cable, the terminal device is enclosed around the object by the spring and the object is grasped [13, 6, 27, 28, 29, 30, 19]. A VC terminal device is kept opened by a spring in its default state. In order to grasp an object, the prosthetic user actively closes the terminal

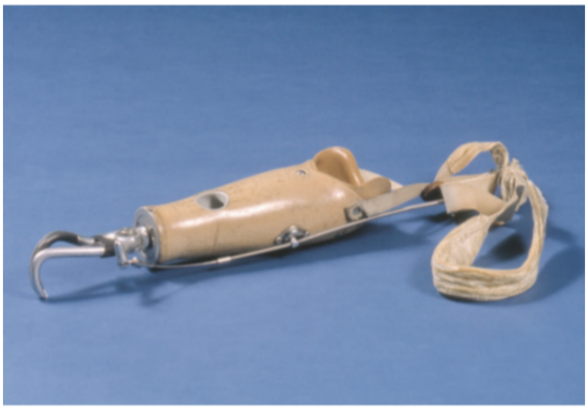

Figure 3: Example of the standard split-hook prosthesis. The split-hook prosthesis owned its name to its terminal device which is a cloven hook. Movement of the cloven hook is harness-controlled [22].

Figure 4: The WILMER appealing prehensor. The terminal device is based on the standard split-hook prosthesis. The cosmetic cover allows the prosthetic user to adjust the color to their preferences[22].

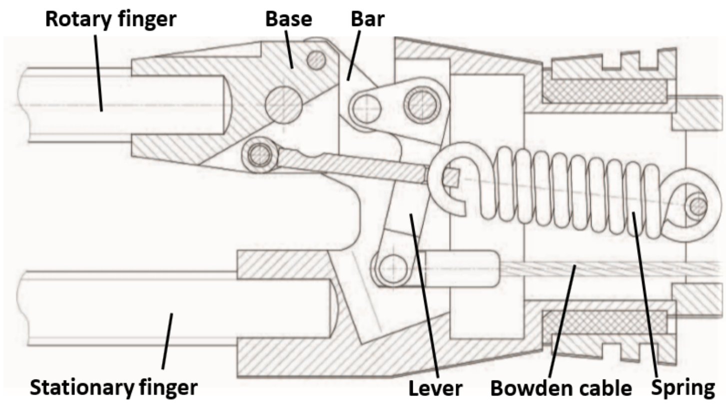

Figure 5: Cross section of the VO Tweezer. The four-bar linkage mechanism enables VO prehension. Modified from [22].

device around the object by bringing the Bowden cable under tension. In order to hold the object, the Bowden cable must be kept under tension [13, 6, 27, 28, 29, 30, 19].

Just like most BP prostheses, prehension of the WILMER appealing prehensor is VO. The Bowden cable is connected to a lever. The lever is linked to the base of the rotary finger via a bar-linkage. Tensioning of the Bowden cable results in a counterclockwise rotation of the lever, causing a displacement of the bar. The displacement of the bar results in a clockwise rotation of the rotary finger, and thus opening of the terminal device. Once the tension in the cable is released, the terminal device is closed again by the spring (Figure 5).

Voluntary opening vs. Voluntary closing

The VO prehension of the WILMER appealing prehensor shows one clear advantage: once an object is grasped and the terminal device is enclosed around the object, the grip force to hold the object is provided by the spring. Therefore, the prosthetic user can relax while holding the object and moving it around [13, 31, 6, 7, 32, 33, 27, 34]. However, the VO prehension also has its flaws. The amount of grip force generated with a VO terminal device cannot be actively controlled, but is determined by the stiffness and pre-tension of the spring closing the device. This means that the prosthetic user cannot exert more force than generated by the spring, limiting the variety of objects which can be handled. Furthermore, each time the user of a VO terminal device grasps an object, the force of the spring must be overcome. For some objects the grip force generated by the spring is larger than necessary, resulting in excessive energy expenditure [13, 6, 33, 27]. In contrast, VC prehension provides the ability to regulate grip force. The prosthetic user can apply the exact grip force necessary by adjusting the tension in the Bowden cable. Therefore, a wide variety of objects can be handled with a VC terminal device and no excessive energy expenditure is required [13, 35, 6, 32, 36, 37, 27, 38].

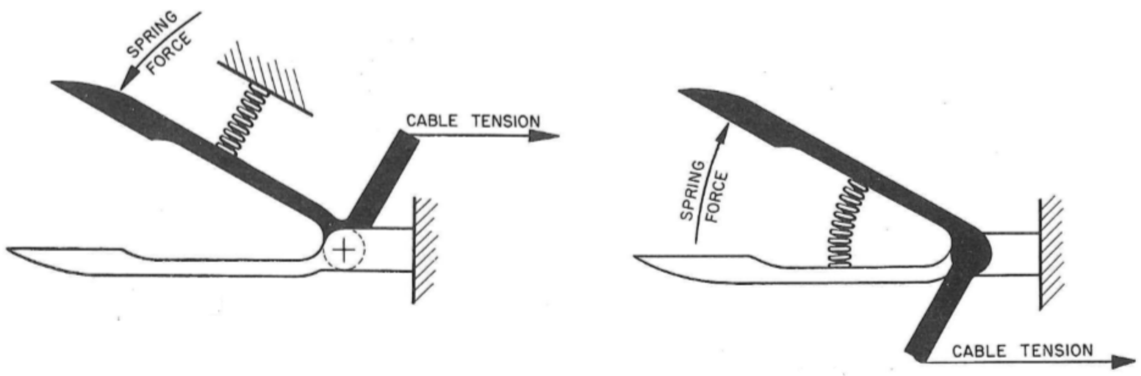

Figure 6: *Left:* VO prehension. *Right:* VC prehension. A compression spring returns the terminal devices back to their default state once cable tension is released. [6]

As mentioned previously, an important feature of BP terminal devices is that the prosthetic user receives force feedback via proprioceptive cues. This applies for both VO and VC prehension. However, the working mechanism of a VO terminal device is exactly opposite to that of an anatomical hand, making it difficult to interpret the force feedback. The working mechanism of a VC terminal device is compatible with the functionality of an anatomical hand. This compatibility results in logical force feedback for the prosthetic user. Therefore, force feedback is more easily assimilated using a VC terminal device instead of a VO terminal device [14, 5, 31, 33, 17, 36, 34, 29, 30, 19].

VC prehension also shows some drawbacks. To hold an object, the prosthetic user must keep the Bowden cable under tension in order to maintain grip force. This often causes fatigue and discomfort when an object has to be held for a prolonged period [13, 7, 27, 28]. Furthermore, the open default state of VC prehension is often considered as less attractive, and increases the wear and tear of clothing [13, 39, 28, 7]. However, both these problems could be solved by equipping the prosthesis with a locking mechanism. With a locking mechanism the prosthetic user is able to lock its terminal device and maintain grip force, allowing the prosthetic user to relax after grasping an object [13, 7, 39, 28]. When not in use, the terminal device can be locked in the closed state, improving the outward appearance and reducing the wear and tear of clothing.

Berning et al. (2014) compared the performance of two VO and VC terminal devices of similar size, weight and orientation. According to Berning et al. (2014), neither of the prehension types could offer superior performance for everyday living. Preference for a prehension type appeared to be task specific. In general, VC prehension was preferred for tasks involving heavy objects and tasks in which it was important not to drop the objects. VO prehension was preferred for tasks involving simultaneous movement of joints [13].

Problem statement

Currently, the WILMER appealing prehensor is only provided to prosthetic users with VO prehension. However, VC prehension could offer the prosthetic user some clear advantages, especially when equipped with a locking mechanism. Furthermore, for certain tasks VC terminal devices perform even better than VO terminal devices. Some prosthetic users might prefer a VC terminal device over a VO terminal device. Other prosthetic users might like to have both a VO and VC terminal device, so that it is possible to interchange depending on the tasks needed to be performed. Providing prosthetic user both the VO and VC terminal device will give them the opportunity to choose their preferred prehension type or interchange between prehension types, hopefully making living with a prosthesis less of a burden.

Objective

In order to provide the prosthetic user with a VC version of the WILMER appealing prehensor, a VC controlling mechanism for the WILMER appealing prehensor is desired. Considering the high appreciation for the outward appearance if the WILMER appealing prehensor, the main objective of this thesis is to redesign the controlling mechanism of the WILMER appealing prehensor from VO to VC while preserving its outward appearance. The grasping function of the terminal device should be controlled with a comfortable cable operating force. Furthermore, the terminal should be comfortable to wear, and the opening width should enable grasping of a wide variety of objects relevant for the prosthetic users. A prototype of the WILMER appealing prehensor with VC controlling mechanism will be made and tested.

Thesis outline

This thesis is divided into several parts. The next part contains the scientific paper which summarizes the main objective of this study. First, it elaborates on the design requirements the VC controlling mechanism for the WILMER appealing prehensor needs to fulfil. Then a detailed description of the final concept and the mechanical tests performed with it is given. Lastly, the most important test results are provided and discussed.

The subsequent parts provide a more complete illustration of the work performed in the run-up to the final product. Appendix A describes the conceptual designs and the evaluation of these based on the design requirements. Appendix B contains the technical drawings of all parts of the VC controlling mechanism. Appendix C elaborates on the necessary characteristics for the spring added to the VC controlling mechanism and its influence on the cable operating force. In appendix D technical drawings of the test set-up can be found. In appendix E the Matlab codes are provided which are used to evaluate test results. Appendix F contains a technical drawing of a part of the VC controlling mechanism which needed to be redesigned. Lastly, in appendix G and estimation has been made of the frictional forces present in the VC controlling mechanism.

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Scientific paper

A voluntary closing mechanism for the WILMER appealing prehensor

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September 4, 2020

Abstract

The WILMER appealing prehensor is a body-powered (BP) prosthesis for people with a trans-radial upper limb deficiency, which is highly appreciated because of its outward appearance and functionality. Currently, prehension of the WILMER appealing prehensor is voluntary opening (VO). Voluntary closing (VC) prehension could offer the prosthetic user some clear advantages, especially equipped with a locking mechanism. A VC controlling mechanism is designed and evaluated in order to provide prosthetic users a VC version of the WILMER appealing prehensor. Furthermore, an adequate locking mechanism is searched for. A final prototype of the VC WILMER appealing prehensor is evaluated. By preserving the outline of its VO equivalent, a high appreciation for its outward appearance is secured. With a mass of only 99 gr, the VC WILMER appealing prehensor is comfortable to wear. The terminal device has an adequate opening width of 53.5 mm, enabling its prosthetic users to grasp a wide variety of objects. The hysteresis of one cycle of the VC WILMER appealing prehensor is very low, indicating that the terminal device is very efficient. Preliminary results show that there is room for improvement regarding the cable operating force and locking mechanism. At larger apertures the cable operating force necessary to get an adequate grip force slightly exceeds comfortable limits. The VC WILMER appealing prehensor is equipped with the vertical mount Sure-Lok. Although the vertical mount Sure-Lock is a more effective locking mechanism than locking mechanisms tested in literature, the drop in grip force induced after activation is still quite large.

Introduction

The WILMER appealing prehensor, currently also known as the Tweezer, is a body-powered (BP) prosthesis for people with a trans-radial upper limb deficiency (Figure 1). The outward appearance of the WILMER appealing prehensor is highly appreciated by its prosthetic users. The terminal device is a split hook consisting of a stationary and rotary finger of which the outline and volume are adjusted to an anatomical hand. All mechanical parts are placed out of sight and the connection to the forearm is smooth and harmonic. Especially the cosmetic cover enclosing the terminal device compliments its outward appearance. This cover can have any color preferred by the prosthetic user, giving the prosthesis a personal touch. The cover can be easily removed to be interchanged if another color is preferred. The mechanism underneath the cover remains easily accessible if maintenance is necessary. Also the functionality of the WILMER appealing prehensor is appreciated by prosthetic users. The adequate force transmission ratio of the terminal device results in low necessary input forces to operate its grasping function. Furthermore, the output force is constant over the full range of motion of the terminal device [1, 2].

In figure 2, a cross section of the WILMER appealing prehensor is depicted, exposing the four-bar linkage mechanism which enables its grasping function. The terminal device is kept closed in its default state by the spring. In order to grasp an object, the prosthetic user must actively open the terminal device by tensioning the Bowden cable. The Bowden cable is attached to the lever, which is connected to the base of the rotating finger via a bar-linkage. Tensioning of the Bowden cable results in a counterclockwise rotation of the lever, causing a displacement of the bar. Displacement of the bar results in a clockwise rotation of the rotary finger, and thus opening of the terminal device. Once the tension in the cable is released, the terminal device is enclosed around the object by the spring and the object is grasped. This type of prehension is known as voluntary opening (VO) prehension (Figure 3) [3, 4, 5, 6, 7, 8, 9].

For some BP prostheses, the grasping function of the terminal device is operated exactly opposite to that of the WILMER appealing prehensor. Prehension of these terminal devices is known as voluntary closing (VC). A VC terminal device is kept opened by a spring in its default state. In order to grasp an object, the prosthetic user actively closes the terminal device around the object by bringing the control cable under tension. In order to hold the object, the control cable must be kept under tension (Figure 3) [3, 4, 5, 6, 7, 8, 9].

The VO prehension of the WILMER appealing prehensor shows one clear advantage: once an object is grasped and the terminal device is enclosed around the object, the grip force to hold the object is provided by the spring. Therefore, the prosthetic user can relax while holding the object and moving it around [3, 10, 4, 11, 12, 13, 5, 14]. However, the VO prehension also has its flaws. The amount of grip force generated with a VO terminal device is determined by the stiffness of the spring closing the device. The prosthetic user cannot ex-

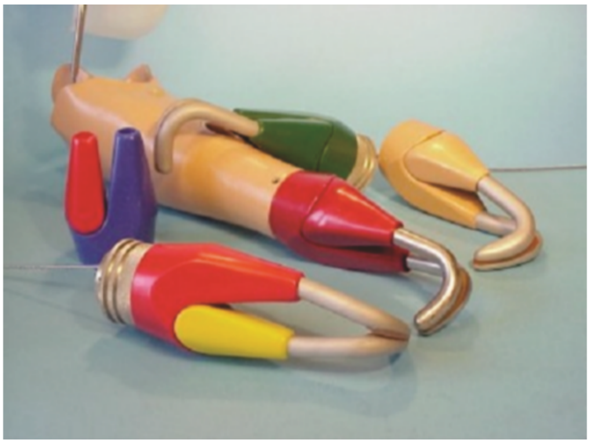

Figure 1: The WILMER appealing prehensor. A BP prosthesis for people with a trans-radial upper limb deficiency. The cosmetic cover allows the prosthetic user to adjust the color to their preferences [1].

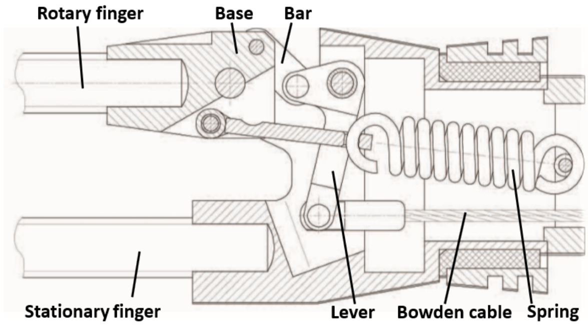

Figure 2: Cross section of the WILMER appealing prehensor. The four-bar linkage mechanism enables the grasping function of the terminal device. The type of prehension of terminal device of the WILMER appealing prehensor is known as VO prehension. Modified from [1].

ert more force than generated by the spring, limiting the variety of objects which can be handled. Furthermore, each time the user of a VO terminal device grasps an object, the force of the spring must be overcome. For some objects the grip force generated by the spring is larger than necessary, resulting in excessive energy expenditure [3, 4, 13, 5]. In contrast, VC prehension provides the user with the ability to regulate grip force. The prosthetic user can apply the exact grip force necessary by adjusting the tension in the control cable. Therefore, a wide variety of objects can be handled with a VC terminal device and no excessive energy expenditure is required [3, 15, 4, 12, 16, 17, 5, 18].

An important feature of BP terminal devices is that the prosthetic user receives force feedback via proprioceptive cues [19, 20, 11, 21, 22, 23, 9]. This applies to both VO and VC prehension. However, the working mechanism of a VO terminal device is exactly opposite to that of an anatomical hand, making it difficult to interpret the force feedback. The working mechanism of a VC terminal device is compatible with the functionality of an anatomical hand. This compatibility results in logical force feedback for the prosthetic user. Therefore, force feedback is more easily assimilated using a VC terminal device instead of a VO terminal device [19, 24, 10, 13, 23, 16, 14, 7, 8, 9].

VC prehension also shows some drawbacks. To hold an object, the prosthetic user must keep the control cable under tension in order to maintain grip force. This often causes fatigue and discomfort when an object has to be held for a prolonged period [3, 11, 5, 6]. Furthermore, the open default state of VC prehension is often considered as less attractive, and increases the wear and tear of clothing [3, 25, 6, 11]. However, both these problems could be solved by equipping the prosthesis with a locking mechanism. With a locking mechanism the prosthetic user is able to lock its terminal device and maintain grip force, allowing the prosthetic user to relax after grasping an object [3, 11, 25, 6]. When not in use, the terminal device can be locked in the closed state, improving the outward appearance and reducing the wear and tear of clothing.

Both prehension types have their advantages and disadvantages, which affect the performance of a terminal device. Berning et al. (2014) directly compared the performance of two VO and VC terminal devices of similar size, weight and orientation, in order to evaluate the impact of the prehension types on activities of daily living. The VC terminal device was not equipped with a locking mechanism. According to Berning et al. (2014),

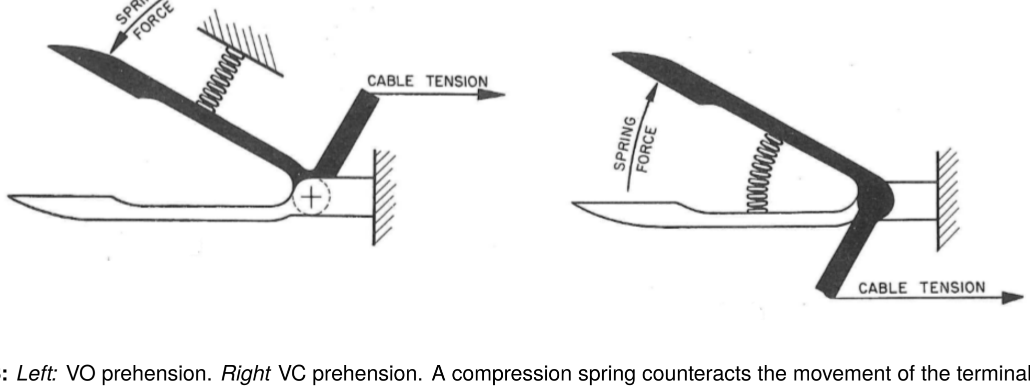

Figure 3: *Left:* VO prehension. *Right* VC prehension. A compression spring counteracts the movement of the terminal device as a consequence of cable tension. [4]

neither of the prehension types could offer superior performance for everyday living. Preference for a prehension type appeared to be task specific [3].

Problem statement

Currently, the WILMER appealing prehensor is only provided to prosthetic users with VO prehension. However, VC prehension could offer the prosthetic user some clear advantages, especially when equipped with a locking mechanism. For certain tasks VC terminal devices show better performance than VO terminal devices [3]. Some prosthetic users might prefer a VC terminal device over a VO terminal device. Other prosthetic users might like to have both a VO and VC terminal device, so that it is possible to interchange depending on the tasks needed to be performed. Providing prosthetic users both the VO and VC terminal device will give them the opportunity to choose their preferred prehension type or interchange between prehension types, hopefully making living with a prosthesis less of a burden.

Objective

In order to provide the prosthetic user a VC version of the WILMER appealing prehensor, a VC controlling mechanism for the WILMER appealing prehensor is desired. Therefore, the main objective of this thesis is to design and prototype a VC controlling mechanism for the WILMER appealing prehensor. Considering the high appreciation, the outward appearance of the WILMER appealing prehensor should be preserved. Furthermore, the grasping function of the terminal device should be controlled with a comfortable cable operating force, the terminal should be comfortable to wear, and the opening width should enable grasping of a wide variety of objects relevant for the prosthetic users. Additionally, an adequate locking mechanism is searched for to tackle the flaws of VC prehension.

Methods

A body-powered design

The BP control of the WILMER appealing prehensor will be preserved for the VC controlling mechanism. BP prostheses are often preferred by prosthetic users because of their simplicity, low weight, low cost, quiet and fast operation, high reliability and independence from external energy sources. Furthermore, BP prostheses show clear advantages in terms of feedback compared to externally-powered (EP) prostheses [19, 11, 21, 23, 26, 9]. BP prostheses are controlled entirely mechanical. Prehension of a BP prosthesis is directly coupled to the movement of intact joints. The movement of the intact joints is captured and transferred to the terminal device via a Bowden-cable. Force and displacement of the terminal device are thus directly coupled to the force and displacement in the Bowden-cable. Therefore, BP prostheses have the ability to provide the prosthetic user with direct feedback through proprioception. EP prostheses, on the other hand, rely mainly on visual feedback. Proprioceptive feedback is much faster and easier to interpret than visual feedback [3, 19, 20, 11, 27, 21, 28, 22, 23, 26, 9]. Because of the presence of proprioceptive feedback, a BP prosthesis can be controlled more intuitively and the need for visual monitoring is reduced compared to EP prostheses.

Design requirements

The BP VC controlling mechanism should meet the following design requirements:

1. *Size:* The VO WILMER appealing prehensor is highly appreciated because of its outward appearance [1, 2]. In order to reach the same level of appreciation, the outward appearance of the terminal device should be preserved. The VO WILMER appealing prehensor is available in three sizes: small, medium and large. The volume and outline of the small VO WILMER appealing prehensor are derived from the hand of a 4-to-6-year-old child [1]. Initially, the VC controlling mechanism will be designed for children, since enlarging a design is easier than narrowing it down. The VC controlling mechanism should therefore fit within the small-sized VO WILMER appealing prehensor. Figure 4 shows the dimensions of the outline of the small-sized VO WILMER appealing prehensor. The interior is allowed to be adjusted for the VC controlling mechanism, as long as the outline is preserved. By preserving the outline of the VO WILMER appealing prehensor, the cosmetic cover could be used for the VC WILMER appealing prehensor without major adjustments.
2. *Mass:* The mass of the VO WILMER appealing prehensor for children equals 120 gr. This mass is experienced as comfortable by its prosthetic users. Wearing comfort of a terminal device is for a large extent determined by its mass. Terminal devices are often rejected by prosthetic users due to high mass [29, 30, 28, 26]. Therefore, the WILMER appealing prehensor with VC controlling mechanism should not exceed the weight of its VO equivalent (120 gr).
3. *Opening width:* The opening width should enable grasping of a wide variety of objects. For adults, an opening width of approximately 70 mm is generally excepted [6, 26]. For children, the opening width could be a bit smaller. The small-sized VO WILMER appealing prehensor has an opening width of 50 mm. To satisfy the prosthetic user, the VC controlling mechanisms should allow an opening width of at least 50 mm. The distance between the axle and the tip of the rotating finger is 70 mm. In order to achieve an opening width of 50 mm, the VC controlling mechanism should therefore allow an opening angle of 45.6^{o}.
4. *Output forces:* A grip force of 10 N is considered to be sufficient for children to perform most activities of daily living (ADL) [31]. The VC controlling mechanism should allow the prosthetic user to exert a grip force of 10 N fatigue free, so that most ADL tasks can be performed by the prosthetic user without tiring out.

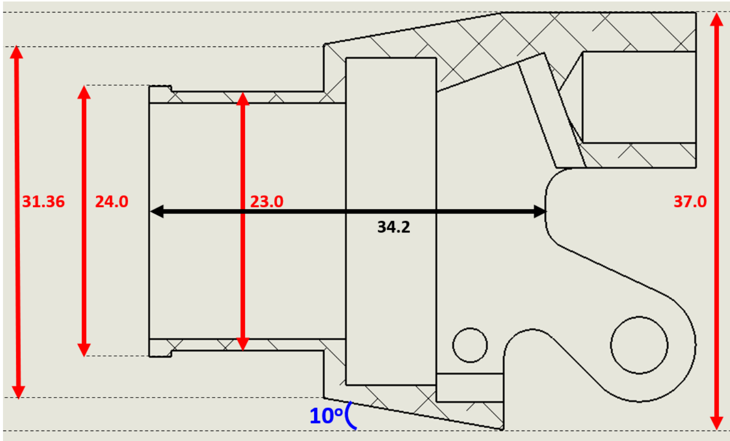

Figure 4: Dimensions of the outline of the WILMER appealing prehensor for children (Distances in mm). The new VC controlling mechanism must not interfere with these dimensions, so that the outline is preserved and the same cosmetic cover can be used.

5. *Cable operating force:* According to Hichert (2017), a shoulder-harness-controlled BP prosthesis can be operated fatigue-free with cable operation forces up to 38±17 N by adult females 66±23 N by adult males [21]. Unfortunately, there is no literature documenting on the fatigue-free cable operation forces for children. However, Shaperman, Setoguchi and LeBlanc (1992) evaluated the upper limb strength of children with a below-elbow upper limb deficiency. Upper limb strength was measured in four different motions relevant for operating a BP prosthesis: shoulder flexion, shoulder abduction, shoulder girdle elevation, and shoulder girdle protraction. The children appeared to be the strongest during shoulder girdle elevation, reaching a force of 62 N [32]. This force is set to be the maximal cable operating force. According to Monod (1985), a continuous contraction can be performed fatigue-free at 15-20% of the maximal voluntary contraction (MVC), corresponding to a cable operating force of approximately 11 N. An intermittent contraction with a work-rest-ratio of 0.5 can be performed fatigue-free at 38% MVC, corresponding to a cable operating force of 23.5 N [33]. Therefore, the VC controlling mechanism should allow the desired grip force of 10 N to be produced with a cable operating force of 23.5 N or less.
6. *Cable displacement* The amount of cable displacement which can be achieved with a shoulder-harness-controlled BP prosthesis is limited. According to Taylor (1954), adults can achieve a cable displacement of 56.9±15mm through movement of the shoulder. There is no literature documenting on the achieved cable displacement through shoulder movement of children. In order to get an estimate of the cable displacement which could be achieved by 4-to-6-year-old children, the achievable cable displacement of adults is scaled with a factor of 0.5 based on the ratio between the body sizes of adults and 4-to-6-year-old children. Therefore, the new VC controlling mechanism should allow the rotating finger to fully close with a cable displacement of maximally 28.4 mm.
7. *Reliability:* The VC controlling mechanism should not be vulnerable to wear and tear and environmental influences such as liquid, dust or sand, so that it can properly function in wet and dirty conditions and the prosthetic user does not need to worry about their device [22, 26, 9].
8. *Locking mechanism:* VC prehension has one major drawback: to hold an object, the prosthetic user must keep the control cable under tension in order

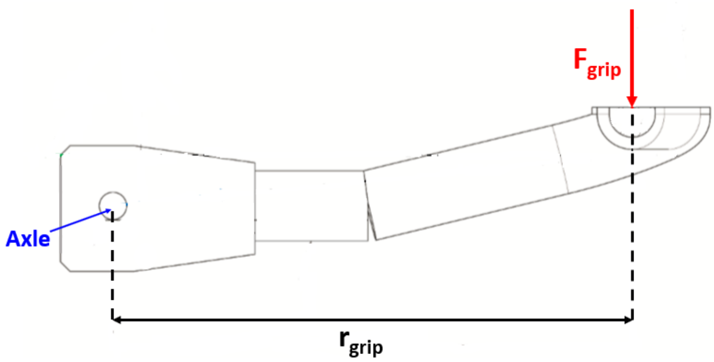

Figure 5: Grip force applied to the tip of the rotary finger. The work line of the grip force is assumed to be exactly perpendicular to the axle. F_{grip} = 10 N, r_{grip} = 70 mm.

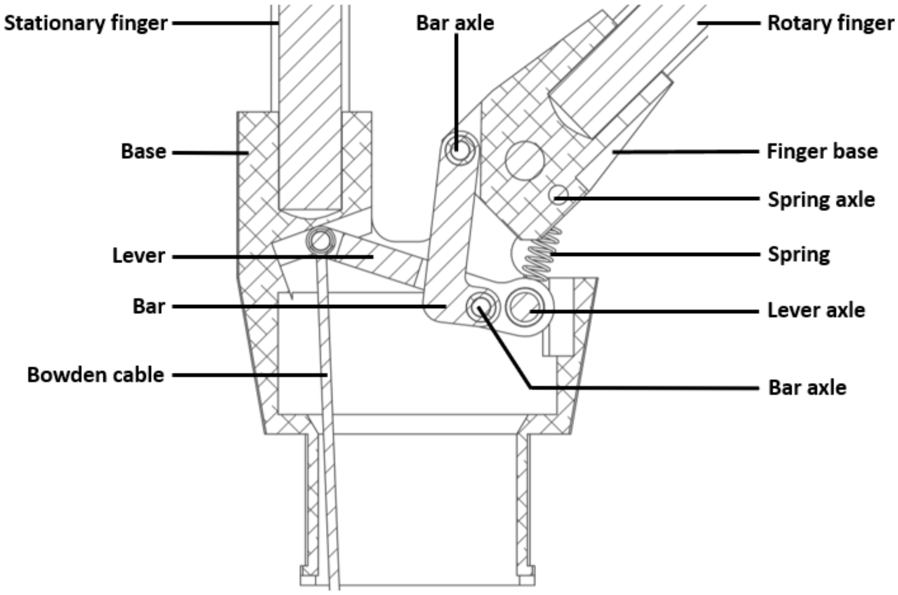

Figure 6: Cross section of the VC controlling mechanism in its default state. The terminal device is kept open in its default state by the spring. Tensioning of the Bowden cable results in a counterclockwise rotation of the rotary finger, and thus closure of the terminal device. Once tension in the Bowden cable is released, the terminal device is reopened by the spring.

to maintain grip force. This often causes fatigue and discomfort when an object has to be held for a prolonged period [3, 11, 5, 6]. This problem could be solved with a locking mechanism. With a locking mechanism the prosthetic user is able to lock its terminal device and maintain grip force. The locking mechanism prevents fatiguing by allowing the prosthetic user to relax after grasping an object [3, 11, 25, 6]. Furthermore, the open default state of VC prehension is often considered as less attractive, and increases the wear and tear of clothing [3, 25, 6, 11]. This problem can also be addressed with the locking mechanism. When not in use, the terminal device can be locked in the closed state, improving the outward appearance and reducing the wear and tear of clothing. Thus, the VC controlling mechanism should be provided with an adequate locking mechanism.

Grip force

In order to come up with an adequate VC controlling mechanism, first the consequence of the desired grip force (F_{grip} = 10 N) at the tip of the rotary finger needs to be understood. The distance between the tip and axle of the rotary finger equals 70 mm. F_{grip} is assumed to be exerted exactly perpendicular to the surface of the rotary finger over the full range of opening. This assumption results in a worst case scenario, the largest possible moment arm (r_{grip} = 70 mm) for F_{grip} (Figure 5). The resulting moment of F_{grip} therefore equals:

$$\begin{aligned} M &= r_{\text{grip}} * F_{\text{grip}} \\ &= 70 * 10 \\ &= 700 \text{ Nm} \end{aligned}$$

over the full range of closing. The BP VC controlling mechanism needs to be able to counteract this moment, while meeting the design requirements. There are 3 mechanical possibilities to drive the VC controlling mechanism: gears, pulleys, or bar linkages. In Appendix A, conceptual designs considering these possibilities for a VC controlling mechanism are discussed in detail, eventually resulting in a conceptual design which meets all design requirements in theory. This conceptual design is described in the following section and will be manufactured into a prototype and tested.

Conceptual design

The preservation of the outline of the WILMER appealing prehensor and the consequences of the desired grip force led to a redesign of the VO four-bar linkage mechanism. The VC controlling mechanism in its default state (fully opened) is depicted in figure 6. The location of the finger axle and lever axle are preserved from the VO WILMER appealing prehensor, since the base of the VO WILMER appealing prehensor is reused for the prototype of its VC equivalent. The Bowden cable is connected to the lever at a distance of 22 mm from the lever axle. A bar linkage connects the lever to the rotary finger. The bar linkage is attached to the base of the rotary finger via an axle with a bearing which is placed at 6.72 mm from the finger axle. The bar linkage is attached to the lever via an axle with a bearing which is placed at 4.5 mm from the lever axle in an extension of the lever. The angle between the lever and its extension equals 18°. The terminal device is kept open in its default state by the spring which is spanned between the lever axle and a spring axle. The spring axle is placed 4.85 mm horizontally from the finger axle. The configuration of the VC controlling mechanism is discussed in more detail in Appendix A. Technical drawings of all parts can be found in Appendix B. The necessary characteristics of the spring are discussed in detail in Appendix C.

In order to grasp an object, the prosthetic user must actively close the terminal device by tensioning the Bowden cable. Tensioning of the Bowden cable results in a counterclockwise rotation of the lever, causing a displacement of the bar. The displacement of the bar results in a counterclockwise rotation of the rotary finger, and thus closing of the terminal device. Once tension in the Bowden cable is released, the terminal device is reopened by the spring.

In theory, the configuration of the four-bar linkage mechanism meets all design requirements (see appendix A and C), excluding the design requirements *Mass* and *Locking mechanism* since these can only be evaluated when a prototype is available. The outline of the VO WILMER appealing prehensor is preserved by reusing the base, so that the cosmetic cover can be utilized with out major adjustments. The angle between the stationary and rotary finger in the default state equals 45.6^o, so that an opening width of 50 mm is achieved. The configuration of the four-bar linkage mechanism results in an adequate ratio between the moment arms of the present forces within the system, so that the desired F_{grip} of 10 N can be generated with a satisfactory F_{in} over the full range of closing (Figure 7). The lever needs to rotate over an angle of 82.7^o in order to fully close the terminal device. The necessary cable displacement then equals:

$$
\begin{aligned}
Displ &= L * (sin(18.0) + sin(64.7)) \\
&= 22 * (sin(18.0) + sin(64.7)) \\
&= 26.7 \text{ mm}
\end{aligned}
$$

A bar linkage system is very reliable. Chances of wearing out are low for axle connections with proper use of bearings to connect the bar linkage. Furthermore, the axle connections are not vulnerable to environmental influences.

Locking mechanism

As mentioned previously, a locking mechanism could tackle the flaws of VC prehension [3, 11, 25, 5, 6]. Unfortunately, locking mechanisms evaluated in literature appear to perform inadequately. Smit and Plettenburg (2010) evaluated the effectiveness of the built-in locking mechanisms of several currently available VC terminal devices. After activating the locking mechanism, all terminal devices showed a drop in grip force. This drop varied from 50-90% of the initial grip force [6].

TRS prosthetics offers prosthetic users a manually controllable locking mechanism, called the Sure-Lok. The Sure-lok is mounted on the prosthetic socket, in line with the Bowden cable. Prosthetic users can manually activate the locking mechanism by flipping the Sure-lok. After activation, the locking mechanism restricts Bowden cable movement and therefore grip force is maintained [35]. There are two versions of the Sure-lock avaiable which differ in orientation; the surface mount Sure-Lok and vertical mount Sure-Lok (Figure 8).

Gemmell et al. (2016) evaluated the effectiveness of the surface mount Sure-Lok. After the locking mechanism was activated and the prosthetic user relaxed, the surface mount Sure-Lok showed a grip force drop of 35% of the initial grip force [25]. This is a significantly lower grip force drop than the locking mechanisms evaluated by Smit and Plettenburg (2010) showed, indicating a more effective locking mechanism. However, the drop in grip force is still relatively high. A drop in grip force after activation makes locking mechanisms unreliable. Chances are high that an object falls after activation of the locking mechanisms.

No quantitative measures have been documented in literature on the effectiveness of the vertical mount Sure-lok. However, the locking mechanism seems to work adequately. In order to tackle the flaws of VC prehension, the VC WILMER appealing prehensor will be equipped with the vertical mount Sure-lok. Effectiveness of the vertical mount Sure-lok will be evaluated.

Experimental tests

The following parameters will be measured in order to evaluate the efficiency of the VC controlling mechanism and whether the VC controlling mechanism meets the

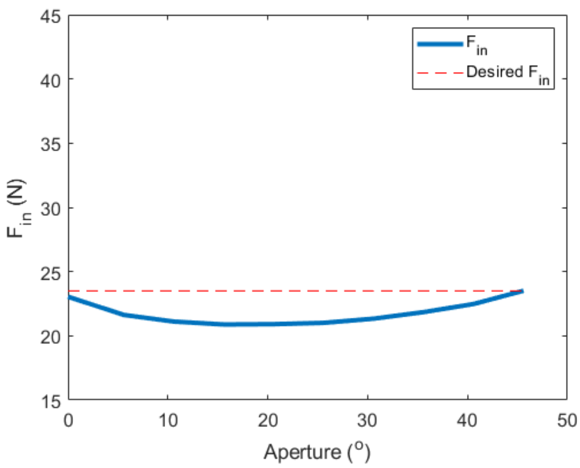

Figure 7: Necessary cable operating force (F_{in}) over the full range of closing to generate the desired grip force (F_{grip} = 10 N). An aperture 0^o represents a fully closed terminal device.

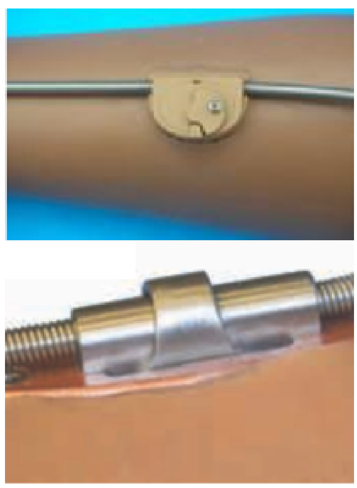

Figure 8: The TRS Sure-lok, a manually controllable locking mechanism restricting Bowden cable movement. *Above:* Surface mount. *Below:* Vertical mount. [34]

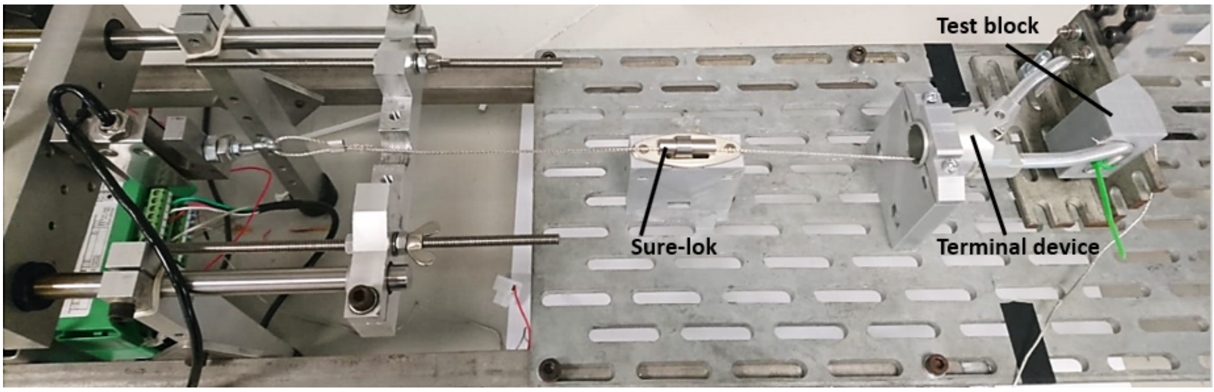

Figure 9: Test set-up. The WILMER appealing prehensor and Sure-lok are installed on the custom build test bench from Smit and Plettenburg (2010) using 3D printed support pieces. The test block contains a cavity in which the custom build grip force sensor from Smit and Plettenburg (2010) is placed.

design requirements:

- Mass of the terminal device;
- Maximum opening width;
- Amount of cable displacement necessary to fully close the terminal device;
- Cable operating force needed to generate a grip force of 10 N over the full range of closure;
- Grip force drop induced by the Sure-lok;
- Hysteresis of one cycle (closing and reopening).

The custom-build test bench, grip force sensor and data acquisition interface from Smit and Plettenburg (2010) were used to measure cable operating force, cable displacement, and grip force. Support pieces were designed and 3D-printed to install the WILMER appealing prehensor and Sure-lok onto the test bench (Figure 9). Technical drawings of the support pieces can be found in Appendix D. The test bench was operated manually. All tests were repeated four times, in order to obtain an average value. Acquired data was processed in MATLAB. MATLAB codes can be found in Appendix E.

The necessary cable operating force to generate a grip force of 10 N was measured at 5 different apertures (5°, 15°, 25°, 35°, and 45°). To set the grip force, the custom-build grip force sensor was placed between the fully opened fingers of the WILMER appealing prehensor. The grip force sensor was attached directly to the finger tip of the stationary finger for the 5° aperture. For the other apertures, special test blocks were designed and 3D-printed to achieve the correct distance between the finger tips. These test blocks could be attached to the stationary finger using a tie-wrap and double-sided tape, and contained a cavity for the placement of the grip force sensor (Figure 9). At each aperture, the Bowden cable was pulled until a grip force of 10 N was reached. This grip force was held for 3 seconds. The necessary cable operating force at each aperture was determined by calculating the mean cable operating force over the 3 seconds.

Corresponding to Smit and Plettenburg (2010), the effectiveness of the Sure-lok was evaluated by measuring the drop in grip force after activation of the locking mechanism. The effectiveness of the Sure-lok is determined at an aperture of 25° using the corresponding test block. A grip force of 10 N was set. Thereafter, the Sure-lok was activated and the tension in the Bowden cable was released. The grip force was measured for the following 3 seconds. The effectiveness of the Sure-lok was determined by calculating the mean grip force drop after activation of the locking mechanism.

Also in accordance with Smit and Plettenburg (2010), the efficiency of the VC controlling mechanism is evaluated in terms of hysteresis. Hysteresis is defined as the difference between the amount of work needed for closing and returned during reopening of a terminal device. A low hysteresis indicates an efficient mechanism. In order to determine hysteresis, the cable operating force and cable displacement were measured during one full cycle (closing en reopening). The amount of work was calculated by plotting the cable operating force against cable displacement and determine the area under the curve. Hysteresis was then calculated as the difference between the work needed for closing and returned during opening.

Results

Prototype

The resulting prototype is shown in figure 10. The base, fingers and finger base are made of aluminium. The axles, lever and bar are made of stainless steel, and the bearings are made of PCTFE (Appendix B).

The base of the prototype is the same as the base of the WILMER appealing prehensor. Furthermore, the dimensions of the finger base are preserved. Therefore, the outline of the prototype corresponds to the outline of the VO WILMER appealing prehensor, enabling utilization of the cosmetic cover (Figure 10).

In order to fit the VC controlling mechanism in the base, the interior of the base was adjusted. To generate more space, some material inside the base was removed through milling. Finally, the interior of the base was polished to prevent the Bowden cable from jamming against the base.

The lever is build up out of three layers of stainless steel glued together. The layers are laser cut and have a thickness of 1.5 mm. The outer two layers represent the shape of the lever. The middle layer is a small rectangle

Figure 10: Prototype of the WILMER appealing prehensor with VC controlling mechanisms. *Left*: Without cosmetic cover. *Right*: With cosmetic cover.

Figure 11: *Left*: Original design of the bar linkage, which got deformed during the experimental tests. *Right*: New design of the bar linkage.

(7mm by 3 mm) and creates the slots for the Bowden cable and bar linkage.

In order reopen the terminal device, the TEVEMA T40700 spring is spanned between the spring axle and lever axle. This spring has a spring constant of 1.33 N/mm, an effective work range of 6.34 mm, and a rest length of 8.50 mm. In order to achieve the necessary preload of 2.40 N, the spring is prestretched over 1.80 mm, resulting in a suspension length of 10.30 mm (Appendix C). Since the distance between the suspension points equals 13.8 mm, a small ring with a diameter of 3.5 mm is added between the spring and lever axle to be able to bridge this distance. This suspension of the spring indeed appeared to be sufficient to reopen the terminal device.

During the first mechanical tests, the design of the bar linkage appeared to be inadequate, resulting in a deformation of this part (Figure 11). To prevent this from happening, the thickness of the bar linkage is altered from 1.0 mm to 1.5 mm. Furthermore, the bar linkage is attached to the finger base and lever without bearings. Therefore, the diameter of the holes can be altered from 3 mm to 2 mm (Figure 11). This design for the bar linkage appeared to be adequate to withstand the forces it needs to transfer through the VC controlling mechanism. A technical drawing of the altered bar linkage can be found in Appendix F.

Test results

An overview of the results of the experimental test is given in table 1. The mass of the prototype equals 68 gr, resulting in a total mass for the terminal device (prototype with cosmetic cover and ring for attachment to socket) of 99 gr. The prototype has a maximum opening width of 53.3 mm. In order to fully close the prototype, the Bowden cable needs to displace over 28.6±0.3 mm. The cable operating force needed to generate a grip force of 10 N at the measured apertures is plotted in figure 12 together with the predicted and desired cable operating force. After activation of the Sure-Lok and release of the tension in the Bowden cable, a drop in grip force of 1.9±0.6 N occurred. The measured cable operating force and cable displacement during the closing and reopening of the terminal device are plotted in figure 13. The amount of work needed to fully close the terminal device equals 26.0±0.8 Nmm, and the amount of work returned during reopening equals 11.7±0.8 Nmm. Resulting in a hysteresis of one cycle of 14.3±1.2 Nmm.

Discussion

Socket and Bowden cable connection

The connections between the terminal device and socket and between the Bowden cable and the VC controlling mechanism were beyond the scope of this thesis and were adopted from the VO WILMER appealing prehensor.

The connection between the terminal device and socket is realised by casting. The proximal ending of the base is enclosed by a bearing and a casting ring. The casting ring is completely embedded into the prosthetic socket. The grooved surface of the casting ring enables a firm connection between the terminal device and prosthetic socket (Figure 14).

The Bowden cable is connected to the lever of the VC controlling mechanism via a pulling sleeve. The pulling sleeve is connected to the cable axle with a bearing. The Bowden cable is fastened in the pulling sleeve, where it

Table 1: Overview of the results of the experimental tests.

			Cable operating force (N)						
Mass (gr)	Opening width (mm)	Cable displacement (mm), n=4	5^o, n=4	15^o, n=4	25^o, n=4	35^o, n=4	45^o, n=4	Grip force drop (N), n=4	Hysteresis (Nmm), n=4
99	53.5	28.6±0.3	21.6±0.7	22.1±0.2	24.1±0.6	23.6±0.5	25.1±0.7	1.9±0.6	14.3±1.2

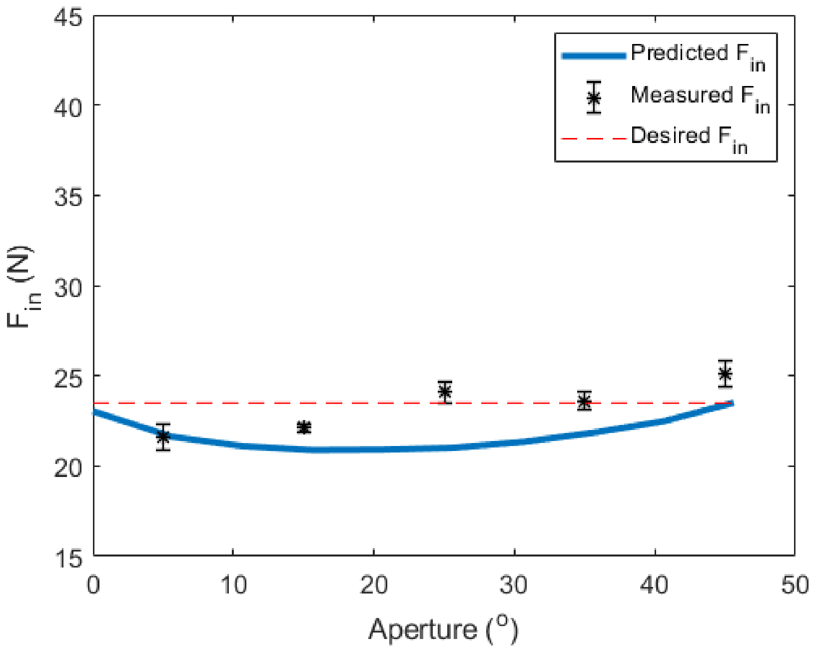

Figure 12: Predicted, measured and desired cable operating force (F_{in}) over the full range of closing to generate the desired grip force (F_{grip} = 10 N). An aperture of 0^o represents a fully closed terminal device.

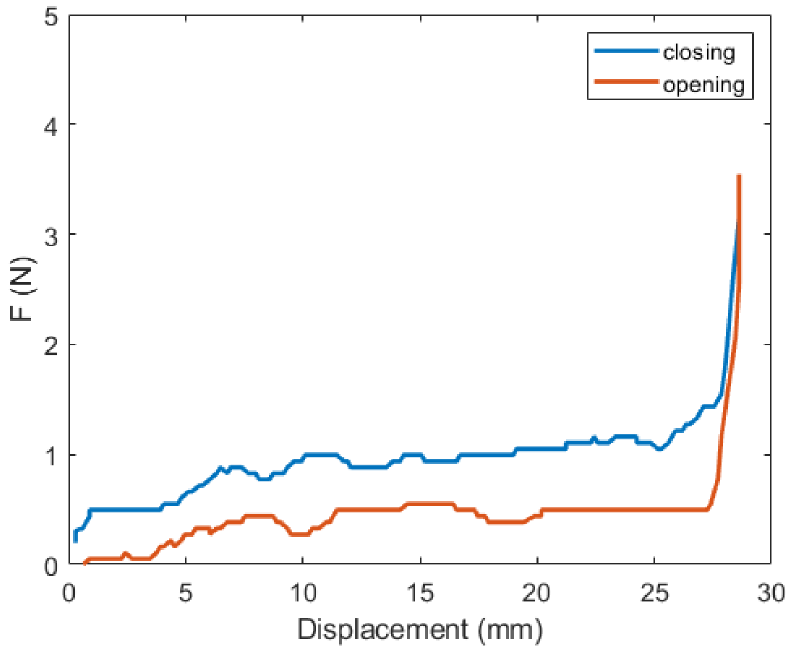

Figure 13: Measured cable operating force as a function of cable displacement. The test started in the default state of the terminal device (fully opened) with a cable displacement and cable operating force of 0 mm and 0 N respectively. At the maximum reached cable displacement and cable operating force, the terminal device is fully closed. The area under the curves represent the amount of work necessary for closing and returned during reopening.

is still able to rotate freely (Figure 14). The pulling sleeve creates an adequate connection between the Bowden cable and VC controlling mechanism, however, the size of the pulling sleeve caused a disturbance. Polishing of the interior of the base was necessary to reduce the chance of the pulling sleeve jamming against the interior of the base. A smaller connection between the Bowden cable and the VC controlling mechanism would be preferred, in order to prevent jamming of the Bowden cable connection against the interior of the base.

Size

Since the outer dimensions of the base, finger base and fingers of the VC WILMER appealing prehensor are the same as the VO WILMER appealing prehensor, the cosmetic cover can be used for the VC WILMER appealing prehensor (Figure 10). However, a small adjustment needed to be made to the cosmetic cover, due to the placement of the spring. In the default state, the spring of the VC WILMER appealing prehensor interfered with the cosmetic cover. Therefore, a small bite needed to be taken out of the cosmetic cover, in order for the terminal device to open entirely smoothly and rapidly.

Since the cosmetic cover can easily be used for the VC WILMER appealing prehensor and no major adjustments are necessary, the design requirement *Size* is met. The cosmetic cover provides prosthetic users with the ability to add a personal touch to their prosthetic device, resulting in a highly appreciated outward appearance [1, 2].

Mass

The VC WILMER appealing prehensor appears to have a mass of 99 gr. This is well below the mass of the VO WILMER appealing prehensor, which was set as a maximum in order for the terminal device to be experienced as comfortable. Wearing comfort of a terminal device is for a large extent determined by its mass. Terminal devices are often rejected by prosthetic users due to a high mass [29, 30, 28, 26]. With a mass of 99 gr, the VC WILMER appealing prehensor should be experienced as comfortable to wear.

The VO WILMER appealing prehensor has a mass of 120 gr, resulting in a mass difference of 21 gr with the VC WILMER appealing prehensor. This mass difference is partly a consequence of the removed material inside the base. The base of the VO WILMER appealing prehensor has a mass of 29.6 gr. After milling, the mass of the base of the VC WILMER appealing prehensor was 25.5 gr. Polishing of the interior of the base to prevent jamming of the Bowden cable reduced the mass of the base slightly further. Another cause of the mass difference is the used springs and their suspension in the the terminal devices. The VO WILMER appealing prehensor is kept closed by the TEVEMA T42050 spring, which is a RVS spring with a thread diameter of 1.6 mm and a rest length of 25.3 mm. The TEVEMA T42050 has a thread diameter four times as large and a rest length three times as large as the TEVEMA T40700 spring used in the VC WILMER appealing prehensor. Furthermore, the spring of the VC WILMER appealing prehensor is suspended directly between the spring axle and lever axle. For the suspension of the spring of the VO WILMER appealing prehensor, three additional parts were added to the mechanism. In summery, the spring used for the VC WILMER appealing prehensor has a significantly lower mass than the spring used for the VO WILMER appealing prehensor, and no additional parts were used for the suspension of the spring, resulting in a reduced mass for the VC WILMER appealing prehensor.

Especially the mass of the distal endings of a terminal device affects wearing comfort. Reducing the mass of the distal endings has two benefits. First, the terminal device itself becomes lighter. Second, the centre of mass (COM) shifts closer to the body. Both will reduce the forces on the residual limb of the prosthetic user [28, 36]. The COM of the VC WILMER appealing prehensor without its cosmetic cover lies half way between the proximal ending at the base and the distal endings at the finger tips. The cosmetic cover does not enclose the fingers, and will therefore only increase the mass of the proximal half of the terminal device. As a consequence, the COM lies in the proximal half of the VC WILMER appealing prehensor, which is beneficial for wearing comfort.

Opening width

A minimum opening width of 50 mm is set for the VC WILMER appealing prehensor, in order for its prosthetic users to be able to grasp a wide variety of objects relevant for 4-6-year old children. After manufacturing, the opening width of the VC WILMER appealing prehensor appeared to be 53.5 mm, and thus the design requirement *Opening width* is met.

TRS prosthetics provides a VC hook-like terminal device for 3-to-5-year-old children, the Adept e4, and for 5-to-9-year-old children, the Adept c2. These terminal devices have an opening width of 40 mm and 51 mm respectively. The VC WILMER appealing prehensor is designed for 4-to-6-year-old children. With an opening width of 53.5 mm the VC WILMER appealing prehensor is comparable to the Adept c2, indicating that this opening width will be suitable for 4-to-6-year-old children.

Cable displacement

In order to fully close the VC WILMER appealing prehensor, a necessary cable displacement of 26.7 mm was predicted. This cable displacement would have satisfied the design requirement *Cable displacement*. However, as a consequence of the larger than predicted opening width (53.5 mm instead of 50 mm), the necessary cable displacement to fully close the terminal device turned out to be 28.6$\pm$0.3 mm. In order to meet the design requirement, the necessary cable displacement to fully close the terminal device should have been less than 28.4 mm. This implies that some users will not be able to fully close the VC WILMER appealing prehensor. However, cable displacement exceeds the stated maximum cable displacement by only 0.2 mm. Considering the ratio between cable displacement and opening width, this corresponds to an opening width of 0.4 mm. Although some prosthetic users might not be able to fully close the prosthetic device, every object with a significant thickness could still be grasped.

Work and hysteresis

No literature is available documenting on the amount of work and hysteresis of hook-like VC terminal devices for children. Smit and Plettenburg (2010) did evaluate the amount of work needed for closing and the hysteresis of one cycle of several VC terminal devices available for adults. Two of these terminal devices are hook-like terminal devices, the Hosmer APRL hook (52601) and

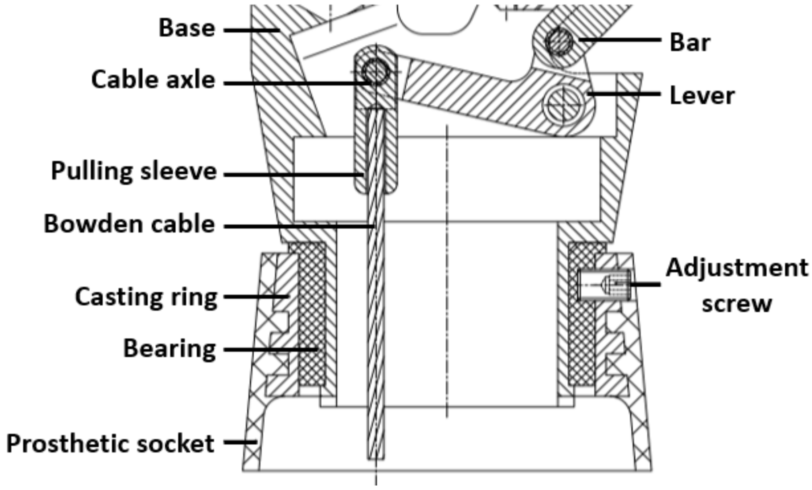

Figure 14: Cross section of the VO WILMER appealing prehensor, exposing the connection between the terminal device and socket and between the Bowden cable and the controlling mechanism. These connections are realised in the same manner for the VC WILMER appealing prehensor.

Table 2: Estimated frictional forces in the finger axle and lever axle.

Aperture (°)	$F_{rfinger}$ **(N)**	F_{rlever} **(N)**
5	123.0	93.6
15	119.0	89.6
25	117.0	86.9
35	117.3	85.9
45	120.4	87.1

TRS hook Grip 2s. The amount of work needed to fully close these terminal devices was 720$\pm$6.0 and 284$\pm$3.0 Nmm respectively. The amount of hysteresis of one cycle equaled 138$\pm$3.0 and 52$\pm$1.0 Nmm respectively.

Compared to these terminal devices, the amount of work necessary to fully close the VC WILMER appealing (26.0$\pm$0.8 Nmm) is very small. The small amount of work is a direct consequence of the low spring force which counteracts the closing movement. The spring used to reopen the VC WILMER appealing prehensor has a low spring constant (1.33 Nmm). Therefore, a low cable operating force is sufficient to close the terminal device. Furthermore, the use of bearings between the base and finger base, and around the majority of the axles decreased frictional effects, resulting in an efficient mechanism.

The hysteresis of one cycle of the VC WILMER appealing prehensor (14.3$\pm$1.2 Nmm) is also low compared to the terminal devices evaluated by Smit and Plettenburg (2010), indicating a high efficiency of the VC WILMER appealing prehensor. The low hysteresis goes hand-in-hand with the low amount of work necessary to fully close the VC WILMER appealing prehensor. However, hysteresis as a percentage of the amount of work needed for closing is relatively high. The hysteresis as a percentage of the work needed for closing is 55%, compared to 19% and 18% for the Hosmer APRL hook (52601) and TRS hook Grip 2s respectively. Since the VC WILMER appealing prehensor is reopened by an extension spring, and hysteresis does not occur in springs, the relatively high hysteresis present in the VC WILMER appealing prehensor should be a consequence of frictional effects. Because of the bar-linkage mechanism, the VC WILMER appealing prehensor has a relatively high amount of axles. With five axles present in the mechanism, and friction occurring in each axle, frictional effects are relatively high. Frictional effects are minimized by the use of bearings around the axles. However, due to the redesign of the bar linkage, the bearings around the two axles that connect the bar linkage to the finger base and lever were removed. The efficiency of the VC WILMER appealing prehensor can thus be further improved by adding bearings around these axles, so that the frictional losses in these axles are minimized.

Cable operating force

For the apertures 15° and larger, the cable operating force to generate a grip force of 10 N turns out to be higher than predicted. For the apertures of 25°, 35°, and 45°, the cable operating force to generate a grip force of 10 N exceeds the maximum cable operating force for comfortable control with 0.6 N, 0.1 N and 1.6 N respectively (Figure 12). The maximum cable operating force for comfortable control is set for intermittent contractions with a work-to-rest ratio of 0.5. Tasks performed with objects inducing apertures of 25° or larger and performed with an 0.5 work-to-rest ratio could therefore be experienced fatiguing.

The higher than predicted cable operating force at larger apertures could be a consequence of the orientation of the fingers with respect to each other. At an aperture of 5°, the stationary and rotary finger are orientated in parallel. At the larger apertures, the rotary and stationary finger are at an angle. Because of the angle between the stationary and rotary finger, the forces applied by the fingers onto the test blocks with grip force sensor were also aligned at an angle, causing shear movement of the test blocks. At the larger apertures, the cable operating force thus also needed to overcome shear forces, causing higher cable operating forces than predicted. The test blocks and grip force sensor used to set a grip force of 10 N at a certain aperture were very stiff objects, making it hard to get a firm grip and thus facilitating shear movement. Shear movement could be reduced by covering the surface of the fingers tips with anti-slip materials.

Another cause of the higher than predicted cable operating force could be the larger opening width of the VC WILMER appealing prehensor. The prediction of the cable operating force was purely based on the ratio between the moment arms of the forces acting on the VC controlling mechanism. The larger opening width could have caused a less adequate ratio between these moment arms, resulting in a higher necessary cable operating force to generate a grip force of 10 N.

Furthermore, for the prediction of the necessary cable operating force to generate a grip force of 10 N, friction effects were disregarded. However, as explained previously in terms of hysteresis, friction is present in the mechanism. An estimation of the frictional forces in the finger axle ($F_{rfinger}$) and lever axle (F_{rlever}) is made based on the predicted cable operating force, spring force and forces executed on the lever and finger base by the bar linkage in Appendix G. Results for the frictional forces at the measured apertures during the experimental test are listed in table 2. As can be seen, frictional forces are comparable for each measured aperture. Frictional effects depend on the magnitude of the frictional forces and the angular displacement of the rotary finger and lever. For the larger apertures, angular displacement is actually small. This indicates that the higher than predicted cable operating force at larger apertures is not a consequence of frictional effects. This is also implied by the low hysteresis of the mechanism.

Locking mechanism

The vertical mount Sure-Lok showed a pinch force drop of 1.9±0.6 N, which is 19% of the initial grip force. This is a significantly lower grip force drop than shown by the surface mount Sure-Lok [25] and the locking mechanism evaluated by Smit and Plettenburg (2010), indicating that the vertical mount Sure-Lok is a more effective locking mechanism. However, the 19% grip force drop is still quite large. In order to maintain a tight grip and prevent the grasped object from falling, a larger initial grip force is required.The maximum producible grip force is limited by the object strength and capacity of the prosthetic user [6]. For certain objects, the necessary cable operating force to generate the larger initial grip force could be experienced as uncomfortable or may even be unreachable, withholding the prosthetic user from using the locking mechanism. In future designs, locking mechanisms should be improved so that grip force is maintained after activation.

It is possible to keep the VC WILMER appealing prehensor closed in its default state with the vertical mount Sure-Lok. This will improve its outward appearance and reduces the wear and tear of clothing.

Future research

Future research should concern functionality testing. Frequently used functionality assessment tools are the Nine Hole Peg Test (NHPT), the Box and Block Test (BBT), and the Southampton Hand Assesment Procedure (SHAP). The NHPT an BBT both evaluate one specific dexterity. In contrast, the SHAP consists 26 different tasks, including 12 abstract tasks and 14 activities of daily living (ADL).The tasks of the NHPT, BBT, and SHAP need to be performed as fast and accurate as possible, only using the prosthetic device. Task completion time is used as a functionality measure for prosthetic devices [17, 37, 38, 39, 40]. Performing (one of) these functionality assessment tools with the VC WILMER appealing will provide a standardized functionality score for the terminal device, enabling comparison with other commercially available terminal devices. Furthermore, insight will be given in the experiences of prosthetic users with the VC WILMER appealing prehensor.

Due to their opposite controlling mechanisms, it is hard to compare the VO and VC WILMER appealing prehensor based on mechanical parameters. However, the previously mentioned functionality assessment tools could be used for the comparison of the terminal devices. Berning et al. (2014) used the SHAP to compare the performance of two VO and VC terminal of similar size, weight and orientation, in order to evaluate the impact of the prehension types. Additional, subjects answered a questionnaire to clarify their overall and task specific experiences with the terminal devices. To my knowledge, Berning et al. (2014) is the only study performed with comparable VO and VC terminal devices, resulting in reliable information about prehension type. Performing a similar study with the VO and VC WILMER appealing prehensor will amplify Berning et al. (2014), providing more insight in the impact of prehension type in ADL. Furthermore, it could be clarified whether prosthetic users prefer either the VO or VC terminal device, or would prefer to have both, so that interchange is possible depending on the task needed to be performed.

Conclusion

This thesis presents the design and evaluation of the VC WILMER appealing prehensor and the search for an adequate locking mechanism to tackle the flaws of VC prehension.

- A high appreciation for the outward appearance of the VC WILMER appealing prehensor is secured by preserving the outline of its VO equivalent, enabling utilization of the cosmetic cover.
- With a mass of only 99 gr, the VC WILMER appealing prehensor is comfortable to wear.
- The VC WILMER appealing prehensor has an adequate opening width of 53.5 mm, enabling grasp-

ing of a wide variety of objects relevant for 4-to-6-year-old children.

- The VC WILMER appealing prehensor is a very efficient terminal device, with a hysteresis of one cycle of only 14.3±1.2 Nmm.
- The vertical mount Sure-Lok is capable of locking the terminal device in its closed state, which favours its outward appearance and reduces wear and tear of clothing.

The following recommendations can be given for future research:

- At larger apertures the cable operating force necessary to get an adequate grip force should be lowered, since it slightly exceeds comfortable limits.
- Locking mechanisms should be improved so that grip force is maintained after activation.
- The functionality of the VC WILMER appealing prehensor and the experiences of its prosthetic users in ADL should be evaluated.

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Appendices

Appendix A: Conceptual designs

There are 3 mechanical possibilities to drive the VC controlling mechanism: gears, pulleys, or bar linkages. In the following sections conceptual designs considering these possibilities for a VC controlling mechanism will be given. The conceptual designs will be evaluated according to the design requirements, with the exception of the design requirements *Mass* and *Locking mechanism*, since these can only be evaluated when a prototype is available.

Gear system

The first concept is a gear system. The Bowden cable is connected to a lever which drives the gear system. The mechanism consist of three gears. Gear 1 is placed on top of the finger axle, gear 2 is placed on top of the lever axle. Closure of the rotary finger is achieved by placing a third gear between gear 1 and gear 2, so that the counterclockwise rotation of the lever results in a counterclockwise rotation of the finger (Figure 1).

In order to determine the necessary F_{in} to generate a F_{grip} of 10 N over the full range of closing, Free Body Diagrams (FBD's) have to be made for the situation around the finger axle and lever axle (Figure 2-3). Gear forces simply transfer from gear to gear, therefore the third gear is not important for the FBD's. Since we are dealing with gears, the moment arms r_{gear1} and r_{gear2} correspond to the radius of gear 1 and gear 2 respectively and will thus not change during motion. F_{gear1} can be expressed as follows:

$$\sum M_{\text{finger}} = 0 \tag{1}$$

$$r_{\text{grip}} * F_{\text{grip}} - r_{\text{gear1}} * F_{\text{gear1}} = 0 \tag{2}$$

$$F_{\text{gear1}} = \frac{r_{\text{grip}} * F_{\text{grip}}}{r_{\text{gear1}}} \tag{3}$$

Subsequently, F_{in} can be expressed as follows:

$$\sum M_{\text{lever}} = 0 \tag{4}$$

$$r_{\text{gear2}} * F_{\text{gear2}} - r_{\text{in}} * F_{\text{in}} = 0 \tag{5}$$

$$F_{\text{in}} = \frac{r_{\text{gear2}} * F_{\text{gear2}}}{r_{\text{in}}} \tag{6}$$

$$F_{\text{gear2}} = F_{\text{gear1}} \tag{7}$$

$$F_{\text{in}} = \frac{\frac{r_{\text{gear2}}}{r_{\text{gear1}}} * r_{\text{grip}} * F_{\text{grip}}}{r_{\text{in}}} \tag{8}$$

$$r_{\text{in}} = L * cos(\beta) \tag{9}$$

$$F_{\text{in}} = \frac{\frac{r_{\text{gear2}}}{r_{\text{gear1}}} * r_{\text{grip}} * F_{\text{grip}}}{L * cos(\beta)} \tag{10}$$

with r_{grip} = 70 mm, F_{grip} = 10 N, L being the length of the lever and β being the input angle of the lever varying during motion.

From equation 10 can be derived that F_{in} depends on the ratio between r_{gear1} and F_{gear2}, lever length L, and lever input angle β. The lever length L is restricted to the interior space of the WILMER appealing prehensor and the starting value of β. Furthermore, β depends on the necessary rotation of the lever, which is also determined by the ratio between r_{gear1} and r_{gear2}. A smaller ratio will result in a larger necessary rotation of the lever, eventually resulting in a small r_{in} and thus a high necessary F_{in}. In order to reduce F_{in} as much as possible, the ratio between r_{gear1} and r_{gear2}, the lever length L, and the starting value for β need to be optimized.

The optimal F_{in} is achieved with a ratio of 0.55 between r_{gear1} and r_{gear2}, a lever length of 23 mm and β starting at 16^o. To fulfill the dimensional constraints, a radius of 6.9 mm is chosen for gear 1 and a radius of 3.80 mm (6.9*0.55 = 3.80) is chosen for gear 2. The axle of gear 1 corresponds to the axle of the rotary finger, which is preserved from the VO WILMER appealing prehensor. The axle of gear 2 is positioned on top of the lever axle of which the position is also preserved from the VO WILMER appealing prehensor, 15 mm from the axle of the rotary finger (Figure 4). A linking gear with a radius of 3.5 mm is placed between gear 1 and gear 2.

Figure 1: Concept 1: Gear system. The mechanism consist of three gears. Rotation of the lever is transferred through the gear system, causing the finger to close.

The rotary finger needs to close over an angle of 45.6º to achieve an opening width of 50 mm. Therefore, the lever needs to rotate over an angle of 82.9º (45.6/0.55 = 82.9). The necessary cable displacement then equals:

$$\begin{aligned} Displ &= L * (sin(16.0) + sin(66.9)) \\ &= 23 * (sin(16.0) + sin(66.9)) \\ &= 27.50 \text{ mm} \end{aligned}$$

Figure 5 shows the necessary F_{in} over the range of motion of the rotary finger. It can be seen that the desired grip force of 10 N can be exerted with an acceptable cable operating force at an aperture of 18º or larger. For smaller apertures, F_{in} exceeds the acceptable cable operating force due to a too small r_{in}.

Concerning the reliability of the gear system, gear teeth are vulnerable to wear and tear. The force transmission between the gears will eventually cause the teeth to wear down. Furthermore, gears are vulnerable to dust and sand.

Fulfillment of the design requirements is summarized in Table 1. The gear system meets the design

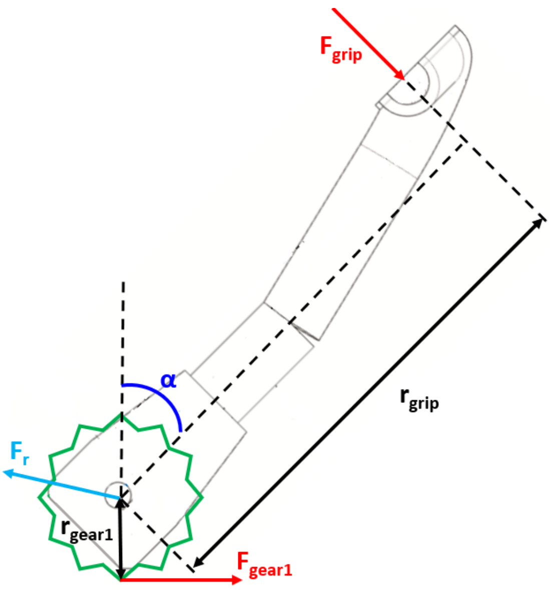


Figure 2: Concept 1: Gear system. FBD of the finger, with α being the opening angle rotary finger, and F_r the reaction force in the finger axle.

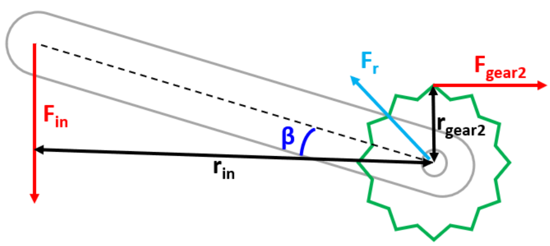


Figure 3: Concept 1: Gear system. FBD of the lever, with β being the input angle lever, and F_r the reaction force in the lever axle.

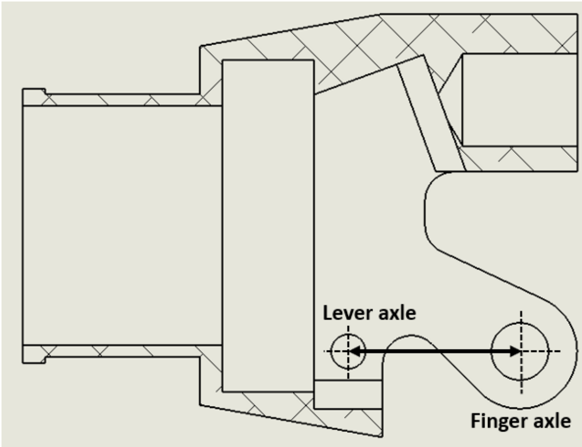


Figure 4: Positions of the finger axle and lever axle of the VO WILMER appealing prehensor. The distance between the axles equels 15mm

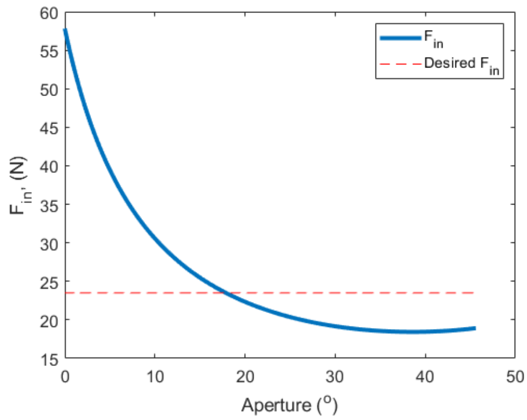


Figure 5: Cable operating force over the range of motion of the rotary finger for concept 1: Gear system and concept 2: Pulley system. 0^{o} represents a fully closed terminal device.

requirements *Size*, *Opening width*, *Output force* and *Cable displacement*. The design requirements *Cable operating force* and *Reliability* can not be satisfied.

Table 1: Concept 1: Gear system. Satisfaction of design requirements.

Size	✓
Opening width	✓
Output force	✓
Cable operating force	x
Cable displacement	✓
Reliability	x

Pulley system

The second concept is a pulley system. The Bowden cable is connected to a lever which drives the pulley system. The mechanism consist of two pulleys. Pulley 1 is placed on top of the finger axle, pulley 2 is placed on top of the lever axle. Closure of the rotary finger is achieved by connecting the pulleys with a belt, so that the counterclockwise rotation of the lever results in a counterclockwise rotation of the finger (Figure 6).

In order to determine the necessary F_{in} to generate a F_{grip} of 10 N over the full range of closing, FBD's have to be made for the situation around the finger axle and lever axle (Figure 7-8). Since we are dealing with pulleys, the moment arms $r_{pulley1}$ and $r_{pulley2}$ correspond to the radius of pulley 1 and pulley 2 respectively and will thus not change during motion. $F_{pulley1}$ can be expressed as follows:

$$\sum M_{\text{finger}} = 0 \tag{11}$$

$$r_{\text{grip}} * F_{\text{grip}} - r_{\text{pulley1}} * F_{\text{pulley1}} = 0 \tag{12}$$

$$F_{\text{pulley1}} = \frac{r_{\text{grip}} * F_{\text{grip}}}{r_{\text{pulley1}}} \tag{13}$$

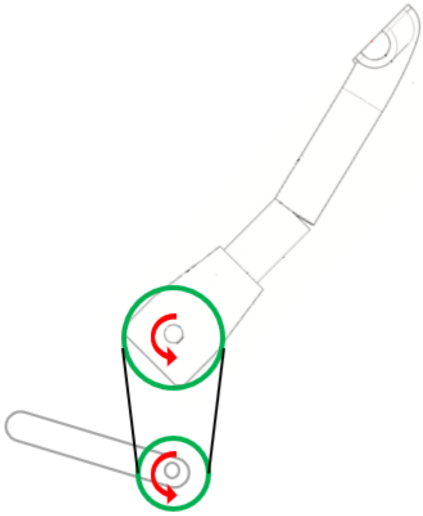


Figure 6: Concept 2: Pulley system. The mechanism consist of two pulleys. Rotation of the lever is transferred through the pulley system, causing the finger to close.

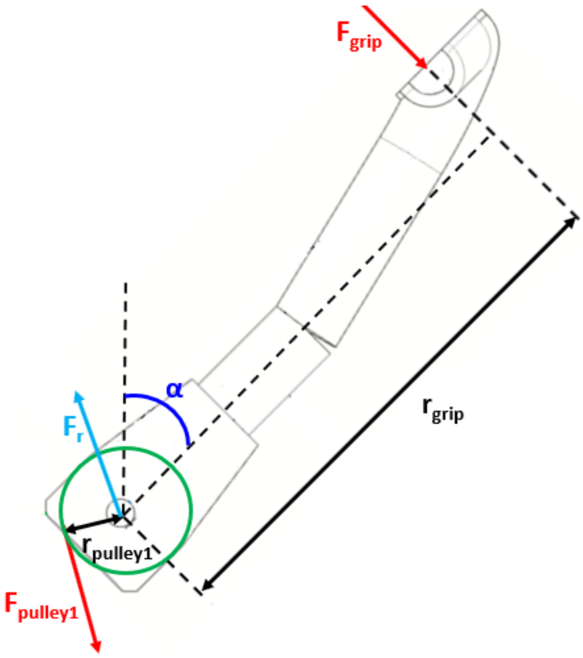


Figure 7: Concept 2: Pulley system. FBD of the finger, with α being the opening angle rotary finger, and F_r the reaction force in the finger axle.

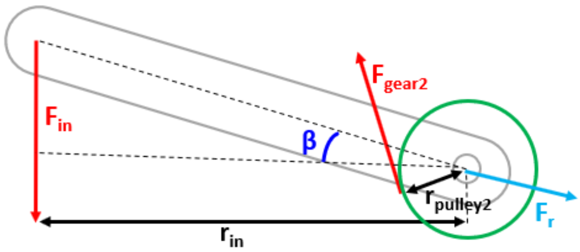


Figure 8: Concept 2: Pulley system. FBD of the lever, with β being the input angle lever, and F_r the reaction force in the lever axle.

Subsequently, F_{in} can be expressed as follows:

$$\sum M_{\text{lever}} = 0 \tag{14}$$

$$r_{\text{pulley2}} * F_{\text{pulley2}} - r_{\text{in}} * F_{\text{in}} = 0 \tag{15}$$

$$F_{\text{in}} = \frac{r_{\text{pulley2}} * F_{\text{pulley2}}}{r_{\text{in}}} \tag{16}$$

$$F_{\text{pulley2}} = F_{\text{pulley1}} \tag{17}$$

$$F_{\text{in}} = \frac{\frac{r_{\text{pulley2}}}{r_{\text{pulley1}}} * r_{\text{grip}} * F_{\text{grip}}}{r_{\text{in}}} \tag{18}$$

$$r_{\text{in}} = L * cos(\beta) \tag{19}$$

$$F_{\text{in}} = \frac{\frac{r_{\text{pulley2}}}{r_{\text{pulley1}}} * r_{\text{grip}} * F_{\text{grip}}}{L * cos(\beta)} \tag{20}$$

with r_{grip} = 70 mm, F_{grip} = 10 N, L being the length of the lever and β being the input angle of the lever varying during motion.

The expression for F_{in} (Equation 20) appears to be the same as the expression of F_{in} for the gear system (Equation 10), indicating that the relations for the gear system also exist for the pulley system. Therefore, for the pulley system the same dimensions are chosen as for the gear system ($r_{pulley1}$=r_{gear1}, $r_{pulley2}$=r_{gear2}, L=23 mm, β starting at 16°), resulting in the same F_{in} (Figure 5) and cable displacement for the pulley system as the gear system.

The belt between the pulleys causes some concerns for the reliability of the system. A belt is likely to wear out over time.

Fulfillment of the design requirements is summarized in Table 2. The pulley system meets the design requirements *Size*, *Opening width*, *Output force* and *Cable displacement*. The design requirements *Cable operating force* and *Reliability* can not be satisfied.

Table 2: Concept 2: Pulley system. Fulfillment of design requirements.

Size	✓
Opening width	✓
Output force	✓
Cable operating force	x
Cable displacement	✓
Reliability	x

Bar linkage systems

The third concept is a bar linkage mechanism. Again, the Bowden cable is connected to a lever. A bar linkage connects the lever to the rotary finger (Figure 9). The bar linkage is attached to the lever and the base of the rotary finger by axles. Counterclockwise rotation of the lever results in a displacement of the bar linkage, subsequently causing a counterclockwise rotation the rotary finger and thus closure of the terminal device.

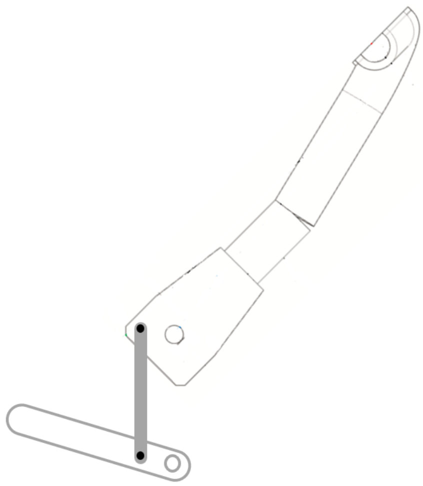


Figure 9: Concept 3: Bar linkage system. The lever is connected to the base of the rotary finger via a bar linkage. Counterclockwise rotation of the lever causes a counterclockwise rotation of the rotary finger and thus closure of the terminal device.

In order to determine the necessary F_{in} to generate a F_{grip} of 10 N over the full range of closing, FBDs have to be made for the situation around the finger axle and lever axle (Figure 10-11). The forces exerted by the bar linkage on the finger base (F_{bar1}) and lever (F_{bar2}) are always directed along the bar linkage. F_{bar1} can be expressed as follows:

$$\sum M_{\text{finger}} = 0 \tag{21}$$

$$r_{\text{grip}} * F_{\text{grip}} - r_{\text{bar1}} * F_{\text{bar1}} = 0 \tag{22}$$

$$F_{\text{bar1}} = \frac{r_{\text{grip}} * F_{\text{grip}}}{r_{\text{bar1}}} \tag{23}$$

Subsequently, F_{in} can be expressed as follows:

$$\sum M_{\text{lever}} = 0 \tag{24}$$

$$r_{\text{bar2}} * F_{\text{bar2}} - r_{\text{in}} * F_{\text{in}} = 0 \tag{25}$$

$$F_{\text{in}} = \frac{r_{\text{bar2}} * F_{\text{bar2}}}{r_{\text{in}}} \tag{26}$$

$$F_{\text{bar2}} = F_{\text{bar1}} \tag{27}$$

$$F_{\text{in}} = \frac{\frac{r_{\text{bar2}}}{r_{\text{bar1}}} * r_{\text{grip}} * F_{\text{grip}}}{r_{\text{in}}} \tag{28}$$

$$r_{\text{in}} = L * cos(\beta) \tag{29}$$

$$F_{\text{in}} = \frac{\frac{r_{\text{bar2}}}{r_{\text{bar1}}} * r_{\text{grip}} * F_{\text{grip}}}{L * cos(\beta)} \tag{30}$$

with r_{grip} = 70 mm, F_{grip} = 10 N, L being the length of the lever and β being the input angle of the lever varying during motion. From equation 30 follows that F_{in} depends on the ratio between r_{bar1} and r_{bar2}, lever length L, and lever input angle β.

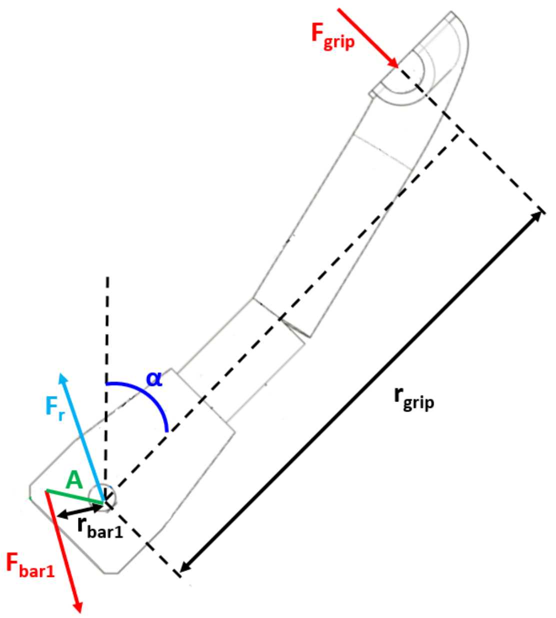


Figure 10: Concept 3: Bar linkage system. FBD for the finger, with α being the opening angle of the finger, and F_r the reaction force in the finger axle.

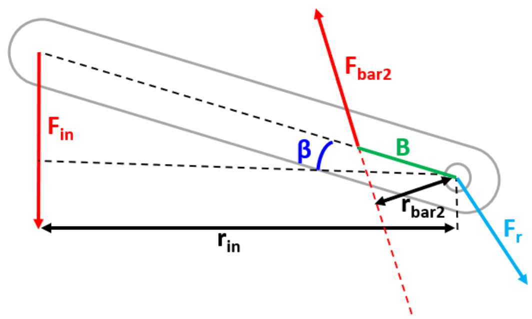


Figure 11: Concept 3: Bar linkage system. FBD for the lever, with β being the input angle of the lever, and F_r the reaction force in the lever axle.

In order to minimize F_{in}, the moment arm r_{bar1} needs to be as large as possible and the moment arm r_{bar2} as small as possible. As can be seen in figure 10, r_{bar1} depends on the orientation of F_{bar1} and the distance between the finger axle and application point of F_{bar1} (A). As can be seen in figure 11, r_{bar2} depends on the orientation of F_{bar2} and the distance between the lever axle and application point of F_{bar2} (B). The distances A and B are restricted to the available space on the finger base and lever respectively and the necessary space for the connection of the bar linkage to these components. For an adequate connection, a cavity with a diameter of 3 mm is necessary to fit an axle with a bearing. The distance between the cavity and the edges of the components needs to be at least 0.5 mm. In reality, the application points of F_{bar1} and F_{bar2} will displace over the edge of the cavities during motion. However, the work line of these forces will always go through the centre of the cavity, since this is the pivot point of the connection axle. Therefore, the centres of the cavities are chosen as the application points for F_{bar1} and F_{bar2}.

In order to maximize r_{bar1}, the distance A should be as large as possible. Taking into account the dimensional constraints of the finger base and an adequate connection for the linkage bar, the largest possible distance A equals 6.72 mm. This distance is achieved with a horizontal distance of 5.4 mm and a vertical distance of 4 mm between the finger axle and the application point of F_{bar1} (Figure 12).

In order to minimize r_{bar2}, the distance B should be as small as possible. However, the distance B also influences the necessary rotation of the lever. A smaller distance B will result in a larger necessary rotation of the lever, eventually resulting in a small r_{in} and thus a high necessary F_{in}. In order to reduce F_{in} as much as possible, the distance B needs to be optimized.

When preserving the position for the finger axle and lever axle from the VO Tweezer (Figure 4), the optimal distance B appears to be 4 mm. This is the smallest possible distance which can be achieved between the lever axle and the application point of F_{bar2} concerning the dimensions of the lever axle and the cavity for the connection of the bar linkage. The optimal lever length L appears to be 23 mm with β starting at 16°.

With this composition, the lever needs to rotate over an angle of 84.0°, in order to fully close the rotating finger. The necessary cable displacement then equals:

$$\begin{aligned} Displ &= L * (sin(16.0) + sin(68.0)) \\ &= 23 * (sin(16.0) + sin(68.0)) \\ &= 27.7 \text{ mm} \end{aligned}$$

Figure 13 shows the necessary F_{in} over the range of motion of the rotating finger. It can be seen that the desired grip force of 10 N can be exerted with an acceptable cable operating force with an aperture of 8° or larger. For smaller apertures, F_{in} exceeds the acceptable cable operating force, due to an inadequate ratio between the moment arms r_{bar1} and r_{bar2} and a decreasing r_{in}.

A bar linkage system is very reliable. Changes of wearing out are low for axle connection with proper use of bearings to connect the bar linkage. Furthermore, the axle connections are not vulnerable to environmental influences.

Fulfillment of the design requirements is summarized in Table 3. The gear system meets all the design requirements, with the exception of the *Cable operating force*.

Table 3: Concept 3: Bar linkage system. Satisfaction of design requirements.

Size	✓
Opening width	✓
Output force	✓
Cable operating force	x
Cable displacement	✓
Reliability	✓

Unlike gears and pulleys, of which only the diameters can be varied, bar linkages provide the advantage that both the length and orientation can be varied. Therefore, adjusting the length and orientation of the linkage bar might result in an acceptable F_{in} over the full range of closure. As mentioned previously, F_{in} eventually exceeds the acceptable cable operating force due to an in adequate ratio between the moments arms r_{bar1} and r_{bar2}. In order to achieve an acceptable F_{in} over the full range of closure, r_{bar2}

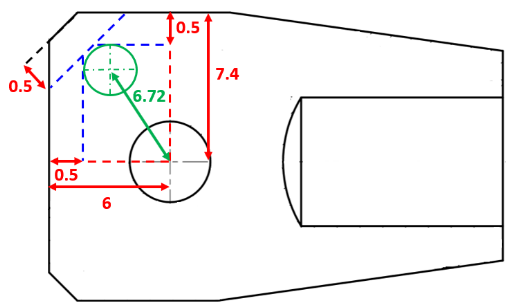


Figure 12: Dimensional constraints (mm) of the finger. The pivot point of the axle for the bar linkage is positioned 6.72 mm from the finger axle in order to maximise distance A.

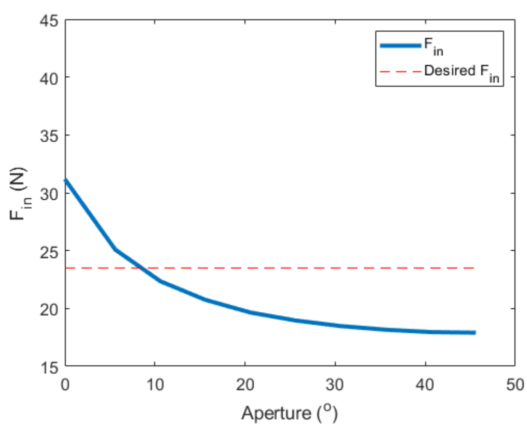


Figure 13: Cable operating force over the range of motion of the rotating finger for concept 3: Bar linkage system. 0° represents a fully closed terminal device.

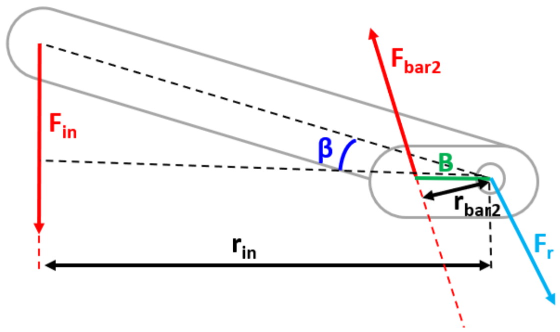


Figure 14: Concept 4: Bar linkage system with lever extension. FBD for the lever, with β being the input angle of the lever, and F_r the reaction force in the lever axle.

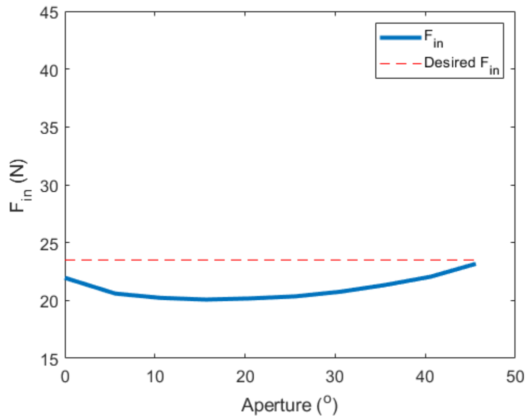


Figure 15: Cable operating force over the range of motion of the rotating finger for concept 4: Bar linkage system with lever extension. 0^o represents a fully closed terminal device.

can be decreased by bringing the work line of F_{bar2} closer to the lever axle. In the fourth concept, this is achieved with an extension of the lever (Figure 14). In order to fulfill the the *Cable operating force* design requirement, a lever with length L = 22 mm and starting at β = 18^o is chosen. The angle between the lever and its extension equals 18^o. The distance between the lever axle and the application point of F_{bar2} (B) equals 4.5 mm. Figure 15 shows the necessary F_{in} over the full range of motion of the rotating finger. It can be seen that the lever extension indeed results in an acceptable F_{in} over the full range of motion of the rotation finger, fulfilling the *Cable operating force* design requirement.

The lever extension also results in a different necessary rotation of the lever. With the lever extension, the lever needs to rotate over an angle of 82.7^o, in order to fully close the rotating finger. The necessary cable displacement then equals:

$$\begin{aligned} Displ &= L * (sin(18.0) + sin(64.7)) \\ &= 22 * (sin(18.0) + sin(64.7)) \\ &= 26.7 \text{ mm} \end{aligned}$$

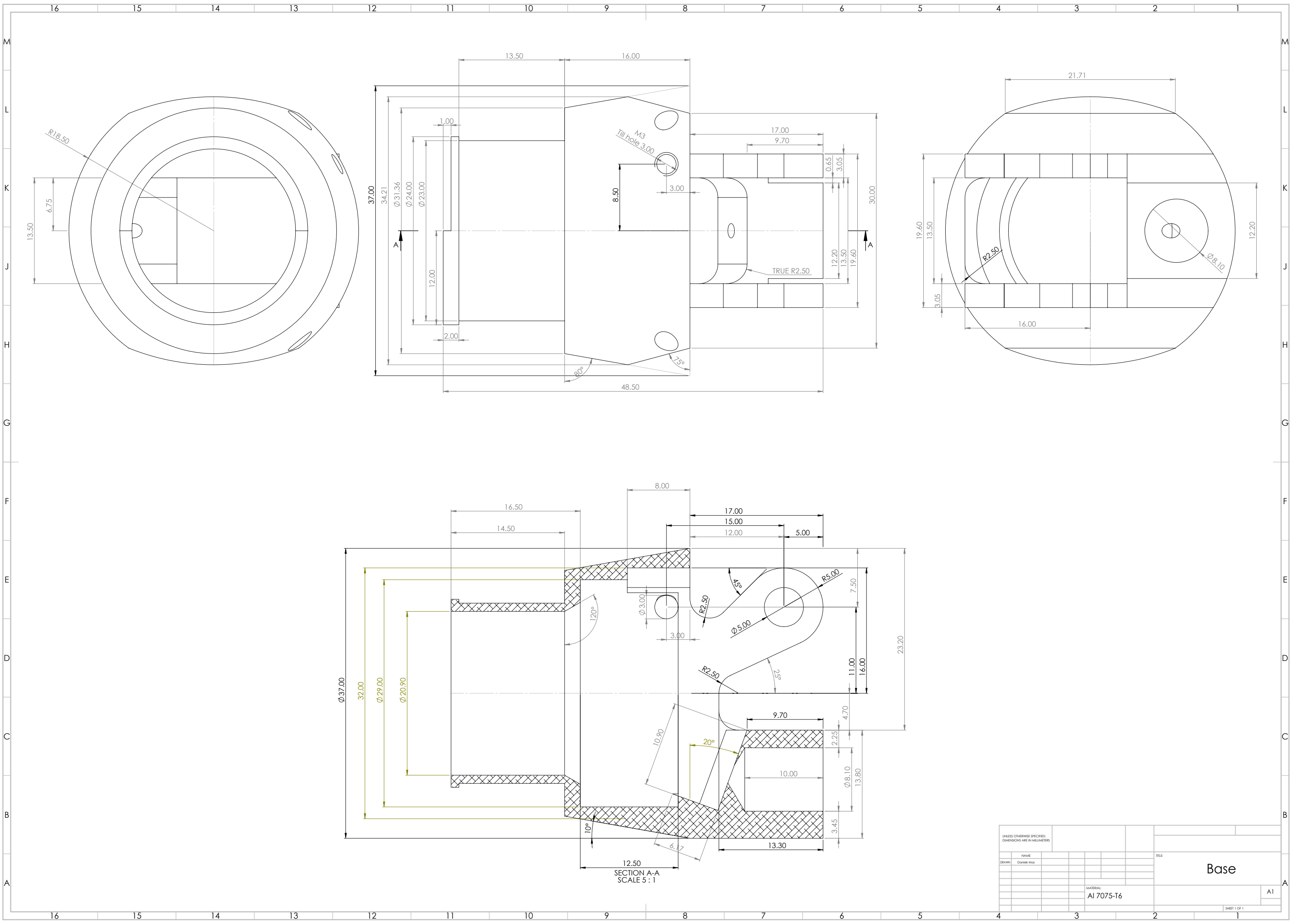
Hence, the *Cable displacement* design requirement is still met with the lever extension. Thus, the bar linkage system with lever extension fulfills all design requirements (Table 4).

Table 4: Concept 4: Bar linkage system with lever extension. Satisfaction of design requirements.

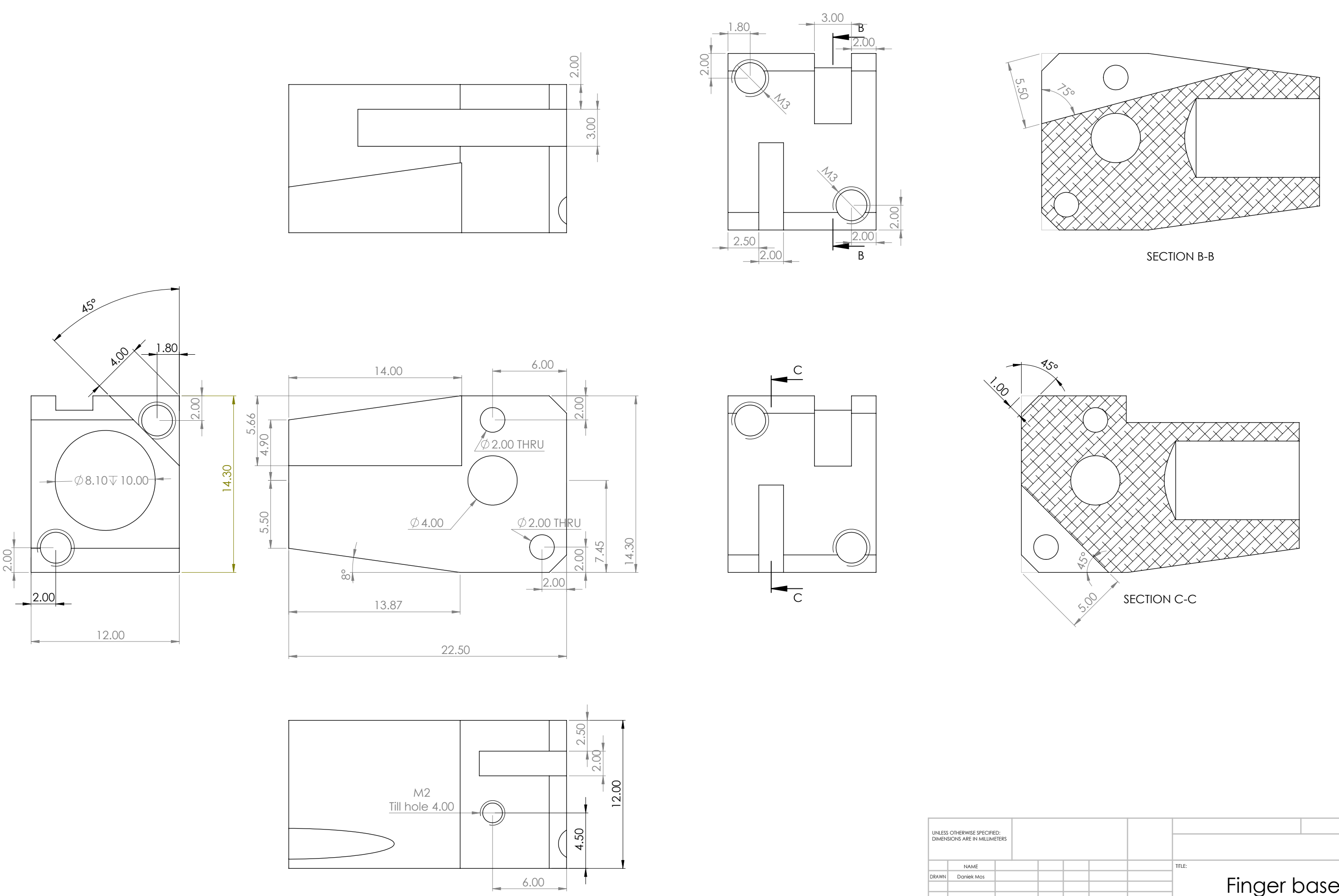
Size	✓
Opening width	✓
Output force	✓
Cable operating force	✓
Cable displacement	✓
Reliability	✓

A prototype is made of the bar linkage mechanism with lever extension. This prototype is tested subsequently, in order to evaluate whether the concept indeed fulfills all the design requirements.

Appendix B: Technical drawings parts VC controlling mechanism



M3
Till hole 3.00
TRUE R2.50
SECTION A-A
SCALE 5 : 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
NAME
DRAWN
Daniek Mos
TITLE:
Base
MATERIAL:
Al 7075-T6
A1
SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

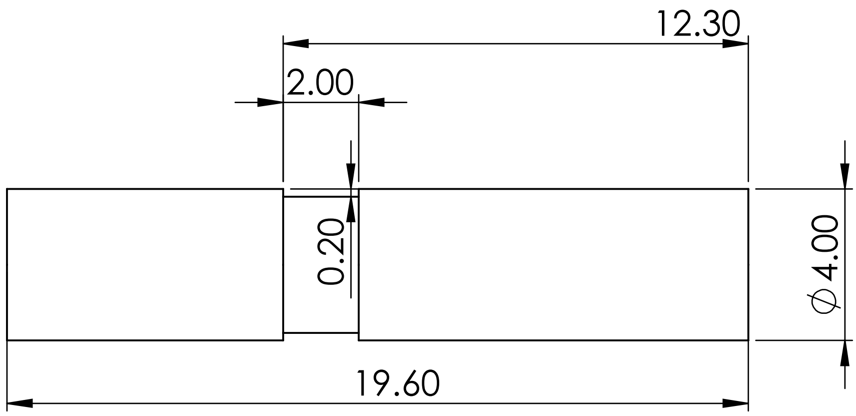
	NAME
DRAWN	Daniek Mos

TITLE:

Finger base

MATERIAL:
7075-T6 (SN)

A2



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

	NAME
DRAWN	Daniek Mos

TITLE:

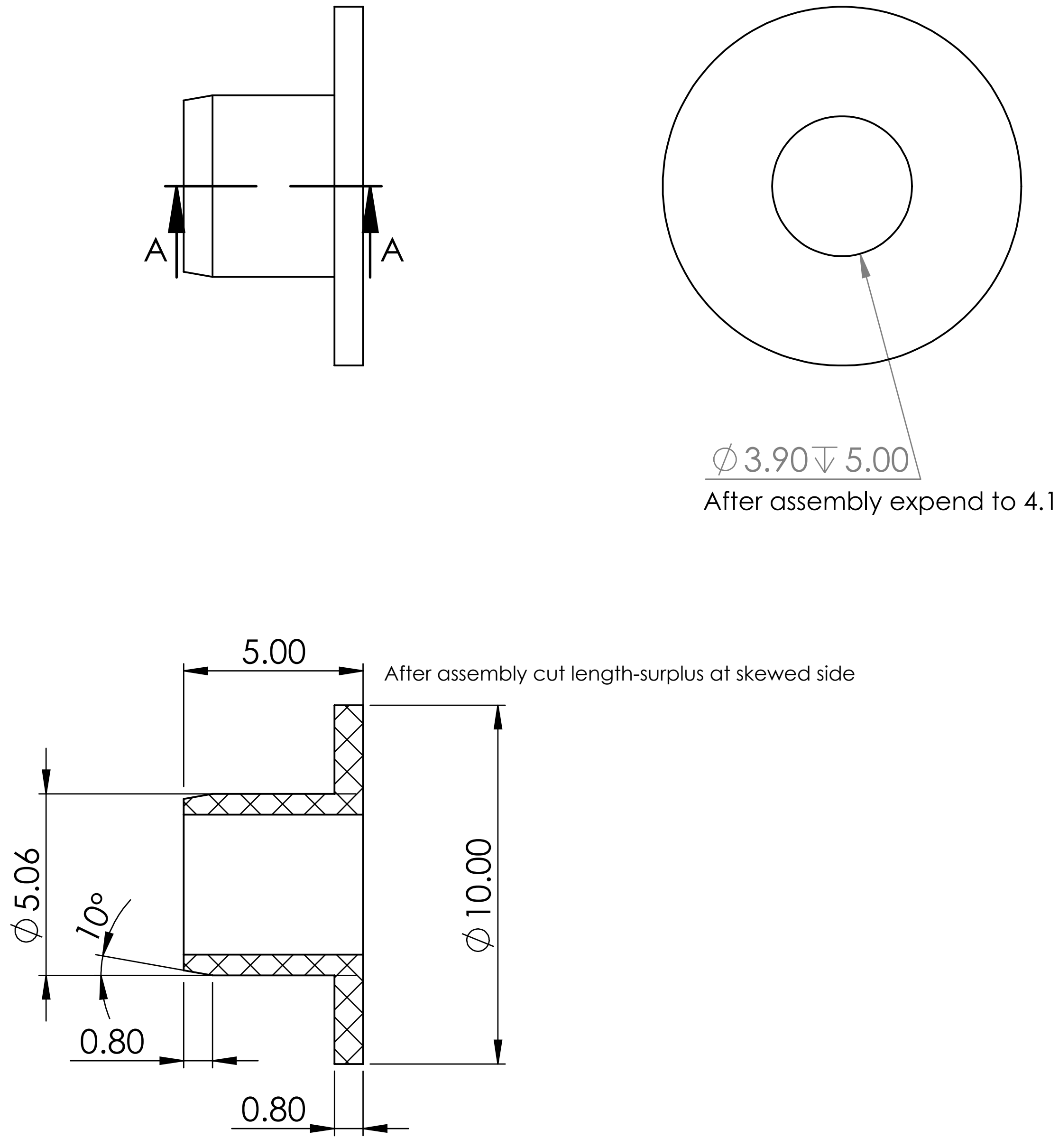
Finger axle

MATERIAL:
RVS 303

DWG NO.

A4

SHEET 1 OF 1



SECTION A-A

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

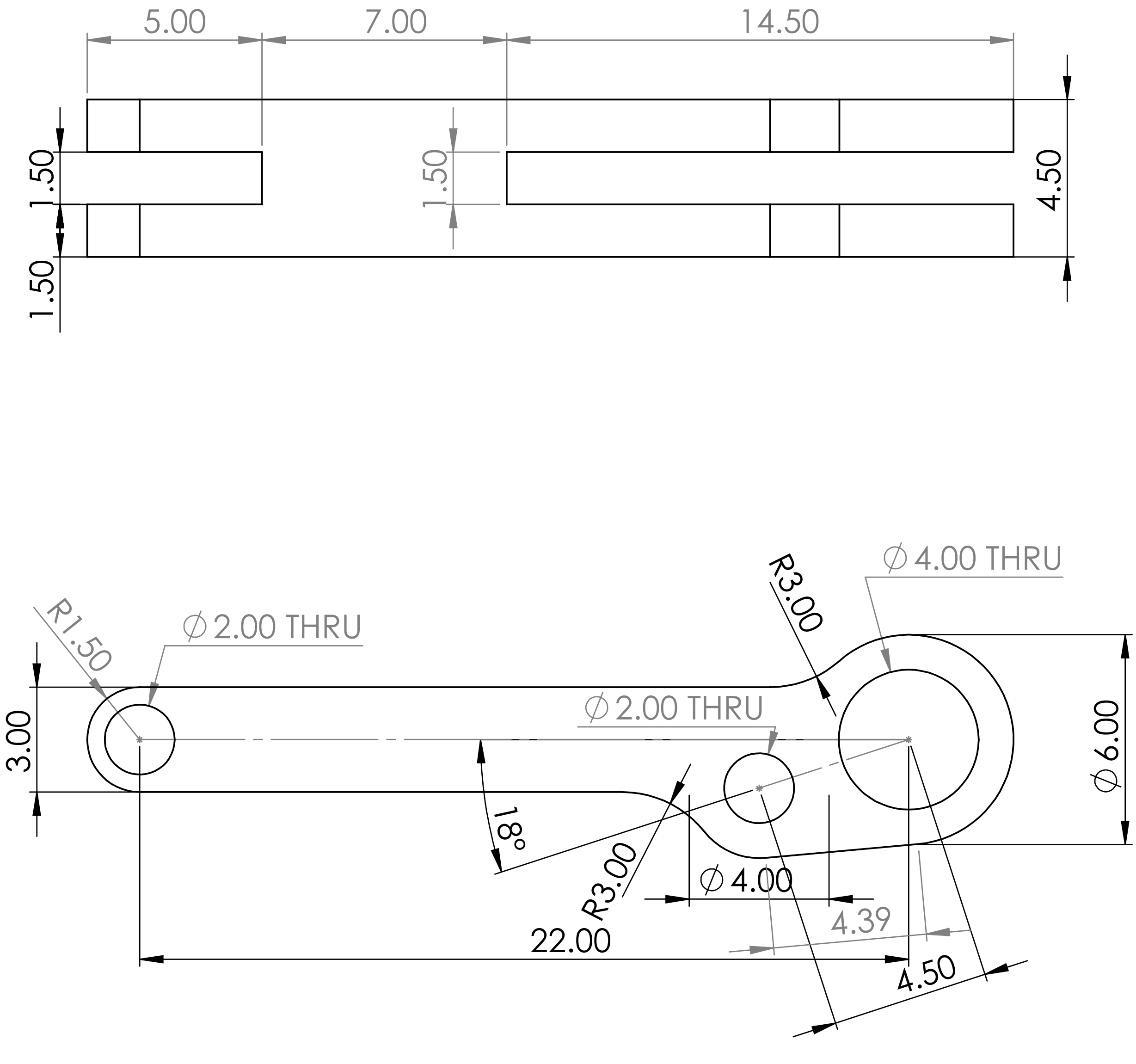
	NAME
DRAWN	Daniek Mos

MATERIAL:
PCTFE (Eriflon)

TITLE:

Finger bearing

A4



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

	NAME
DRAWN	Daniek Mos

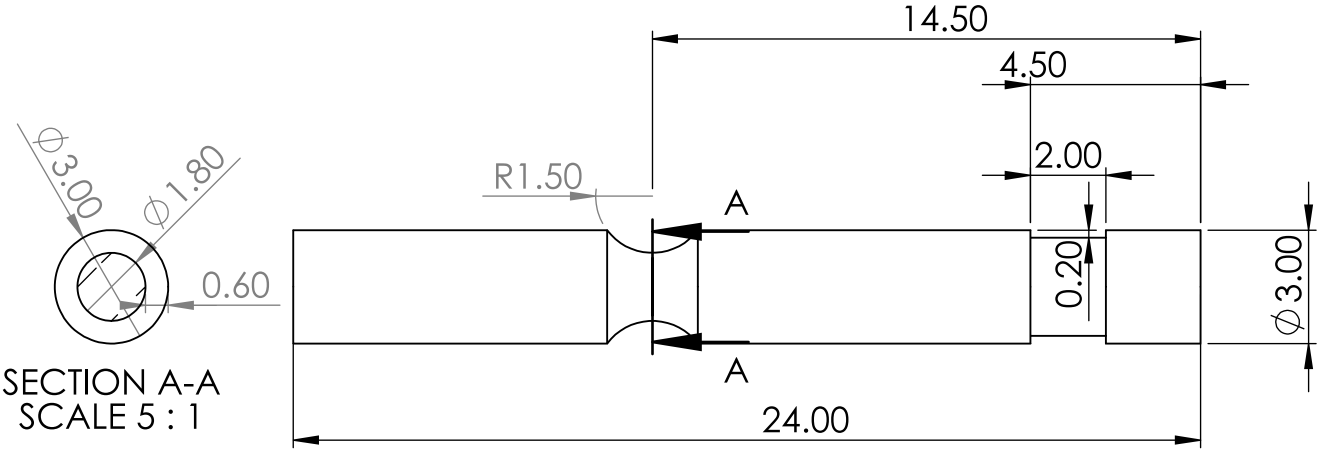
TITLE:

Lever

MATERIAL:

RVS 304

A4



SECTION A-A
SCALE 5 : 1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

NAME	
DRAWN	Daniek Mos

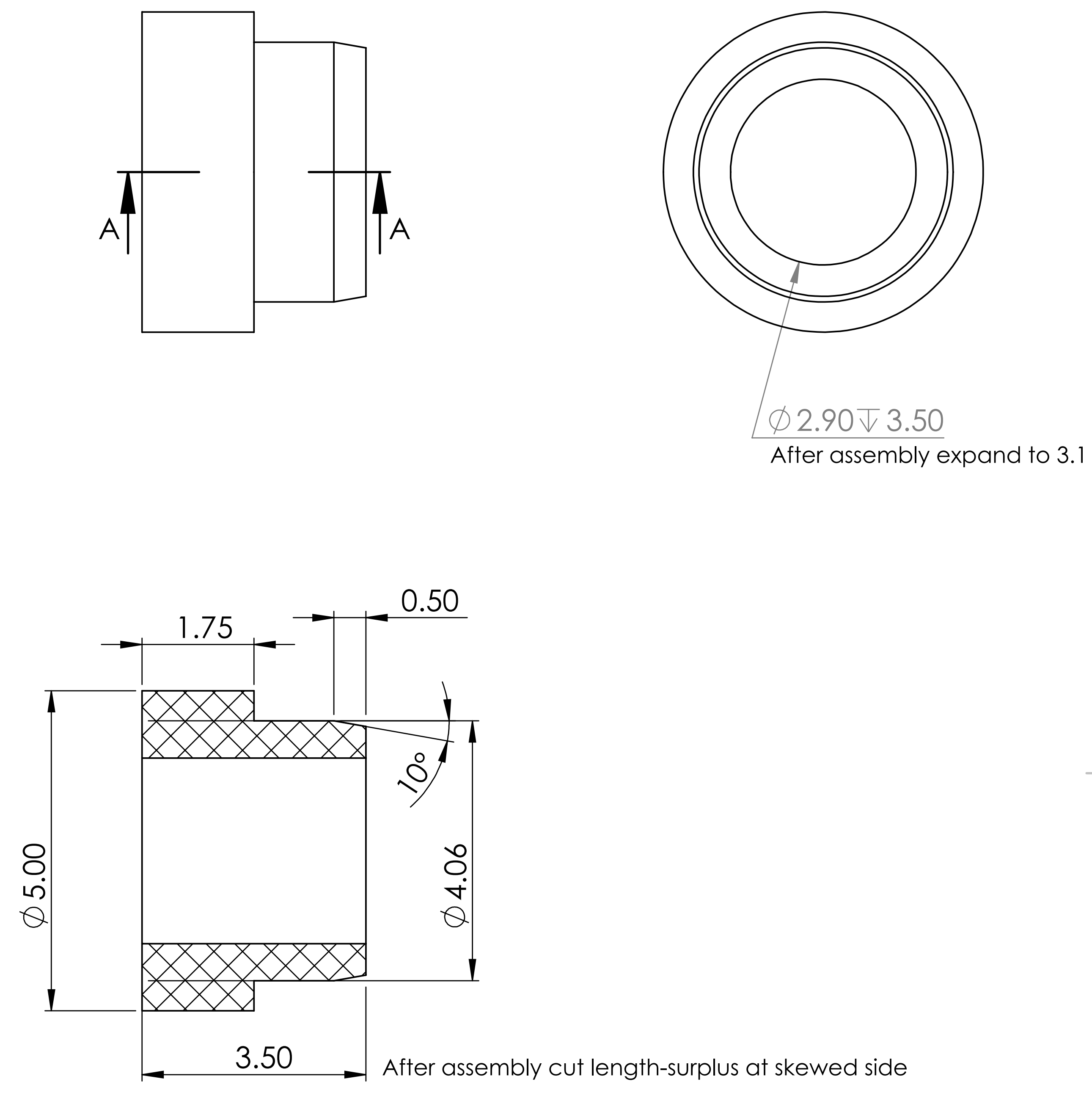
TITLE:

Lever axle

MATERIAL:

RVS 303

A4



SECTION A-A

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

	NAME
DRAWN	Daniek Mos

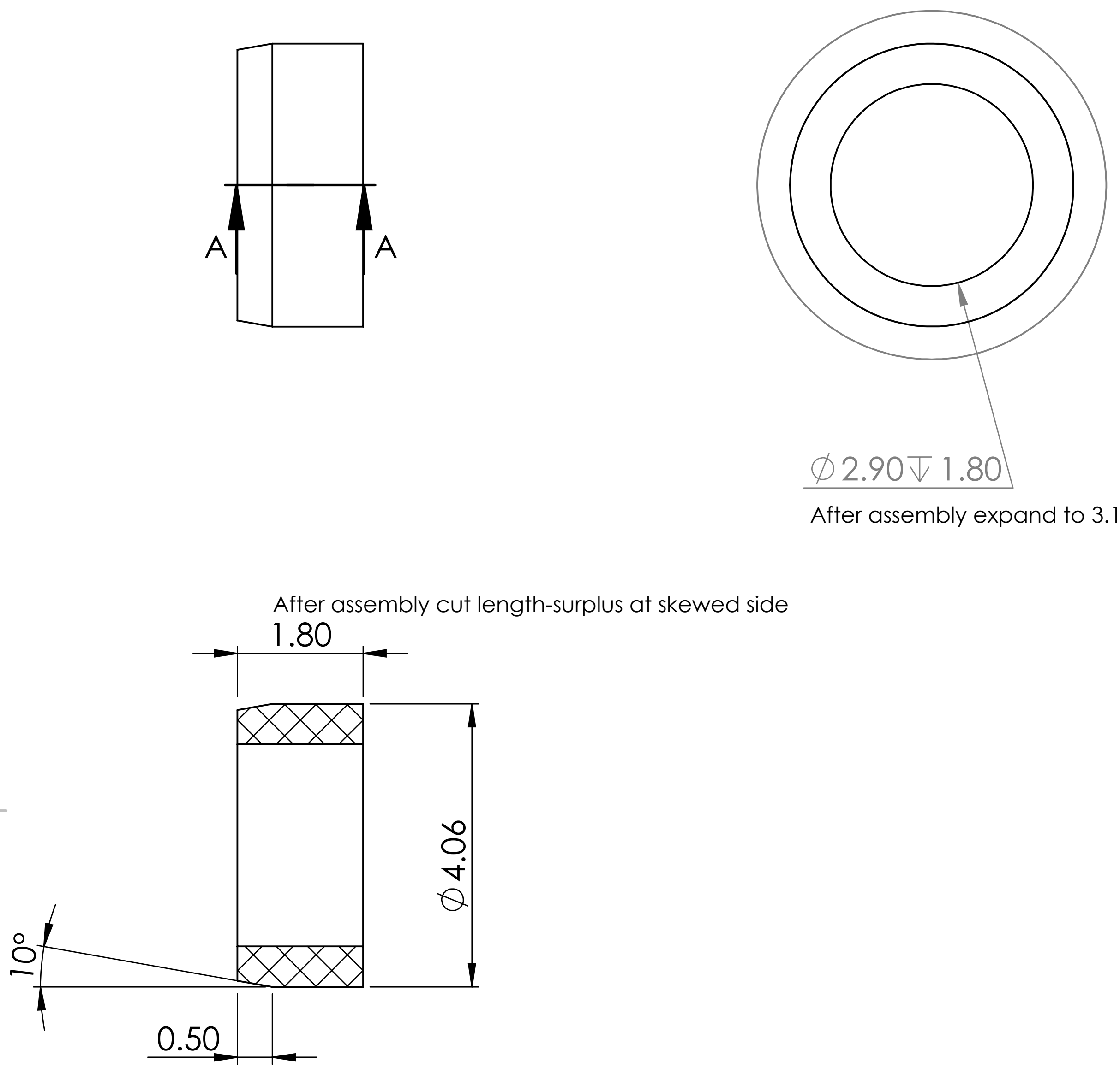
TITLE:

Lever bearing 1

MATERIAL:

PCTFE (Eriflon)

A4



SECTION A-A

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

	NAME
DRAWN	Daniek Mos

TITLE:

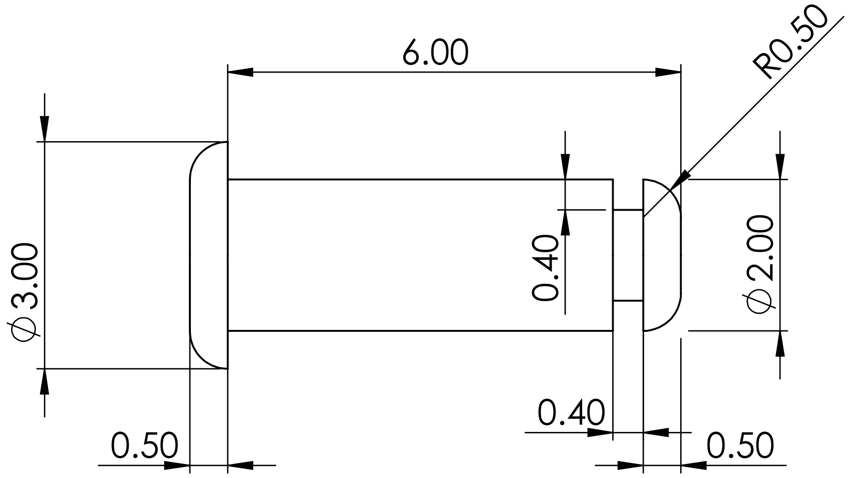
Lever bearing 2

MATERIAL:
PCTFE (Eriflon)

DWG NO.

A4

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

	NAME
DRAWN	Daniek Mos

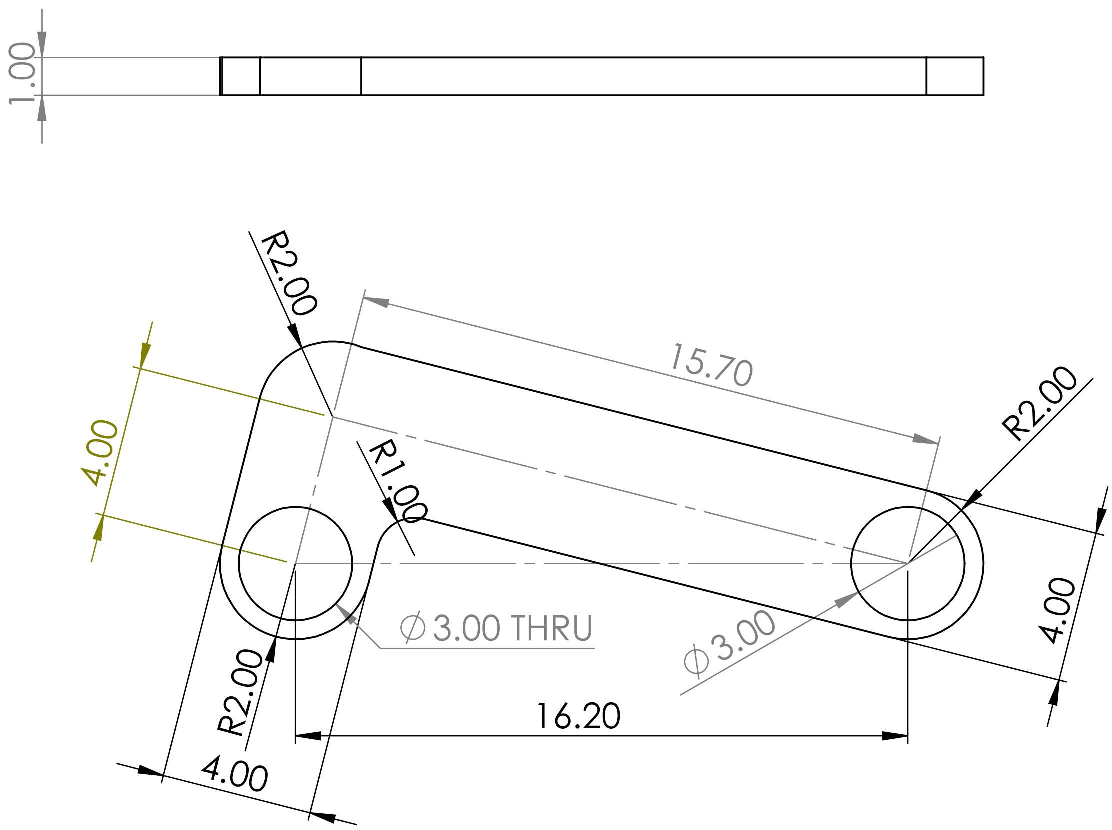
TITLE:

Cable axle

MATERIAL:

RVS 303

A4



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

	NAME
DRAWN	Daniek Mos

TITLE:

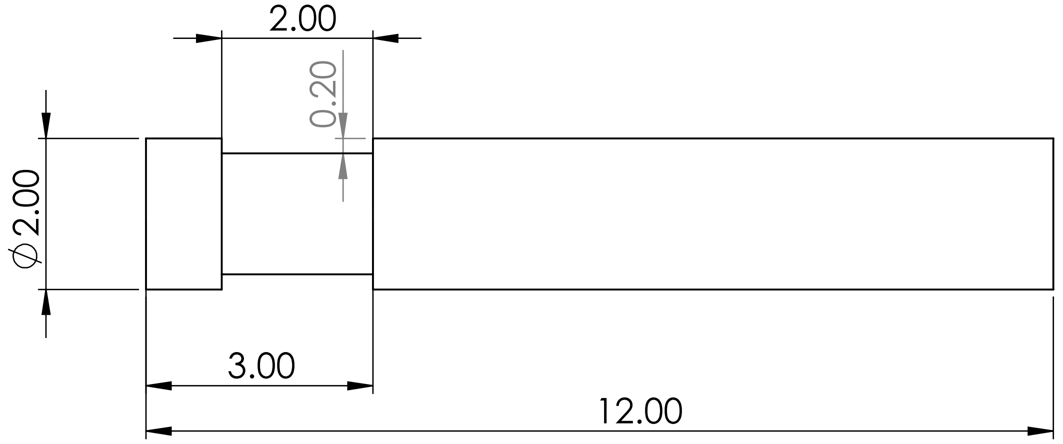
Bar

MATERIAL:

RVS 304

A4

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

	NAME
DRAWN	Daniek Mos

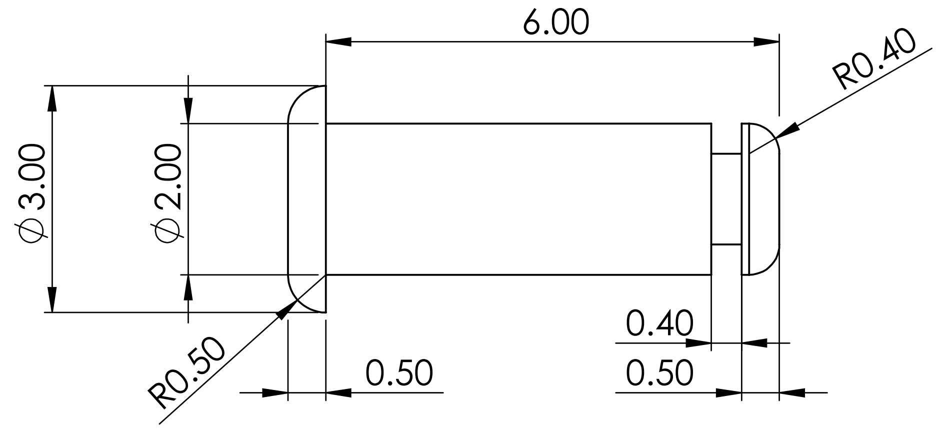
TITLE:

Bar axle 1

MATERIAL:
RVS 303

A4

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

	NAME
DRAWN	Daniek Mos

TITLE:

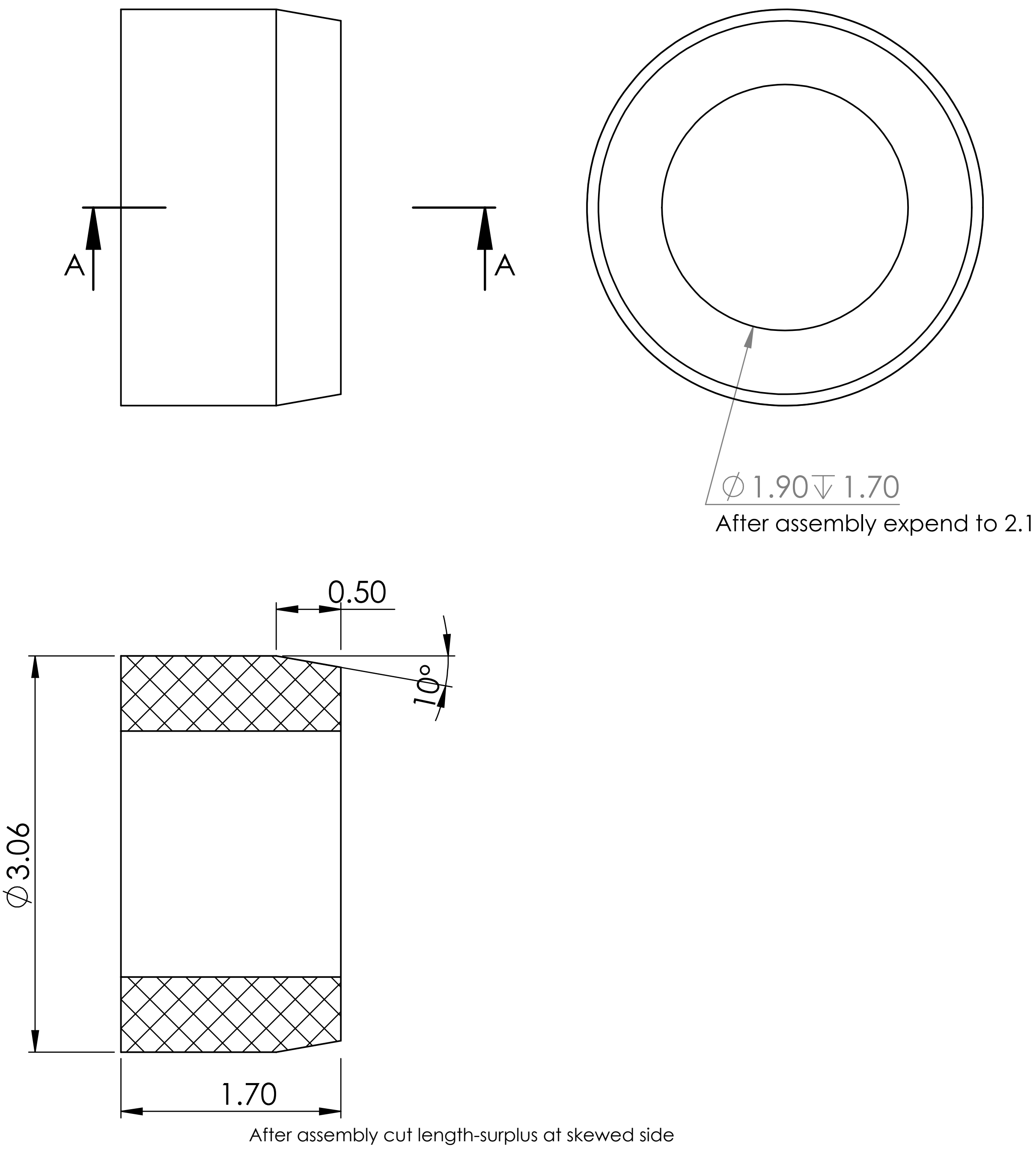
Bar axle 2

MATERIAL:

RVS 303

A4

SHEET 1 OF 1



SECTION A-A

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

	NAME
DRAWN	Daniek Mos

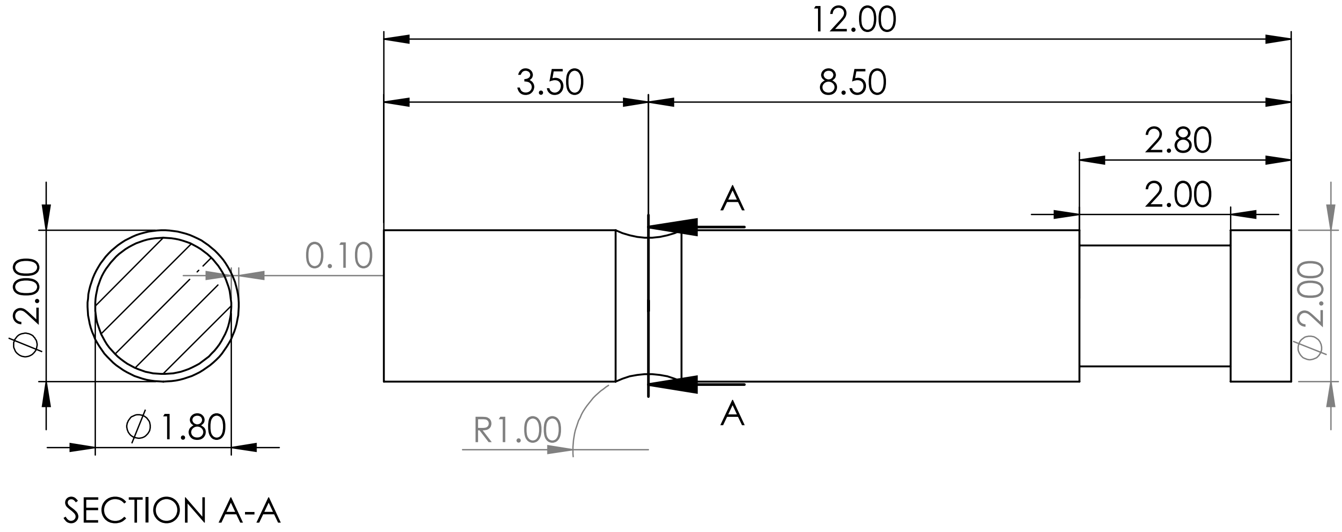
TITLE:

Bar bearing

MATERIAL:
PCTFE (Eriflon)

A4

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

	NAME
DRAWN	Daniek Mos

TITLE:

Spring axle

MATERIAL:
RVS 303

A4

Appendix C: Spring characteristics

The spring that needs to reopen the terminal device needs to have certain characteristics. The distance between the suspension points (the lever axle and spring axle) equals 13.8 mm. In order to keep the terminal device completely opened in its default state, a certain preload in the spring is necessary. This preload is determined by the spring constant and can be varied by prestretching the spring for a certain amount. The necessary preload depends on the present friction in the mechanism. In order to keep the terminal fully opened in the default state, the preload must overcome this friction. Since the VC controlling mechanism counts the same amount of axles as the VO controlling mechanism, the mechanisms will be comparable in terms of friction. Therefore, the present friction is estimated from the VO WILMER appealing prehensor. After removal of the spring of the VO WILMER appealing prehensor, the amount of force necessary at the finger tip to overcome friction was estimated by opening the terminal device against a scale and measuring the necessary mass. The necessary mass appeared to be 15 gr. So, in order to overcome friction, a force of 0.015 N is necessary at the finger tip. The length of the finger equals 70 mm. Assuming the 0.015 N to be perpendicular to the finger tip, friction causes a moment of 10.39 N/mm around the finger axle. The spring axle is placed 4.85 mm horizontally form the finger axle, in order to achieve a sufficient moment arm for the spring force over the full range of motion of the rotary finger. When fully opened, the moment arm of the spring force equals 4.29 mm. Therefore, in order to overcome friction, a preload of 2.40 N is necessary in the spring. When the terminal device is fully closed, the spring will be extended over a total distance of 3.78 mm.

With these factors in mind, the TEVEMA T40700 was chosen for the mechanism. This spring has a spring constant of 1.33 N/mm, an effective work range of 6.34 mm, and a rest length of 8.50 mm. In order to achieve a preload of 2.40 N, the spring is prestretched over 1.80 mm, resulting in a suspension length of 10.30 mm. Since the distance between the suspension points equals 13.8, a small ring with a diameter of 3.5mm is added to the spring to be able to bridge this distance and achieve a preload of 2.40 N. Figure 16 shows the necessary F_{in} over the full range of of motion of the rotary finger. As can be seen, the design requirement *Cable operating force* is still met after inclusion of the spring.

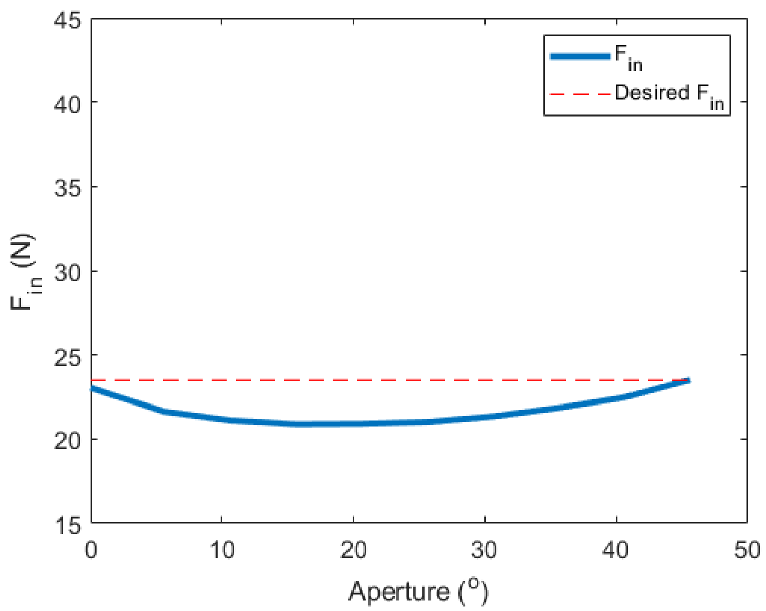
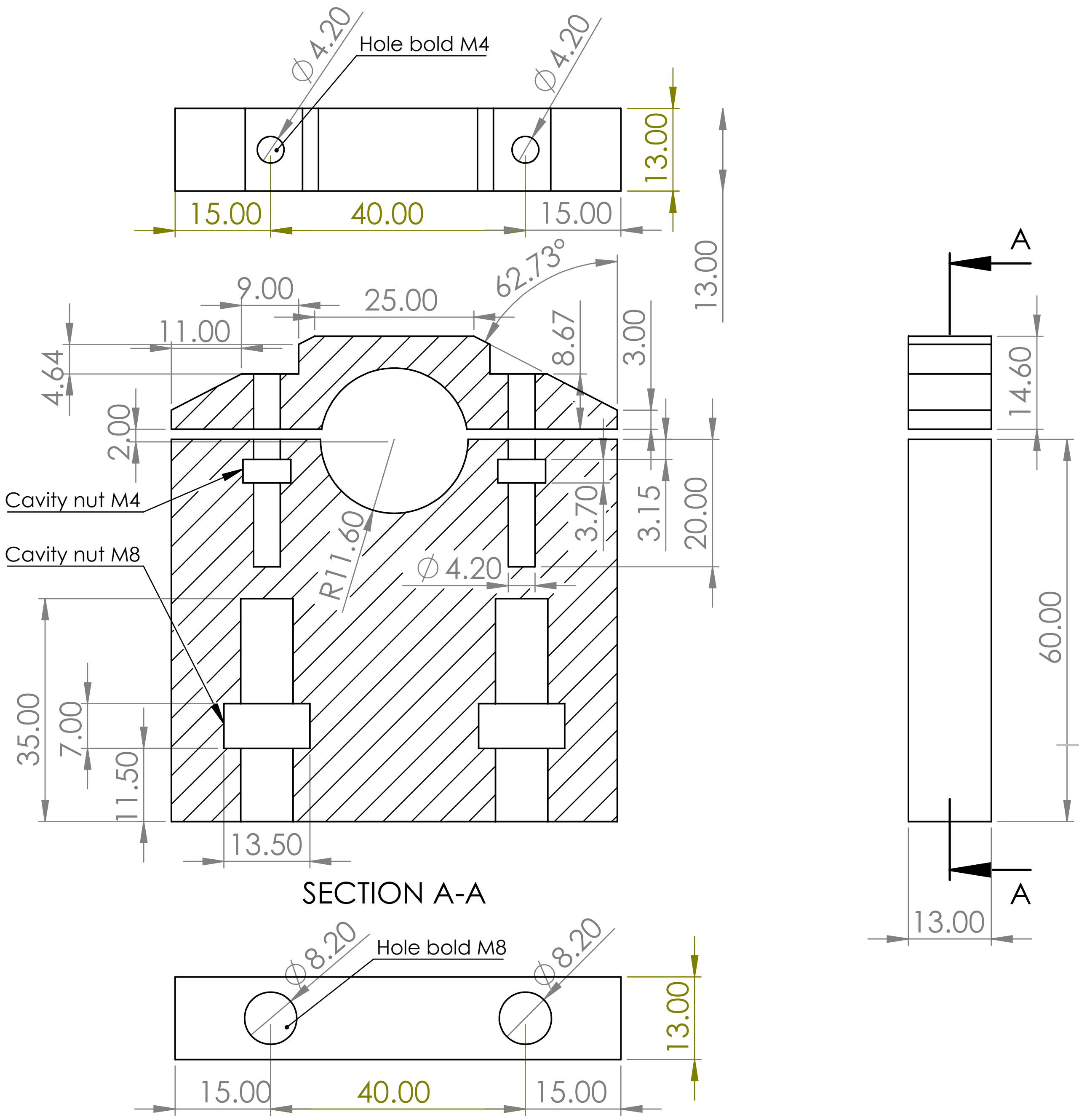


Figure 16: Necessary cable operating force (F_{in}) to generate the desired grip force (F_{grip} = 10 N) over the full range of motion of the rotary finger when the TEVEMA T40700 spring is added to the bar linkage system with lever extension (concept 4).

Appendix D: Technical drawings support pieces



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

FINISH:

	NAME
DRAWN	Daniek Mos

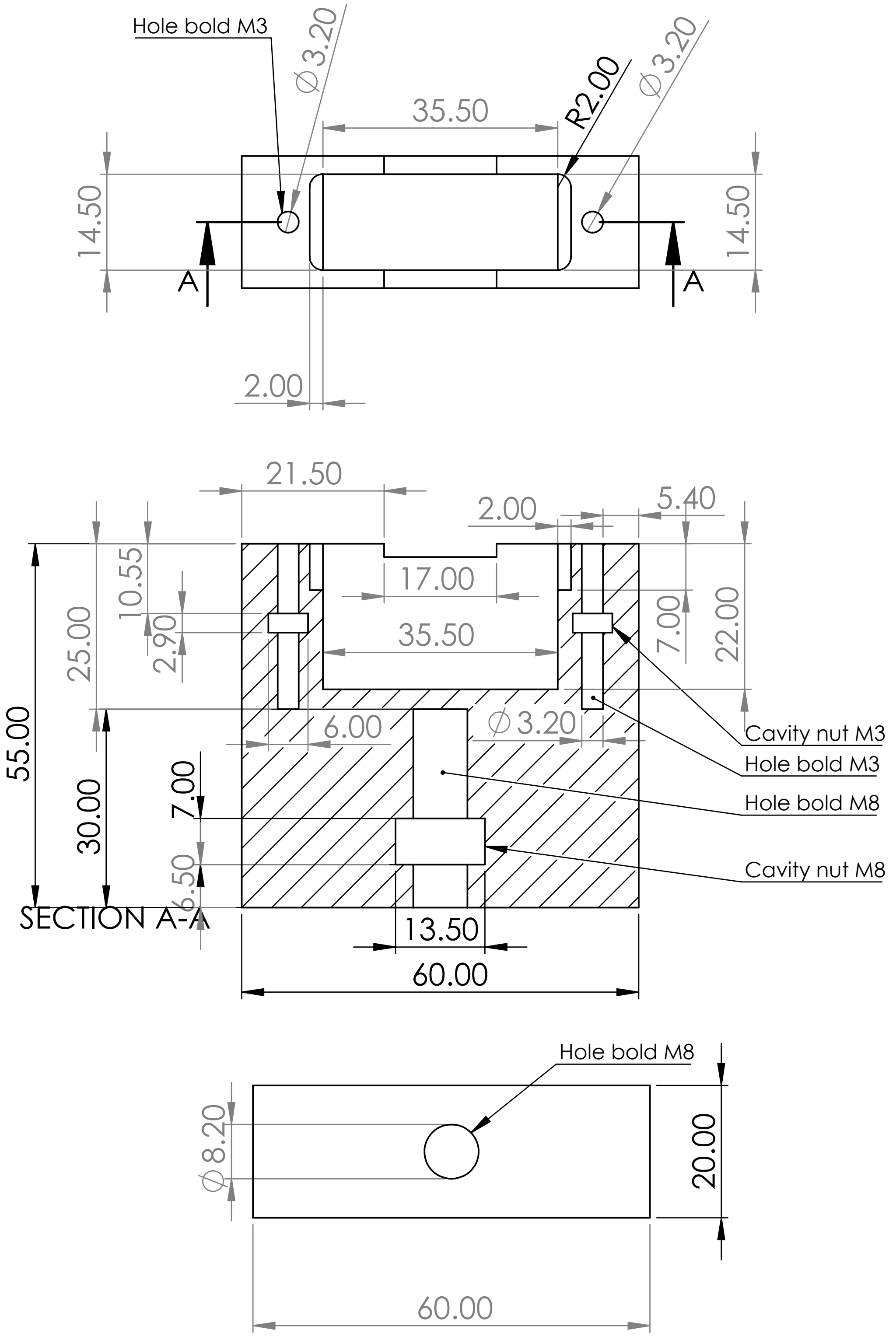
TITLE:

Support WILMER appealing prehensor

MATERIAL:

PLA

A4



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

	NAME
DRAWN	Daniek Mos

MATERIAL: PLA

TITLE: Support Sure-Lok

A4

Appendix E: MATLAB codes: Experimental tests

Amount of cable displacement necessary to fully close the terminal device

```
% Amount of cable displacement necessary to fully close the terminal device
clear all
close all
clc

%% Test 1
test1 = importdata('Displacement_1.txt');

displacement1 = test1.data(:,9); % Cable displacement in mm
displacement1 = displacement1(end); % Terminal device fully closed

%% Test 2
test2 = importdata('Displacement_2.txt');

displacement2 = test2.data(:,9);
displacement2 = displacement2(end);

%% Test 3
test3 = importdata('Displacement_3.txt');

displacement3 = test3.data(:,9);
displacement3 = displacement3(end);

%% Test 4
test4 = importdata('Displacement_4.txt');

displacement4 = test4.data(:,9);
displacement4 = displacement4(end);

%% Average
displacement = mean([displacement1 displacement2 displacement3 displacement4])
std = std([displacement1 displacement2 displacement3 displacement4])
```

Cable operating force needed to generate a grip force of 10 N

```
% Cable  operating  force  needed  to  generate  a  gripforce of 10 N
clear all
close all
clc

% Data cable operating force at opening width of 5deg
% Matlab scripts for other apertures are the same

%% Test 1
test1 = importdata('5deg_1.txt');

time = test1.data(:,1); % Time sample each 100 ms
pinch_force = test1.data(:,11); % Pinch force in N
pull_force = test1.data(:,8); % Cable operating force in N

figure()
plot(time, pinch_force, time, pull_force);
    xlabel ('Time (ms)')
    ylabel ('F (N)')
    legend ('Pinch', 'Cable')
    title ('Test1')

cable_force = [pull_force((end-30):end)]; % Cable operating force during last 3secs (when pinch force = 10N)
cable_force_1 = mean(cable_force) % Mean value cable oprating force when pinch force = 10N
%% Test 2
test2 = importdata('5deg_2.txt');
```

```
time = test2.data(:,1); % Time sample each 100 ms
pinch_force = test2.data(:,11); % Pinch force in N
pull_force = test2.data(:,8); % Cable operating force in N

figure()
plot(time, pinch_force, time, pull_force);
    xlabel ('Time (ms)')
    ylabel ('F (N)')
    legend ('Pinch', 'Cable')
    title ('Test2')

cable_force = [pull_force((end-30):end)];
cable_force_2 = mean(cable_force)

%% Test 3
test3 = importdata('5deg_3.txt');

time = test3.data(:,1); % Time sample each 100 ms
pinch_force = test3.data(:,11); % Pinch force in N
pull_force = test3.data(:,8); % Cable operating force in N

figure()
plot(time, pinch_force, time, pull_force);
    xlabel ('Time (ms)')
    ylabel ('F (N)')
    legend ('Pinch', 'Cable')
    title ('Test3')

cable_force = [pull_force((end-30):end)];
cable_force_3 = mean(cable_force)
%% Test 4
test4 = importdata('10mm_4.txt');

time = test4.data(:,1); % Time sample each 100 ms
pinch_force = test4.data(:,11); % Pinch force in N
pull_force = test4.data(:,8); % Cable operating force in N

figure()
plot(time, pinch_force, time, pull_force);
    xlabel ('Time (ms)')
    ylabel ('F (N)')
    legend ('Pinch', 'Cable')
    title ('Test4')

cable_force = [pull_force((end-30):end)];
cable_force_4 = mean(cable_force)

%% Average
cable_operating_force = mean ([cable_force_1 cable_force_2 cable_force_3 cable_force_4])
std = std ([cable_force_1 cable_force_2 cable_force_3 cable_force_4])
```

Grip force drop induced by the Sure-lok

```
% Efficiency Locking mechanisms 'Sure-Lok'
clear all
close all
clc

%% Test 1
test1 = importdata('Lock10_1.txt');

time1 = test1.data(:,1); % Time sample each 100 ms
pinch_force1 = test1.data(:,11); % Pinch force in N

figure()
plot(time1, pinch_force1);
    xlabel ('Time (ms)')
    ylabel ('F (N)')
    title ('Test1')
```

```
pinch = [pinch_force1((end-30):end)]; % Pinch force during the last three seconds
pinch1 = mean(pinch) % Mean value pinch force after activation Sure-Lok

%% Test 2
test2 = importdata('Lock10_2.txt');

time2 = test2.data(:,1); % Time sample each 100 ms
pinch_force2 = test2.data(:,11); % Pinch force in N

figure()
plot(time2, pinch_force2);
    xlabel ('Time (ms)')
    ylabel ('F (N)')
    title ('Test2')

pinch = [pinch_force2((end-30):end)];% Pinch force during the last three seconds
pinch2 = mean(pinch) % Mean value pinch force after activation Sure-Lok

%% Test 3
test3 = importdata('Lock10_3.txt');

time3 = test3.data(:,1); % Time sample each 100 ms
pinch_force3 = test3.data(:,11); % Pinch force in N

figure()
plot(time3, pinch_force3);
    xlabel ('Time (ms)')
    ylabel ('F (N)')
    title ('Test3')

pinch = [pinch_force3((end-30):end)]; % Pinch force during the last three seconds
pinch3 = mean(pinch) % Mean value pinch force after activation Sure-Lok

%% Test 4
test4 = importdata('Lock10_4.txt');

time4 = test4.data(:,1); % Time sample each 100 ms
pinch_force4 = test4.data(:,11); % Pinch force in N

figure()
plot(time4, pinch_force4);
    xlabel ('Time (ms)')
    ylabel ('F (N)')
    title ('Test4')

pinch = [pinch_force4((end-30):end)]; % Pinch force during the last three seconds
pinch4 = mean(pinch) % Mean value pinch force after activation Sure-Lok

%% Average
drop = 10 - (mean([pinch1 pinch2 pinch3 pinch4])) % Pinch force drop
std = std(10-[pinch1 pinch2 pinch3 pinch4])
```

Hysteresis of one cycle

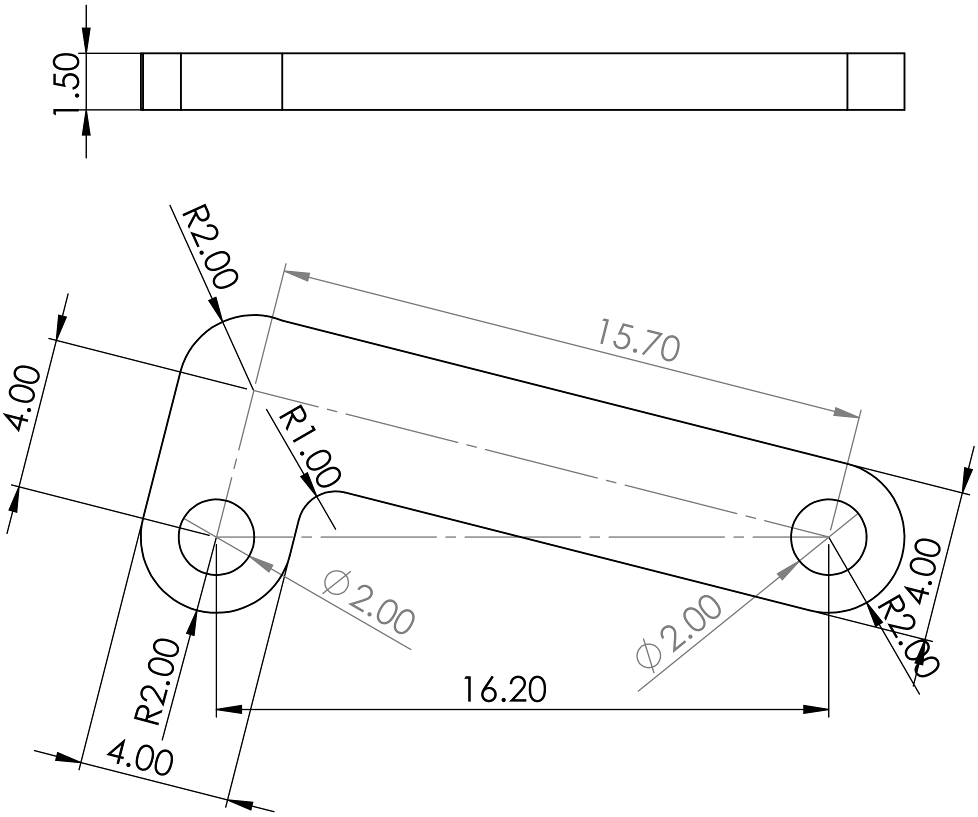
```
% Hysteresis of one cycle
clear all
close all
clc

%% Test 1
test1 = importdata('Hysteresis_1.txt');

pullforce = -test1.data(:,8); % Cable operating force in N
displacement = test1.data(:,9); % Displacement in mm

pull_force = smoothdata(pullforce); % Filter data
[disp, i] = (max(displacement)); % Terminal device fully closed
closing = displacement(1:i); % Cable displacement during closing
opening = (displacement(i+1:end-25)); % Cable displacement during reopening
pull_close = pull_force(1:i); % Cable operating force during closing
```

```
pull_open = (pull_force(i+1:end-25)); % Cable operating force during opening

work_close1 = (trapz(closing, pull_close)); % Amount of work needed for closing
work_open1 = (trapz(flip(opening), flip(pull_open))); % Amount of work returned during reopening
hysteresis1 = work_close1 - work_open1;

figure()
plot(displacement, pullforce);
hold on
plot(displacement, pull_force);
hold off
xlabel ('Displacement (mm)')
ylabel ('F (N)')
axis ([0 30 0 5])
title ('Test 1')
legend ('raw', 'smooth')

figure(2)
subplot(2,2,1)
plot(closing, pull_close);
hold on
plot(opening, pull_open);
xlabel ('Displacement (mm)')
ylabel ('F (N)')
axis ([0 30 0 5])
title ('Test 1')
legend ('closing', 'opening')

%% Test 2
test2 = importdata('Hysteresis_2.txt');

pullforce = -test2.data(:,8); % Cable operating force in N
displacement = test2.data(:,9); %Displacement in mm

pull_force = smoothdata(pullforce);
[disp, i] = (max(displacement));
closing = displacement(1:i);
opening = (displacement(i+1:end-23));
pull_close = pull_force(1:i);
pull_open = (pull_force(i+1:end-23));

work_close2 = (trapz(closing, pull_close));
work_open2 = (trapz(flip(opening), flip(pull_open)));
hysteresis2 = work_close2 - work_open2;

figure()
plot(displacement, pullforce);
hold on
plot(displacement, pull_force);
xlabel ('Displacement (mm)')
ylabel ('F (N)')
axis ([-5 30 0 5])
title ('Test 2')
legend ('raw', 'smooth')

figure(2)
subplot(2,2,2)
plot(closing, pull_close);
hold on
plot(opening, pull_open);
xlabel ('Displacement (mm)')
ylabel ('F (N)')
axis ([0 30 0 5])
title ('Test 2')
legend ('closing', 'opening')

%% Test 3
test3 = importdata('Hysteresis_3.txt');

pullforce = -test3.data(:,8); % cable operating force in N
displacement = test3.data(:,9); %displacement in mm
```

```
pull_force = smoothdata(pullforce);
[disp, i] = (max(displacement));
closing = displacement(1:i);
opening = (displacement(i+1:end-18));
pull_close = pull_force(1:i);
pull_open = (pull_force(i+1:end-18));

work_close3 = (trapz(closing, pull_close));
work_open3 = (trapz(flip(opening), flip(pull_open)));
hysteresis3 = work_close3 - work_open3;

figure()
plot(displacement, pullforce);
hold on
plot(displacement, pull_force);
xlabel ('Displacement (mm)')
ylabel ('F (N)')
axis ([0 30 0 5])
title ('Test 3')
legend ('raw', 'smooth')

figure(2)
subplot(2,2,3)
plot(closing, pull_close);
hold on
plot(opening, pull_open);
xlabel ('Displacement (mm)')
ylabel ('F (N)')
axis ([0 30 0 5])
title ('Test 3')
legend ('closing', 'opening')

%% Test 4
test4 = importdata('Hysteresis_4.txt');

pullforce = -test4.data(:,8); % cable operating force in N
displacement = test4.data(:,9); %displacement in mm

pull_force = smoothdata(pullforce);
[disp, i] = (max(displacement));
closing = displacement(1:i);
opening = (displacement(i+1:end-30));
pull_close = pull_force(1:i);
pull_open = (pull_force(i+1:end-30));

work_close4 = (trapz(closing, pull_close));
work_open4 = (trapz(flip(opening), flip(pull_open)));
hysteresis4 = work_close4 - work_open4;

figure()
plot(displacement, pullforce);
hold on
plot(displacement, pull_force);
xlabel ('Displacement (mm)')
ylabel ('F (N)')
axis ([0 30 0 5])
title ('Test 4')
legend ('raw', 'smooth')

figure(2)
subplot(2,2,4)
plot(closing, pull_close);
hold on
plot(opening, pull_open);
xlabel ('Displacement (mm)')
ylabel ('F (N)')
axis ([0 30 0 5])
title ('Test 4')
legend ('closing', 'opening')

%% Average
hysteresis = mean([hysteresis1 hysteresis2 hysteresis3 hysteresis4])
std_hysteresis = std([hysteresis1 hysteresis2 hysteresis3 hysteresis4])
```

```
work_close = mean([work_close1 work_close2 work_close3 work_close4])
std_work_close = std([work_close1 work_close2 work_close3 work_close4])

work_open = mean([work_open1 work_open2 work_open3 work_open4])
std_work_open = std([work_open1 work_open2 work_open3 work_open4])
```

Appendix F: Technical drawing redesigned bar linkage



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

	NAME
DRAWN	Daniek Mos

TITLE:

Redesign Bar

MATERIAL:
RVS 304

A4

SHEET 1 OF 1

Appendix G: Estimation of frictional forces

An estimation of the frictional forces in the finger axle and lever axle can be made based on the predicted cable operating force, spring force and forces executed on the lever and finger base by the bar linkage. In order to estimate the frictional forces FBD's are made for the situation around the finger axle and lever axle (Figure 17-18). F_{grip} represents grip force which is assumed to be exerted perpendicular to the surface of the rotary finger. F_{in} represents the cable operating force which is assumed to be exerted vertically. F_{spring} represents the force exerted by the spring on the finger base. F_{bar1} and F_{bar2} represent the forces exerted by the bar linkage the finger base and lever respectively, and are always directed along the bar linkage. $F_{rfinger}$ and F_{rlever} represent the reaction forces in the finger axle and lever axle respectively, and will be used as an estimation for the frictional forces. $F_{rfinger}$ is determined as follows:

$$\sum F_{\text{xfinger}} = 0 \tag{31}$$

$$F_{\text{grip}} * cos(\alpha) + F_{\text{spring}} * cos(\beta) + F_{\text{bar1}} * cos(\theta) + F_{\text{rfingerx}} = 0 \tag{32}$$

$$F_{\text{grip}} * cos(\alpha) + F_{\text{spring}} * cos(\beta) + F_{\text{bar1}} * cos(\theta) = F_{\text{rfingerx}} \tag{33}$$

$$F_{\text{grip}} * sin(\alpha) + F_{\text{spring}} * sin(\beta) + F_{\text{bar1}} * sin(\theta) + F_{\text{rfingery}} = 0 \tag{34}$$

$$F_{\text{grip}} * sin(\alpha) + F_{\text{spring}} * cos(\beta) + F_{\text{bar1}} * sin(\theta) = F_{\text{rfingery}} \tag{35}$$

$$F_{\text{rfinger}} = \sqrt{F_{\text{rfingerx}}^2 + F_{\text{rfingery}}^2} \tag{36}$$

Likewise, F_{rlever} is determined as follows:

$$\sum F_{\text{xlever}} = 0 \tag{37}$$

$$F_{\text{in}} * cos(\gamma) + F_{\text{bar2}} * cos(\theta) + F_{\text{rleverx}} = 0 \tag{38}$$

$$F_{\text{in}} * cos(\gamma) + F_{\text{bar2}} * cos(\theta) = F_{\text{rleverx}} \tag{39}$$

$$F_{\text{in}} * sin(\gamma) + F_{\text{bar2}} * sin(\theta) + F_{\text{rlevery}} = 0 \tag{40}$$

$$F_{\text{in}} * sin(\gamma) + F_{\text{bar2}} * sin(\theta) = F_{\text{rlevery}} \tag{41}$$

$$F_{\text{rlever}} = \sqrt{F_{\text{rleverx}}^2 + F_{\text{rlevery}}^2} \tag{42}$$

The angles α, β, θ and γ represent the alignment of the forces. $F_{rfinger}$ and F_{rlever} are calculated for the measured apertures during the experimental tests. Results for $F_{rfinger}$ and F_{rlever} are listed in table 5.

Table 5: Estimated frictional forces in the finger axle and lever axle.

Aperture (°)	**$F_{rfinger}$ (N)**	**F_{rlever} (N)**
5	123.0	93.6
15	119.0	89.6
25	117.0	86.9
35	117.3	85.9
45	120.4	87.1

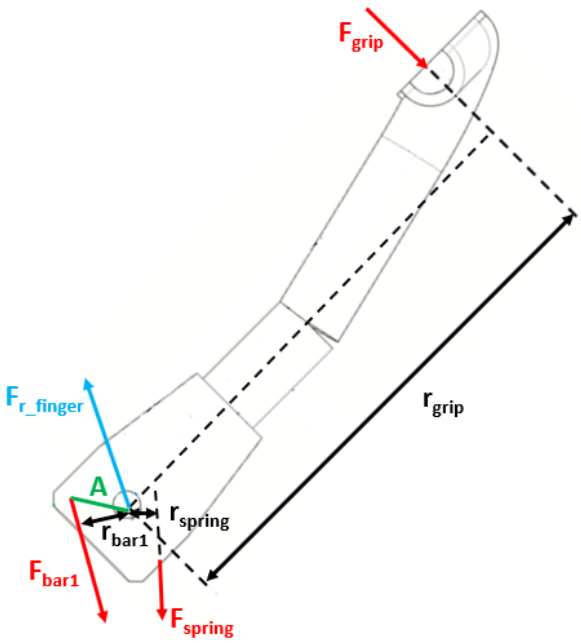


Figure 17: FBD for the finger. F_{grip} represents grip force, F_{spring} represents the force exerted by the spring on the finger base, F_{bar1} represents the force exerted by the bar linkage the finger base, and $F_{rfinger}$ represents the reaction forces in the finger axle.

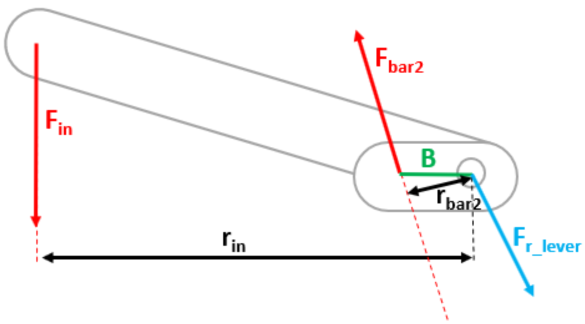


Figure 18: FBD for the lever. F_{in} represents cable operating force, F_{bar2} represents the force exerted by the bar linkage the lever, and F_{rlever} represents the reaction forces in the lever axle.